MATADOR

Contract JOE3-CT97-0081

Final Report of Task 2

Testing methods for vehicles with conventional and alternative drivelines

This MATADOR Task 2 final report is the result of a co-operative research project carried out between January 1998 and June 2000 by the following partners:

- TNO Automotive (the Netherlands), project leader
- ENEA / ERG (Italy)
- Institut für Kraftfahrwesen - IKA (Germany)
- Institute for Automotive Engineering (the Netherlands)
- Automobile Technology Department of HTA Biel-Bienne (Switzerland)

Task 2 was part of the overall MATADOR project, sponsored by the Commission of the European Union (contract nr. JOE3CT970081) and co-ordinated by Novem (the Netherlands).

Part I of this report has been composed by TNO Automotive on the basis of input by the various project partners. It describes the research carried out in Task 2 of MATADOR and summarizes the main results and conclusions. Also contained in part I are so-called Frameworks with outlines for future testing methods, drawn up by IKA and ENEA. Part II of this report contains Subtask Reports, written by individual project partners, who each have conducted research on one or more topics related to the testing of battery-electric, hybrid and fuel cell vehicles.

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Subtask reports

Abbreviations and symbols

2WD	2 Wheel Drive (Dynamometer)
A	Frontal area
a_A	Actual deceleration
AC	Alternating Current
AC-city	Aachen city driving cycle (developed by IKA)
ACEA	Association des Constructeur Européens d'Automobiles
Ah	Ampere-hour. Unit for electrical charge (and even battery capacity)
APU	Auxiliary Power Unit (generally an ICE with generator)
APU op1, APU op2	APU operating point 1 resp. 2
APU1, APU2, APU3	APU control strategy No.1, 2, or 3
AS_I	Asymmetry between battery resistance in charge and in discharge at step current I
AUT.TR.	Automatic Transmission
BAT	Battery
BEV	Battery Electric Vehicle
BS1-Vehicle	Vehicle, with a braking strategy according: Braking Strategy: 1
BS2-Vehicle	Vehicle, with a braking strategy according: Braking Strategy: 2
BSFC	Brake Specific Fuel Consumption
C	Battery capacity. The electrical charge, in Ah, that a battery can deliver under defined discharge conditions
C/5 or C_5	Discharge rate at constant current equal to the battery capacity divided by 5
CARB	Californian Air Resources Board
Cdl	Double Layer Capacitance
CEN	European Committee for Standardisation
CFD	Computational Fluid Dynamics
CHEV	Combined HEV
CH-HEVs	Charge-sustaining Hybrid Electric Vehicles
C_n	Discharge rate at constant current equal to the battery capacity divided by n
CNG	Compressed Natural Gas
CO	Carbion monoxide emission
CO2	Carbon dioxide emission
CORIVAMIA	Italian Research Consortium for low emission vehicles
CorrCoeff	Linear correlation coefficient
Cp	Parallel Capacitance
CRT	Continuously Regenerating Trap
CS	Control Strategy
Cs	Series Capacitance
CVT	Continuously Variable Transmission
C_w	Air drag coefficient
D.O.E.	Department of Energy
DC	Direct Current
DFT	Dependent Full Charge Test
DIFF	Differential gear
DOD	Depth Of Discharge. It is the ratio in percent of the capacity in Ah divided the nominal capacity of a battery
DPT	Dependent Partial Charge Test
DST	Dynamic Stress Test
DUBC	Dutch Urban Bus Cycle
E	Energy
E_B	Braking energy
EC	Energy Consumption
ECE	City Cycle, Urban Part of NEDC
ECE15	Cycle profile for vehicle and even battery testing

E_D	Driving energy
EE	Electrochemical Equivalent (820 Ah/kg per zinc)
EIS	Electrochemical Impedance Spectroscopy
El. Flywheel	Electro mechanical flywheel
ELR	European Load Response test
EM	Electric Motor
E_M	Mechanical braking energy
EM	Electric motor
$E_{M,D}$	E_M, on the **dynamometer**
$E_{M,R}$	E_M, on the **road**
Emf	Electromotive force
EN	European Norm
E_{NRB}	Energy consumption of an electric vehicle with a non-rechargeable battery
EOD	End of Discharge
EOT	Engine Only Test
E_R	Regenerated energy
ESC	Engine Stationary Cycle
ESS	Energy Storage System
ETC	European Transient Cycle
EUCAR	European Car Research Committee
EUDC	Extra Urban Driving Cycle, part of NEDC
EV	Vehicle with (Hybrid) Electric Drive System (including BEVs and HEVs)
EVT	Electric Vehicle Test
E_{zinc}	Energy required for converting the spent zinc in metallic zinc
F_a	Acceleration (or deceleration) force
F_A	Air resistance
FC	Fuel Cell
F_C	Speed (linear) dependent resistance
FCEV	Fuel Cell Electric Vehicle
FCHEV	Fuel Cell Hybrid Electric Vehicle
FiGE	Forschungsinstitut für Gerausche und Erschütterung
f_R	Rolling resistance coefficient
F_R	Rolling resistance
FT	Failure Time
F_T	Total driving forces
FTP	Federal Test Procedure
FW	Flywheel
FWHV	Flywheel Hybrid Vehicle
g	Gravity acceleration ($g=9{,}81308\ m/s^2$)
GE	Generator
genset	Generator set (Auxiliary Power Unit)
GRPE	Group of Reporters on Pollution and Energy
GVW	Gross Vehicle Weight
HC	Hydro carbonate emission
HD	Heavy-Duty (generally vehicles > 3.5 tons)
HEV	Hybrid Electric Vehicle
HSFW	High Speed FlyWheel
HV	Hybrid Vehicle
HWFET	Highway Fuel Economy Test (standard driving cycle in USA)
Hyz. H.	Hyzem Highway driving cycle
Hyz. R.	Hyzem Rural driving cycle
Hyz. U.	Hyzem Urban driving cycle
Hyzem H	Hyzem Highway driving cycle
Hyzem R	Hyzem Rural driving cycle
Hyzem U	Hyzem Urban driving cycle
ICE	Internal Combustion Engine
ICEV	(Conventional) Internal Combustion Engine Vehicle

IEC	International Electrotechnical Commission
IFT	Independent Full Charge Test
IKA	Institut fur Kraftfahrwesen, Aachen
IPT	Independent Partial Charge Test
IR	Internal Resistance (Ohmic resistance different from R_{int})
I_R, I_b	Current during regeneration
ISO	International Standards Organisation
IU	Charge profile composed by a constant current I phase and constant voltage U phase
Jap1015	Japanes 10-15 Mode Hot driving cycle
LCA	Life-Cycle Analysis
LD	Light-Duty (generally vehicles < 3.5 tons)
LPG	Liquefied Petroleum Gas
LSFW	Low Speed FlyWheel
m	Vehicle mass
Macrocycle	Definition of a driving/test cycle including test sequence, standstill and charging phase
MATADOR	Management Tool for the Assessment of Driveline TechnOlogies and Research
MODEM	MODEM driving cycle
MV	Medium Voltage
NC	Number of Cells of which the battery is composed
NEDC	New European Driving Cycle, also known as MVEG-A
n_{EE}	Rotational speed of an electric engine
NiCd	Nickel-Cadmium (Alkaline battery)
NiMH	Nickel Metal Hydride (Alkaline battery)
Ni-Zn	Nickel-Zinc Battery
NO_x	Nitrogen oxide emission
OCV	Battery Open Circuit Voltage
OCV^{ch}	Battery Open Circuit Voltage at the beginning of charge
OCV^{dch}	Battery Open Circuit Voltage at the end of discharge
OICA	Organisation Internationale des Constructeurs d'Automobiles
OVC	Off Vehicle Charge Capable
PEM	Proton Exchange Membrane or Polymer Electrolyte Membrane
PG	Planetary gear
PHEV	Parallel Hybrid Electric Vehicle
PHEVbat	Parallel HEV with battery
PHEVfw	Parallel HEV with flywheel
PM	Permanent Magnet
PNGV	Partnership for a New Generation of Vehicles
PRB	Parallel regenerative braking system
Qext	Extracted electrical charge. Amount of electrical charge delivered or extracted by the battery
R	Ratio: front versus rear axle braking capabilities
RB	Roller Bench
Rct	Charge Transfer Resistance
RD	Recharge Dependent
RED	Reduction gear
RI	Recharge Independent
R_{int}^{ch}	battery internal resistance during charge
R_{int}^{dch}	battery internal resistance during discharge
RME	Rape Methyl Ester
Rp	Parallel Resistance
Rs	Series Resistance
S	generic ‘source term’ CFD equations
SAE	Society of Automotive Engineers
SC03	SC03 Air Conditioning driving cycle
SFUDS	Simplified Federal Urban Driving Schedule
SG	Specific Gravity (of battery electrolyte)
SHEV	Series Hybrid Electric Vehicle

SHEVbat	SHEV with battery and load-follower strategy
SHEVfw	SHEV with flywheel
SOC	State Of Charge (of the electric energy storage device)
ΔSOC	The variation of State of Charge, calculated between the final SOC and the initial SOC. Initial and final refer to the starting and the completion of a test sequence
SOC*	Corrected SOC, defined as the extracted charge referred to the actual available charge (%)
SOH	Battery State Of Health
SOV	State of Voltage
SRB	Sequential regenerative braking system
TC	Technical Committee of the European standard setting body CEN
THS	Toyota Hybrid System
TNO	Netherlands Organisation for Applied Scientific Research
TNO-ADVANCE	TNO Automotive DriVeline Analysis and Concept Evaluation (simulation tool)
TR	Transmission
UDC	Urban Driving Cycle, part of NEDC
UDDS	Urban Dynamometer Driving Schedule, also known as (US)FTP72
ULEV	Ultra Low Emission Vehicle
UN-ECE	United Nations Economic Commission for Europe
UPS	Uninterruptable Power Systems
US06	Supplemental Federal Test Procedure High Load Cycle
USABC	United States Advanced Battery Consortium
v	Vehicle speed
VEH	Vehicle
V_{MAX}	Maximum vehicle speed during climbing
VRLA	Valve Regulated Lead- Acid batteries
WH	Wheels
ZEV	Zero Emission Vehicle
Zn-air	Zinc-air
ρ	Air density
η_c	Charging /regeneration efficiency of zinc-air battery
η_{zinc}	Conversion efficiency to obtain 1 kg of metallic zinc from zinc oxide in a specific plant
Γ (gamma)	Diffusion coefficient

Help - Matador Task 2 Final Report

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How to read this report

The final report of Task 2 of MATADOR consists of two parts, containing the following elements:

Part I:

- Executive Summary
- Introduction
- Conclusions from Subtasks 1 – 14
- Frameworks for test procedures
- Overall conclusions and recommendations

Part II:

- Subtask Reports

Part I is the main Task 2 report. In the "Conclusions from Subtasks 1 – 14" the proposed solutions for the identified test problems are described in a self-contained manner. The "Frameworks for test procedures" can therefore be read and largely understood without knowledge of the detailed results of the research activities performed in the Subtasks. The chapter "Overall conclusions and recommendations" provides conclusions that are relevant to the development of test procedures and the performance of test in general. Recommendations are formulated to assist the EU, vehicle manufacturers and standard setting bodies in determining their strategy towards the definition of adequate test procedures. Also areas where additional research is required are identified.

For technical and detailed insight in the problems studied in Task 2 and for the motivation behind the proposed solutions the reader is referred to the Subtask Reports contained in part II.

Links and search tools

There are several ways to find a specific section of your interest. First of all, Acrobat Reader will show a table of contents to the left of the document. Clicking on one of the chapters or paragraphs listed will directly show the accompanying section.
At the beginning of the document, an extensive Table of Contents is listed as well. This creates a well structured overview for all of the information contained in this final report. In this table you are also able to click on the titles to jump to the accompanying section.

For specific search actions after words or phrases, Acrobat Reader provides several search tools with the software. Use the help of Acrobat Reader to learn about using these tools.

Abbreviations

There is a variety of abbreviations used throughout the text. The Subtask Reports each have their own list of abbreviations and symbols. However, for reasons of user friendliness, an overall list of Abbreviations and symbols has been drawn up, which can easily be accessed from the Table of Contents shown besides the document in Acrobat Reader.

Remarks

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TNO Automotive
Attn. I.J. Riemersma
P.O. Box 6033
2600 JA Delft
The Netherlands

Telephone +31 15 269 67 45
Fax: +31 15 269 68 74
e-mail: Riemersma@wt.tno.nl

Contract JOE3-CT97-0081

MATADOR

MANAGEMENT TOOL for the ASSESSMENT of DRIVELINE TECHNOLOGIES and RESEARCH

Contract JOE3-CT97-0081

Task 2:
Testing methods for vehicles with conventional and alternative drivelines

Final Report – Part I

Research funded in part by THE COMMISSION OF THE EUROPEAN UNION
in the framework of the JOULE III Programme sub-programme

Abstract

In Task 2 of the MATADOR-project[1] measurement methods have been developed for the evaluation of the energy consumption and emissions of vehicles with advanced propulsion systems, such as battery-electric, hybrid-electric and fuel cell vehicles. Based on an inventory of existing and prospective standard test procedures and of technology-specific problems associated with testing electric, hybrid and fuel cell vehicles, a number of topics have been selected for in-depth study. Computer simulations and vehicle tests have been performed to analyse these problems and to evaluate possible solutions. This research has resulted in recommendations for test and evaluation methods for dealing with test problems related to the various electric propulsion systems. Using these recommended test methods in combination with elements from existing (draft) test procedures, frameworks have been developed that sketch the general structure and contents of test procedures for battery-electric, hybrid and fuel cell vehicles. The MATADOR-project has started in January 1998 and has ended June 2000.

[1] Research funded in part by the Commission of the European Union in the framework of the JOULE III Programme, sub-programme Energy Conservation and Utilisation, Contract JOE3-CT97-0081

Contents

Executive Summary

1 Introduction

In the near future a wide range of vehicles with advanced propulsion system will come on the market or will be subjected to real-life testing in large-scale demonstration and implementation projects. Vehicle and driveline testing is of paramount importance for the assessment of technological progress in the field of electric, hybrid and fuel cell propulsion as well as for the evaluation and homologation of advanced vehicles coming on the market. Evaluation and approval testing of these vehicles calls for adequate measurement methods and test procedures to measure energy consumption and emissions. Procedures for type approval of these new types of vehicles are currently under development in Europe, the USA and Japan. Battery-electric vehicles are included in the ECE-directives for homologation testing, but for hybrid and fuel cell vehicles such regulatory test procedures are not yet in effect.

Implementation of homologation procedures is mandatory for a successful market introduction of these new technologies. Development of adequate test procedures, however, is hindered by technology specific test problems associated with the complexity of these new technologies and uncertainty about the types of configurations that will be introduced on the market. The latter aspect is especially important. The exact definition of regulations and test procedures, in combination with the associated legislative emission limits, is critical as this definition in itself influences the relative performance of different technologies subjected to a test procedure. This fact is already known from homologation testing of conventional vehicles. The goal of homologation testing and emission regulations is to lower the environmental impacts of vehicles on the road. However, wrong definitions of the structure of the procedure and the laboratory test conditions may induce sub-optimal technical solutions. Technologies that score well on a laboratory test do not necessarily perform better than their alternatives when used in actual traffic.

Although there are a lot of activities in progress aimed at making homologation test procedures more representative for actual vehicle use, it will take a decade or more before these procedures will be in effect. In the mean time, therefore, besides strict homologation test procedures also laboratory test methods are required that enable realistic comparisons between different propulsion technologies and that produce energy consumption and emission results which are representative for actual use of the vehicles. These two criteria of comparability and representativity are often not met by existing (draft) homologation procedures for electric, hybrid and fuel cell vehicles.

Under Task 2 of the MATADOR-project (Management Tool for the Assessment of Driveline Technologies and Research) research has been carried out, aimed at the development of adequate measurement methods and test procedures for the evaluation of energy consumption and emissions of vehicles with advanced power trains. Task 1 of the MATADOR-project concerned the operation and expansion of the database developed in a previous EU-funded programme [1]. In Task 3 a decision support system (called MATADOR Interactive Guide or MIG) has been developed, that will assist policy makers and fleet managers in making choices for the implementation of vehicles with advanced propulsion technologies in demonstration projects and vehicle fleets.

In comparison with conventional vehicles with internal combustion engines (ICEVs) the testing of electric, hybrid and fuel cell powered vehicles poses measurement problems that are specific for the technologies used. After analysing existing and draft standard test procedures and an inventory of the above-mentioned technology-specific problems, a number of topics have been selected for in-depth study.

Computer simulations and actual vehicle tests have been performed to analyse the selected problems and to evaluate possible solutions. The proposed solutions for different measurement problems have subsequently been combined to formulate consistent frameworks for the definition of adequate test procedures meeting the criteria described above.

Due to their technical complexity especially hybrid-electric vehicles pose a challenge for the definition of measurement methods and test procedures. A crucial characteristic of hybrid vehicles is the fact that the instantaneous fuel consumption and emissions are decoupled from the instantaneous road load. The energy supplied by the battery during an acceleration, for instance, has been generated by the engine and generator some time before the acceleration occurs. In combination with the complex and sometimes discrete nature of the powertrain control strategy this leads to a highly non-linear response of the energy consumption and emissions of hybrid vehicles to changes in the test circumstances, as specified by e.g. the vehicle conditioning (battery state-of-charge, soaking temperature, etc.), the dynamics and length of the driving cycle and the accuracy with which the cycle is followed.

As already stated above, when talking about test methods or test procedures a distinction has to be made between test methods for approval testing and test methods for technology assessment and product evaluations. For approval testing it is essential to find out whether a vehicle meets e.g. emissions standards over a certain driving cycle in a worst case condition with regard to the available drive modes. A parallel hybrid such as the Audi DUO III with a 3-mode switch should be able to meet the European emission limits over the NEDC-cycle in its ICE-only mode. Whether the vehicle would do better in the hybrid mode is of no relevance for the homologation. For a product evaluation, however, the question is what benefits a new technology brings under realistic driving conditions. In that case a test in hybrid mode is essential, preferably over a driving cycle that is representative for the actual vehicle application.

An important point to realise here is that policy evaluation and monitoring of environmental impacts requires energy consumption and emissions factors of vehicles on the road. In absence of sufficient data measured under conditions of actual use, emission factors are usually generated on the basis of the results of homologation tests (either from the type approval procedure or produced by In-Use-Compliance testing). Powertrain and vehicle modelling have to be used to “translate” the homologation test results to emission factors that are more representative for real use of the vehicles. With modern conventional and alternative propulsion technologies, however, this translation becomes more and more difficult. This further motivates the need for more realistic homologation test procedures.

Within Task 2 of the MATADOR-project the main focus has been on developing or selecting vehicle test methods that allow a good comparison of vehicles and that yield results which are representative -or at least meaningful indications- for the energy consumption and emissions under real-life driving conditions. Most of the results of the project, however, are of great value for the development of homologation test procedures. It is our strong belief that in the near future homologation test procedures will have to become more representative for real-life driving in order to make sure that manufacturers apply technologies in their vehicles that do not just make the vehicle meet legislated emission limits under laboratory test conditions, but that have a minimal impact on the environment when the vehicle is in actual use. In the present European situation, with a non-representative modal test cycle for LD-vehicles, the emissions of vehicles with modern engine technology and advanced motor management systems, as measured with the standard homologation procedure, may be up to an order of magnitude lower than those measured over realistic driving cycles, derived from speed-time patterns recorded on the road under average driving conditions.

This executive summary will introduce the reader to the various topics studied in Task 2 of MATADOR and will summarise the main conclusions, illustrated by some eye-opening results from measurements and computer simulations.

2 Measurement problems studied in Task 2

Task 2 of the MATADOR-project has been subdivided into Subtasks, each covering one of the selected research topics or activities in support of the other Subtasks. Table A lists the different Subtasks, their subjects, the institute that acted as Subtask Leader, and the institutes that have participated in the research carried out in each Subtask.

Table A: The structure of Task 2 of MATADOR

Nr.	Subtask subject	Subt. Leader	Participants
2.1	Categorisation of EV configurations	IKA	TNO, ENEA
2.2	Development of simulation tools	IKA, TNO	
2.3	Evaluation of existing (draft) standards	IKA	TNO, ENEA, IAE, HTA
2.4	ΔSOC correction methods for HEVs	TNO	IKA, ENEA
2.5	Determination of SOC or ΔSOC in general	ENEA	TNO, IKA
2.6	Comparing electricity and fuel consumption	TNO	
2.7	FCEV test procedures.	ENEA	TNO, IKA
2.8	Driving cycles for LD vehicles	TNO	IKA, ENEA, IAE, HTA
2.9	Test methods and driving cycles for HD vehicles	TNO	IKA, ENEA
2.10	Dealing with EVs not meeting the demands of test cycles	HTA	ENEA, IAE
2.11	Accuracy and tolerances	IKA	TNO, ENEA, IAE, HTA
2.12	Regenerative braking on 2WD dynamometers	IAE	TNO, HTA
2.13	Non-rechargeable batteries	ENEA	TNO
2.14	Self-discharge and heating energy	ENEA	IKA, HTA

Research activities on these topics have comprised information collection, computer simulations and actual vehicle testing. For each of the identified problems the following steps have been taken:

- assessment of the nature, size and impact of the problem;
- identification and evaluation of possible solutions;
- proposal of adequate measurement methods and other recommendations.

Existing (draft) procedures (references [2]–[7]) have been evaluated with respect to the above listed topics. Below for each Subtask the main findings will be presented.

3 Results from the various Subtasks

Subtask 2.1 Categorisation of propulsion system configurations

A general and theoretical categorisation framework (for conventional, advanced conventional and alternative propulsion systems) is necessary, not for its own sake but as an instrument for the evaluation and visualisation of simplified categorisation schemes to be developed for practical test procedures. As test procedures can be used for different purposes, also categorisation scheme should be tailored to different purposes, being:

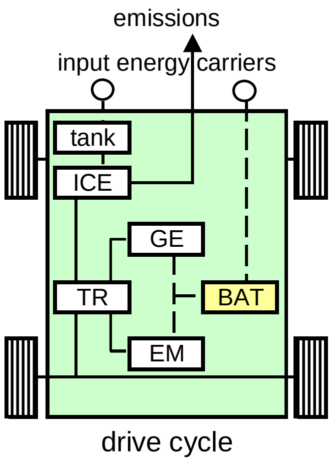
- Classification of vehicles in terms of research and development
- Classification for comparative/technology assessments
- Classification for homologation and associated test procedures

Categorisation schemes can be constructed on the basis of the following aspects:

- Driveline type and structure
- Power and energy storage device
- (driver selectable) Driving modes (hybrid, thermal, pure electric mode, etc.)
- Operating strategy
- Charging strategy
- "Fuel" (Gasoline, Diesel, Natural Gas, Hydrogen, Electricity, …)
- Application areas (e.g. urban vs. highway or different vehicle applications).

How many of these are relevant, as distinguishing parameters will depend on the application for which the categorisation is used.

The inclusion of application areas in the above list becomes evident from e.g. the discussion on test methods for heavy-duty vehicles with alternative powertrains. The conclusion is, in contrast to the current engine-based test procedures, that for these vehicles a vehicle-based test using a transient driving cycle is necessary. The characteristics of such a driving cycle should relate to the vehicle type and its application, requiring a categorisation of application areas and different cycles for each application.



It must be stressed, however, that for most purposes, including homologation testing, a formal and detailed definition of driveline morphologies in terms of series-, parallel and all kinds of combined systems is absolutely irrelevant. The vehicle should be considered as a black box as much as possible, in the sense that one should want to know as little about what is inside the vehicle as is strictly necessary to perform a correct test. Only the interactions with the vehicle's environment should determine the categorisation. These interactions include inputs such as the drive cycle imposed on the vehicle and the type(s) of input energy carrier(s), and outputs such as the emissions produced. Whether or not the vehicle has a battery or other storage device, however, is a relevant characteristic for categorisation as the battery state-of-charge in e.g. a series-hybrid interacts with the consumed energy as measured from the outside (see Subtask 2.4).

In this Subtask various options for vehicle categorisation have been analysed, including the categorisations used in the prEN1986-2 [3] and SAE J1711 [5] procedures. The categorisation proposed by SAE J1711 is considered too complex for homologation purposes, but is applicable for technology assessment. For homologation purposes a categorisation is proposed that strongly resembles the scheme that is used in prEN1986-2.

Subtask 2.2 Development of simulation tools

Many Subtasks have contained computer simulations as part of the work. IKA and TNO both have developed their own advanced computer simulation tools and have gained vast experience with the use of these tools in various projects. It was agreed that coherence of the results of Task 2 could be greatly improved by performing all essential simulations with the aid of a common consistent set of vehicle / driveline models, using the models of TNO and IKA. TNO and IKA have each worked out such a set of vehicle / driveline models within their own simulation tool, and have performed simulations in support of research tasks carried out by the other participants. Based on this experience it can be concluded that computer simulation of advanced vehicles and powertrains is a powerful tool for developing and analysing test methods and procedures for future vehicle technologies.

Subtask 2.3 Evaluation of existing (draft) standards

In this Subtask existing (draft) standards for testing battery-electric and hybrid vehicles (references [2]–[7]) have been analysed. The focus has been in the prEN1986-2 [3] and SAE J1711 [5] procedures for hybrid vehicles. Important differences are e.g. the level of complexity and the driving cycles used.

The tests of the Audi DUO, a parallel hybrid electric vehicle, show that the prEN 1986-2 can be applied without any problems. During the test according to SAE 1711, major problems occur, because this procedure obviously does not cover the typical characteristic of a typical "European" parallel hybrid vehicle where the electric performance is only orientated on urban conditions.

In prEN 1986-2 for charge depleting hybrids, the energy consumption in hybrid mode is measured over a number of cycles, which is equal to the number, which can be driven in pure electric mode, plus one. This has the effect that the number of cycles to be driven depends on the vehicle. For a comparative assessment, this is obviously a not a good solution, a.o. because of varying weights of different driving modes for different vehicles and the underestimation of cold start emissions. For a new test procedure, therefore a fixed cycle should be used also for charge depleting hybrid vehicle.

Subtask 2.4 ΔSOC correction methods for HEVs

For a correct measurement of energy consumption and emissions of charge sustaining HEVs the SOC (state-of-charge) at the end of the test should be the same as at the beginning. If this can not be realised, then the occurring ΔSOC has to be determined and accounted for in a calculation of energy consumption and emissions. Also, the SOC may have to be influenced for conditioning of a HEV prior to testing. Various options for ΔSOC-correction have been identified and have been evaluated. The three main options are:

- Measuring fuel consumption over a given driving cycle by driving a large number of cycles, so that the effect of SOC-variations dampens out. Obviously this method is fundamentally correct. When used in actual tests, however, this method requires driving a large number cycles. In simulations this method has been used to calculate the true asymptotic fuel consumption of vehicles, with which the outcome of other methods can be compared;
- Extension of the test until $\Delta SOC = 0$ is reached. This can be done by continuation of the prescribed driving cycle or by a procedure defined by the manufacturer. The latter could e.g. be charging the battery from the engine-generator while the vehicle is at standstill or driving a prescribed constant speed. This method is used in the draft CEN-procedure for thermal hybrids [3]. The energy consumption and emissions measured during the extension can

either be attributed to the distance driven on the cycle or to the total distance driven during the entire test (cycle + extension);
- A graphical correction method for which fuel consumption and ΔSOC over a given driving cycle need to be measured several times, with different values for the initial state of charge. By plotting fuel consumption against ΔSOC for each cycle driven the fuel consumption at ΔSOC = 0 can be estimated by interpolation or linear regression.

From these three options the graphical correction method is found to be the most promising. It generally requires only a limited number of cycles to be driven, and it does not introduce test circumstances that are not representative for the driving characteristics of the driving cycle used. As an indicator for ΔSOC it generally suffices to integrate the battery current during the cycle, yielding a ΔQ in Ah.

Within the project two variations of the graphical correction method have been identified, which have been named:
- the linear regression method;
- the linear interpolation method.

In the regression method one cycle is driven to condition the vehicle so that the SOC is within the control bandwidth that is typical for the cycle used. Subsequently, cycles are driven until at least one point with positive ΔSOC and one with negative ΔSOC are found. The fuel consumption at ΔSOC = 0 is then calculated by linear regression using all measured points.

In the interpolation method the battery of the vehicle is manipulated so that one test is performed with an initial SOC that is much higher than the average SOC over the cycle and one with an initial SOC that is much lower than the average SOC over the cycle. This manipulation can generally be done by driving the vehicle for some time under an extreme condition that either charges or depletes the battery. These initial SOC-values are generally outside the bandwidth in which the SOC is controlled when the cycle is driven continuously. These two measurements automatically yield one point with a large positive ΔSOC and one with a large negative ΔSOC. The fuel consumption at ΔSOC = 0 is then calculated by linear interpolation between these two points.

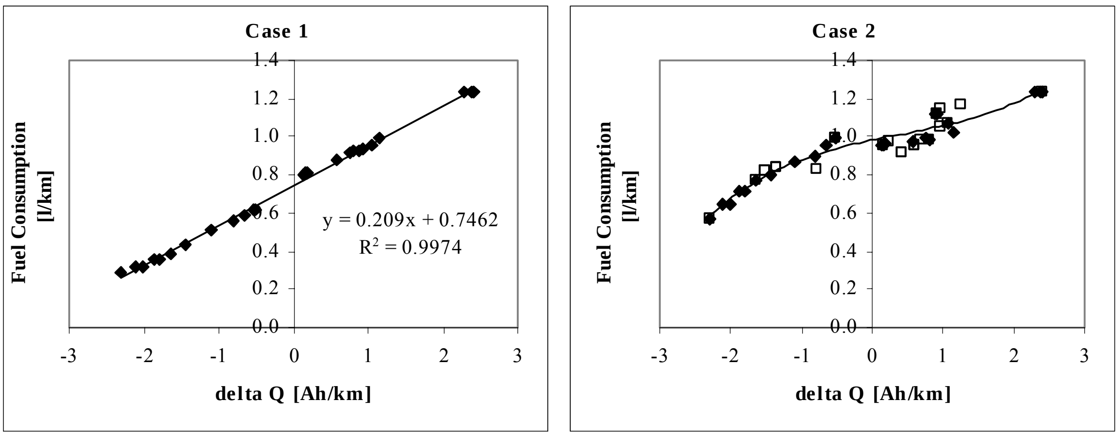


Figure 1: Simulation results of fuel consumption versus ΔSOC over a single drive cycle for a series-hybrid urban bus with an APU operated at two operating points. Case 1: both APU operating points have about the same BSFC. Case 2: APU operating points have BSFCs that are a factor of 2 different. Closed checkers are for separately driven cycles with various values of the pre-set initial SOC. Open squares represent consecutively driven cycles. [data TNO]

Both graphical methods assume that the relation between ΔSOC and fuel consumption is (approximately) linear. From measurements and simulations it is found that this is the case in most realistic circumstances. One of our simulations, however, proved that the relation is not fundamentally linear. This simulation concerned a series-hybrid urban bus with a battery and an engine-generator set with two operating points. A thermostat control strategy with hysteresis governs the engine switch-on/off and the choice between the high power and low power operating point. When the engine efficiency (expressed as BSFC) in the two operating points is extremely different, and a large number of points is simulated, a non-linear trend clearly emerges, as can be seen from Figure 1.

The example shown in Figure 1 is, of course very unrealistic, but it unveils a theoretical characteristic of the relation between fuel consumption and ΔSOC. In all realistic simulations, however, as well as in measurements on various vehicles the graphical ΔSOC correction method is found to work well, in the sense that the derived fuel consumption at ΔSOC = 0 corresponds satisfactorily with the asymptotic value obtained from driving a large number of consecutive cycles. An example is given in Figure 2.

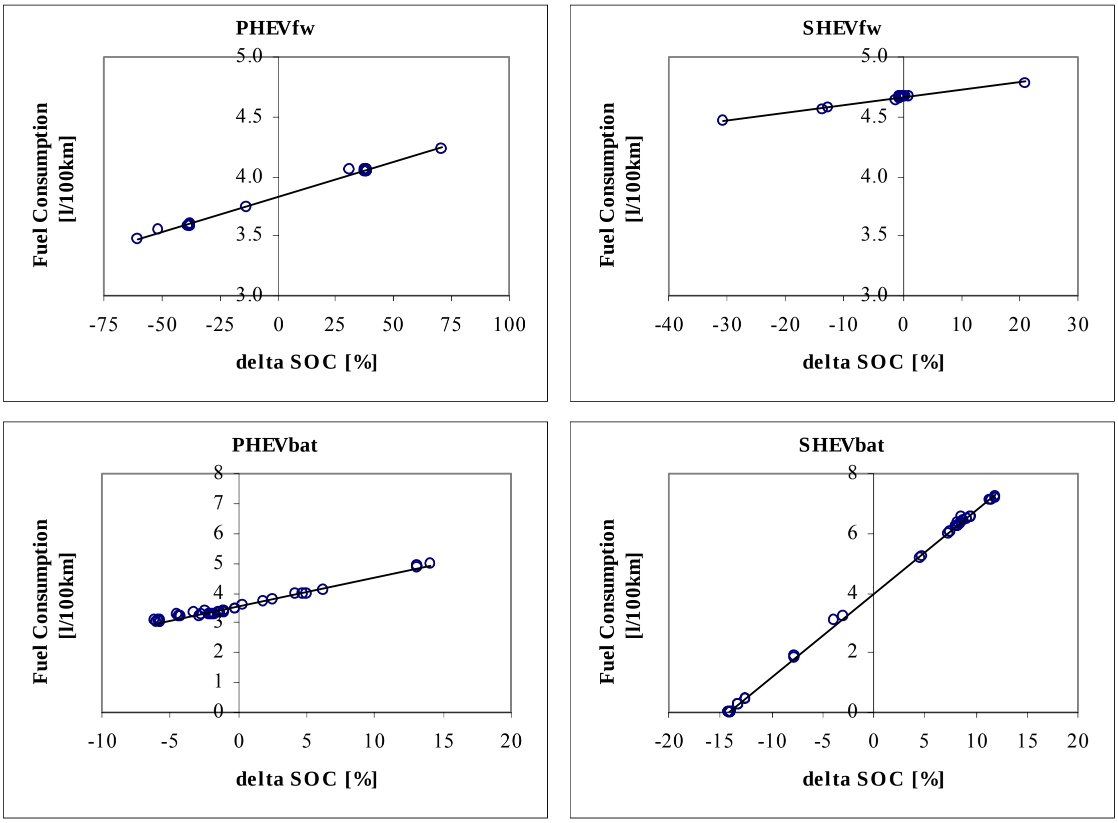


Figure 2: Results from computer simulations showing strong correlation between fuel consumption and ΔSOC for consecutively driven UDDS cycles with different initial SOC. The simulated hybrid passenger cars include a parallel hybrid (PHEVfw) and a series hybrid (SHEVfw) with an electric flywheel (72 kW, 270 Wh), and a parallel hybrid (PHEVbat) and a series hybrid (SHEVbatt) with a battery (72 kW, 11.5 kWh).[data IKA]

One of the vehicles that has been tested is the Toyota Prius (Japanese version). In this vehicle the hybrid powertrain and its control strategy have a large degree of freedom to optimise the power flows in the vehicle to the instantaneous power demand at the wheels. As a result the SOC fluctuates in an exceptionally narrow band when the vehicle is driven over a cycle. This reduces the added value of a graphical ΔSOC correction method in comparison to simply averaging the fuel consumption results of different measurements. For most of the cycles over which the Prius was driven the spread in fuel consumption results was less than 5 % of the absolute value of the fuel consumption.

In the experiments with the Toyota Prius also emissions have been measured. As becomes clear from Figure 3 the graphical ΔSOC correction method does not seem to work very well for emissions due to a larger random spread in measured emission values as a function of ΔSOC. So far we have not been able to come up with an improved method for the ΔSOC correction of emission measurements. For vehicles with larger ΔSOC values, the graphical method may, however, work more satisfactorily.

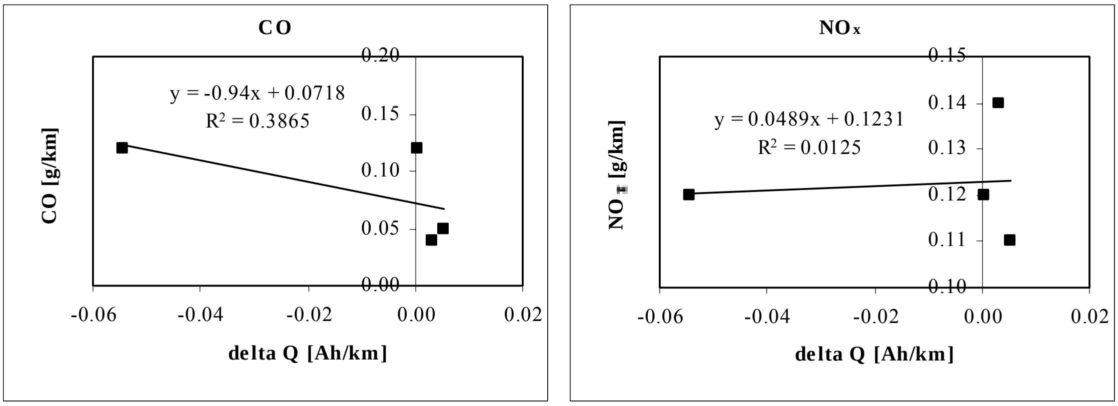


Figure 3: Emissions vs. ΔQ measured on a Toyota Prius with hot engine over four consecutive Hyzem Urban driving cycles. [data TNO]

Subtask 2.5 Determination of SOC or ΔSOC in general

Accurate determination of the SOC is a fundamental problem for all battery types. The solution of this problem is outside the scope of MATADOR. However, within MATADOR it was considered useful to evaluate existing methods for SOC determination, and to evaluate how these methods relate to the issue of testing vehicles with alternative powertrains.

For determining energy consumption of charge sustaining hybrid vehicles it suffices to accurately determine the ΔSOC in combination with the fuel consumed over a cycle. This in principle is possible by Ah-monitoring, as long as the battery is in a reversible regime (e.g. no hydrogen formation, or Coulombic efficiency =1). For vehicles with (relatively) new batteries it may be assumed that the hybrid control system does maintain the battery within this regime. When a battery gets older, however, the effective capacity may decrease dramatically. It is not clear to what extent the battery's SOC-monitor or the hybrid controller are able to deal with this. When vehicles with older batteries are tested, it is therefore recommended that the effective capacity of the battery is measured prior to testing the vehicle. This way it can be assessed whether the battery's SOC stays within the reversible regime. If this is not the case, Ah-measurement can not be considered an accurate indication for the ΔSOC.

There are significant variations of battery behaviour with the operating conditions (temperature, ageing, and discharge current), easily detectable with the monitoring of the internal resistance at low current pulse. In addition to Ah-counting, therefore, internal resistance monitoring is proposed as useful technique for SOC- and ΔSOC-measurement.

Subtask 2.6 Comparing electricity and fuel consumption

For comparing energy and emission performance of vehicles with different propulsion systems fuel consumption and electricity consumption must be brought on a comparable basis. This is also necessary to evaluate the performance of charge depleting hybrids that consume both fuel and electricity. The general approach is to compare primary energy consumption and total (= direct + indirect) emissions, taking into account all energy losses and emissions in the various well-to-wheel energy chains. A cradle-to-grave or life-cycle analysis (LCA) may be added to also include environmental and energy impacts from manufacturing and decommissioning the vehicle.

It is recommended to the EU that a practical common methodology should be formulated for calculating indirect emissions and energy consumption on the basis of final electricity and fuel consumption at vehicle level. It should be possible to apply the method on a European and on a national level. Conversion factors should preferably be based on average efficiencies and average indirect emissions of electricity production and fuel refining in Europe. It seems appropriate to limit the system boundary to the energy input flows to refineries and electricity generation plants in Europe (or in a country if factors are generated on a national level). For fuels and electricity imported from outside Europe average conversion factors may be assessed. The EU should establish a formal body (organisation or network) that collects all data necessary for applying the common methodology, and that generates conversion factors on the EU level for all energy carriers that are currently used on a significantly large scale (gasoline, diesel, LPG, electricity, and maybe a few more). This body should periodically update the conversion factors to account for changes in the energy supply and demand systems. When new energy carriers are introduced to the market this body should adapt the methodology to include the new energy carrier and should perform an assessment to generate conversion factors. Based on these conversion factors appropriate emission legislation and associated test procedures for vehicles with alternative power trains can be defined. Each country should be allowed to define national conversion factors based on the same methodology and data set for use in a national policy context.

Subtask 2.7 FCEV test procedures

Two types of fuel cell electric vehicles can be discerned. In vehicles without an electric energy storage system the output of the fuel cell is directly connected to the input of the electric machine(s) driving the wheels (further called FCEV). Besides this also a hybrid configuration is possible where a battery assists the fuel cell when peak power is required and stores energy during regenerative braking (further called FCHEV). Light duty FCEVs with a reformer running on a carbon-based fuel can be tested according to the same procedures as are applicable to conventional LD vehicles (ICEVs). These procedures can also be applied to vehicles running on hydrogen, provided that a standardised method is defined for measuring the consumption of hydrogen. With similar provisions light duty FCHEVs can be tested using the procedures that are to be defined for hybrid vehicles with a thermal energy source. Heavy-duty fuel cell vehicles should also be tested over a transient driving cycle. For these vehicles see Subtask 2.9. A remaining uncertainty is the possible presence of an intermediate hydrogen or reformate storage tank in vehicles with a fuel processor. If the content of this fuel storage at the end of a test can differ from the content at the beginning of a test, similar problems occur as with the ΔSOC in hybrid vehicles. Obviously a similar solution could be applied. Given the uncertainty about future fuel cell vehicle configurations this problem has not been studied for the moment.

Subtask 2.8 Driving cycles for LD vehicles

An important focus of the research in MATADOR has been driving cycles. The characteristics of a driving cycle (average power, dynamics, etc.) strongly influence energy use and emissions and also influence the results of comparisons between vehicles with different propulsion systems. It has been shown (see e.g. Figure 4)that the fuel consumption of four different hybrid drive train configurations may differ by a factor of 2 over one cycle, while being almost equal over another cycle.

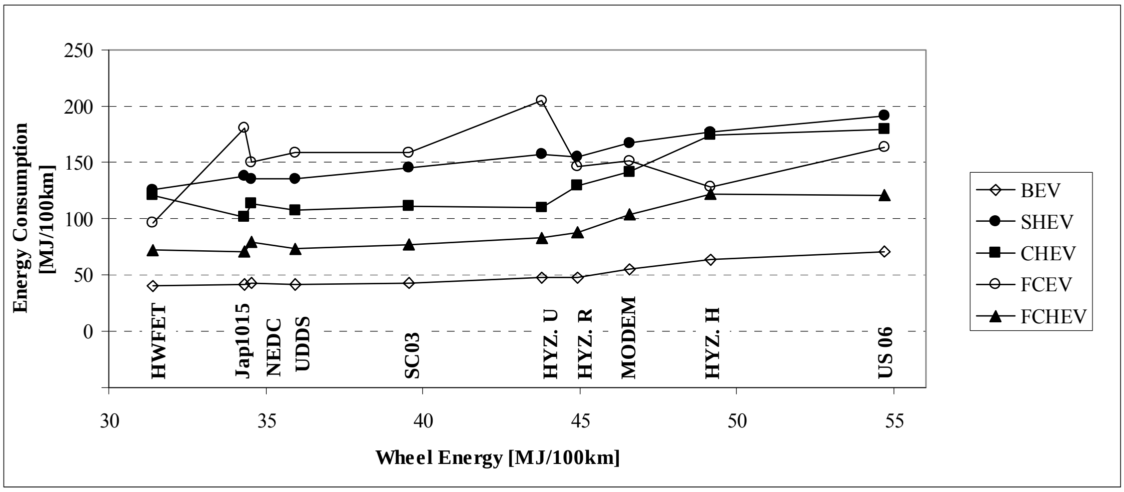


Figure 4: Energy consumption for the LD vehicle models over different driving cycles (ranked for wheel energy demand)

Current standard cycles, especially in Europe and Japan, bear relatively little resemblance to the conditions of actual vehicle use. This is clearly shown in Figure 5 in which different standard cycles (NEDC – SC03) are compared with cycles derived from measurements of representative driving patterns on the road (Modem and Hyzem). RPA stands for relative positive acceleration, which is an indication of the dynamics of the cycle. In general average speed and RPA correlate strongly with energy consumption and emissions [8]. It is clear that especially the modal cycles (NEDC and Japanese 10-15) are much less demanding than the cycles based on real-life driving. Figure 6 presents energy consumption data of two vehicles measured over different cycles.

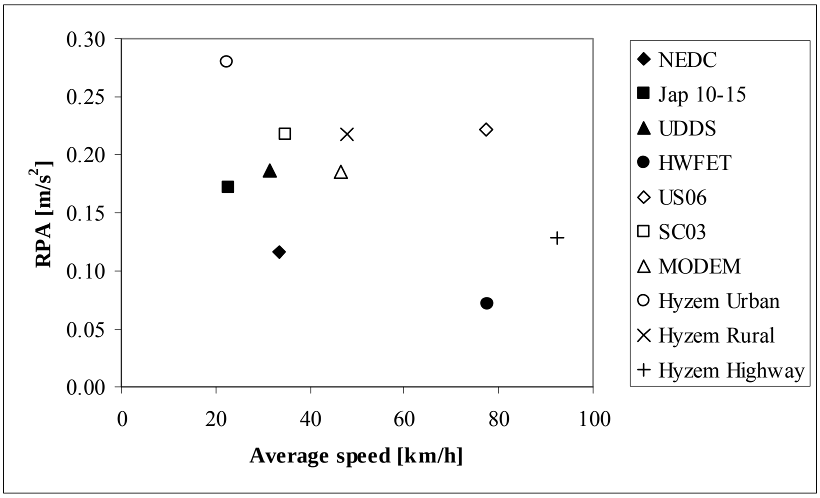


Figure 5: Characterisation of different standard and realistic cycles.

This issue of representativity is also under discussion for testing of ICE-vehicles, as results from standard tests are not only used for technical evaluation and homologation procedures but also for e.g. the calculation of energy consumption and emission factors used in policy studies or for policy measures stimulating clean and efficient vehicles. For vehicles with electric and hybrid power trains the problem is even more pressing as vehicles can be designed and optimised for very specific purposes and will perform differently on different drive cycles.

Selecting a cycle that is representative for actual use not only requires that the cycle has representative average dynamics. It also requires that the cycle has a representative mix of road types (urban, rural and highway) and that the cycle has a representative length. This assures a representative weighting of e.g. the steep acceleration and deceleration associated with the highway part of the cycle, and it may also help to solve problems that are more specific to hybrids and battery-electric vehicles. One of these problems is to assure that the thermal engine does actually switch on during the test and that the energy consumed and the emissions produced with the engine on are weighted in the final results in a representative way.

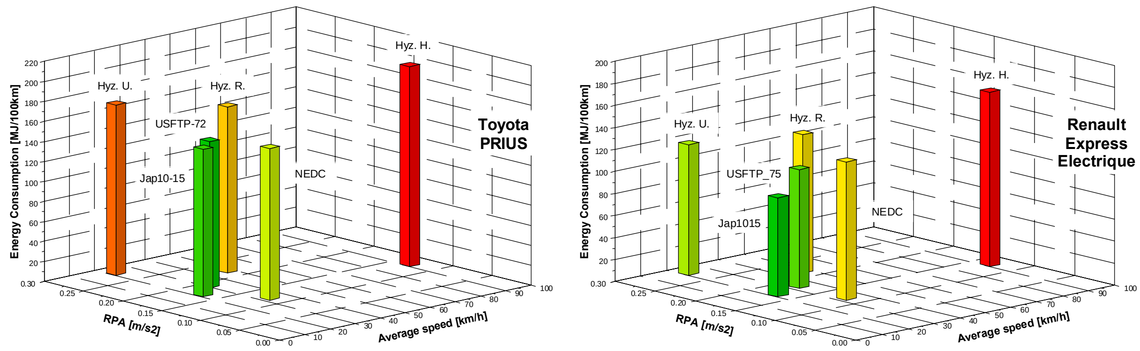


Figure 6: Energy consumption of the Toyota Prius [data TNO] and the Renault Express Electrique [data IAE Arnhem] for 6 different driving cycles as a function of RPA and average speed. Note that the vertical axes are different.

Subtask 2.9 Test methods and driving cycles for HD vehicles

Current standard test methods for heavy-duty vehicles are not applicable to HD BEVs, HEVs and FCEVs. The standard test in Europe for conventional HD vehicles is the 13-mode test, which is a static engine test. A meaningful translation of this engine test procedure to alternative propulsion systems for HD vehicles is not possible. The driveline as a whole (or even better, the vehicle as a whole) needs to be tested on a driving cycle. In order to obtain a meaningful test result, the test conditions need to represent real-life driving conditions. Each HD vehicle category (e.g. heavy truck, urban bus, refuse collection vehicle) that has a distinctive type of use therefore needs its own dedicated driving cycle. The test cycle characteristics will have to be representative for the ‘average use’ within the HD vehicle category. The best way to obtain a representative test result for HD vehicles, is to test the vehicle using a driving cycle on a HD transient rollerbench. However, there are also more pragmatic (and less expensive) ways of testing that can be thought of.

One such pragmatic way of testing HD vehicles with advanced powertrains is formed by measuring the power output of the ICE, APU or fuel cell together with battery current and voltage, during a driving cycle driven on a test track. Using these recorded data the ICE, APU or fuel cell can be tested for energy consumption and emissions in the laboratory. For ICEs the engine is subjected to the recorded load pattern on a transient engine test bed. In case of an APU (engine-generator set) the load is applied electrically, e.g. by using a programmable battery cycling system. Depending on the powertrain configuration it may even suffice to perform a static test on the engine, APU or fuel cell in one or several operating points.

When testing electric and hybrid HD vehicles in this way the same test methods can be used to solve technology specific test problems as is proposed for LD vehicles (see e.g. Subtask 2.4 and 2.12).

Subtask 2.10 Dealing with EVs not meeting the demands of test cycles

Prototype and (pre-)commercial EVs often have limited performance so that they are unable to follow a prescribed driving cycle (speed-time pattern). If deviations from a cycle are allowed, then results of measurements may be incomparable to results obtained on other vehicles, e.g. due to incorrect weighting of high-power parts in the driving cycle. Simulations have shown that for BEVs and series-HEVs the energy consumption over a cycle (i.e. measured consumption divided by measured driven distance) generally increases with increasing "failure time" (= total time that the vehicle is unable to follow the cycle). The following recommendations have been formulated to deal with this issue:

- The test cycle should be split in a low power and a high power part (e.g. urban and extra-urban) so that most vehicles will at least meet the requirements of the low power cycle;
- When a vehicle is unable to meet the prescribed speed profile of the cycle the vehicle should be operated at maximum power ("full throttle") until the vehicle speed coincides again with the prescribed speed;
- Energy consumption and emissions should be measured separately for both cycles, together with the failure time. The failure time should be presented together with test results on energy consumption and emissions for both cycles.

Subtask 2.11 Accuracy and tolerances

Measurement accuracy and reproducibility of new test methods should be comparable to existing methods. Accuracy and reproducibility include the accuracy with which the cycle is followed and the effects of variations (within the allowed bandwidths) in vehicle conditioning or the execution of the test on the vehicle control strategy, the frequency and duration of ICE operation periods for HEVs, and subsequent effects on energy consumption and emissions. For conventional vehicles the allowed tolerances already cause significant variations in the test results. For hybrids, with discrete switching actions (e.g. ICE on or off) in response to external parameters (e.g. road load) or internal parameters (e.g. battery SOC), the effects may be even more dramatic. In various simulations variations between 10 and 20% in energy consumption have been seen in response to variations of test parameters within allowed tolerances. Table B shows the results of measurements performed on the charge depleting parallel-hybrid Audi DUO, operated in the hybrid ("DUO") mode on the NEDC cycle. The difference between a driver that smoothly follows the prescribed speed pattern and one with a more "nervously" fluctuating speed is clearly reflected in the fuel and electricity consumption. Also the initial engine temperature, determined by the temperature during the prescribed soak period (required to be between 20 and 30 ^{o}C), has a significant impact. This is the result from the fact that in DUO mode the Audi-DUO always switches on the engine after start-up. It is switched off again after the normal engine operating temperature is reached, which takes significantly longer with a low initial engine temperature. Significant impacts are also seen for variations of the gear upshift speed. In all the above cases the vehicle is able to follow the prescribed acceleration from 70 to 100 km/h with the ICE switched off. Using a kick-down, however, the engine can be started in this part of the cycle, which dramatically alters the ratio between fuel consumption and electricity consumption.

Table B: Influence of different parameter variations within allowed bandwidths on the energy consumption of the parallel hybrid Audi DUO measured on the NEDC cycle [data IKA].

case	Fuel consumption [l/100km]	charging energy from mains [Wh/km]	electric motor energy [Wh/km]	DC/DC-converter energy [Wh/km]	ICE-generator energy [Wh/km]	charging efficiency [%]
well balanced driver	1.95	263.9	144.4	12.0	6.1	59.3
nervous driver	2.05	260.5	142.4	11.7	6.3	59.2
initial ICE temperature 23 °C	2.09	274.1	141.6	11.5	7.0	55.9
initial ICE temperature 27 °C	1.95	263.9	144.4	12.0	6.1	59.3
upshift speed at 3000 1/min	2.10	257.8	136.8	11.3	6.4	57.4
upshift speed at 2000 1/min	2.24	251.6	134.3	10.8	6.9	57.7
kickdown applied at acceleration from 70 to 100 km/h	3.08	198.7	101.7	10.7	7.4	56.6

Based on the above the following recommendations are made:

- Human drivers should be able to perform the driving cycles as stated in standard procedures. Therefore, the speed tolerances should be maintained. For hybrid vehicles, however, the manufacturer should provide a list of operation procedures. On this list, the driver would be informed at what times/operating points which pedals or pedal positions (e.g. kickdown) should be applied. For conventional vehicles with manual transmission this is already done for the clutch pedal at standstill in the European procedures;
- Also, the shifting points should be defined for hybrid vehicles with manual transmission. The use of the existing points for conventional vehicles seems obvious. Since hybrid vehicles are often designed for many different applications, which may influence the normal use of the transmission, manufacturers may provide a list of shifting points themselves, if it can be shown that the vehicle is not able to follow the speed track within the specified tolerances when driving by the default shifting points;
- In order to keep the influence of ambient temperature as low as possible, the starting temperature of the internal combustion engine should be defined at 25 ± 1°C, measuring the temperature with a thermal sensor at the outside of engine cylinder head. As an alternative, the temperature tolerances of conditioning the soak room could be tightened at this value.
- As a means of minimising the influence of remaining inaccuracies on energy consumption and emissions, the test should be performed several times (e.g. 3 times). The results to be displayed would then be determined by calculating the mean values of the separate tests.

Subtask 2.12 Regenerative braking on 2WD dynamometers

Depending on the vehicle's braking strategy the yield of regenerative braking may be measured too high on two-wheel drive (2WD) dynamometers, as all braking energy is taken up through the driven wheels and none is dissipated by braking the non-driven wheels. For the vehicles analysed in the MATADOR-project the measured energy consumption was found to have no significant error due to the testing on a 2WD dynamometer. Simulations, however, showed that with more sophisticated braking strategies, the error can be of the order of 5 – 10 % on more demanding driving cycles. To deal with this problem three major options exist:

- Ideally the test should be performed on a 4WD chassis dynamometer. This, however, greatly increases the costs of test facilities;
- A numerical correction method could be envisaged that uses parameters recorded during the test on a 2WD dynamometer to estimate the error. Within the project, however, no satisfactory method could be identified;
- A "hardware" correction method is given in the SAE J1634 procedure [4], based on a mechanical interference with the operating system of the 2WD dynamometer during deceleration periods. This method, however, requires uncertain assumptions about the distribution of the braking force over both axles.

Concluding, it can be stated that no completely satisfactory solution has been found so far. On the other hand the size of the problem has also been difficult to assess due to limited availability of state-of-the-art vehicles with sophisticated braking strategies. When more (especially hybrid) vehicles have come to the market additional experimental assessments are necessary to determine whether or not provisions for dealing with this problem have to be incorporated in the test procedures.

Subtask 2.13 Non-rechargeable batteries

Vehicles with e.g. Zn-air batteries can not be charged from the grid, so that electricity consumption can not be measured in the way prescribed by e.g. EN 1986-1 [2]. To compare the energy consumption of these vehicles with other BEVs the efficiency of recycling non-rechargeable batteries needs to be accounted for. The input energy source for this process is generally electricity. This efficiency parameter, however, is process and plant specific. The following procedure is proposed:

- Current and voltage of the battery need to be measured while driving the test cycle. Vehicle conditioning and test sequence can largely follow existing procedures;
- Calculate the spent zinc by the electrochemical equivalent of the discharged capacity;
- The weight of the spent zinc is multiplied by a regeneration conversion factor (kWh/kg) for the recycling plant and divided by the travelled distance;
- The regeneration conversion factor (kWh/kg) for the recycling plant should be provided by the battery manufacturer/recycler and is to be certified by an independent body.

Subtask 2.14 Self-discharge and heating energy of batteries

Batteries with high self-discharge and high-temperature batteries loose energy also during standstill. In the current procedures such losses are not measured separately, but do influence the test results. In general the influence of self-discharge and battery heating will strongly depend on the use of the vehicle (e.g. km/day driven, or standstill during weekends). In order to provide input for an assessment of the impact of battery heating and self-discharge in relation to the vehicle use pattern it is recommended to specify a standstill test in addition to the energy consumption test over a test cycle. For a BEV this procedure starts at 100% SOC. The vehicle, with the power train switched off, should be disconnected from the grid for 48 hours after which period the battery is charged again and the consumed energy is measured.

Existing procedures for BEVs specify rather long maximum allowed time intervals between disconnecting the vehicle from the grid and commencing the energy consumption test as well as between the end of the test and connecting the vehicle to the grid for charging. Especially for high-temperature batteries this can have a significant effect on the measured energy consumption. It is proposed that these allowed time intervals should be shorter and more precisely defined. Similarly the prescribed time for connecting the battery to the grid for charging should be reconsidered. In most cases this period is too long (SAE J1634: 12 hour charge / EN 1986-2: 24 hour charge) so that energy consumption for battery heating may dominate the measured charging energy. This has been verified experimentally for vehicles with Zebra-batteries.

4 Frameworks for test procedures

The results of the research tasks described above can be viewed as building blocks for composing test procedures for vehicles with advanced propulsion systems. As a deliverable of this project frameworks have been drawn up for the synthesis of complete tests methods and procedures for testing of vehicles with battery electric, hybrid electric and fuel cell electric propulsion systems. In these frameworks solutions for the different measurement problems have been combined and tailored to the various vehicle and propulsion system types.

It must be emphasised that it has not been the goal of Task 2 or MATADOR to develop complete procedures in detail. This is the work of standard setting bodies. The frameworks developed here basically place the test methods proposed in the research tasks in a consistent context, and sketch the general structure and contents of test procedures for battery-electric, hybrid and fuel cell vehicles.

Initially a division of frameworks for LD and HD vehicles was foreseen, as the test procedures for these vehicle categories are generally different. A general conclusion of the research, however, is that for HD vehicles with battery-electric, hybrid and fuel cell propulsion systems a test on the vehicle level is required on the basis of a transient driving cycle. Such procedures would have largely the same structure as procedures for LD vehicles. Therefore in the reports on this Subtask the frameworks for LD and HD vehicles have been integrated.

In this report the following frameworks are described:

- Test method framework for BEVs
- Test method framework for HEVs
- Test method framework for FCEVs

Frameworks cover all different aspects that have to be included in test procedures, such as vehicle categorisation, test preparation and vehicle preconditioning, specification of various measurements and the processing and reporting of test results. Flow charts have been drawn to visualise the structure of the frameworks, the connection between the different elements, and the decisions to be taken at different point is the process.

5 General conclusions and recommendations

With hybrid vehicles coming on the market in Europe in the year 2000, it is of paramount importance that standardised test and homologation procedures are developed and implemented as soon as possible. EU emission legislation and related directives for vehicle homologation need to be revised to include hybrid vehicles. In view of the announced introduction of fuel cell vehicles around 2003 or 2004 it is necessary to include fuel cell vehicles at the same time.

Development of adequate test procedures is hindered by technology specific test problems associated with the complexity of these new technologies and uncertainty about the types of configurations that will be introduced on the market. The work of standard setting bodies and the EU legislators therefore needs to be supported by technical research of the type that has been performed in Task 2 of MATADOR.

Based upon the insights gained in MATADOR several choices and definitions made in the procedures for hybrid vehicles proposed by CEN TC301/WG could have been made differently. Also for battery electric vehicles MATADOR has produced results and insights that would motivate a revision of the already adopted procedure (EN 1986-1). It is recommended that the CEN organises an evaluation of its electric and hybrid vehicle procedures within 3 to 5 years from now. Based on the results of research in MATADOR and other projects, knowledge of new technologies coming to the market and experience with the use of the present procedures, proposals can be formulated for improvements of the present procedures.

The results of Task 2 of MATADOR, together with the knowledge already reflected in the CEN and SAE procedures, provide a thorough –albeit not yet complete– basis for dealing with measurements of the energy consumption of battery-electric, hybrid and fuel cell vehicles in an appropriate way. The applicability of various procedures and test methods to the measurement of the exhaust emissions of hybrid and fuel cell vehicles, however, remains questionable. More theoretical and experimental research is necessary to provide a solid basis for the definition of test procedures for emission measurements.

In view of the above it is recommended that the EU sets up a project with active participation of the European automotive industry, standard setting bodies and relevant legislative bodies and advisory groups to systematically co-ordinate the process of establishing standardised test procedures for battery-electric, hybrid and fuel cell vehicles. Research services in this project should be provided by independent research organisations and advanced vehicle test laboratories.

The availability of objective, complete and reliable data on the energy consumption and emissions of hybrid and fuel cell vehicles is extremely limited. As such data are essential for developing R&D and implementation policies, it is recommended that the EU establishes a network of independent vehicle test laboratories in Europe to perform objective evaluations of vehicles with advanced propulsion systems and of components for these vehicles. In analogy to the PNGV programme this network could also be used to evaluate vehicles and components developed by EU-sponsored or financed R&D projects.

In the near future homologation test procedures will have to become more representative for real-life driving. This is not only relevant to governments but is also in the interest of the automotive manufacturers. Their main concern is to develop vehicles that meet the expectations of customers. Design criteria and development targets can only be formulated in a consistent way when the performance demands of homologation procedures and emission legislation are in correspondence with the performance demands set by customer expectations and the actual applications for which vehicles are designed.

Although there are a lot of activities in progress aimed at making homologation test procedures more representative for actual vehicle use, it will take a decade or more before these procedures are in effect. Still, by virtue of their purpose, homologation test procedures will always be more general than test procedures required for the detailed evaluation of vehicles in specific applications (technology assessment or evaluation). Therefore, also for the purpose of product evaluations and technology assessment the development of more or less standardised laboratory test methods is required. These would:

- make the results of different R&D projects more understandable and comparable;
- enable a realistic comparisons between different propulsion technologies;
- produce energy consumption and emission results which are representative for actual use of the vehicles.

Concluding it can be stated that Task 2 of MATADOR has produced in-depth insights into the technology-specific measurement problems associated with testing battery-electric, hybrid and fuel cell vehicles. The participants in Task 2 hope that these results will make a positive contribution to the development by the EU and standard setting bodies of adequate test procedures for these new vehicles, as well as to the successful development and implementation of these vehicles by the automotive industry.

Introduction

This report presents the final results of Task 2 of the MATADOR-project. In this Task research has been carried out to solve technology specific problems associated with measurement of the energy consumption and emissions of battery-electric, hybrid-electric and fuel cell vehicles.

1 The MATADOR project

The main objective of the MATADOR-project (Management Tool for the Assessment of Driveline Technologies and Research) has been to develop tools that will enable fleet managers and operators of test and demonstration fleets to assess and compare the technical aspects and implications of vehicles with conventional and alternative drivelines. To this end the MATADOR-project has consisted of three Tasks:

Task 1: Extension, expansion and operation of a database

This Task builds on work done in the Programme for Collaboration between CEU and National Programmes on Electric Vehicles in Europe, a project which was carried out between 1995 and 1997 by 28 institutes involved in field tests and demonstration projects with electric vehicles. The database developed in that programme has been extended and adapted to meet the needs of research and developments in the MATADOR-project. Task 1 has been co-ordinated by ECN Policy Studies (contact person: Ans van den Bosch, ECN Policy Studies, P.O. Box 1, 1755 ZG Petten, the Netherlands).

Task 2: Testing methods for vehicles with conventional and alternative drivelines

Assessment of the possible benefits of new driveline technologies requires laboratory testing. In Task 2 of the MATADOR-project research has been carried out to support the development of adequate test procedures for the evaluation of energy consumption and emissions of vehicles with advanced power trains, such as battery-electric, hybrid-electric and fuel cell vehicles. Various technology specific problems have been studied and solutions for measurement and evaluation methods are proposed. Task 2 has been co-ordinated by TNO Automotive (contact person: Richard Smokers, TNO Automotive, P.O. Box 6033, 2600 JA Delft, the Netherlands).

Task 3: Development of a decision support system

Partly based on the work in the other Tasks, Tasks 3 has set out to develop a decision support tool (called MATADOR Interactive Guide or MIG) that will assist policy makers and fleet managers in making choices for the implementation of vehicles with advanced propulsion technologies in demonstration projects and vehicle fleets. Based on the results of a survey among potential users an interactive guidebook has been developed which guides users through various steps of the decision process of selecting, purchasing and employing alternatively powered vehicles. Task 3 has been co-ordinated by JRC ISIS (contact person: Donald Bain, JRC ISIS, T.P. 650, 21020 Ispra (VA), Italy).

The MATADOR-project has started at the beginning of 1998 and has ended in July 2000. The MATADOR-project as a whole has been co-ordinated by Novem, the Netherlands (contact person: Remco Hoogma, Novem, P.O. Box 8242, 3503 RE Utrecht, the Netherlands). MATADOR has been partly sponsored by the Commission of the European Union in the framework of the JOULE III Programme (contract nr. JOE3-CT97-0081)

This report presents the results of Task 2 of MATADOR. Separate reports of Task 1 and Task 3 are available from the Task Co-ordinators.

2 Motivation for Task 2 of MATADOR

In the near future a wide range of vehicles with advanced propulsion system will come on the market or will be subjected to real-life testing in large-scale demonstration and implementation projects. Vehicle and driveline testing is of paramount importance for the assessment of technological progress in the field of electric, hybrid and fuel cell propulsion in general as well as for the evaluation and homologation of advanced vehicles coming on the market. Evaluation and approval testing of these vehicles calls for adequate measurement methods and test procedures to measure energy consumption and emissions. Procedures for type approval of these new types of vehicles are currently under development in Europe, the USA and Japan. Battery-electric vehicles are included in the ECE-directives for homologation testing, but for hybrid and fuel cell vehicles such regulatory test procedures are not yet in effect.

Implementation of appropriate homologation procedures is mandatory for a successful market introduction of these new technologies. Without type approval vehicles can not be marketed and sold in large volumes. Also, type approval gives customers the guarantee that vehicles meet all legally required safety, environmental and durability standards. Development of adequate test procedures, however, is hindered by technology specific test problems associated with the complexity of these new technologies and uncertainty about the types of configurations that will be introduced on the market. The latter aspect is especially important. The exact definition of regulations and test procedures, in combination with the associated legislative emission limits, is critical as this definition in itself influences the relative performance of different technologies subjected to the test procedures. This fact is already known from homologation testing of conventional vehicles. The goal of homologation testing and emission regulations is to lower the environmental impacts of vehicles on the road. However, wrong definitions of the structure of the procedure and the laboratory test conditions may induce sub-optimal technical solutions. Technologies that score well on a laboratory test do not necessary perform better than their alternatives when used in actual traffic.

Although there are a lot of activities in progress aimed at making homologation test procedures more representative for actual vehicle use, it will take a decade or more before these procedures are in effect. In the mean time, therefore, besides strict homologation test procedures also laboratory test methods are required that enable realistic comparisons between different propulsion technologies and that produce energy consumption and emission results which are representative for actual use of the vehicles. These two criteria of comparability and representativity are often not met by existing (draft) homologation procedures for electric, hybrid and fuel cell vehicles.

Under Task 2 of the MATADOR-project (Management Tool for the Assessment of Driveline Technologies and Research) research has been carried out, aimed at the development of adequate measurement methods and test procedures for the evaluation of energy consumption and emissions of vehicles with advanced power trains.

As already stated above, when talking about test methods or test procedures a distinction has to be made between test methods for approval testing and test methods for technology assessment and product evaluations. For approval testing it is essential to find out whether a vehicle meets e.g. emissions standards over a certain driving cycle in a worst case condition with regard to the available drive modes. A parallel hybrid such as the Audi DUO III with a 3-mode switch should be able to meet the European emission limits over the NEDC-cycle in its ICE-only mode. Whether the vehicle would do better in the hybrid mode is of no relevance for the homologation. For a product evaluation, however, the question is what benefits a new technology brings under realistic driving conditions. In that case a test in hybrid mode is essential, preferably over a driving cycle that is representative for the actual vehicle application.

It is our strong belief that in the near future homologation test procedures will have to become more representative for real-life driving in order to make sure that manufacturers apply technologies in their vehicles that do not just make the vehicle meet legislated emission limits under laboratory test conditions, but that have a minimal impact on the environment when the vehicle is in actual use. In the present European situation, with a non-representative modal test cycle for LD-vehicles, the emissions of vehicles with modern engine technology and advanced motor management systems, as measured with the standard homologation procedure, may be up to an order of magnitude lower than those measured over realistic driving cycles, derived from speed-time patterns recorded on the road under average driving conditions.

Due to their technical complexity especially hybrid-electric vehicles pose a challenge for the definition of measurement methods and test procedures. A crucial characteristic of hybrid vehicles is the fact that the instantaneous fuel consumption and emissions are decoupled from the instantaneous road load. In combination with the complex and sometimes discrete nature of the powertrain control strategy this leads to a highly non-linear response of the energy consumption and emissions of hybrid vehicles to changes in the test circumstances. This makes the use of representative test procedures even more crucial.

3 The scope of Task 2 of MATADOR

Technology Assessment versus Homologation

Within Task 2 of the MATADOR-project the main focus has been on developing or selecting laboratory test methods that allow a good comparison of vehicles and that yield results which are representative -or at least meaningful indications- for the energy consumption and emissions of these vehicles under real-life driving conditions. This application is referred to as technology assessment or comparative testing.

The results of Task 2 also contain valuable insights that may improve the data collection and evaluation in field testing and demonstration programmes.

It must be stated explicitly that it has not been the scope of this project to define standards for (homologation) test procedures. This is primary the role of standard setting bodies. Most of the results of the project, however, are of great value for the development of homologation test procedures. For this reason also co-operation with standard setting bodies has been established in the course of the project.

Energy consumption versus exhaust emissions

In general the same basic test procedure (in terms of e.g. vehicle conditioning and driving cycle) is used for the determination of energy consumption and for measuring exhaust gas emissions. The aim of Task 2 has therefore been to provide test solutions for measuring both the energy consumption and the emissions of vehicles with advanced propulsion systems. Practical limitations, however, have inhibited a thorough validation of the applicability of the proposed methods for determining vehicle emissions. The main reasons for this are:

- It is at present extremely difficult to model the production of exhaust gas emissions in computer simulation models of both conventional vehicles and e.g. hybrid and fuel cell vehicles. The computer simulations carried out in Task 2 therefore only provide results with respect to the energy consumption of the vehicles under study.
- Most vehicles available for testing in Task 2 were battery-electric vehicles. The number of hybrid vehicles available for testing at the time the project was executed was limited to the Toyota PRIUS, the Audi DUO and some prototypes available at the participating institutes. These vehicles only cover a small part of the whole range of possible powertrain

configurations. In addition, not all institutes are in possession of laboratory equipment for emission monitoring.

4 The organisation of Task 2 of MATADOR

In comparison with conventional vehicles with internal combustion engines (ICEVs) the testing of electric, hybrid and fuel cell powered vehicles poses measurement problems that are specific for the technologies used. After analysing existing and draft standard test procedures and an inventory of the above-mentioned technology-specific problems, a number of topics have been selected for in-depth study. Literature research, computer simulations and actual vehicle tests have been performed to analyse the selected problems and to evaluate possible solutions. The proposed solutions for different measurement problems have subsequently been combined to formulate consistent frameworks for the definition of adequate test procedures meeting the criteria described above.

4.1 The participants in Task 2

The following institutes have collaborated in this project:

Institute: TNO Automotive, P.O. Box 6033, 2600 JA Delft, the Netherlands, http://www.automotive.tno.nl
Contact person: Richard T.M. Smokers, tel: +31-15-2697511, fax: +31-15-2696874, e-mail: Smokers@wt.tno.nl

Institute: Institut für Kraftfahrwesen (IKA), Steinbachstrasse 10, 52074 Aachen, Germany, http://www.ika.rwth-aachen.de/index-e.htm
Contact person: Jan-Welm Biermann, Servé Ploumen, tel: +49-241-805616, fax: +49-241-8888147, Biermann@ika.rwth-aachen.de

Institute: ENEA – Advanced Energy Technology Division, Via Anguilarese 301, 00060 Rome, Italy, www.enea.it
Contact person: Mario Conte, tel: +39-06-30484829, fax: +39-06-30486306, e-mail: Conte@casaccia.enea.it

Institute: Institute for Automotive Engineering Arnhem, P.O. Box 7003, 6826 CC Arnhem, Netherlands, www.htsautotechniek.nl
Contact person: Leo Buning, tel: +31-26-3849308, fax: +31-26-3849385, e-mail: Bun@ft.han.nl

Institute: HTA Biel, P.O. Box 1180, 2501 Biel, Switzerland, www.hta-bi.bfh.ch/A/e.html
Contact person: Karl Meier-Engel, tel: +41-32-3216362, fax: +41-32-3216500, e-mail: Karl.Meier@hta-bi.bfh.ch

TNO Automotive has acted as Task Leader of Task 2. Company profiles of the participants are included in Section 7 of this introduction. All partners have served as Subtask Leaders.

4.2 Organisation of the research work

Table C: The structure of Task 2 of MATADOR

Nr.	Subtask subject	Subt. Leader	Participants
Research tasks			
2.1	Categorisation of EV configurations	IKA	TNO, ENEA
2.2	Development of simulation tools	IKA, TNO	
2.3	Evaluation of existing (draft) standards	IKA	TNO, ENEA, IAE, HTA
2.4	ΔSOC correction methods for HEVs	TNO	IKA, ENEA
2.5	Determination of SOC or ΔSOC in general	ENEA	TNO, IKA
2.6	Comparing electricity and fuel consumption	TNO	
2.7	FCEV test procedures.	ENEA	TNO, IKA
2.8	Driving cycles for LD vehicles	TNO	IKA, ENEA, IAE, HTA
2.9	Test methods and driving cycles for HD vehicles	TNO	IKA, ENEA
2.10	Dealing with EVs not meeting the demands of test cycles	HTA	ENEA, IAE
2.11	Accuracy and tolerances	IKA	TNO, ENEA, IAE, HTA
2.12	Regenerative braking on 2WD dynamometers	IAE	TNO, HTA
2.13	Non-rechargeable batteries	ENEA	TNO
2.14	Self-discharge and heating energy	ENEA	IKA, HTA
Synthesis tasks			
2.15	Definition of frameworks for test procedures	TNO	ENEA, IKA, HTA
	- Test method framework for LD BEVs	ENEA	HTA
	- Test method framework for HD BEVs	ENEA	
	- Test method framework for LD HEVs	IKA	TNO
	- Test method framework for HD HEVs	IKA	TNO
	- Test method framework for LD FCEVs	ENEA	
	- Test method framework for HD FCEVs	ENEA	
2.16	Editing of final report	TNO	IKA, ENEA, IAE, HTA
Support tasks			
2.17	Co-operation with industry	TNO	IKA, ENEA
2.18	Co-ordination with standard setting bodies	TNO	IKA, ENEA
2.19	Document list	ENEA	TNO, IKA, IAE, HTA
2.20	Dissemination	TNO	IKA, ENEA, IAE, HTA

Research on the various topics has been organised in so-called Subtasks. Each Subtask deals with one of the selected topics or contains research in support of the other Subtasks. Besides these Research Subtasks also some Synthesis Subtasks and Support Subtasks have been carried out. Each Subtask has had its own Subtask Leader carrying out most of the work within the Subtask and co-ordinating the input by other participants in the form of e.g. results of computer simulations, measurements and technical discussions. The Subtask Leaders have produced the reports for their Subtasks, as included in Part II of this Task 2 report. Part I of this report is compiled by the Task Leader on the basis of input provided by all Subtask Leaders.

5 Contents of the various Subtasks

Research tasks

Subtask 2.1 Categorisation of EV configurations

A general and theoretical categorisation framework (for conventional, advanced conventional and alternative propulsion systems) is necessary, not for its own sake but as an instrument for the evaluation and visualisation of simplified categorisation schemes to be developed for practical test procedures. Categorisation should cover three axes:

- driveline types;
- (driver selectable) driving modes;
- application areas (e.g. urban vs. highway or different vehicle applications).

In this Subtask existing categorisation frameworks have been analysed and a proposal has been made for the categorisation to be used for the test methods and procedures to be developed in Task 2 of MATADOR.

Subtask 2.2 Development of simulation tools

Many Subtasks contain computer simulations as part of the work. IKA and TNO both have developed their own advanced computer simulation tools and have gained vast experience with the use of these tools in various projects. Other partners mainly use simulation tools developed by other institutes. It was agreed that coherence of the results of Task 2 could be greatly improved by performing all essential simulations with the aid of a common consistent set of vehicle / driveline models, using the models of TNO and IKA. TNO and IKA have each worked out such a set of vehicle / driveline models within their own simulation tool, and have performed simulations in support of research tasks carried out by the other participants.

Subtask 2.3 Evaluation of existing (draft) standards

Currently a number of (draft) test procedures for BEVs and HEVs are existing or are under development. Within this project the (draft) procedures developed by SAE for the US and by CEN for Europe have been considered (Reference [2]–[7]). Also various institutes have developed their own procedures. Examples within MATADOR are a simplified HEV test procedure and an adapted BEV test procedure by HTA-Biel and a BEV test procedure used by ENEA. In this Subtask these procedures have been analysed to:

- gain insight in the accuracy, reproducibility and suitability of existing (draft) standards;
- gain insight in the consequences of choices and assumptions made in existing (draft) standards;
- identify which parts of existing procedures can be applied to the frameworks to be developed in Task 2;
- formulate comments and recommendations as input for future improvements.

Subtask 2.4 ΔSOC correction methods for HEVs

For a correct measurement of energy consumption and emissions of charge sustaining HEVs the SOC (state-of-charge) of the battery at the end of the test should be the same as at the beginning. If this can not be realised, then the occurring ΔSOC has to be determined and accounted for in a calculation of energy consumption and emissions. Also, the SOC may have to be influenced for conditioning of a HEV prior to testing. Various options for ΔSOC-correction have been evaluated by means of computer simulations and vehicle testing to identify the most promising method.

Subtask 2.5 Determination of SOC or ΔSOC in general

Accurate determination of the SOC is a fundamental problem for all battery types. The solution of this problem is outside the scope of MATADOR. However, within MATADOR it was considered useful to evaluate existing methods for SOC determination, and to evaluate how these methods relate to the issue of testing vehicles with alternative powertrains.

Subtask 2.6 Comparing electricity and fuel consumption

For comparing energy and emission performance of vehicles with different propulsion systems, fuel consumption and electricity consumption must be brought on a comparable basis. This is also necessary to evaluate the performance of charge depleting hybrids that consume both fuel and electricity. The general approach is to compare primary energy consumption and total (= direct + indirect) emissions, taking into account all energy losses and emissions in the various well-to-wheel energy chains. A cradle-to-grave or life-cycle analysis (LCA) can be added to also include environmental and energy impacts from manufacturing and decommissioning the vehicle. In this Subtask a practical recommendation to the EU is formulated to allow inclusion of this aspect into homologation procedures in a well-defined and standardised way.

Subtask 2.7 FCEV test procedures

Two types of fuel cell electric vehicles can be discerned. In vehicles without an electric energy storage system the output of the fuel cell is directly connected to the input of the electric machine(s) driving the wheels (further called FCEV). Besides this also a hybrid configuration is possible where a battery assists the fuel cell when peak power is required and stores energy during regenerative braking (further called FCHEV). For both types of propulsion systems adequate methods need to be developed to measure energy consumption and emissions of fuel cell vehicles. This is the subject of this Subtask.

Subtask 2.8 Driving cycles for LD vehicles

An important focus of the research in Task 2 of MATADOR has been driving cycles. The characteristics of a driving cycle (average power, dynamics, etc.) strongly influence energy use and emissions and also influence the results of comparisons between vehicles with different propulsion systems when tested over a driving cycle. Current standard cycles, especially in Europe and Japan, bear relatively little resemblance to the conditions of actual vehicle use. It is found that especially the modal cycles (e.g. NEDC and Japanese 10-15) are much less demanding than cycles based on real-life driving. The issue of representativity is also under discussion for testing of ICE-vehicles, as results from standard tests are not only used for technical evaluation and homologation procedures but also for e.g. the calculation of energy consumption and emission factors used in policy studies or for policy measures stimulating clean and efficient vehicles. For vehicles with electric and hybrid power trains the problem is even more pressing as vehicles can be designed and optimised for very specific purposes and will perform differently on different drive cycles. This Subtask has studied the influence of driving cycle characteristics on the energy consumption of battery-electric, hybrid and fuel cell vehicles.

Subtask 2.9 Test methods and driving cycles for HD vehicles

Current standard test methods for heavy-duty vehicles are not applicable to HD BEVs, HEVs and FCEVs. The standard test in Europe for conventional HD vehicles is the 13-mode ESC test, which is a static engine test. A meaningful translation of this engine test procedure to alternative propulsion systems for HD vehicles is not possible. The same is true for the transient ETC cycle, simply because it is an engine based cycle. The driveline as a whole (or even better, the vehicle as a whole) needs to be tested on a driving cycle. In this Subtask the options for testing HD vehicles with advanced propulsion systems have been explored, and a proposal for a test method has been worked out.

Subtask 2.10 Dealing with EVs not meeting the demands of test cycles

Prototype and (pre-)commercial EVs often have limited performance so that they are unable to follow a prescribed driving cycle (speed-time pattern). If deviations from a cycle are allowed, then results of measurements may be incomparable to results obtained on other vehicles, e.g. due to incorrect weighting of high-power parts in the driving cycle. Simulations have been performed to analyse the influence of so-called “failure time” on the energy consumption of BEVs and HEVs over a cycle, and recommendations have been formulated for dealing with this issue in (standardised) test procedures.

Subtask 2.11 Accuracy and tolerances

Measurement accuracy and reproducibility of new test methods should be comparable to existing methods. Accuracy and reproducibility include the accuracy with which the cycle is followed and the effects of variations (within the allowed bandwidths) in vehicle conditioning or the execution of the test on the vehicle control strategy, the frequency and duration of ICE operation periods for HEVs, and subsequent effects on energy consumption and emissions. For conventional vehicles the allowed tolerances already cause significant variations in the test results. For hybrids, with discrete switching actions (e.g. ICE on or off) in response to external parameters (e.g. road load) or internal parameters (e.g. battery SOC, ICE temperature), the effects may be even more dramatic. In this Subtasks these aspects have been quantified and recommendations for modifications of existing test procedures and conditions have been formulated.

Subtask 2.12 Regenerative braking on 2WD dynamometers

Depending on the vehicle’s braking strategy the yield of regenerative braking may be measured too high on two-wheel drive (2WD) dynamometers, as all braking energy is taken up through the driven wheels and none is dissipated by braking the non-driven wheels. In this Subtask the size of this problem has been analysed as well as approaches to deal with the problem.

Subtask 2.13 Non-rechargeable batteries

Vehicles with e.g. Zn-air batteries can not be charged from the grid, so that electricity consumption can not be measured in the way prescribed by e.g. EN 1986-1 [2]. To compare the energy consumption of these vehicles with other BEVs the efficiency of recycling non-rechargeable batteries needs to be accounted for. A procedure is proposed that allows for this on the basis of a vehicle test and certified information to be supplied by the battery manufacturer/recycler.

Subtask 2.14 Self-discharge and heating energy

Batteries with high self-discharge and high-temperature batteries lose energy also during standstill. In the current procedures such losses are not measured separately, but do influence the test results. In general the influence of self-discharge and battery heating will strongly depend on the use of the vehicle (e.g. km/day driven, or standstill during weekends). In this Subtask the size and nature of the problem have been analysed and proposals have been drawn up to deal with this issue both in homologation testing and in vehicle evaluations under realistic test conditions.

Synthesis tasks

Subtask 2.15 Definition of frameworks for test procedures

The results of the research tasks described above can be viewed as building blocks for composing test procedures for vehicles with advanced propulsion systems. In this Subtask frameworks have been drawn up for the synthesis of complete tests methods and procedures for testing of vehicles with battery electric, hybrid electric and fuel cell electric propulsion systems. In these frameworks, solutions for the different measurement problems have been combined and tailored to the various vehicle and propulsion system types. It must be emphasised that it has not been the goal of Task 2 or MATADOR to develop complete procedures in detail. This is the work of standard setting bodies. The frameworks developed here basically place the test methods proposed in the research tasks in a consistent context, and sketch the general structure and contents of test procedures for battery-electric, hybrid and fuel cell vehicles.

Initially a division of frameworks for LD and HD vehicles was foreseen, as the test procedures for these vehicle categories are generally different. A general conclusion of the research, however, is that for HD vehicles with battery-electric, hybrid and fuel cell propulsion systems a test on the vehicle level is required on the basis of a transient driving cycle. Such procedures would have largely the same structure as procedures for LD vehicles. Therefore in the reports on this Subtask the frameworks for LD and HD vehicles have been integrated. Special aspects related to HD vehicles are indicated when appropriate.

In this report the following frameworks are described:

- Test method framework for BEVs
- Test method framework for HEVs
- Test method framework for FCEVs

Initially it was also foreseen that Task 2 would provide a test method framework for other alternative propulsion systems. These would include non-electric alternatives such as mechanical hybrids with a flywheel. Given the limited role of these vehicles in the international R&D and the limited chances for market introduction of these vehicles on the short or mid term, it was decided to concentrate the efforts of Task 2 entirely on vehicles with (hybrid) electric propulsion systems.

Subtask 2.16 Editing of final report

This synthesis task has been split of as the integration of the multitude of results produced by the various Subtasks and the formulation of overall recommendations is a task in itself.

Support tasks

Subtask 2.17 Co-operation with industry

Actual testing of drivelines and vehicles has been an important research tool in Task 2 of MATADOR. A co-operation with the European or other automotive industries was considered essential to enable the MATADOR-project to test a wide variety of state-of-the-art vehicles. On the other hand also the sharing of ideas and insights in such a co-operation could serve to align the research in Task 2 with the interests of the automotive industry.

In the first year of the project contacts have been made with representatives of various European automobile manufacturers. The interest from these manufacturers to establish a formal co-operation with the project, however, has been minimal. To make vehicles available for testing in MATADOR the participants have decided to use their own networks and contacts through other running projects. In many cases manufacturers or other clients of these projects allowed dedicated tests for MATADOR to be performed on their vehicles or allowed the use of certain test results within MATADOR. Also participants have tested vehicles that they have developed or purchased by themselves.

No separate report of this activity is made.

Subtask 2.18 Co-ordination with standard setting bodies

In the same way as a project like MATADOR can not operate independent of the European automotive industry, also various reasons existed to strive for a close co-operation with international standard setting bodies. For battery-electric vehicles standard test procedures have been developed and adopted (EN 1821-1, EN 1986-1, ISO/DIS 8714-1, ISO/DIS 8715-2, SAE J 1634, SAE J 1666). As stated above these procedures do not appropriately account for vehicles with e.g. high-temperature or non-rechargeable batteries. For hybrid-electric vehicles test standards are currently under preparation or adopted (prEN 1821-2, prEN 1986-2, SAE J1711). In the course of the project intensive contacts have been maintained with SAE representatives, and especially with the workgroup within CEN that is responsible for drawing up test standards for electric vehicles, CEN TC301/WG1. Members of Task 2 have participated in various meetings of this workgroup to gain insight in the philosophy behind the procedures developed by this workgroup and to present the views of the MATADOR consortium. Also contacts have been maintained with Japanese representatives from NEDO and JARI involved in the definition of test procedures for hybrid vehicles in Japan.

No separate report of this activity is made.

Subtask 2.19 Document list

For the research in Task 2 a large body of literature on standards and test methods has been collected by various participants. To improve accessibility of information and to expand the common knowledge base within Task 2, a list of collected references has been drawn up. This list is for use by the partners only, and is not a deliverable of the project.

Subtask 2.20 Dissemination

An important goal of Task 2 is to disseminate its results to industry, standard setting bodies and other relevant target groups. Besides direct approaches of these target groups (see Subtasks 17 and 18) also more generic dissemination activities have been carried out.

The most important dissemination activity has been the presentation of papers on Task 2 at EVS-15 and EVS 16 [9][10]. A paper for EVS-17 in October of 2000, presenting the final results, has also been submitted [11].

Furthermore some of the results of Task 2 have been discussed in Annex VII of the IEA Implementing Agreement for Hybrid and Electric Vehicle Technologies and Programmes.

This final report will be disseminated widely to automotive manufacturers, standard setting bodies and other target groups. An important forum for dissemination will be the EU-sponsored thematic networks ELEDRIVE and ENIGMATIC. Additional dissemination activities may be defined in separate projects to be carried out after the completion of MATADOR.

No separate report of this activity is made.

6 How to read this report

The final report of Task 2 of MATADOR consists of two parts, containing the following elements:

Part I:

- Executive Summary
- Introduction
- Conclusions from Subtasks 1 – 14
- Frameworks for test procedures
- Overall conclusions and recommendations

Part II:

- Subtask Reports

Part I is the main Task 2 report. In the “Conclusions from Subtasks 1 – 14” the proposed solutions for the identified test problems are described in a self-contained manner. The “Frameworks for test procedures” can therefore be read and largely understood without knowledge of the detailed results of the research activities performed in the Subtasks. The chapter “Overall conclusions and recommendations” provides conclusions that are relevant to the development of test procedures and the performance of test in general. Recommendations are formulated to assist the EU, vehicle manufacturers and standard setting bodies in determining their strategy towards the definition of adequate test procedures. Also areas where additional research is required are identified.

For technical and detailed insight in the problems studied in Task 2 and for the motivation behind the proposed solutions the reader is referred to the Subtask Reports contained in part II.

7 Company profiles

TNO Automotive, Delft, the Netherlands

TNO is the Netherlands Organisation for Applied Scientific Research with around 4200 staff, at the forefront of research, development and application of new technology in many different areas. It provides a link within the innovation chain between fundamental research as a source of knowledge and practical application as the use of knowledge which can be commercially exploited. The company is divided into 14 institutes for the different research areas.
The TNO Automotive institute concentrates on vehicle dynamics, powertrains, crash safety, advanced transport systems, and homologations. The powertrains department of the institute performs a wide range of fundamental and applied research, development work and contract engineering on internal combustion engines and alternative powertrains. Feasibility and environmental studies, engine optimisation and endurance tests are performed for clients all over the world.

Future powertrains will combine a variety of components ranging from combustion engines and electric machine to batteries and fuel cells. TNO's multidisciplinary organisation enables the integration of most essential technologies into practical propulsion systems that meet extreme demands in terms of fuel consumption, exhaust emissions and noise levels.

TNO Automotive has nationally and internationally recognised expertise in the field of emission monitoring and environmental studies. In this capacity, TNO is engaged in monitoring the emissions from the fleet of vehicles currently on the road, by an extensive In-Use Compliance program for both LD and HD vehicles. Therefore, it has a unique position to develop accurate emission models for road vehicles. Using transport statistics and measurements in actual traffic as a basis, TNO Automotive develops representative test cycles for use in future homologation testing and for the evaluation of vehicles and engines in specific transport applications and under realistic traffic conditions.

The ISO certified Engine and Emission Laboratory of TNO Automotive can carry out a wide variety of standardised and non-standardised tests. Five engine test beds (including a fully transient Heavy Duty one) and three vehicle test stands, as well as much auxiliary equipment are operated by a well-trained staff. TNO Automotive has built a unique test facility where all types of electric power sources and powertrains can be tested under realistic conditions. This facility (based on a 300 kWe Digatron electrical test bench) is one of the largest and most modern of its kind in the world.

ENEA, Rome, Italy

ENEA, the Italian National Agency for New Technology, Energy and the Environment, is a scientific research and technology development organisation with vast, internationally recognised experience in conducting advanced research programmes and implementing complex projects.

Nearly half of ENEA's approximately 4000 employees are researchers and engineers operating in ten research centres located across Italy. ENEA fields of competence include engineering, materials science, chemistry, physics, geology, mathematics, agriculture, oceanography, information science and technology, meteorology, biology and many others. ENEA works with the Ministries of Industry, Environment, Research, Agriculture and Cultural Resources on designing and conducting projects involving the European Union, and other international organisations such as the United Nations and the OECD. Among its main scopes, there is the research, development and promotion of environmentally safe and energy saving technologies.

In the transport sector, ENEA is involved, together with research organisations, industries and users, in many programmes at national and international level. The aim of such programmes is to promote energy-efficient technologies with low environmental impact by means of: development of advanced mobility and traffic management systems (computer tools for traffic evaluation and control); research and development of innovative (with advanced engines, combustion control systems and alternative fuels) and advanced (pure battery-powered and hybrid with intelligent controls, lithium batteries and polymer electrolyte fuel cells) vehicles. An integrated systems of testing facilities has been created able to characterise components (injectors, gaseous fuel tanks, thermal engines and electrical motors, batteries, fuel cells), subsystems (storage, propulsion, electronic devices, complete drivelines) and vehicles (with bench, track and field tests). ENEA has been participating in numerous European Community projects, among which: FLEETS, JUPITER, MATADOR, SCOPE, ELEDRIVE, and so on. ENEA is also the Italian representative in some International Energy Agency (IEA) Implementing Agreements including those on Electric and Hybrid Vehicles and Fuel Cells.

Institut für Kraftfahrwesen (ika), Aachen, Germany

The ika- Institut für Kraftfahrwesen Aachen is a well known university research institute for automotive engineering of the Aachen University of Technology (RWTH Aachen). Our activities focus on developments towards innovative mobility, resulting in superior products and consistent concepts. Thus we support our partners in the automotive industry to face competition successfully by aquiring advantageous positions.

The performance profile of ika purposely meets these challenges. Ika excells in the following fields:

Automotive Research and Development

The research and development work that is carried out at ika ranges from public sponsored, i.e. independent fundamental research projects to vehicle specific advanced and series development. With about 200 staff members it covers almost all fields of automotive engineering in the segments: Chassis, Body, Drive-Train, Electronics, Acoustics/NVH an Traffic (Telematics, Driver-Assistance). Due to the wide range of subjects covered by the activities in different vehicle segments, ika is also able to integrate new developments into the vehicle concept as a whole. Therefore full vehicle competence can be provided if necessary.

Product Strategy and organizational Consultancy

In addition to pure R+D activities ika is a valuable project partner that combines technological developments and product strategy. The investigations focus on the product portfolios as well as on the effects of new products on the market and on competition.

Education and Advanced Training

Besides the training and education of tomorrow's industrial elite the combination of research, teaching and industry oriented service and consulting offers the possibility of further education to specialists already active in the industry. The spectrum of further educational events is considerable. It ranges from workshops on vehicle specific issues offered to individual companies to international seminars and major events like the "Aachen Colloquium for Automobile and Engine Technology"

Institute of Automotive Engineering, Arnhem, the Netherlands

The Institute of Automotive Engineering in Arnhem was established in 1942. It has a unique position within the environment of college and university education, as it is the only educational institution within the Benelux which provides a specific curriculum in automotive engineering. The automotive industry is greatly in need of graduates in this field. Each year approximately 120 graduates with a Bachelor's degree in Automotive Engineering enter the labour market. These graduates usually have no difficulty in finding work. This is one of the reasons that the students at the Institute of Automotive Engineering in Arnhem are a well-motivated student body. The Institute of Automotive Engineering is one of the departments within the Faculty of Mechanical Engineering at the University of Professional Education of Arnhem and Nijmegen.

Intensive contact is maintained between (the automotive) industry and the Institute in various ways, e.g. while students are carrying out their work experience, and also during their graduation assignments. Companies can also request retraining and refresher courses for their personnel, in the fields of motor vehicle and transport technology.

The Institute of Automotive Engineering is not only an educational institution. It also has a research and test centre. The Department of Contract Research, which is a separate department within the Institute, carries out *practical* and *applied* research and detailed tests, as specified by the client, and in accordance with instructions received from various companies and institutions. The precise kind of research is dependent upon the requirements of the client: comparative research; expertise provided by professional consultants, and/or measurements, made in accordance with EEC regulations if required; quality assessments and design.

The scope of the projects can vary. It is possible to request one-off or small scale investigations. This could, for example, be an assessment of an invention or component, or structural investigations. On the other hand, the Institute also carries out long-term projects which sometimes take a number of years to complete.

Besides research into commercial vehicles and passenger cars, the Institute can also carry out investigations into other types of vehicles, such as motor bicycles.

Automobile Technology Department of HTA Biel-Bienne, Switzerland

The Automobile Technology Department is the only Engineering College for Automobile Technology in Switzerland. 1070 students have finished their studies up to 2000.

One class a year in: a “general Automobile Technology”
b “vehicle manufacturing”

Teaching is held in two languages (French an German) simultaneously.

3 years studies with the main points: 1st year: basic information
2nd year: basics for engineer
3rd year: Engineering application

Possible jobs after the college’s diploma are:

- teacher of vocational schools
- customer services, technical service or instruction of the service people at importers
- Constructors (Body manufactering; vehicle industry)
- Experts in analysis of accidents
- Manager or responsible of a garage
- Owner of a garage

The following laboratories are used for education purpose:

- Business management
- Combustion engine
- Electrical Engineering and Electronic
- Vehicle mechanics

These laboratories are also used for research and development projects which are performed for customers.

Conclusions from Subtasks 1 – 14

Subtask 2.1 Categorisation of EV configurations

In Task 2 of the MATADOR-project test methods (Management Tool for the Assessment of Driveline Technologies and Research, EU-contract JOE3-CT97-0081) for battery-electric, hybrid-electric and fuel cell vehicles are analysed in order to support the development of new test procedures for these vehicles with alternative drivelines. The development and definition of test procedures for vehicles with alternative drivelines in order to determine the fuel consumption and emissions requires a detailed work on the technical aspects, which depend strongly on the vehicle's technology. This is obviously more complicated for the development of procedures for a comparative assessment of technologies, which must cover even more different aspects, than procedures needed for homologation, where values for the fuel consumption and the emissions are most relevant. As a basis for the development of new procedures, in this subtask report classification schemes are developed and analysed compared to existing schemes.

In the scope of this subtask, different classifications of alternative vehicles have been defined. Due to the complexity of hybrid systems and the many different possible structures and energy storage components, it is not easy to assign a system to only one class clearly. Classification can only be done according to special aspects of the hybrid system.

Depending on the purpose, the categorisation scheme is divided in a different number of categories. For homologation it is desirable to have as few classes as possible, while a categorisation for research and development has to cover all the different aspects of the systems internals and therefore may be more extended.

Classification can be made due to the following aspects:

- Charging strategy
- Power and energy storage device
- Driving modes (hybrid, thermal, pure electric modes, …)
- Driveline type and structure (driver selectable)
- Operation strategy
- "Fuel" (Gasoline, Diesel, Natural Gas, Hydrogen, Electricity …)

All these categories are important for research and development, while for homologation it can be reduced to the first two aspects. Only in hybrid vehicles, which have no hybrid mode, but only a pure electrical and a pure thermal mode, the driving mode is of interest.

The aspects of the existing drafts for testing hybrid vehicles (SAE J1711 and prEN1986-2) are discussed in this report. prEN1986-2 provides a categorisation scheme similar to the categorisation scheme for homologation delivered in this report. SAE J1711 additionally considers the aspect of the charge dependency. The complexity of the tests to be performed according SAE J1711 shows that with this procedure a more detailed assessment of vehicles rather than testing only for homologation purposes is conducted.

The different aspects of hybrid systems are described and, beside explanations, examples are given to illustrate the abstract definitions.

In the scope of this subtask, different classifications of alternative vehicles have been defined. The classification criteria are the driveline structure, the power and energy storage capacity, the available driving modes and the charging strategy. Beside explanations, examples are given to illustrate the abstract definitions.

Subtask 2.2 Development of simulation models

The goal of Subtask 2.2 was the '*Development of simulation models*' that could be used to investigate many aspects which were defined as key issues in the MATADOR Task 2 project. Both IKA and TNO already had tools for dynamic driveline simulation at their disposal, called IKASIM and TNO-ADVANCE respectively.

Both partners have built an extensive set of driveline models, together comprising many of the possible powertrain configurations. Main functionality for the models is showing representative driveline behaviour. The working of components therefore has to be similar to real-life operation. Many components have not actually been validated however. The results of the simulation, therefore, may only be compared qualitatively. Ranking the different powertrain configurations is also not allowed due to the lack of actual validation. All models are meant to give insight into the differences in driveline behaviour for various types of powertrains, not to rank them in terms of energy efficiency.

At IKA the following Light-Duty driveline models have been set up:

- 3 x Parallel Hybrid Electric Vehicle
  - Battery storage system (Charge sustaining & depleting)
  - Flywheel storage system (Charge sustaining)
- 3 x Series Hybrid Electric Vehicle
  - Battery storage system (Charge sustaining & depleting)
  - Flywheel storage system (Charge sustaining)

At TNO the following (charge sustaining) driveline models now are available:

- 1 x Battery Electric Vehicle (Light-Duty)
- 1 x Parallel Hybrid Electric Vehicle (Heavy-Duty)
- 2 x Series Hybrid Electric Vehicle (Light-Duty & Heavy-Duty)
- 1 x Combined Hybrid Electric Vehicle (LD)
- 1 x Fuel Cell Electric Vehicle (LD)
- 1 x Fuel Cell Hybrid Electric Vehicle (LD)

All of these models are used to support the research conducted in other subtasks of the MATADOR Task 2 project and have proven to be very useful for this purpose. Quite often in the Subtask Reports, the models are referenced to with an abbreviation, which will be included in the list of abbreviations. Detailed information on the models, however, is only presented in this subtask report.

Simulations can never fully replace actual measurements. A computer model's representativity is always limited by factors like the influence of temperatures or tyre pressure that can hardly be modelled. Practical reasons can also be the cause for not modelling known effects. Detailed models can result in time-consuming simulations and also obtaining necessary, meaningful data can be a problem (e.g. which and how do you measure transient effects on for instance fuel use and emissions of combustion engines). Well-known effects then are not included into the models.
The models described in this document are generic models, which can very well be used to research driveline behaviour and energy consumption, yet that cannot produce useful information on the emission of a certain driveline type. The models do contain all the essential physics so that the response to changing test conditions is adequately simulated.

Subtask 2.3 Evaluation of existing (draft) standards

In Task 2 of the MATADOR-project, test methods (Management Tool for the Assessment of Driveline Technologies and Research, EU-contract JOE3-CT97-0081) for battery-electric, hybrid-electric and fuel cell vehicles are analysed in order to support the development of new test procedures for these vehicles with alternative drivelines. In the subtask report presented here the applicability of different standards was investigated both by test and simulation. The goal was to find possible problems of these standards by performing tests according to the standards. The experience and aspects that might turn out into possible problems encountered during the test allow for a deep understanding of the problems of applying and defining test procedures. The standards, which were analysed, are:

- EN 1986-1: Electrically propelled road vehicles – Measurement of energy performances – Part 1: Pure electric vehicles
- SAE J 1634: Electric vehicle energy consumption and range test procedure

Additionally, two testing procedures, which have been established for internal use in the specific institutes, have been discussed too.

- HTA-Biel: Mendrisio BEV Test Procedure
- ENEA: BEV Test Procedure

For hybrid vehicles the following procedures are investigated:

- prEN 1986-2: Electrically propelled road vehicles – Measurement of energy performances – Part 2: Thermal electric hybrid vehicles (Draft)
- SAE J 1711: Recommended practice for measuring the exhaust emissions and fuel economy of hybrid vehicles (Draft)
- California Air Resources Board (CARB): Californian exhaust emission standards and test procedures for 2003 and subsequent model zero-emissions vehicles, and 2001 and subsequent model hybrid electric vehicles, in the passenger car, light-duty truck and medium-duty vehicle class (adopted 5.8.1999)

In the first step, the different standards were analysed. A comparison of the speed profiles shows big differences between the European standards and the US standards. The European ECE-cycle and the NEDC are artificial, consisting of periods with constant velocities and slopes with constant acceleration. These are so called ‘modal’ or ‘stylistic’ cycles. However, the American cycles (UDDS, HWFET, SC03 and US06) are derived from real world driving patterns, giving second by second values for the speed with no constant phases for velocity or acceleration. These are so called ‘transient’ cycles. They generally are more power demanding, especially the US06 test. From the matrices of power over speed it can be seen, that most of the parallel hybrid vehicles, where the power of the electric motor is lower than that of the ICE, might fail to follow the US06 driving schedule in pure EV-mode. As expected, the tested Audi Duo was not able to follow this driving schedule. The key point to solve this problem is the question of the representativity of the driving schedules prescribed in the standards for the given vehicle.

A second difference is the used test weight. The European standards define the test weight at the vehicle curb weight plus 100 kg, whereas the US standards use curb weight plus 136 kg. The resulting influence on energy consumption of 36 kg weight difference may be negligible compared to other uncertainties resulting from the complexity of hybrid drives with different operating modes.

Regarding the vehicle preconditioning, it was evaluated, that especially the condition of the tires has a great influence on the rolling resistance and therewith on energy consumption. This is no special characteristic of BEV or HEV. Conventional vehicles have the same dependency. Therefore , there is no need to warm up the tires before testing, but great care must be taken on the monitoring of pressure and temperature before testing. The temperature should be the same before every test by storing the vehicle at controlled constant ambient temperatures. Existing standards already demand a corresponding time duration between two tests to ensure cold start conditions.

Research on the influence of failure time indicates, that this parameter has an influence on the energy consumption. The energy consumption increases when failure time occurs. Therefore it is reasonable to measure this time during the test. Also all the standards demand to record the time, that a vehicle is not able to follow the cycle. They do not make a difference between allowed deviation times caused by shifting and deviations caused by lack of power. Only these times caused by lack of power should be accounted for as failure time. New procedures should clearly define this difference.

For testing pure electric vehicles, it was recognised that especially heating losses are not consequently regarded by the test procedures. Due to possible differences in charging time, the amount of energy needed for heating can significantly vary, influencing the overall energy consumption. In the European standard EN 1986-1, the recharge duration can vary between minimal 17.98 hours and maximal 23.3 hours. The charge duration according SAE J 1634 is minimal 12 hours, the maximum duration depends on the battery capacity and recharge power and is twice the time of energy capacity (kWh) divided by recharge power (kW). Tests performed with a BEV with a high temperature battery, which has reasonable heating losses, showed a variation in energy consumption due to different recharging times of up to 38 %. If energy consumption of electric vehicles in a broader sense should be comparable to each other, the charging procedures of SAE J1634 and EN 1986-1 should be combined, using a realistic and representative charging duration. Additionally, an extra measurement of the standstill losses should be introduced into the standards.

The tests of the Audi DUO, a parallel hybrid electric vehicle, show, that the prEN 1986-2 can be applied without any problems. During the test according to SAE J1711, major problems occur, because this procedure obviously does not cover the typical operating characteristics of a typical "European" parallel hybrid vehicle of which the electric performance is only intended for urban conditions. Especially, one inconsistency was found. Following the test procedure, an IPT (recharge independent hybrid mode test) should be performed, but the Audi DUO does not have such a mode. Additionally, the range in the DFT (Dependent Full Charge Test) and EVT (Electric Vehicle Test) is much lower than intended in the test procedure. Thus, the utility values to calculate the daily travel results should be adapted to the lower range, but the procedure does not clearly state how to do that.

Although the SAE J1711 is very complex and demands a high number of different tests in each operation mode, it obviously fails to cover the behaviour of the Audi DUO and its operating strategy. Therefore it is recommended for development of new standards, that new standards should demand a much simpler procedure. If the driving schedule and the pattern for the use of the car (including standstill and recharging times) applied for a test are representative, there should be no need to perform tests in four different cycles and all operating modes to perform a weighting afterwards.

The analysis of the Californian standard shows, that the tolerance given there for the allowed change in the state of charge for a charge sustaining hybrid may be applicable to other cycles than the UDDS, but it needs preparation of the vehicle. The initial state of charge of the batteries must be settled to a value in such a way, that the final state of charge after the test falls within the defined tolerance. To evaluate such procedures could be very complicated, and might not be acceptable, in terms of time and costs. Thus the correction methods analysed in subtask 2.4 are an easier way to determine the energy consumption of charge sustaining hybrids.

An additional analysis of the prEN 1986-2 standard was performed by simulation. For charge depleting hybrids, the energy consumption in hybrid mode is measured over a number of cycles, which is one more than the number, which can be driven in pure electric mode. As a result, the number of cycles to be driven depends on the vehicle. For a comparative assessment, this obviously is not a good solution, if each vehicle is tested over a different number of cycles. A second effect is, that by the repetition of cycles the cold start emissions are underestimated, because the higher emission of the cold start are averaged with the lower hot emissions in the following cycles. For a new test procedure, therefore a fixed number of cycles should be used for charge depleting hybrids also.

Subtask 2.4 ΔSOC correction methods for HEVs

The research in this subtask report concentrates on methods to determine the actual energy consumption and emissions of charge sustaining vehicles on a driving cycle. For a correct measurement of the energy consumption and emissions of such a vehicle, the State-of-Charge (SOC) of the energy storage system at the end of a test should be the same as at the beginning. If this cannot be realised, then the occurring ΔSOC has to be determined and accounted for in a calculation of energy consumption and emissions.

It is investigated whether the problem of ΔSOC will occur and what the effect then will be. By means of computer simulation and vehicle measurements, answers to these questions are given.

State-of-Charge and the problem (Chapter 2)

- The State-of-Charge (SOC) shows periodic behaviour over multiple consecutively driven cycles (Figure 40). This could be expected as a periodic stimulus (multiple driving cycles) is imposed on a controlled non-linear dynamic system (the driveline and control).

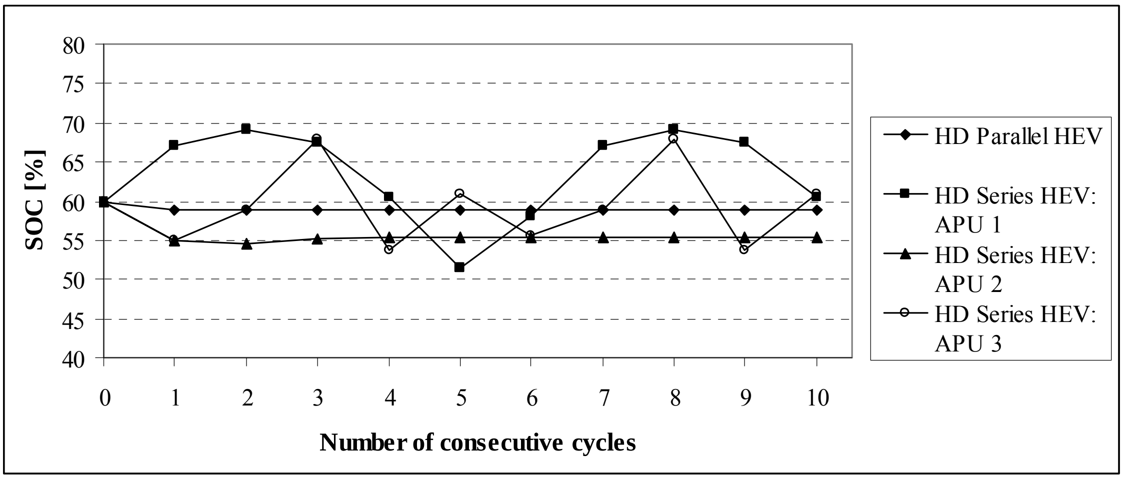


Figure 40: SOC history for four different hybrids: one HD parallel HEV and a HD series HEV with three different APU operating strategies

- The cyclic response has a period time that equals an integer number of driving cycles. In the simulations this behaviour can easily be found. In actual measurements, the response of the driver will not be identical for each consecutive driving cycle of the same type, and, as a result of that, the system might not settle into a clearly recognisable repetitive pattern. The Toyota Prius measurements showed that the SOC history was fairly similar over the successively driven cycles.
- Before settling into a repetitive SOC pattern, several cycles are needed for the system to adapt to the load pattern (the initial conditions first have to dampen out). It may therefore

take a lot of time before the SOC pattern can be recognised and the period time can be determined.

- Different initial conditions for the SOC influence the on/off operation of the internal combustion engine. This does not influence the occurrence of periodic response. Simulations show that it might result in a phase shift though.
- The size of the energy storage system can affect the period time of the SOC. This was found in the simulations of a series and combined hybrid electric vehicle with a small and a large battery (Figure 8). In case of a control strategy solely based on the State-of-Charge, a large influence was found, while the influence was much smaller in case of a control strategy that uses the instantaneous power request at the wheels. The series hybrid with a simple on/off control for the APU, showed a period time of one driving cycle for the low energy battery, and a longer period time for the higher energy battery. The response of the combined hybrid vehicle model was hardly influenced by the change of battery energy content.

Apart from the SOC behaviour, which has given insight into HEV operation, the simulations and measurements were needed to confirm the existence of the ΔSOC problem. Both in simulations and measurements, the SOC showed that significant variations are possible. A large ΔSOC, however, does not necessarily have a large influence on the determined energy consumption of the vehicle. The energy content corresponding to the ΔSOC in this respect is more important. The Californian Air Resources Board (CARB) for this reason has defined a criterion for acceptable change of battery energy content over the cycle. When the change is within 1% of the used fuel's energy, then no correction or other tests are necessary. The ΔSOC, which is a relative measure, has to be put into perspective of the real amount of energy associated with it.

The analyses in Chapter 2 clearly indicates that the ΔSOC problem exists, and thus calls for a method that can accurately account for it. Various options for ΔSOC correction have been identified and discussed.

ΔSOC correction and energy consumption determination

In Chapter 3 the ΔSOC correction methods are fully explained and in 4 they are further analysed and evaluated. The methods are shortly described and discussed here.

1. *Energy consumption without ΔSOC correction (Section 3.1, page 33)*
   The energy consumption and emissions of a vehicle are determined from one measurement on one driving cycle. For conventional and battery electric vehicles this yields the correct value for the environmental performances, since these vehicles are only powered from one energy source (either the fuel tank or the battery). For hybrid vehicles, this measurement results in a misrepresentation of the actual energy consumption and emissions over the cycle. Especially in case of significant ΔSOC (change of energy content), this would lead to large errors.

2. *Averaging multiple cycles (Section 3.2, page 34)*
   For charge sustaining vehicles, the SOC will increase and decrease for consecutively driven cycles. The fuel consumption will vary correspondingly. By driving a large number of cycles, the effect of SOC-variations (ΔSOC) will dampen out. Eventually, the (average) fuel consumption and emissions calculated are the representative values for a cycle. This method is fundamentally correct, yet, when used in actual tests, an (unpredictable) large number of cycles are required. An advantage is that the SOC does not have to be measured (although it has to be known that the vehicle is charge sustaining), since it is not included in the energy consumption calculation. In simulations, this method has been used to determine the true asymptotic fuel consumption of vehicles, with which the outcome of other methods can be compared.

3. *Extension of the test (Section 3.3, page 34)*
   In case of ΔSOC, the measurement is continued until ΔSOC = 0 is reached. At that point the test is finished. The options are:
   1. Same driving cycle is driven until the stop criterion is met. The energy consumption and emissions then can be determined by either attributing the additional fuel use and emissions to the distance driven on the cycle or to the total distance (cycle + extension). From the simulations these methods turned out to be inaccurate and unreliable.
   2. A manufacturer defined test is applied in case that a negative ΔSOC occurs (no correction is applied when a positive change results from the test). The vehicle manufacturer defines a charging procedure. This procedure can be at standstill, driving at a constant speed or any other speed profile to be maintained until zero ΔSOC is reached. This method is currently used in the draft CEN-procedure for thermal hybrids (prEN 1986-2). With respect to simplicity for the body performing the test(s), it is not desired that each manufacturer defines a (different) procedure.

   Another shortcoming of these correction methods is that the additional part of the test is not representative for the test cycle, since it most likely will have other characteristics than the test cycle. These methods, therefore, do not give a solid basis for a consistent comparison of energy consumption and emissions.

4. *Linear regression (Section 3.4.1, page 36)*
   This method requires a driving cycle to be driven several times. During each test, the ΔSOC and fuel consumption/emissions are measured. Each measurement thus results in a data set, and by plotting the consumption/emissions against the ΔSOC (Figure 41, left), the actual energy consumption and emissions at ΔSOC=0 can be estimated.
   The use of this method requires the measurement of the (change of) SOC of the reversible energy carrier. The measurement to be carried out furthermore follows the same procedures as are currently already used for conventional vehicles.
   On the basis of the simulation results, this method provides quite good accuracy. Due to the low number of vehicle tests, actual validation of the method is only limited. Yet as far as results have been obtained, this method seems promising.

5. *Linear interpolation (Section 3.4.2, page 37)*
   Even more than the linear regression method, from which it is derived, this method assumes a linear relationship between the ΔSOC and the energy consumption/emissions. This linear interpolation method requires the cycle to be driven twice. The energy storage system of the vehicle is manipulated so that one test is performed with an initial SOC much higher than the average value over the cycle, and the second test with an initial SOC that is much lower than the average over the cycle. These initial SOC values can generally be reached by driving the vehicle under an extreme condition that either charges or depletes the battery. Due to the high and low initial SOC, this method automatically yields a large positive and negative ΔSOC. The energy consumption and emissions then can be found through linear interpolation (Figure 41, right).
   With respect to the current (conventional) procedure, this method, just like the regression method, requires the additional measurement of ΔSOC. Besides that, it also requires the battery to be specially conditioned (manipulated) prior to driving the cycle.

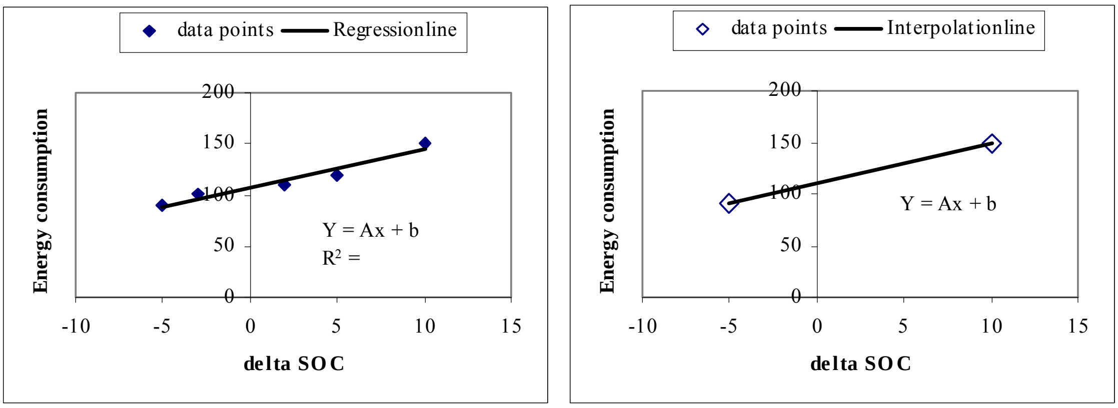


Figure 41: Regression (left) and interpolation (right) method for energy consumption

Proposed ΔSOC correction method

The research of this subtask learns that, on the basis of a presumed linear relation between ΔSOC and energy consumption and emissions, two methods seem possible to account for the change of charge content over the driving cycle. Both linear regression and linear interpolation give quite accurate and similar results. This is not surprising since both methods have the same assumptions. Main differences are found in the battery conditioning prior to conducting the test and the number of cycles to be driven. Furthermore, the ΔSOC that will be found in the test is also different (one starts from extreme initial values and thus is bound to give large ΔSOC, while the other will probably vary around the average SOC) and, along with this, the area over which linearity is assumed is much wider when starting from extreme initial SOC values. The implementation of these methods in a test procedure depends on several practical considerations like feasibility for battery manipulation, cold engine starts, or the total amount of test time needed. In the test procedure framework for (charge sustaining) hybrid electric vehicles these conditions are taken into account and a workable measurement procedure is given there.

Recommendation

Unfortunately, only a limited number of measurements could be carried out, since only a few (charge sustaining) hybrid vehicles were available for tests. This limited number of tests does not provide a very solid basis for conclusions. It therefore is highly recommended that, when more hybrid vehicles come available, more tests are performed to validate the applicability of the proposed ΔSOC correction methods.

Subtask 2.5 Determination of SOC and ΔSOC in general

Problem definition

Accurate determination of the SOC is a fundamental problem for most battery types and for specific applications, particularly under transient conditions in which charging and discharging modes are frequently involved. Many methods are investigated and proposed: Ah- counting, internal resistance, specific gravity, open circuit voltage, voltage derivative, impedance analysis, and so on. Each of these methods presents advantages and drawbacks, which make it hard to find a general method/device, which suits every battery and every working conditions. For testing purposes, particularly for HEVs, it seems sufficient to determine the ΔSOC, and, possibly, be sure that ΔSOC=0 at the end of the test sequence. This determination can be done by using an Ah-meter, when irreversible phenomena occurring in the battery can be avoided or neglected. Literature survey and experimental activities, described in this document, show that is apparent that the Ah-counting is not a reliable and accurate way to measure the SOC and ΔSOC in any vehicle working conditions and state of the battery. One basic aspect is that the Coulombic efficiency of the various batteries varies at different charging/discharging rates and with battery ageing. The measured values of SOC (or ΔSOC) may be different from the real values up to 20-30%, giving a wrong indication to the drivers and a bad reference for testing purposes. For lead-acid batteries, the strong variations of many parameters, including SOC and ΔSOC, have been experimentally verified. The study of the correlation between some significant parameters (internal resistance, temperature, OCV) and the SOC (and SOH) can then suggest an ageing effect correction to the SOC and ΔSOC assessment. Temperature effects need to be carefully considered both for OCV and R_{int}^{dch} variations. Tests on different gelled electrolyte modules are needed, in order to verify the possibility to extend such procedure to other lead-acid battery technology and also to other battery types. The literature behind this experimental work and analysis clearly demonstrates the work still needed to solve this problem. The determination of SOC and ΔSOC is not only useful for evaluating the accuracy of testing procedure, but also for battery models useful for (hybrid) electric vehicle simulation.

SOC determination for testing purpose and battery models

More than 90 articles have been analysed in order to provide a survey of methods and devices about the evaluation of the state of charge for different battery models and uses. Error estimation was also indicated, whenever the data were available from the experimental tests. From such analysis the main results are:

1. A large research work on logic models and devices (fuzzy logic and neural networks) is underway. The SOC estimation method may vary (impedance techniques, characteristic curve techniques, Ah-counting, on-load voltage control) and has been applied to different battery technologies, with good results.

2. There are various attempts to apply the EIS (electrochemical impedance spectroscopy) results to simplified devices. Such method, in spite of a sophisticated and expensive technology, is an affordable tool for SOC determination, meaningful for the battery SOH and operating conditions.

3. It is difficult to define a largely accepted ageing correction factor to the electric models, meanwhile for temperature and current rate effects on available capacity some correction factors have been identified.

Referring to EIS applications, in order to develop methods to correct the Ah-counting, some impedance technique results are:
1. internal impedance and internal resistance are strongly affected by battery ageing.
2. at high current rate, impedance is in non-linear conditions. In this case an asymmetric behaviour between charge and discharge internal resistance is more evident than at low current rate. Such asymmetry is dependent on the SOC.

While the impedance analysis requires sophisticated instrumentation and the data analysis requires complex non-linear least squares methods, internal resistance monitoring is proposed as on-line technique useful to the battery ageing.

Finally, as far as charge sustaining hybrid electric vehicles (CH-HEVs) are concerned, an interesting State Of Voltage (SOV) battery controller has been proposed. The aim is not to predict the end of effective charge, but to maximise ‘power processing efficiency and capability while maintaining some degree of charge balance over time’. The SOV control method shifts the battery SOC towards levels, which offer high power cycle efficiencies.

Battery models analysis

The literature survey on models, methods and devices for the SOC and ΔSOC evaluation has considered various battery models. They have been divided in four groups:

1. static electrical models,
2. dynamical electro-chemical models,
3. physico-chemical models, and
4. logic models.

The first and last groups are most useful for the SOC determination and for a ΔSOC computing. The first group includes both coulometric (Ampere-hour counting) and OCV measurements. A combination of these two monitoring techniques is often utilised in order to correct the Ah-counting, strongly affected by the rate of discharge, the duration of resting periods, as well as temperature and ageing effects. OCV measurements avoid the accumulation of errors of the Ah-counting with a periodical correction.
Although the OCV shows a little dependency on the temperature and the history of a battery, it needs a long stabilisation period after the load is turned off. A three-hour resting period is usually considered necessary (EUCAR procedure) for full stabilisation, but it is unsuitable in common vehicle use. For this reason the OCV technique does not provide a good and continuous indication of the SOC, particularly in BEVs and HEVs.
The second and the third group of battery models are quite sophisticated and not useful for on-board SOC-indicators; nevertheless monitoring techniques, such as the electrochemical impedance measurement, underline the importance of ageing effects in the internal parameter variations.
The logic models will be a simple and economic solution to the SOC determination problem: up to now, they need some improvements and more experimental tests.

As regards to the electric models, some simulations have been performed with a simple Thevenin's equivalent circuit. The battery is represented as an electric dipole, characterised by an OCV and IR, both dependent on the SOC of the battery. SOC is calculated integrating the current rate (Ah-counting) and correcting the integral sum with suitable coefficients depending upon the discharge current rate as in the Peukert's equation.
Such a model is able to reproduce only constant current discharge profiles, providing the battery voltage measured at the battery poles. In real driving profiles the results are not satisfactory.
Its importance lies in the possibility to represent a universal model for different battery technologies.
Furthermore, the main effects neglected in such description are the temperature and the ageing effects; in the ΔSOC computing the actual capacity cannot be substituted with the nominal capacity value. The temperature affects the actual available capacity for about 0.8%/°C, while the ageing effect has been quantified in a maximum variation of ±20 % of the nominal capacity.

Experimental tests

On the basis of the literature survey and with the MATADOR goals in mind, experimental tests have been performed. The aim has been to investigate possible corrections for Ah-counting and electrical models for simulations, as well as the battery State Of Health (SOH) evaluation, in the simple electric models. In order to investigate the ageing effect, a test procedure, which considers the whole service life of the batteries, has been designed.

Capacity variation with ageing (cycling)

Figure 17 clearly shows the variation of the actual battery capacity with cycling (the curve refers to a lead-acid battery). This behaviour may cause the maximum error in the ΔSOC evaluation when the battery is at the end of the service life. Considering a charge variation of 10 Ah for a 50 Ah module, the ΔSOC of 30% (even if very rare and undesired) may be underestimated up to 20 %, in the extreme cases of a battery fully degraded with a real capacity of 35 Ah (70% of the nominal one).

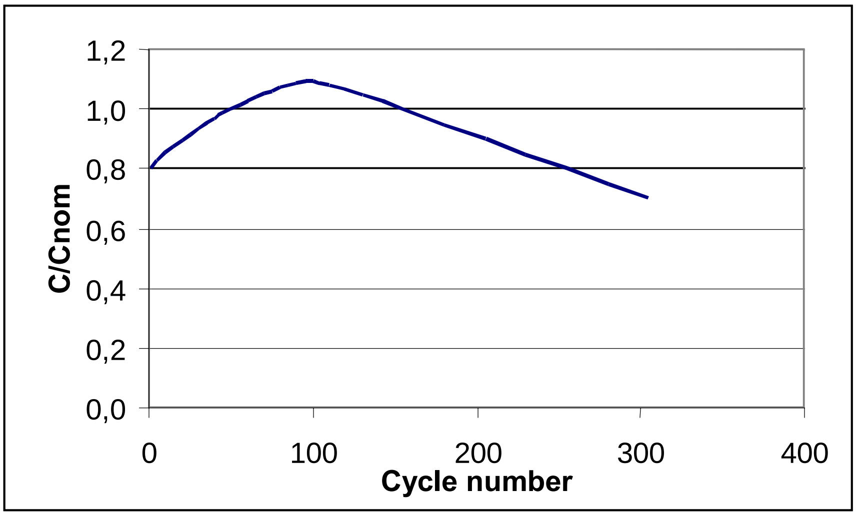


Figure 17: Capacity versus deep discharge cycle number for lead-acid modules

Discharge Internal Resistance as SOH indicator

The discharge internal resistance obtained at low current rate (6A) was named R_{int}^{dch} . This parameter as function of SOC depends on the temperature of the test in the first part of the discharge period, until the voltage drops to about 80% of the actually available capacity. Such temperature dependency is monotonous, but non-linear.

When the modules are almost completely discharged, the R_{int}^{dch} increases quickly from 5 to 10 times the initial value. This resistance variation is strongly affected by the SOH of the battery: the continuous monitoring of R_{int}^{dch} provides an indication of the residual capacity in the final part of the SOC range, also when a discharge at constant rate is no longer possible.

In Figure 18, R_{int}^{dch} is plotted as SOC function and at different SOH.

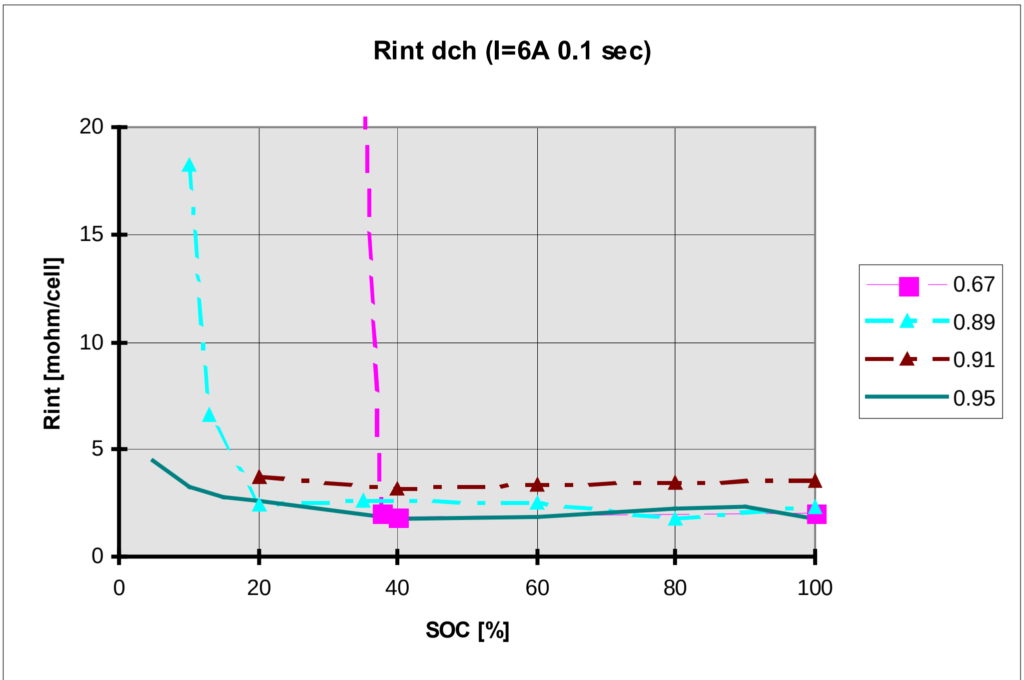


Figure 18: R_{int}^{dch} at 6A current pulses, in the SOC range 0-100 %; the SOH of the modules is varying between 0.67 and 0.95

R_{int}^{dch} is proposed as SOH indicator, interrupting the discharge when the resistance change exceeds 1 mOhm/cell in ΔSOC=10 %. The extracted charge, corresponding to such a discharge limit, will be considered as 80 % of the available capacity in the actual operating conditions.
It is then possible the calculation of a '*corrected* ' SOC, indicated as SOC*, defined as the extracted charge referred to the actual available charge. For example, if the SOH of a 50 Ah-module is deduced from the resistance monitoring as 80% and the extracted charge during the functioning is measured as 25 Ah, the corresponding SOC* will be 62.5 % is spite of 50%.
The SOC* is more conveniently used instead of SOC, which is referred to the nominal capacity.

Asymmetry and OCV as SOC function*

Monitoring charge and discharge internal resistance at high current rate ($R^{ch}_{I(A)}$ and $R^{dch}_{I(A)}$ respectively) the asymmetry between them is a monotone function of the SOC, weakly affected by temperature effects.
At current rates lower than or equal to C/1, the asymmetry $AS_{I(A)}$ as SOC function is quite uniform and equal to 1 ($R^{ch}_{I(A)} = R^{dch}_{I(A)}$), at high current rates it may be considered a good SOC indicator in the range 50-100 % of the SOC.
Tests have been performed at 75 A and have been corrected with the ageing effects by using the SOC* as state of charge and state of health indicator.
Furthermore OCV with a resting period of three hours after the load setting off has been measured for different temperature and SOH conditions; neglecting the temperature dependency that has shown to be quite complex (non-linear and non-monotone), the SOH effects may be considered by representing OCV versus SOC*.

Battery efficiency

The charge/discharge efficiency varies with SOH and SOC of the battery. Table 5 presents overall efficiency with deep discharge, using a current profile (ECE15) on the four lead-acid modules in different state conditions.

Table 5: Constant current discharges at C/5 rate and following IU-recharges

Ah dch	Ah ch	Efficiency
-41.05	47.89	85.7%
-42.65	53.43	79.8%
-45.72	49.67	92.0%
-49.36	53.26	92.7%
-50.73	55.29	91.7%
-51.41	58.97	87.2%

Furthermore, the charge/discharge efficiency depends on SOH. Table 6 presents charge/discharge efficiency at various SOH.

Table 6: Ah discharged and Ah charged on deep discharge (final SOC=20%) performed on ECE15 cycles

Ah ch	Ah disch	Efficiency	SOH
-40.379	43.65	92.5%	0.96
-39.99	43.46	92.0%	0.96
-39.949	43.37	92.1%	0.96
-39.929	43.36	92.1%	0.96
-39.906	43.45	91.8%	0.96
-39.698	43.89	90.4%	0.96
-39.469	44.88	87.9%	0.96
-39.47	43.25	91.3%	0.96
-39.31	43.8	89.7%	0.96
-39.401	44.16	89.2%	0.96
-39.446	42.09	93.7%	0.92
-39.348	41.66	94.4%	0.92
-39.361	41.69	94.4%	0.92
-39.113	41.65	93.9%	0.92
-39.22	41.65	94.2%	0.92
-39.243	41.66	94.2%	0.92
-39.288	41.58	94.5%	0.92
-39.231	41.51	94.5%	0.92

Recommendations for simulation models and testing

In the framework of the MATADOR Project, SOC and ΔSOC determination is of great importance for testing and comparing electric and hybrid vehicles. In the Subtask 2.5, an analysis on determination methods and devices is pointed out as an essential tool for energy consumption computing. The hypothesis not to take into account the capacity variations in the ΔSOC determination seems to be inadequate to the general purpose of hybrid and electric traction. Particularly for assessment of technologies in real operating conditions, the ageing and efficiency aspects ought to be taken into account.
Starting from the most accepted techniques to estimate the SOC and the battery capacity prediction, the integration of current in time (Ah-counting) requires correction factors in order to account for ageing and temperature effects. OCV, IR and asymmetry between charge and discharge resistance are proposed as ageing indicators; experimental tests have been performed only on lead-gel modules, but IR variations due to ageing of the batteries are common to other battery technologies. The overall results of the literature analysis and test work direct to some recommendations for battery simulation models and ΔSOC determination.

Simulation models

The use of simulation models for batteries may help to correct the Ah-counting and improve accuracy in energy consumption determination. The advantage of using models is twofold: increased accuracy in SOC and ΔSOC assessment and better determination of other parameters (current and voltage) needed to calculate energy consumption, if not directly measured. Main problems are shortly described and addressed.

There are significant variations of battery behaviour with the operating condition (temperature, ageing, and discharge current), easily detectable with the monitoring of the internal resistance at low current pulse.

Proposal:
1. Electrical models can be used, but they must include a parabolic function for the calculation of the internal resistance (IR).
2. The definition of a corrected SOC (SOC*) provides useful information on the state of health of the battery pack.
3. The asymmetry between charge and discharge resistance (at high current pulse) can be a useful and more precise SOC indicator (the OCV after a three-hour resting period may be used as verification test). For OCV at high discharge rates, it is more realistic to use a 3rd order polynomial function.

Recommendations for ΔSOC determination in testing procedures

The ΔSOC evaluation is performed accounting for the Ah-capacity drawn from the battery pack and the Ah-capacity provided to the pack during recharge or by the ICE during the vehicle operation.
The ΔSOC is obtained dividing the total Ah-counting by the nominal capacity of the storage battery. A related problem is the calculation of the electrical energy associated with the measured ΔSOC, when different from zero.
The main limits of such method are:

1. The total Ah-counting refers to the nominal capacity, which can be different from the actually available capacity, because the battery capacity varies with the battery ageing, the operating temperature, the discharge current rate, and so on.

2. The battery charge and discharge efficiencies change with SOC and are not considered in the Ah-counting, which assumes the efficiency constant and equal to 1. The available capacity at the end of the operation (or test sequence) depends upon the operating point into the SOC range during which the battery has been charged or discharged.

3. Batteries, other than lead-acid types, require further investigation to clearly identify other correction factors. For example, NiCd batteries deteriorate mainly because of electrolyte losses. Their capacity can be determined with a small error by measuring the internal resistance IR (with a charge current pulse) and using the following equation:
   $Q_{ext} = a\ ln(IR) + b$, where Q_{ext} is the extracted capacity, IR is the internal resistance, and a and b are constants.

For the first problem, exclusively the nominal capacity variations due to the ageing effect are considered, in order to quantify the importance of neglecting such an aspect. As an example, a lead-acid battery subjected to constant current deep discharge cycles (SOC=20%) can be considered.

For the second problem, the control strategy of HEVs (at least the battery management unit) may impose that the storage system is operated in a fixed SOC range, maximising the battery efficiency and limiting significant variations during charge and discharge phases.

As a practical recommendation and proposal to solve such accuracy problems, which are online with the current trend of verifying performances at varying age (distance travelled) of any vehicle, a periodic test (e.g. every 50.000 km), should be performed. Such test should be aimed at updating the values of chief parameters related to ageing effects (e.g. battery capacity versus temperature and rates) and ΔSOC determination.

Subtask 2.6 Comparing electricity and fuel consumption

Conventional vehicles and vehicles with alternative powertrains consume energy (fuel and/or electricity). Most of them also produce emissions while driving. For an honest comparison of technologies not only the direct energy consumption and direct emissions during driving need to be considered, but also the indirect emissions and energy losses occurring e.g. in the production of fuels and electricity as well as in the manufacturing and disposal of vehicles. In general quantifying and comparing overall energy consumption and emissions of vehicles with different powertrains is necessary for:

1. R&D purposes
2. scientific purposes
3. user and market related purposes
4. legal and policy purposes (including emission regulation and homologation)

For purposes 1 & 2 researchers have the freedom to choose the system boundaries and the methodology according to the needs of the study. Unification, however, would benefit international scientific discussions. Especially purposes 3 & 4 require a simple and clear procedure for expressing electricity and fuel consumption in a single unit and for accounting relevant indirect emissions and energy losses in the overall comparison.

Defining system boundaries is an important part of the methodology. This determines to which extent a complete "well-to-wheel" analysis or life-cycle analysis (LCA) is performed. Indirect emissions and energy losses can be attributed to the various steps in the energy chain or life cycle using two main methodologies:

- incremental emissions & energy efficiency
- average emissions & energy efficiency

The first methodology is more scientifically correct, but requires complex modelling of the energy system and detailed assumptions on the size and time distribution of the incremental energy demand. This in itself introduces uncertainties in the results. The second method is more straightforward and eliminates a lot of uncertain assumptions at the expense of some scientific accuracy. In general the "average method" seems most appropriate for generating robust numbers (conversion factors) that have general validity.

The definition of appropriate standardised test procedures for vehicles with alternative powertrains is in progress in Europe and elsewhere. The results of the MATADOR-project contribute to this process. Standardised test procedures are a necessary basis for the definition of emission regulations and possible future regulations on energy consumption. In addition to the definition of measurement procedures, it is of paramount importance to develop evaluation procedures that allow the assessment and comparison of all relevant direct and indirect energy impacts and emissions of vehicles with conventional and alternative powertrains. Inappropriate test and evaluation procedures may lead to the market introduction of vehicles that are sub-optimal with respect to the environmental policy goals.

The following actions are recommended to the EU in order to arrive at useful conversion factors for the above mentioned purposes:

- Formulate a practical common methodology for calculating indirect emissions and energy consumption on the basis of final electricity & fuel consumption at the vehicle level. It should be possible to apply the method both on a European and on a national level. Special attention should be paid to the role of renewable energy sources;
- Conversion factors should preferably be based on average efficiencies and average indirect emissions of electricity production and fuel refining in Europe;
- In comparing the total energy consumption of vehicles with different powertrains only the total consumption of non-renewable energy is relevant. When comparing CO_2-emissions one has to assess the net CO_2-emission, which for e.g. biofuels is relatively low, even

though the emissions at the vehicle level are comparable to those for conventional fuels. In comparing pollutant emissions, all energy sources need to be taken into account;

- It seems appropriate to limit the system boundary to the energy input flows to refineries and electricity generation plants in Europe (or in a country if factors are generated on a national level). For fuels and electricity imported from outside Europe average conversion factors may be assessed;
- Establish a formal body (organisation or network) that collects all data necessary for applying the common methodology, and that generates conversion factors on the EU level and on the national level for all energy carriers that are currently used on a significantly large scale (gasoline, diesel, LPG, electricity, and maybe a few more). This body should periodically update the conversion factors to account for changes in the energy supply and demand systems. When new energy carriers are introduced to the market this body should adapt the methodology to include the new energy carrier and should perform an assessment to generate conversion factors;
- Define appropriate emission legislation and associated test procedures for vehicles with alternative power trains;
- Allow each country to define national conversion factors based on the same methodology and data set.

For scientific purposes and for general policy making it is also useful to be able to express the different environmental and energy impacts of a vehicle in a single number in order to compare the overall environment-friendliness of vehicles with different powertrains. Methodologies are being developed for this, but it is considered outside the scope of the MATADOR-project to make recommendations on this issue.

Subtask 2.7 FCEV Test Procedures

Problem definition

The ongoing development of FCEV creates uncertainties about vehicle classification and definition of measuring and testing methods because of the various fuels proposed, the different fuel cell types, and the various driveline configurations. FCEVs can be similar to ICEVs and HEVs with similar testing problems, but with the main difference of having an onboard energy source (the FC) other than a thermal engine.

The definition of a new test procedure for FCEVs and, subsequently, a standard for measuring energy consumption and emissions presents common aspects to the introduction of a new product with peculiar features, which have been the basic assumption for the analysis carried out in this subtask work:

1. FCEVs are available only at prototype/demonstrator level with a few pre-series products;
2. The configurations investigated until now are various and may present testing problems similar to ICEV, BEV, and HEV, depending on the system chosen.
3. No standard testing procedure is presently available specifically for FCEVs. Current or draft CEN standards only consider BEVs, HEVs with thermal generators and ICEVs.
4. The use of some tests of existing testing procedures for BEV, HEV and even ICEV seems to be applicable, at least for evaluation purposes. For practicality and comparability, it seems wise to look for incremental adaptation to or combination of elements from existing standards.

Three main practical and technical issues have resulted from these preliminary considerations:

1) the FCEVs must be correctly included in the a general classification;
2) the specific needs for measuring FCEV energy consumption and emissions must be defined by, eventually, combining or adapting existing standards for ICEV, BEV, and HEV (with thermal engine); and, finally,

3) the heating energy and the start up time must be analysed to verify whether there are specific features impacting the testing method. Due to the limited availability of experimental results and products, the analysis has been carried out at the major candidate technologies for the fuels (hydrogen, methanol and gasoline), the FC type (proton exchange FC) and configurations.

General classification

The categorisation of FCEV is functional to the definition or to the application of specific testing procedures. The variety of possible fuels and configurations necessitates classification in a systematic way in order to favour the use of specific testing procedure.

Energy consumption and emission measurements

The different fuels and configurations normally require the application of different measuring techniques not always considered in existing (draft) standards. The impact of the problem is relevant particularly when only H_2 is used as fuel. Present standards are exclusively devoted to carbon-based fuels and electricity.

Start up time and heating energy

The problem of start up time is similar to the problem of cold start in ICEVs. Apart from the practical aspect of the vehicle readiness, the impact on the vehicle consumption and emission may be significant depending on the type of fuel and configuration. A one-minute start up time is now considered as the minimum goal of most development programs and has been obtained in FCEV and FCHEV (using battery for the initial vehicle start). Studies have confirmed that a one-minute start up time may imply a consumption of 200 Wh from the battery when that directly powers the electrical motor. This confirms that the impact of start up time is quite negligible, while results of analysis for the effects on emissions require further research for various configurations and fuels. The main detrimental influence on emissions is expected when a fuel reformer is used.

The energy losses are related to the necessity to heat up the fuel cell stack and the fuel reformer, which normally operate at temperatures significantly higher than the ambient temperature (at minimum 80 °C for PEFC stacks). Chemical processes involved in FCs during operation are exothermic, and then FCs will be maintained hot whenever the systems are used for long time or even with short standstill periods. This FC can work at a reduced power output even at room temperature, when no fuel reformers are used. In general, the amount of energy required for making the FC system fully operational seems not relevant with respect to the energy needed during a standard driving cycle. Further studies are needed to quantify the impact of heating losses.

Status of standard procedures

There is no specific standard in the world considering specifically FCEV test procedures. A few years ago EUCAR proposed a test procedure for FC stacks, which, however, never reached a final version. The European standard setting body CEN (TC 301 WG1), has started working on the classification and basic definitions. The “Part 3: Other electric hybrid vehicles than those fitted with a thermal machine” of the European Standard prEN 1986, under the general title “Electrically propelled road vehicles – Measurement of energy performances” is in abeyance. According to the last recent CEN TC 301 meetings [2], FCEV should be included in future standards prEN 1986-3 (for energy consumption) and in prEN 13444-2 for emissions.

FCEV Classification

Two large categories of FCEVs have been proposed. It seems reasonable to consider two large categories and then subdivide them in two other subcategories, based on fuel types.

1 ***Category 1 as an ICEV*** (FCEV without energy storage system other than the fuel tank)
   1.1 Carbon-based fuel
   1.2 Hydrogen

2 ***Category 2 as an HEV (FCHEV)*** (FCEV with an energy storage system other than the fuel tank)
   2.1 Carbon-based fuel
   2.2 Hydrogen

Both categories include the direct methanol FC systems.
This classification is consistent with that proposed by CEN 301/WG 1. The main difference consists in the elimination of non-carbon based fuels different from H_2, e.g., hydrazine used in space applications.

Recommendations for energy consumption and emission measurements

Energy consumption
The present standards for ICEVs and HEVs calculate overall energy consumption by measuring the emissions of HC, CO and CO_2. This method assumes the use of carbon-based fuels and the application of carbon atomic equivalents and measured gas emissions for calculating the energy consumption. This method is obviously not applicable when pure hydrogen is used. The considerations are applicable also to FCHEVs.
Energy consumption for carbon - based fuels
The existing testing methods for ICEV and HEVs can be applied without problems. Attention can be given to the possible sources or outlets for emissions. Recent results of prototypes FCHEV and fuel reformer tests confirm very low exhaust emissions. The use of cleaning and exhaust removal systems to improve the quality of the reformate gases before entering the fuel cell stacks must be carefully evaluated in order to consider possible temporary accumulation of exhaust gases.

Energy consumption for pure hydrogen
In case of H_2-fed FCEVs, there is the need to directly measure the consumed hydrogen. In a FC generator, the fed H_2 is partially converted into water (steam water) and partially recirculated, since it is not used in the reactions. The produced H_2O depends on the consumed H_2 and on both the inlet air composition **and** the humidification process of the reaction gas inside the stack system. Two measuring methods can then be recommended: the measurement of H_2 needed to replenish the storage tank, or the continuous measurement of the fuel supplied to the FC stack. The first one seems to be more practical for testing purposes if an external tank can be used.

Emission measurements
The emissions depend on the characteristics of the inlet fuels. There is no need for any regulated measurement, when pure H_2 is used. For carbon-based fuels, the measuring equipment can be set up after an investigation of the composition of the used fuels and the emissions that must be measured. The analysis of fuel compositions of major fuel candidates (methanol and gasoline) and some experimental data show that regulated emissions are very low in absolute values. Existing (draft) standards (prEN 1986-2 and prEN 13444-1) can be applied.

<u>Start-up time and heating energy</u>
The start-up time does not significantly affect the energy losses and emissions, when H_2 is used as fuel. Present goals of major development programs of one-minute start-up time for the FC generator can make this problem negligible for measuring purposes.
The energy losses due to the heating/cooling of the FC stack and reformers vary extremely and depend on driveline configurations and driving cycles. Specific need for measuring such losses can arise only when long standstill periods are part of the driving patterns. For comparative assessment, rather than for homologation, standstill periods and related heating energy should be recorded to improve accuracy and significance of energy consumption comparisons.

Subtask 2.8 Driving cycles for LD vehicles

An important focus of the research in the MATADOR Task 2 project has been driving cycles. The characteristics of a driving cycle (average power, dynamics, etc.) strongly influence the energy use and emissions and also influence the results of comparisons between vehicles with different propulsion systems. In this report, the influence of driving cycle characteristics on (electric and hybrid) driveline behaviour and environmental performances is evaluated by means of computer simulation and vehicle measurements.

Existing driving cycles

At this moment, a large number of different driving cycles are available for LD vehicles. Several of these are used for legislative testing, while others have been derived from recorded driving patterns and are used for R&D purposes.

The three basic legislations covering the testing of light-duty road vehicles use the following driving cycles:
Europe (West and East, as well as some countries outside Europe)
- New European Driving Cycle (NEDC)

United States (and Canada, several South American and many Asian countries)
- City Cycle (USFTP-75)
- Highway Cycle (HWFET)
- SC03 Air Conditioning Cycle (from January 2000)
- US06 High Speed/High Load Cycle (from January 2000)

Japan
- 11 Mode Cold Cycle
- 10-15 Mode Hot Cycle

Besides these cycles, many institutes, organisations, and universities develop and apply driving cycles from recorded driving patterns that are to represent real-life driving conditions. Examples of these cycles are:
- MODEM
- HYZEM Urban, Rural, and Highway
- Aachen City Cycle
- Casaccia Cycle

The first two cycles are the result of an extensive research on European driving behaviour, conducted by the French research institute INRETS.

All of these driving cycles have different characteristics. In Appendix A of Subtask 2.8, background information and methodology for the development and characterisation of driving cycles is presented. Two of the parameters that can be used to characterise the demands of a driving cycle are the average speed and the Relative-Positive-Acceleration (RPA – m/s^2), which is an indication for the dynamics of a cycle. Research on HD vehicles shows that these parameters have strong correlation with the energy consumption of the vehicles [2]. With increase of these values the wheel energy demands will also be higher. By putting these parameters in one graph, the mutual relation between cycles can be indicated (Figure 32).

Differences between cycles are clearly visible here and most remarkable is that the older legislative cycles (black markers) are less demanding than the more recently developed speed profiles of the MODEM and HYZEM cycles. This indicates that the (modal) standard cycles, especially in Europe and Japan, bear relatively little resemblance to the conditions of actual vehicle use.

This issue of representativity is also under discussion for testing of conventional ICE-vehicles, as results from standard tests are not only used for technical evaluation and homologation procedures but also for e.g. the calculation of energy consumption and emission factors used in policy studies or for policy measures stimulating clean and efficient vehicles. For vehicles with electric and hybrid power trains the problem is even more pressing as vehicles can be designed and optimised for very specific purposes and, therefore, may perform completely different on different driving cycles.

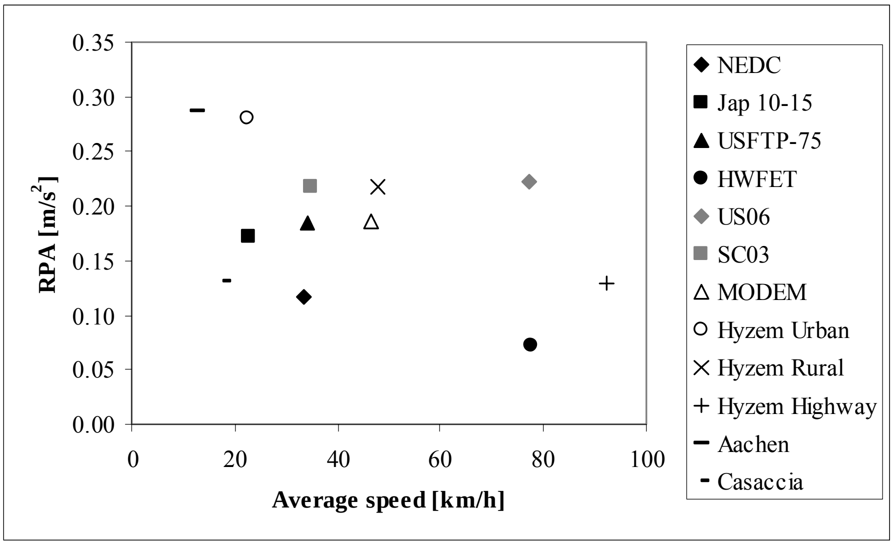


Figure 32: RPA versus Average speed for several driving cycles

Influence of the driving cycle on driveline behaviour and energy consumption
Light-Duty vehicle technologies are compared and evaluated on the basis of the measurement results over driving cycles. It is known that the driving cycle characteristics influence the environmental performance (energy consumption and emissions) of a vehicle. In the past, vehicle and driveline technologies were quite similar, so that the effect was the same for all vehicles. This will change with the introduction of alternatively powered vehicles. In order to make a consistent comparison of technologies, it is necessary that a reliable and representative basis for comparison is available. The research of this subtask concentrates on studying this aspect of driving cycles by means of computer simulation and vehicle measurements.

SOC behaviour
In simulations it is found that the general driveline behaviour shows similarities in the response to different driving cycles. Most important parameter here is the State-of-Charge of a storage system in a hybrid vehicle, which will (eventually) show to have periodic behaviour. As an example the result of simulations of a Series Hybrid Electric vehicle are presented in Figure 33. In practise, this SOC behaviour might not be found due to the fact that a human driver is not capable of driving several driving cycles in exactly the same way. The stimulus posed upon the driveline system then is not as nicely periodic as in the simulations, and the system cannot

adjust and settle for periodic behaviour. Furthermore, the real-life control might significantly influence the system's response, since the powertrains are highly complex and encompass many more system limits than the computer models (for example the influence of temperature on engine operation).

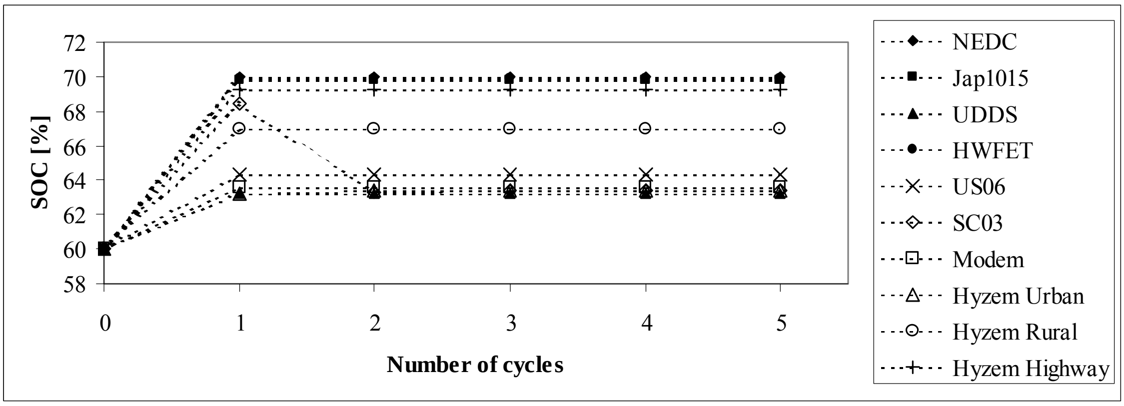


Figure 33: Influence of driving cycle; initial and final SOC for LD SHEV over 5 consecutive cycles

Energy consumption

Once the effect of ΔSOC (Subtask 2.4) is accounted for, the actual energy consumption of a vehicle is determined and a comparison of different drivelines over different driving cycles can be made.

In one of the simulations, five vehicle models were evaluated over the ten driving cycles listed in Figure 33. The energy consumption for these five models is plotted in Figure 34. The influence of different driving cycles is plainly visible. Each cycle results in a different value for the energy consumption and each driveline responds according to its own specific characteristics.

Important note for all results obtained from the simulations is that the figures are <u>not</u> meant to rank different driveline systems mutually, yet only to illustrate the differences between cycles. None of the models has been validated to the extent that energy consumption can be considered as a meaningful prediction of the actual consumption of a real vehicle. The models do, however, contain all the essential physics so that the response to changing test conditions is adequately simulated. Also due to the different energy sources (electricity, petrol, hydrogen), the figures do not provide an honest and consistent basis for comparison.

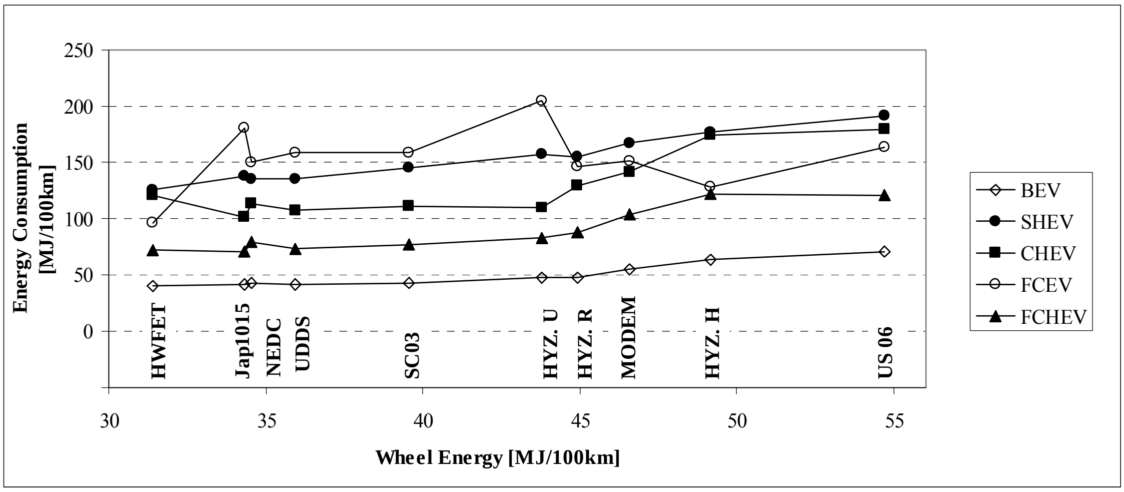


Figure 34: Energy consumption for the LD vehicle models over different driving cycles (ranked for wheel energy demand)

Figure 34 provides information on the relation between the energy demand at the wheels on a certain driving cycle and the energy consumption of those vehicles. The required energy at the wheels, however, depends on several vehicle parameters (amongst others mass, air resistance, etc.) and cannot be measured in practise. The parameters 'RPA' and 'Average speed' are representative for the cycle demands. In Figure 35, the energy consumption of the BEV model and that of a Toyota Prius are plotted for several cycles as function of these two parameters (mind the different Z-scales). These figures are just examples of all the results. In the Appendices, similar figures for other simulations and measurements can be found.

Figure 35 clearly shows that increase of RPA and/or Average speed results in a higher energy consumption. Both in the simulations and the measurements, only one trend is found and this leads to the following conclusions:

1. More demanding cycles generally require more energy. It is possible, though, that with increasing demands at the wheels the overall driveline efficiency increases to such an extent that the energy consumption decreases (the relation between energy consumption and wheel energy then would be parabolic).
2. The influence of different driving cycle characteristics is different for different drivelines.
3. A representative test value (for honest ranking) consequently can only be found when a representative cycle is used.

The introduction of dedicated purpose designed Light-Duty vehicles seems to require that the test enables to account for this specific use. Just like in the current European procedure, it might be necessary to define several cycles (e.g. urban and extra-urban, or urban, rural, and highway patterns) in order to obtain results that represent the actual vehicle use.

The above considerations lead to one main overall conclusion:
In order to enable a consistent comparison, it is essential (maybe even crucial) to use a driving cycle that is representative for the real-life operating conditions of a vehicle. Representativity of the driving cycle implies that the time-speed profile not only has representative average dynamics. It also requires that the cycle has a representative mix of road types (urban, rural, highway) and that the cycle has representative length. This assures a representative weighting of e.g. the steep acceleration and deceleration associated with the highway part of the cycle, and it may also help to solve problems that are more specific to vehicles with advanced propulsion systems.

Recommendation

In order to get more insight into all related aspects in testing (advanced) vehicles, it is highly recommended that more measurements are conducted on vehicles with different hybrid or other alternative powertrains. Especially the influence of driving cycle characteristics on the exhaust emissions still has to be determined. Due to the very limited availability of hybrid vehicles, it has not yet been possible to investigate this. It is expected that the differences between drivelines will show even more clearly in the emission results than that they already do in the energy consumption figures.

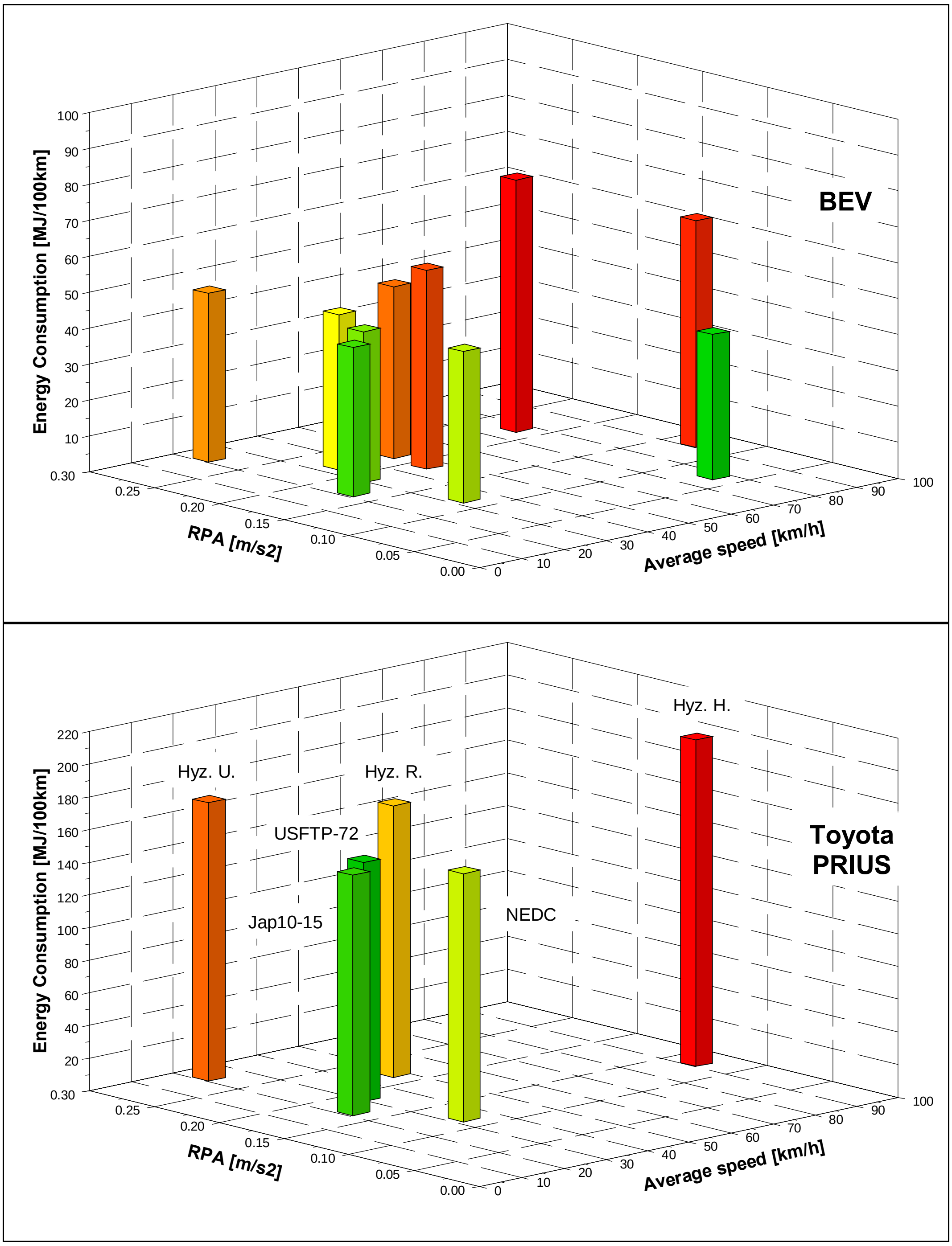


Figure 35: Energy consumption for BEV and Toyota Prius vs. RPA and Average speed

Subtask 2.9 Test methods and driving cycles for HD vehicles

In this subtask report, problems have been identified that arise when current HD test procedures are applied to non-conventional HD drivelines (e.g. BEV, HEV, and FCEV), and requirements for future test procedures have been outlined. As a result of this analysis, there are four options for test procedures that can be distinguished. In order to provide clear interpretation of the argumentation, it is first necessary to clarify the following terminology:

- *Driving condition*: The driving behaviour of HD vehicles, as it is found in real life on the road.
- *Driving pattern*: A recorded speed-time pattern of (real life) driving conditions. The size of this pattern may vary from a few hours to months of data.
- *Representative driving cycle*: A test cycle of limited length (e.g. 30 minutes) that is derived from the driving pattern via a statistical method, which is representative for all of the recorded data in the driving pattern, and thus for the average real-life use.

More information on this subject can be found in Appendix A of Subtask Report 2.8 '*Driving cycles for LD vehicles*', and can also be found in [8].

Now the identified options are discussed:

1. Current 13-mode test procedure without modification
   This procedure is not considered useful, as only the engine is tested, thereby neglecting the driveline behaviour. Specific characteristics of non-conventional HD drivelines (e.g. regenerative braking possibility, engine switching on/off) that have a profound influence on the environmental performances are not accounted for. Furthermore, the engine may be operated in only one or more operating point(s) that do not, or most likely, will not necessarily coincide with those of the 13-mode test.
   At this moment the procedure is not suitable even for conventional engines, as the engines undergo a static test, while transient emissions produced during real-life conditions are becoming more significant.

2. Similar static test procedure as the 13-mode test, but with adaptation of operating points
   This procedure would test the engine only in the actually used operating points. It may seem a very practical way to solve the problem of the rigid operating points prescribed by the 13-mode test. However, this procedure poses a new difficulty, as there is no straightforward method to weigh the test results of each operating point. Because this is still an engine-based test, the remark of option 1 concerning non-conventional driveline characteristics also applies for this procedure.

3. Driving cycle on a transient rollerbench
   In this procedure, the entire vehicle is tested over a driving cycle (speed-time pattern) on a rollerbench. Therefore, the driveline behaviour is implicitly accounted for. As long as the driving cycle is representative for the real-life driving pattern of the observed type of vehicle and its use, a good test result is obtained.
   From a fundamental point of view, this procedure would be most preferable. However, the required test facilities (HD transient rollerbench, dilution equipment) are expensive, and at this moment only available at three research institutes within the whole of Europe.

4. Driving cycle on a test track
   A more pragmatic way of testing is formed by measuring the power output of the ICE (or APU) together with battery current and voltage, during a driving cycle on a test track. Later on, the ICE is tested in the same operating points on an engine testbed. In case of an APU, the load is applied electrically, e.g. by using a Digatron system. The best result is obtained by subjecting the ICE or APU to the same (transient) load pattern, because then the temperature course of the engine (and possible exhaust aftertreatment equipment) is

simulated correctly. It is expected however, that even with static tests representative results can be found, especially if the ICE or APU uses only one or a few operating point(s).

Several possible test procedures have been identified and analysed. Together with the findings of the previous chapter, the following conclusions can now be drawn:

- Current test procedures for conventional HD vehicles are not suitable for non-conventional HD drivelines (BEV, HEV, FCEV);
- The testing of only the engine is not sufficient for a proper comparative test result. The driveline as a whole (or even better, the vehicle as a whole) needs to be tested on a driving cycle;
- In order to obtain a meaningful test result, the test would have to be formed by a driving pattern. This would ensure that all relevant aspects (including cold start emissions) would be taken into account in a representative way. As it is impractical to define a test in which a vehicle is subjected to many hours of driving, this driving pattern may be reduced into a representative driving cycle of more appropriate length;
- Each HD vehicle category that has a distinctive type of use needs its own dedicated driving cycle. The test cycle characteristics will have to be representative for the 'average use' of the HD vehicle category, therefore driving patterns need to be distinguished by vehicle category;
- The best way to obtain a representative test result for HD vehicles, is to use a driving cycle on a transient rollerbench. However, there are also more pragmatic (and less expensive) ways of testing that can be thought of. Especially driving a cycle on a test track seems a promising solution.

These conclusions lead to the following recommendations for future testing of HD vehicles:

- A strict subdivision of HD vehicle categories according to use patterns is needed;
- For each of the identified categories a dedicated cycle needs to be defined, representative for that vehicle type;
- Investments in HD dynamic rollerbenches are needed to obtain enough testing facilities;
- The aspect of regenerative braking on a rollerbench has to be investigated (see also Subtask 2.12 '*Regenerative braking on 2WD dynamometers*');
- Research for more pragmatic methods for testing HD vehicles in a representative way is necessary.

N.B: There are of course easier testing methods that can be thought of, that require much less effort in terms of cycle development and investments. However, the focus of this subtask is to investigate testing procedures that allow for consistent and comparable results, and give a good representation of real-life fuel consumption and emissions. This can only be guaranteed by using representative driving cycles.

Subtask 2.10 Dealing with EVs not meeting the demands of the cycle

Bench tests can be reproduced and are comparable within the same category. For this reason, they provide a useful tool for standards.
Measurements of energy consumption have demonstrated that not all test vehicles are able to complete the prescribed driving cycle, and this means that failure times are obtained that are attributable to inadequate acceleration values or insufficient maximum speeds. It therefore appeared that a direct comparison between the individual vehicles in terms of energy consumption would be difficult.

The maximum electric currents for accelerations and at high speeds produce losses in the battery and the electric conductor. These losses are described by the formula $P = R * I^2$. If BEVs are

used with a high current for a long time these losses will be significant. In the same time the capacity of the battery will decrease.
The influence of this RI^2-phenomena is certainly strong if the accelerator pedal is fully depressed. It is obvious that either the weight of the battery and the maximum electric current are crucial for BEVs.

HTA Biel-Bienne examined the problem with practical measurements on the test bench in Biel. The “low-cost” method developed for the “Large scale experiment for lightweight electric vehicles in Mendrisio” was used for this purpose.
In addition to the measurement at HTA Biel, TNO Automotive (Delft, The Netherlands) carried out a number of simulations.

Both the measurements from HTA Biel and the simulations performed by TNO show that energy consumption will rise when a BEV produces some failure time. The simulation results show a highest extra energy consumption of about 15%. Hence the failure time is of significant importance for energy consumption.
The same can be concluded for the SHEV model simulation, since both vehicles have the same mass and drive powers.

Conclusions
The fact that a vehicle produces failure time on the test bench is obviously important information. Therefore this value has to be reported according to the standard EN1986-1.
The amount of failure time allowed during the gear shifting and below 50 km/h, should not be included in the failure time.

Because of the RI^2-phenomena, EVs will always produce great losses at high velocity. Hence this kind of vehicle has a higher efficiency at lower speed. Therefore, it is not wise to use a test cycle with a maximum speed over 80 km/h.
EN1986-1 already offers the possibility to perform the measurement with the urban cycle with a maximum speed of 50 km/h. This is already a possible solution for the measurement of BEVs with a maximum speed below 120 km/h. But for short range use between suburbs and cities the urban cycle is certainly not an optimal solution.

Most of the actual BEVs are not able to drive with a maximum speed of 120 km/h. If the number of BEVs with a maximum speed of about 80 to 90 km/h will increase in the future, an extra-urban cycle for BEVs has to be discussed.

Definition of failure time
Failure times refers to the amount of time during which the vehicle being tested is unable to perform the prescribed driving cycle due to low acceleration or insufficient maximum speed.

In the simulations by TNO, failure time is counted when the speed deviation is more than 1 km/h (it is within a band of 0.2 km/h when sufficient power is available).

According to EN1986-1 speed tolerances of ±2 km/h are accepted. If the speed of the vehicle is lower or higher than this tolerance the test bench will count this time as failure time.
This is the definition used for the measurement by HTA Biel.

Below 50 km/h EN1986-1 allows a deviation beyond the tolerance as follows:
– at gear changes for a duration less than 5 s, and
– up to five times per hour, for a duration less than 5 s each
If there is a gear shifting needed above 50 km/h there should also be an allowed amount of time out of tolerance.

It seems obvious that the allowed amount of time out of tolerance should not be included in the failure time.

A possible formula for the determination of the failure could be:

$$FT = t_{out} - t_{gs} - t_{50}$$

FT	=	failure time	[s]
t_{out}	=	total time out of tolerance	[s]
t_{gs}	=	the time used for all gear shifting (maximum value of 5 seconds allowed for one gear shifting)	[s]
t_{50}	=	failure times allowed below 50 km/h (five times per hour, for a duration less than 5 s each)	[s]

Recommendation
For standards measurements test benches are certainly still a very useful tool. Because the results of such measurements are usually compared with each other, failure times should be recorded.
Information about energy consumption should also include the failure time.

There is a need of a precise definition of failure time. The formula above could be a possible solution. For such a definition it would be helpful, if not only the deviations beyond the tolerances are reported but also the allowed times for gear shifting and the allowed periods of failure below 50 km/h.

Subtask 2.11 Accuracy and tolerances

In this report, the influence of accuracy and tolerances in testing procedures on the test results has been investigated. In order to do so, various computer simulation experiments and vehicle measurements of mainly mid-class passenger cars with (hybrid) electric propulsion system were carried out.

Research focussed on the following topics:
- Accuracy and specified tolerances with which the desired vehicle speed was followed (computer simulations: simulations of standard speed, measured speed profile and tolerance-adjusted standard speed; vehicle measurements: comparison of different human drivers)
- Definition and influence of shifting strategies in case of vehicles with manual transmission (computer simulations and vehicle measurements)
- Tolerances for the powertrain temperature at the beginning of the testing procedure (vehicle measurements only)

It was shown in general, that while staying within the specified speed tolerances, driver behaviour and the consequently followed speed track have a strong influence on energy consumption and on the start/stop characteristics of the internal combustion engine of hybrid electric vehicles. The start/stop frequency of the engine is related to the pollutant emissions. Especially control strategies which have a direct dependency between start/stop management of the combustion engine and the driver pedal positions may react sensitively on the driver behaviour.

For charge-depleting hybrid vehicles, both electric and fuel consumption change significantly if the simulated speed track differs only slightly from the desired cycle speed. The consumed electric energy increases if the vehicle speed is closer to the lower tolerance bound, and decreases if the vehicle speed moves towards the upper speed tolerance. Differences can amount up to 8% (parallel hybrid vehicle, comparison of standard speed with real speed profile). The trend in fuel consumption seems to be the opposite, where differences of 10% are seen. There are however exceptions to this. For these vehicles, also the number of engine starts per cycle is influenced by the followed speed track. This is on the one hand caused by vehicle-speed thresholds in control strategy and on the other hand by the boost operation of the engine in those cases where power demand is high (e.g. because of high battery weight) and maximum power of the electric motor is insufficient (parallel hybrid). In the Aachen-city cycle for instance, this causes the engine to be started twice as often in a real speed profile simulation when compared to a standardised speed profile simulation.

For the simulated charge-sustaining hybrid electric vehicles, the noticed differences in fuel consumption between results obtained following the standard profile and results obtained following a measured speed profile were small, but significant for each driving cycle. The comparison of the SOC-corrected fuel consumption in the cycles with fluctuations in vehicle speed could prove differences in fuel consumption of up to 0.2 l/100km (4%). The simulation results for these vehicles also showed similar ICE start-up behaviour as for the charge-depleting hybrid vehicles.

Measurements on the Audi DUO showed that a well balanced driver follows the desired speed curve best, the energy flows (fuel and current) are much more steady as for a more nervous driver. The actual velocity stays within the defined tolerance band for both types of driver though. The fuel consumption is considerably higher for a more nervous driver, electric energy consumption is influenced only slightly by different driver behaviour.

However, due to a fundamentally different use of the pedals (while still following the desired speed within the specified tolerances), driver influence can increase fuel consumption by up to 58%, while a decrease in electric energy consumption of 25% occurred in this case. This resulted from a different use of kickdown in the extra-urban part of the NEDC. If the driver does not allow significant differences between desired and actual vehicle speed, kickdown is applied much earlier, resulting in longer engine operation periods. This changes the distribution of fuel and electric energy significantly, which is of main importance for charge-depleting hybrid vehicles (as in contrast to charge-sustaining hybrid vehicles, where the different use of engine/motor is to a large extend corrected by the SOC correction method). If the traction battery is recharged during engine operation also, as in case of the Audi DUO, this effect is increased. For other hybrid vehicles, also the use of other driver pedals like brake and clutch may cause the control strategies to be operated differently.

One option to reach measurement results with a higher reproducibility is to perform the driving cycle with an automatic driving system instead of a human driver. Tests with such a system however have shown, that energy consumption strongly depends on the controller settings. So measurement results may very well vary from one system to another.

Also, the choice of shifting points for hybrid electric vehicles with manual transmission has a significant influence on the energy consumption and ICE start/stop characteristics. Simulation results from the charge-depleting parallel hybrid vehicle showed differences in fuel consumption of up to 0.92 l/100km and differences in recharged energy of up to 18%. Electric energy and fuel consumption generally increase when the upshift speed thresholds in the shifting strategy are increased. The increase in electric energy consumption is only shown in some driving cycles though. For this vehicle, the choice of shifting points also influences the number of ICE starts per cycle for boost purposes. In fact, the choice of shifting points may in some cases decide whether the cycle is driven pure electrically or in hybrid mode. A comparison of the number of ICE starts shows, that only for low upshift thresholds an increase is observed. As soon as the electric motor is able to deliver its maximum power over a broader speed range, the number of ICE-starts remains constant. Again some exceptions are seen in this case, which are mainly caused by a lack of electric motor power at higher vehicle speeds.

The choice of shifting points also influences the warm-up time of the internal combustion engine after a cold start (Warm-up time in this case means the period at the beginning of the test-cycle in which the ICE is operated permanently in order to reach normal operation temperatures. Such behaviour has been seen on the Audi DUO and on the Toyota Prius). When driving mainly in lower gears, the engine warms up much quicker (20%), generally because of lower engine efficiencies at higher ICE speeds. The decrease in fuel consumption can amount up to 6% (Audi DUO).

Generally, the power train's starting temperature has a much stronger influence on energy consumption for hybrid vehicles than for conventional vehicles. The ambient temperature range from 20 °C to 30 °C at which the vehicle has to be soaked and operated during the test (consequently, this is the starting temperature of ICE, tyres etc.), as well as the specified coolant and oil temperature tolerances of ±2°C from ambient, are found to be to big. For the internal combustion engine, a difference of 4 °C in starting temperature already results in a different warm-up time, which is controlled by coolant temperature, and can cause a difference in fuel consumption of about 7% (Audi DUO). The effects of different initial temperatures on SOC correction methods for charge-sustaining hybrid vehicles are still unknown.

Consequently, following recommendations can be made for HEV testing procedures:

- Human drivers should perform the driving cycles as stated in standard procedures. Also, the speed tolerances should be maintained. The manufacturer should provide a list of operation procedures however. On this list, the driver would be informed at what times/operating points which pedals/pedalpositions (e.g. kickdown) should be applied. For conventional vehicles with manual transmission this is already done for the clutch pedal at standstill in the European procedures.
- Also, the shifting points should be defined for hybrid vehicles with manual transmission. The use of the existing points for conventional vehicles seems obvious. Since hybrid vehicles are often designed for many different applications which may influence the normal use of the transmission, manufacturers may provide a list of shifting points themselves, if can be shown that the vehicle is not able to follow the speed track within the specified tolerances when driving by the default shifting points.
- In order to keep the influence of ambient temperature as low as possible, the starting temperature of the internal combustion engine should be defined at 25 °C ± 1°C, measuring the temperature with a thermal sensor at the outside of the engine cylinder head. As an alternative, the temperature tolerances for the conditioning room could be tightened at this value.
- As a means of minimising the influence of remaining inaccuracies on energy consumption and emissions, the driving test should be performed several times (e.g. three times). The results to be displayed would then be determined by calculating the mean values of the separate tests.

Further research on this topic could should include driver-, shifting- and initial temperature influence on pollutant emissions. Also, the topic could be extended to the accuracy of measurement equipment. On a broader scale, also the proposed recommendations for testing procedures could be validated.

Subtask 2.12 Regenerative braking on 2WD dynamometers

Problem definition

When testing a vehicle on a 2 Wheel Drive Dynamometer, the wheels of the non-driven axle are not rotating, thus no energy can be dissipated in the braking system on this axle. Hence, the load simulation on a 2 Wheel Drive Dynamometer is always through the driven axle, which means that the energy, which can be regenerated, is transferred through this axle. This can generate a difference in the simulated road load on the roller bench (RB) and the actual road load on the road:

> When the performance (or energy consumption) of a vehicle is tested, the vehicle is always driven according to a predefined speed cycle. During these cycles there are predefined deceleration periods. During such a period the available amount of energy, which can potentially be regenerated, is significantly higher then under identical road conditions, since the mass simulation is only through the driven axle.
> For example, compared to identical road conditions the following consequences can be identified:
> 1. The additional braking system will be activated and the braking system of the driven axle (i.e. wheels) will dissipate a certain **additional** amount of energy, in order to meet the required speed limit.
> 2. Another consequence could be that the regenerating system would regenerate more energy, when an adaptive braking strategy is applied.

Concluding: Due to the fact that the non-driven wheels cannot dissipate energy, an error **may** occur in the load simulation of the vehicle during the test, in comparison with road tests.

The problem previously described is in this report referred to as: "The 2 Wheel Drive Dynamometer Regeneration Error" (2WDEr).

Quantification of the problem

In general it can be concluded that:

1. The commercially and presently available conventional BEVs are not affected by "The 2 Wheel Drive Dynamometer Regeneration Error", due to the fact that regeneration capabilities are controlled by vehicle speed;
2. With an advanced hybrid drive train configuration, like the Toyota Prius, the influence can be neglected (using the results of the currently conducted tests).
   - 2.1. The error is approximately 1% for fuel consumption, on the NEDC (with hot start) on a 2 Wheel Drive Dynamometer.
   - 2.2. The influence appeared to be zero during a test where the energy consumption was compared between a random driven cycle (and simultaneously recorded) in a typical Japanese urban surrounding and afterwards simulated on a 2 **and** 4 Wheel Drive Dynamometer, separately;
3. Simulations using the model in figure I, showed that a maximum regenerative braking strategy (MAX: Z=Y–X) resulted in a 2WDEr of 13% difference in energy consumption. For the proportional regenerative braking strategy (PROP: Z=½Y) this resulted in a 2WDEr of 6%. Both using the demanding HYZEM Rural cycle.

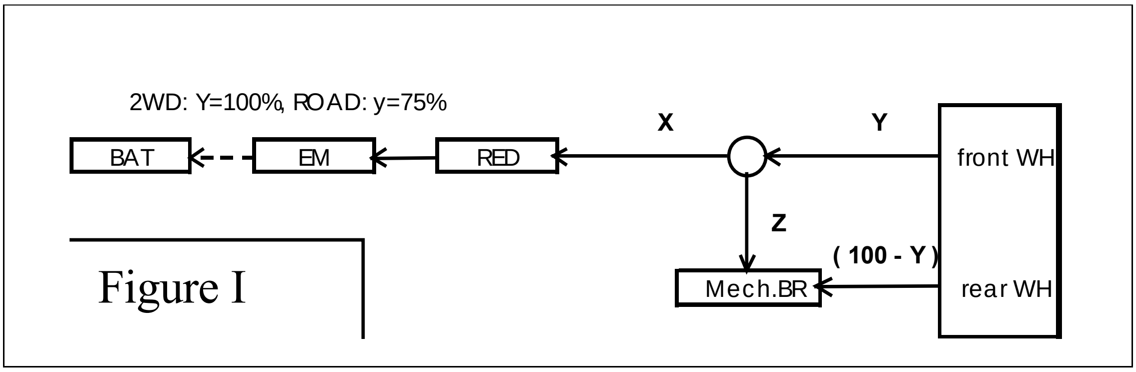


Figure I

The simulation model MAX is quit similar to the strategy used in BEVs evaluated here, with the restriction that the regenerating current is limited to a lower value.

Existing standards

In the existing standards there are no correction methods indicated. An exception to this "rule" is the test proceeding J1634, which contains a mechanical correction procedure for vehicles with regenerative capacities on 2 wheel dynamometers. The correction is established by applying a constant retarding force when the vehicle brakes are applied. Either operated by push button or switch controlled by the taillights or brake pedal. The desired braking force could be calculated prior to the test for each vehicle and used test cycle: $F_D = m * \bar{a} * k$. k is the fraction to the non-driven axle.

Possible solutions (studied)

For the vehicles that are presently (commercially) available, there is no need for a correction method. Since these vehicles are using a more elementary regeneration strategy, which is dependent on the vehicle speed only, maintaining a limited regeneration current.
However, simulations indicate that braking strategies may lead to an influence on the energy consumption when more sophisticated strategies are applied.

The literature study indicates that a correction method can be found in an additional braking force during deceleration periods.

The simulations indicate that a correction procedure might be found in a numerical correction method. Comparing the energy consumption with and without regeneration, obtained from road and test rig measurements, with simulation results, obtained through different braking strategies. In this way a good impression can be obtained of the error due to the "Regeneration Problem". A parallel can be seen with the ΔSOC problem.

Restrictions and remarks for the (studied) solutions

Simulations showed a significant influence of the regeneration problem. But the simulated braking strategies appeared not to correspond to the strategies applied in the presently available vehicles. The Toyota Prius, however, has a braking strategy, which has certain similarities with the proportional user defined strategy, used in the simulations.

The mechanical correction method as indicated in the J1634 standard, can only be applied when the braking ratio over the front and rear axle is either constant or can be predefined.

The advantages of this system are:

1. It can be applied on the available 2 Wheel Drive Dynamometers;
2. The control of the braking force can be sophisticated and (in principal) dependent on several parameters.

N.B. The correction method can be implemented relatively easy in an electronic dynamometer (no mechanical mass simulation). The vehicle mass is then an input parameter for the controlling system, and can thus (again relatively easy) be made dependent on (other) parameters.

The disadvantage is general: every additional system introduces an extra error. But the error is inherently significant when the additional system is dependent on measured parameters, in this case e.g. vehicle mass (constant), speed (variable), braking strategy (dependent of SOC, deceleration, etc.).

Another disadvantage is the definition of the actual braking strategy of the vehicle to be tested, which is obviously necessary. Since this aspect is a part of the total driving strategy, it most likely is not available. Which means that either it must be made available by the manufacturer, or it must be obtained by testing. In the latter case there always is the relevant question "Is the obtained strategy complete and adequate for the simulation process".

Homologation testing versus technology assessment

Since the error, which is introduced by the difference in road load simulation on a 2-wheel drive dynamometer compared to the real road load (due to the fact that the non-driven axle will not dissipate braking energy) has not been quantified yet. It is advised to neglect this influence for both homologation testing and technology assessment.
This proposal is justified by the fact that the evaluated and currently available vehicles with alternative drivelines, are negligibly affected by the phenomena.

Recommendations

Since a "hardware" solution is expected to be expensive the major recommendation is to aim at a numerical solution. Nevertheless, a "hardware" solution would be optimal, provided that the actual braking strategy is adequately known to meet the requirements of the simulated driving cycle.

Evaluation results showed that the comparison of energy consumption on the road versus test rig results of a modulated vehicle with a user defined braking strategy, is affected by the difference in regeneration of energy during a braking period. When it is tested on a two wheel drive dynamometer according to the low demanding NEDC cycle or the high demanding HYZEM Rural cycle definitions.

Since these first elementary simulations indicate that more sophisticated braking strategies can induce an error, it is advised to develop more relevant braking strategies for simulation models and study this phenomena more thoroughly.

In the near future it is to be expected that more intelligent regeneration systems will be developed, taking into account aspects like the:
1. Regeneration potential of the non-driven axle, or;
Interaction between an ABS-system and the driveline strategy (including regenerative braking).

Subtask 2.13 Non-rechargeable batteries

Problem definition

The testing of BEV powered by non-electrically rechargeable batteries (e.g. metal-air systems, such as zinc-air and aluminium-air batteries) poses various fundamental problems related to the measurement of the energy consumption:

1) In which vehicle category can such a vehicle be classified? As a result of the discussion by CEN TC301 Working Group 1 (European Standard Setting body, WG1), for the moment, zinc-air electric vehicles are classified in the group of Pure Fuel Cell Electric Vehicle. This classification seems to be rather inadequate for testing and homologation purposes, because the parameters to be measured for determining the energy consumption of a zinc-air-propelled vehicle are similar to those of a BEV.
2) Can all parameters needed for determining the energy consumption be measured? The testing procedure to be applied in such a case is not yet defined in existing standards. In fact, such a battery, by definition, cannot be electrically recharged from the mains, as required by BEV standards. The batteries are "mechanically recharged" (more properly: regenerated) by exchanging the fully used electrodes (e.g. zinc oxide electrodes in zinc-air batteries) with "fresh" ones (e.g. zinc metal electrodes in zinc-air batteries). The only energy data that can, eventually, be determined during testing is the energy delivered by the battery: this measurement is not included in existing standards, which excludes intrusive measurements.
3) Can the energy required to regenerate the spent zinc electrodes be measured? The regeneration process is carried out in dedicated chemical regeneration plants. Currently there are a few pilot regeneration plants that cannot be surely controlled during the testing procedures. The energy data depends on the characteristics and the production level of the regeneration plant and can only be supplied by the electrode manufacturers.
4) Can the energy needed for zinc regeneration by means of electrochemical reactions be calculated? The basic chemical reactions and electrochemistry cannot be used to calculate the consumed energy from the mains in the regeneration plant, because the value depends on the plant characteristics.

The difference between the energy delivered by the battery and that needed from the mains to regenerate the spent electrodes is relevant. Depending on the characteristics of the regeneration plant, experimental results confirm that the energy consumption (calculated as Wh/km) of the zinc-air battery during bench test with BEV is much less than 50% of the overall energy consumption, if the regeneration energy is taken into account.

Status of standard procedures

Current official (and draft) test procedures do not take into account this specific problem, because it is impossible to measure the energy consumption in a conventional way, that is, directly from the energy meters. CEN WG1 has considered zinc-air batteries in recent meetings and has asked the MATADOR Members to prepare a technical note, in which the elaboration of related principles and a proposal for a procedure for measuring the energy consumption. The basic idea is not, for the moment, to amend any standard or to propose a brand new standard, but to add a technical note describing the test procedure for zinc-air battery vehicles as an Appendix to the appropriate standard (EN1986-1). Furthermore, the classification of zinc-air vehicles should also be clarified, because in terms of test methods, according to previous considerations, seems more appropriate to list zinc-air vehicles as BEV, rather than as Pure Fuel Cell Electric Vehicle.

Possible solutions for measuring energy consumption

The literature survey, the analysis and testing activities suggest, with some warnings about the reliability of the reference data about the regeneration process, two possible methods for the determination of the energy consumption BEV with Zn-air. Both methods require further information from the manufacturers about the zinc content (in kg) of the battery and the energy needed for regenerating 1 kg of zinc in a defined regeneration plant (for comparison the efficiency data of the regeneration process could be valuable to compare different plants).

The first method is based upon data from manufacturers during regeneration of zinc electrode and the specific discharge data of the battery in real service. This solution presents many sources of inaccuracy:

1. The energy delivered by the battery depends on the discharge profile. The number of discharge cycles will affect the discharge efficiency and the specific energy consumption (from the battery). In particular, the energy conversion factor associated with the zinc conversion depends on the driving profile and normally the manufacturer refers to a specific discharge condition.
2. The final result strongly depends on the calculation of battery manufacturers and is plant-specific.
3. The battery should be fully discharged according to a standardised Test Sequence, as in a range test, in order to have the actual overall energy. This allows the determination of the energy delivered and compared to the actual one, and directly associated to the amount of zinc oxide to be regenerated.

The second method presents some positive aspects along with some warnings still related to the information from the regeneration process. In fact, its inaccuracy mainly depends on regeneration process data.

1. The measurement and the calculations are straightforward and based on general constants with the exception of the regeneration consumption.
2. The test sequence and then the DOD influence the final results, because the current increases with increasing DOD when a power profile is used. Figure 5 and Table 2 clearly show the dependency of the voltage on the DOD and discharge conditions.
3. The EN 1986-1 Test Sequences should be applied in order to have an inexpensive and affordable test method.
4. The final result strongly depends on the calculation of battery manufacturers and is plant-specific.

Both measuring and calculation methods, still requiring a complete verification with specific manufacturer data, offer the possibility to just estimate and make comparable the energy consumption of BEV even including Zn-air batteries. The second method has more easy to measure characteristics and is less dependent on reference data during service. Nevertheless, the existing technological fluctuations in the realisation and construction of zinc anode and complete batteries (the variation of weight in zinc content is around 5 %), as well as the not-yet-fixed regeneration process energy balance makes the accuracy obtainable far from that required in standard procedures.

These alternative test methods, with the above mentioned warnings, can be both applied in homologation testing as well as for comparative assessment.

Recommendations for a test procedure

A complete and detailed description of the test procedure is described in Appendix C of Subtask 2.13. This Appendix, according to the request of CEN TC 301, has been written as an Annex (or technical note) for the existing standard EN 1986-1.
A test method and a technical attachment to the Standard EN 1986-1, *specific for non-rechargeable batteries,* must consider the following sequence for measuring the energy consumption:

- The capacity (or charge) (Ah) delivered by the battery should be measured over a standardised number of cycles, according to EN 1986-1:1997. This measurement is not considered in EN 1986-1, but it is mandatory and seems to be technically feasible and quite inexpensive in various testing laboratories. This measurement is necessary to determine the metallic zinc converted in zinc oxide during discharge.

- The calculation of the energy consumption from the mains requires various steps:
  - The amount of metallic zinc consumed can be determined by using the electrochemical equivalent of the discharged capacity. The calculation is based on the following equation:

    $$Zinc \cdot Weight = \frac{C \times NC}{EE} \qquad (1)$$

    where C is the battery capacity measured during the test, NC is the number of cells composing the entire zinc-air battery and EE is the electrochemical equivalent for the zinc (820 Ah/kg_{zinc}).
  - The regeneration process of zinc oxide requires 2.32 kWh/kg (this value only represents the Edison calculation for a defined regeneration plant). Consequently, the energy consumption of the BEV is obtained by multiplying the consumed metallic zinc by the regeneration energy consumption:

    $$E_{zinc} = Zinc.Weight \times \eta_{zinc} \qquad (2)$$

    where E_{zinc} is the energy required for converting the spent zinc in metallic zinc and η_{zinc} is the conversion efficiency to obtain 1 kg of metallic zinc and is plant specific (the value to be used should be certified by the battery manufacturer and indicated in the battery).

The vehicle energy consumption is obtained by dividing the energy consumption for producing the metallic zinc divided by the travelled distance.

Subtask 2.14 Self-discharge and heating energy

Problem definition

There are various energy losses during battery use, which may significantly affect energy consumption of BEVs and HEVs. Storage systems (electrochemical batteries, supercapacitors and flywheels) may have high self-discharge and/or may work at high temperatures. In all these cases, the amount of energy involved may be high, strongly dependent on the use of the vehicle (daily travelled distance, km/day, number of chargings per day or per week), and is not always accounted for in existing testing procedures. Furthermore, high temperature batteries require energy to reach the high operating temperatures. In general, all the energy losses occur during standstill periods. Three separate phases may be considered during which standstill periods, and related energy losses, may be present:

1. Initial battery heating to have the battery at its working temperature before starting the test;
2. Standstill periods before and after driving cycles; (charging, preconditioning and preparation and recharging);
3. Idle times included in driving cycles.

The amount of losses due to self-discharge and heating may significantly impact the energy consumption calculation in BEV and HEV, depending on the measuring conditions and test sequences. Currently, the dimension of such losses may vary from about 50% of the overall vehicle energy consumption (heating energy of $NiCl_2$-Zebra battery for short working time) up to about 45% of the store energy of supercapacitors and 3% for flywheels after 72 h.

Finally, another source of error in energy consumption determination is in BEV with high capacity batteries, suitable to improve up to 4-5 time the present ranges of BEV, which, during standard energy test procedures (SAE and CEN), are only shallowly discharged. The DOD (depth of discharge) reached at the end of the energy consumption test is below 20% with respect to other BEVs reaching up 40-50% of DOD. In such cases, the measured energy consumption may be affected by the variation of charging efficiency of batteries with DOD.

This phenomenon is more significant for high-energy batteries with extremely varying efficiency with DOD, such as alkaline (Ni-Cd, NiMH, Ni-Zn) and lead-acid batteries. Experimental results have given variations in energy consumption of about 15% (dynamometer tests with a NiMH battery BEV) when the battery is discharged at 20% DOD or at 100% DOD. This variation is due to differences in charging efficiency with DOD, while similar tests performed with a BEV powered by a Zebra battery gave no significant variation of energy consumption, due to the high charging efficiency.

All these sources of losses, and then inaccuracy in energy determination, may have impact on testing methods.
The behaviour of high temperature batteries is representative for various problems:

1. The first problem is related to the determination of the time needed for getting the battery fully operational, which affects the preparation of the test and the impact of various driving cycles.
2. A second problem regards the amount of energy needed to heat the battery before starting the test, which is normally not account for in present testing procedures.
3. Finally, a third problem, similar to the self-discharge, is related to the thermal losses during standstill, which reduce battery capacity when not connected to the mains.

For self-discharge losses, further problems are:

1. the lack of a general relationship suitable for calculating the energy losses for any storage system; the limited availability of self-discharge data;
2. the large number of storage systems (batteries, supercapacitors, flywheels);
3. the impossibility to measure the energy remained in the battery when a non-externally rechargeable battery is used.

Finally, the variation in energy consumption values due to charging efficiency may require, depending on the battery type, a modification of the existing test sequence including at least two measurements at two different DOD.

Status of standard procedures

Existing standard test procedures do not specifically address the problems of self-discharge and heating energy losses. As mentioned above, the amount of losses depends on the duration of standstill in various moments of the test sequence. An analysis of CEN (EN 1986-1) and SAE (J1634) standard procedures for BEVs can be done in relation to the three phases of the test sequence identified: initial battery heating; standstill before and after driving cycles; idle time during driving cycles.

Initial battery heating and charging

Both procedures do not measure the energy spent to warm up the battery at its operating temperature. The heating process is included in the test preparation, also said preconditioning. CEN states that the test operator must follow the procedure recommended by the vehicle manufacturer to maintain the battery temperature in the normal operating range. SAE standard only stipulates that the battery shall remain on charge for the duration of soak and until the full charge of the battery is achieved: there is the obligation to verify the battery capacity (Ah) before starting testing. In SAE J1634 the charging period ranges between 12 and 36 hours before the start of the test, while EN 1986-1 does not state any specific duration for vehicle preconditioning. SAE standard requires that the soak and charging duration be recorded.

Standstill before and after driving cycles

After the vehicle, and the battery, is unplugged from mains and before starting the test, there is no measurement carried out in both existing standards. In addition, the same occurs at the end of the test before recharging the battery. In SAE J1634, there is an interval of 1 h available before

the start of the test, whereas EN 1986-1 leaves a maximum of 4 h between the battery disconnection and the start of the test. A minor difference between the two standards after the end of test cycle and before recharging the battery: SAE has a flexibility of 1 hour, whereas CEN has only 30 minutes.
Combining the energy required during the initial heating with the energy losses due to battery temperature regulation (after unplugging the battery), the difference in charging and standstill times before and after test cycles gives place to high variations of energy consumption between SAE and CEN test procedures: measurements on the VW Bora with a high temperature battery (Zebra) have shown differences up to 9% (without initial heating energy) and up to 38% (with initial heating energy). This large discrepancy, partially depending on the driving cycles, but mostly related to test procedure, justifies the recommendation of a unified pre-test (and after test) procedure for both standards.

Idle time during driving cycles

The energy losses occurring during driving cycles are inherently related to the energy economy of the cycles. These losses (self-discharge and heating energy) during BEV tests are normally accounted for in present standards at the end of the test, when the battery is externally recharged from the mains. A problem may rise for non-externally rechargeable HEVs: present (draft) standards (CEN 1986-2 and SAE J1711) do not include any method for measuring losses from the storage systems (battery, supercapacitors, and flywheels).

High capacity batteries

Standard procedures for BEVs (CEN 1986-1 and SAE J1634) allow the measurement of energy consumption by driving a fixed number of defined driving cycles (2 or 7 in CEN and 2 or 4 in SAE). The different test sequences may be chosen alternatively and only SAE standard leaves the possibility to use one or more of them, which may allow the comparison of results from various test sequences corresponding to varying DOD. Both standards also have range tests, which aim to determine the overall range of a BEV over repeated standard driving cycles until the battery is fully discharged. At the end of the range tests, the energy consumption is not measured in CEN standard, whereas SAE standard leaves it optional. The combination of the two tests (energy consumption and range), if energy consumption is measured in any case, may be sufficient to take into account the variation of the measured values, without increasing complexity and costs of the test sequence.

Possible (studied) solutions and principal constraints for their application

There are various options investigated during the analysis of the self-discharge and heating losses of storage systems. The identified options all looked at determining the actual contribution of the energy losses on the energy consumption values and their impact on testing methods.

First of all has been ascertained whether it was possible to have *reliable and repeatable relationships* for self-discharge and heating energy losses of the various systems, which could be easily used for correcting the energy consumption values, by, for example, measuring standstill periods. The technological survey and analysis of current and future storage systems shows a variety of behaviours related to several technologies and configurations developed and produced. General relationships between self-discharge times and capacity losses are available only for a few battery types (Ni-Cd and NiMH) and for supercapacitors (in specific cases). For the other storage systems there are experimental data obtained in specific self-discharge tests.

Another possibility should be the measurement of energy losses from batteries (and other storage systems) separately from the vehicle. There are testing procedures defined by EUCAR and USABC for measuring such losses for batteries and supercapacitors, but there are not yet mandatory for component and vehicle manufacturers.

A third way could be the direct measurement of standstill losses during vehicle tests or to modify test sequence in order to include standstill time in a controlled manner: e.g. reducing time flexibility in all the test phases not included in the driving cycles. This option seems reasonable to avoid mismatching of present standards, in which different charging and preparation times are defined (see the subsection on *Standstill before and after driving cycle*).

For the case of BEV powered with high capacity battery, the only direct way to account for the energy consumption variation with DOD is to have two tests at two different DOD. A straightforward suggestion is to measure the energy consumption from the mains also during range tests and then compare them with the values from energy consumption tests. In this way, only a minor modification of existing standards would be required.

Homologation tests versus comparative assessment

The nature of energy losses, related to self-discharge and heating energy, might strongly modify the results of specific tests, particularly if they are aimed at homologation or comparative (technology) assessment. In general, such losses strongly depend on the use of the vehicle: e.g. km/day, number of parking hours far from charging stations and weekends included in the real service. The energy consumption for homologation purposes is based on the measurement during a defined driving cycle, including idle time typical of a continuous service. The discrepancy between CEN and SAE standards mostly depends on the use of different driving cycles, which also contain different idle times. For technological (comparative) assessment, it is much more representative to use real service duties that are called driving patterns (the entire vehicle duties including, e.g. standstill, driving cycles, off operation stops) in contrast to driving cycles, which try to simulate the real world in a general, simplified manner. In comparative assessment tests, energy losses during standstill are objectively part of the overall energy consumption of the specific technology used if they are included in a specific driving pattern. The proposal for both test procedures is to assure that all the energy consumption can be selectively and separately measured, and to limit as much as possible the time during which the vehicle behaviour is not recorded. The weight of standstill times in various driving patterns should be determined by measuring independently from the energy test the related losses (alternatively self-discharge or heating data, in W/kWh, for the specific storage systems should be supplied by the vehicle manufacturer). The calculation of the real energy consumption will then be weighted using the results from driving cycles and standstill tests.

Recommendations for testing methods

The possible solutions for accounting for energy losses or significant energy determination differences are a combination of *hardware* and *software* routes. The hardware routes have a larger impact on existing testing procedures (mainly, cost, complexity and duration), while the software ones will make easy adaptation of existing procedures or even a compromised utilisation of manufacturer data.

Recommendations for self-discharge and heating losses

A software recommendation to modify existing standard test procedure (CEN EN1986-1) is to strongly limit the time during which the vehicle is not measured and losses occur. The present flexibility of 4 hours in EN 1986-1 between test starting and vehicle unplugging from mains is not acceptable: 1 h is regarded as a good compromise and is also consistent with SAE J1634.

A hardware correction to EN 1986-1 may be to extend the measuring period also to the charging and soaking time and perform a new test: a specific self-discharge (or initial heating for high temperature batteries) test should be carried out separately from the energy consumption test. The proposal is to keep separated energy consumption during driving cycles from energy losses before and after driving cycles. In this way, it will always be possible to weigh the contribution of energy losses in any testing procedure (either for homologation or for comparative assessment). SAE J1634 already requires measuring battery capacity, soak and charge duration and energy consumption at the input (AC energy) and the output (DC energy) of the battery charger. The same data can be recorded even in the CEN EN 1986-1.

A temporary compromise (before the recommended revision of present standards) should be the use of experimental results (Ah or energy per unit of time), achieved by the application of EUCAR and USABC testing procedures for batteries and supercapacitors. Vehicle manufacturers, in collaboration with storage system manufacturers, may supply self-discharge and heating data along with vehicle data profile already required in present standards.

Recommendations for testing BEV with high capacity batteries

A software recommendation to modify existing standard test procedure (CEN EN1986-1) is to measure the energy consumption also during range test. The hardware suggestion is to use the same test sequence applied in energy consumption test: EN 1986-1 allows two test sequences in energy consumption measurement and only one in range test. In case the tests sequence applied in energy consumption test is different from that used in range test, another range test should be done to have the same discharge conditions. The calculation of the energy consumption could be referred to the DOD or at the specific variation among the two tests.

Frameworks for test procedures

MANAGEMENT TOOL for the ASSESSMENT of DRIVELINE TECHNOLOGIES and RESEARCH

MATADOR

Contract JOE3-CT97-0081

Task 2:

Testing methods for vehicles with conventional and alternative drivelines

Framework

Test methods and procedures for Battery Electric Vehicles

20 July, 2000

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THE COMMISSION OF THE EUROPEAN UNION
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Energy Conservation and Utilisation

Nomenclature

Abbreviations

BEV	Battery Electric Vehicle
C	Battery storage Capacity in Ah measured or calculated during test sequence.
C_5	Battery storage Capacity in Ah. The subscript **5** indicates the discharge time in hours to completely discharge the battery under predefined conditions.
DOD	Depth Of Discharge. It is the ratio in percent of the capacity in Ah divided the nominal capacity of a battery
ΔSOC	The variation of State of Charge, calculated between the final SOC and the initial SOC. Initial and final refer to the starting and the completion of a test sequence.
E_{zinc}	the energy required for converting the spent zinc in metallic zinc
EE	Electrochemical Equivalent (820 Ah/kg per zinc)
EoD	End of Discharge
E_{NRB}	energy consumption of an electric vehicle with a non-rechargeable battery
η_c	Charging /regeneration efficiency of zinc-air battery
η_{zinc}	the conversion efficiency to obtain 1 kg of metallic zinc from zinc oxide in a specific plant.
E_{zinc}	the energy required for converting the spent zinc in metallic zinc
EN	European Norm
ENEA	Italian National Agency for New Technology, Energy and the Environment
EoD	End of Discharge Voltage of a battery under specified conditions.
EUCAR	European Car Research Committee
HD	Heavy Duty
IAE	Institute Automotive Engineering - Arnhem.
IKA	Institut für Kraftfahrwesen - Aachen.
LD	Light Duty
Macrocycle	Definition of a driving/test cycle including test sequence, standstill and charging phase
MATADOR	Management Tool for the Assessment of Driveline TechnOlogy and Research
NC	Number of Cells of which the battery is composed.
NiCd	Nickel- Cadmium Battery
NiMH	Nickel- Metal Hydride Battery
NiZn	Nickel - Zinc Battery
OCV	Open circuit voltage
SAE	Society of Automotive Engineers.
SOC	State of Charge. It is given in percent and is equal to 100-DOD.
USABC	United States Advanced Battery Consortium
VRLA	Valve Regulated Lead- Acid batteries.
Zn-air	Zinc-air

Contents

1 Introduction

Task 2 of the MATADOR Project (Management Tool for the Assessment of Driveline Technologies and Research, EU-contract JOE3-CT94-0081) is aimed at developing test methods for homologation and evaluating conventional and alternative vehicles and propulsion systems. These testing methods should also allow for a comparative assessment and benchmarking of such technologies. The testing methods, considered in Task 2, are restricted to the determination of energy consumption and emissions of various vehicles and powertrains. The definition of such testing procedures is strongly affected by the vehicle configuration, the required fuels and the specific driving patterns which may be real or simulated on test benches. In addition, the introduction of alternative technologies and fuels may pose measuring problems when compared with conventional vehicles and standardised procedures. Investigation and critical evaluation of technical issues in relation to the various technologies is the main scope of Task 2, from which specific recommendations for modified or new testing and measuring methods are derived.

Standards for BEVs (battery powered or pure electric road vehicles) have been recently released and made available in USA, Japan and Europe.
Anyway, several technical and practical issues are still open, often originated by the fact that the standards are strictly aimed at homologation the vehicles, more than at technically characterising the various vehicle technologies. Furthermore, BEV standards are derived from the well-established standards designed for ICE powered vehicles. For example, the energy consumption test procedure provides for an urban consumption test, based on the ECE 15, and, in alternative, an extra-urban driving cycle. This cycle, nevertheless, is quite useless, because it is not representative of the real driving cycle and the required maximum speed, 120 km/h, is beyond the technical performances of the majority of current BEVs.

Other problems are battery-related, for example there are batteries with significant self-discharge or energy losses (due to heating or cooling systems in high temperature batteries), other are not electrically rechargeable (as metal-air batteries). The influence of the Depth of Discharge (DOD) on charge and discharge efficiency is another source of inaccuracy, which is related to the driving cycle. All these aspects have impacts on the accuracy of the measurements and the reproducibility of the test.

This document is aimed at proposing a testing framework, as the final recommendation of the European project MATADOR, for measuring energy consumption of BEVs. Even if strictly derived from existing (draft) standards, it differs from those in a number of parts, offering some indications for a better test reproducibility and suggesting some modifications to present standards in order to account for more realistic conditions.

The intention is to schematically describe main testing procedure parts, highlighting technical issues/problems (summarising conclusions of specific subtask reports), which are peculiar of the system to be tested and /or have an impact on existing (draft) standards. The test procedure will be fully structured in a pictorial view in order to drive the reader in a simplified manner through the main topics faced during a testing work:

1. Normative reference
2. Definitions
3. Classification of vehicles/technical issues (self-discharge losses, thermal heating for high temperature batteries, high capacity battery, non-electrically rechargeable storage systems)
4. Test preparation and preconditioning
5. Vehicle testing (test sequence, driving cycles, failure time, tolerance and accuracy, measurement issues)
6. Data processing
7. Data reporting

More than defining a complete testing procedure for homologation or other purposes, the framework will refer to existing standards and specific topics (by using flow diagrams, showing main test routes and, where possible, recalling test steps of existing (draft) standards. Furthermore, motivations and justifications, with a clear description of the proposed methods and differences with existing ones, will be described in Annexes, outlined in flow charts and shortly defined in the text. Figure 1 shows how the schematic presentation will look like by showing the main options (numbered subroutines/actions in the main text) in a testing procedure for energy consumption and emissions measurements. Finally, homologation and comparative assessment will be distinguished and some considerations about the testing methods for heavy-duty (HD) vehicles will be presented.
All in all, this framework of a BEV testing procedure for measuring energy consumption will try to reach a reasonable compromise between affordability (low cost and short time) and quality of test results (accuracy, significance and comparability) for homologation and for comparative technology benchmarking.

2 Scope

This document intends to give a general, but well structured and easy to follow, framework for measuring the energy consumption, (and the range, when required) of Battery Electric Vehicles (BEV) for both homologation and technology assessment (in realistic operating conditions). The proposed testing methods and solutions to main technical problems refer to the conclusions of many subtask reports, prepared under the MATADOR project. This document mainly covers testing needs of light-duty (LD) BEVs, as defined in EN 1986-1. Some considerations and recommendations will also be referred to heavy-duty (HD) BEVs.

3 Normative references

This testing procedure uses as references various publications and standards.

EN1821-1	1996	Electrically propelled road vehicles – Measurements of road operating ability- Part 1: Pure electric vehicles
EN1986-1	1997	Electrically propelled road vehicles – Measurements of energy performances- Part 1: Pure electric vehicles

prEN 13447	1999	Electrically propelled road vehicles – Terminology
SAE J1634	1995	Surface Vehicle Recommended Practice: Electric vehicle energy consumption and range test procedure

The testing procedure framework will only mention main technical problems or differences with respect to existing or under definition standards.

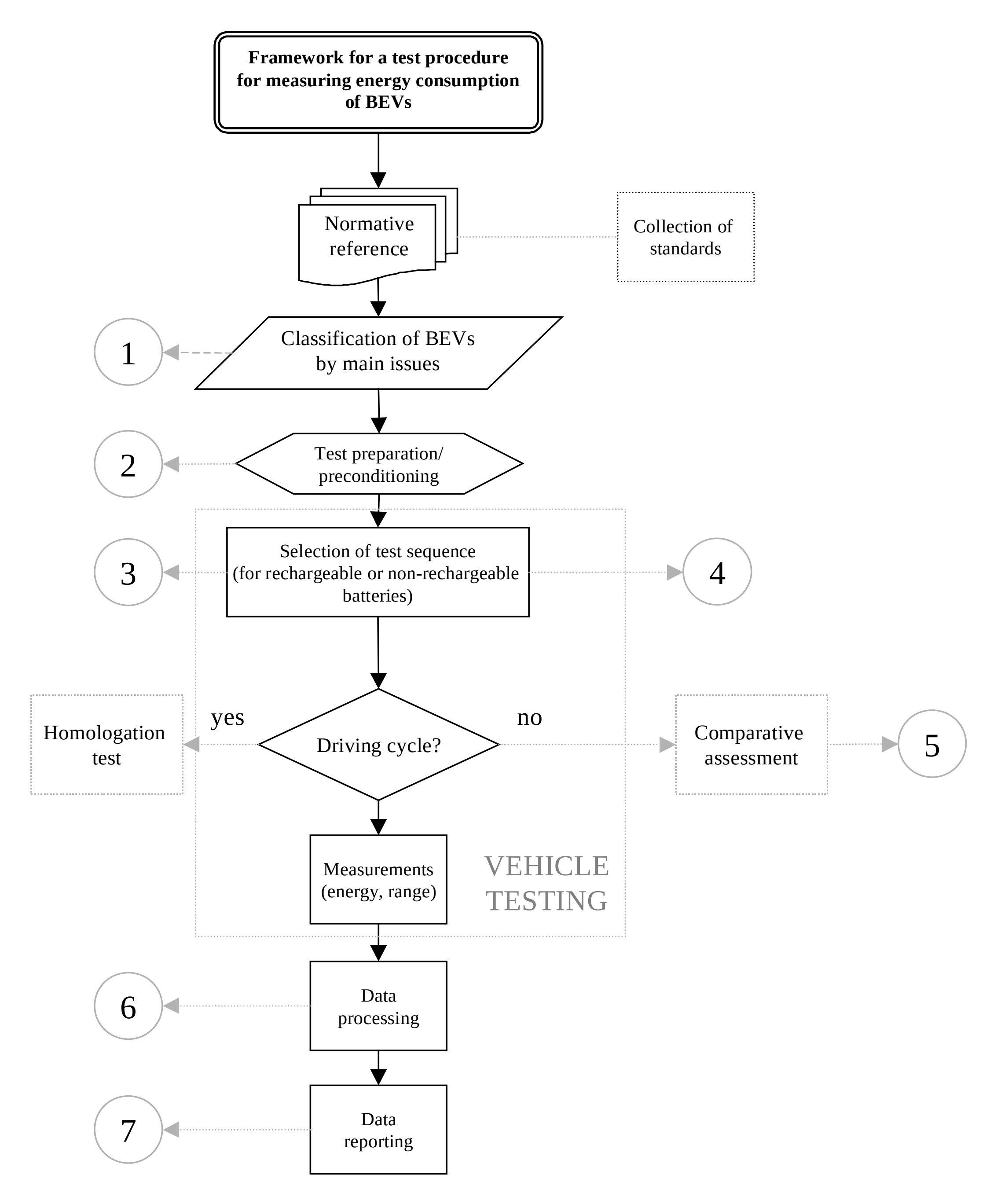

Figure 1: Flowchart of a testing procedure framework for a BEV

4 Definitions and classifications

4.1 Definitions

- Acclimatisation (soak) period: the time needed to thermally condition the vehicle under test to the operating temperature window (usually between 20°C and 30°C for indoor tests).
- Battery capacity: the electrical charge in Ah (or energy in Wh) delivered by the battery under predefined conditions.
- BEV: pure electric road vehicles in which the only electricity source is onboard and is an electrochemical battery.
- Driving profile or cycle: vehicle speed versus time curve.
- Driving pattern: the entire vehicle service including, e.g., standstill, realistic driving cycles, off-operation stops, opportunity charging and so on.
- Failure time: <u>the length of time</u> (duration or amount of time) during which the vehicle being tested is unable to perform the prescribed driving cycle due to low acceleration value or insufficient maximum speed.
- HD: Heavy-Duty, meaning categories of vehicles M3 and N3 (definition to be clarified)
- High-temperature batteries: batteries having an operating temperature of internal components much higher than the ambient temperature.
- High capacity battery: storage systems used in a BEV, which are shallow (less than 40%DOD) during a standard energy consumption test.
- LD: Light-Duty, meaning categories of vehicles M1, M2, N1, N2, motor tricycles and quadricycles.(definition to be clarified)
- Non-rechargeable battery: (primary battery) a battery that cannot be electrically recharged (metal-air batteries: Zinc-air, Aluminium-air).
- Regenerated battery: zinc-air batteries are recharged by substituting used zinc electrodes with zinc metal electrode regenerated in a dedicated plant.
- Regenerative braking: the process of braking not finalised to vehicle deceleration but only the convert vehicle kinetic energy into electrical energy.
- Self-discharge: the amount of charge or energy the battery loses during off-load conditions (more precisely open circuit conditions).
- Zebra battery: high-temperature Sodium-Nickel Chloride battery with an internal temperature of around 300°C.

4.2 Classification of BEV

For testing purposes, BEVs can be classified according to the main characteristics of the batteries. Batteries have peculiar features that may significantly impact the testing procedure in terms of duration, measuring complexity, accuracy and, finally, cost. Figure 2 shows a block diagram (subroutine 1) that gives indications about the way BEVs can be divided in categories according to the properties of the used battery. The classification considers not only the battery types, but also their dimension in the BEV, which may influence test results.

5 Roller bench and vehicle preconditioning

Prior to testing start both vehicle and test bench must be conditioned to have reproducible conditions (mainly temperature) for any test and to make then more comparable the results of different tests on various vehicles. Existing (draft) (EN 1986-1 and SAE J1634) standards give directions before the test. The indications are not consistent among them and may have impact on the overall energy consumption, due to the battery self-discharge and heating [8]. Figure 3 is the flowchart (subroutine 2 of the framework) for the test preparation.

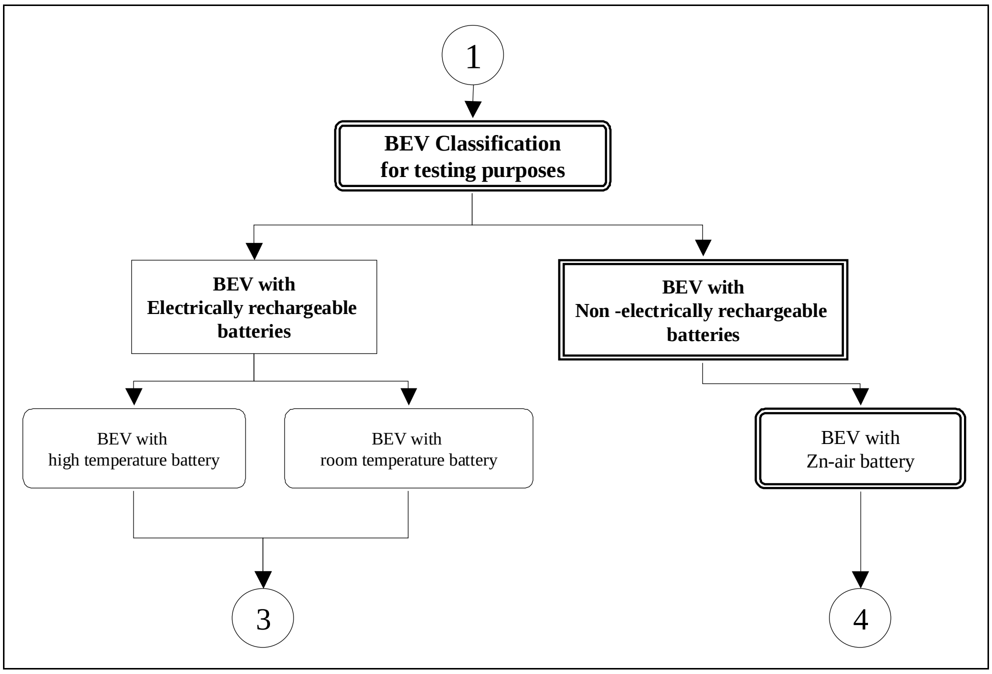

Figure 2: BEV classification for testing purposes. Double lines mean steps not existing standards

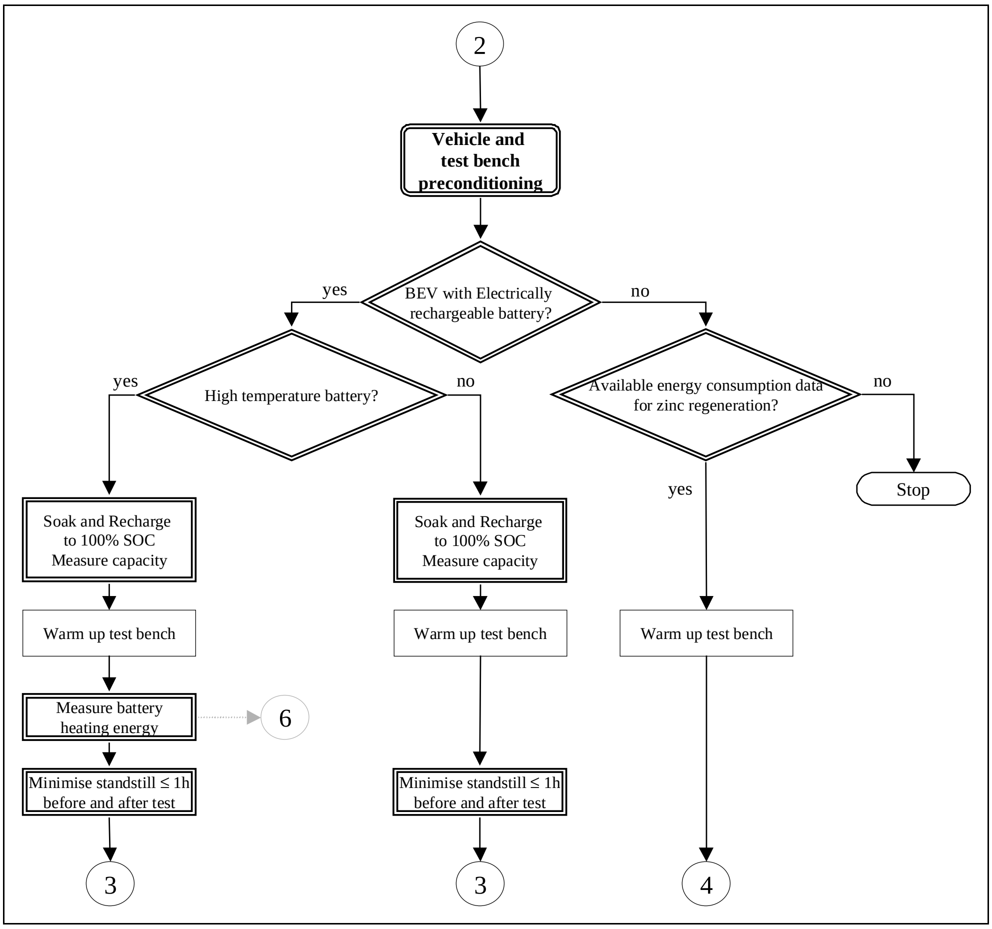

Figure 3: Flowchart for test preconditioning. Double lines mean step not existing in standards

5.1 Test bench preconditioning

The test bench shall be warmed up without the vehicle according to the recommendations of the supplier of the bench. This procedure allows the reduction of negative effects on the cold start of the vehicle, especially tyres changes [5], and then facilitates a proper setting of the road load, which is better represented.

5.2 Vehicle preconditioning

The vehicle preparation mainly follows EN 1986-1, clause 5.4. Vehicle soak should be for 24 hours (and battery on charge during such time) at 25±1 °C. The narrow limit is defined to eliminate the strong influence of the starting temperature on the energy consumption values. Different temperatures have a strong influence on duration and heating energy of the warm-up phase, particularly for high-temperature batteries, and, therefore, small variations can greatly change the result of a test [5].

In order to minimise the effects of the battery self-discharge on the test procedure, the time period between disconnection from mains after recharge and start of the test should be minimised. For the same reason, the time period between end of the test and reconnection to the mains for recharge should be minimised. The sum of both duration should not exceed ***one hour*** [8]: this is a compromise between SAE and CEN standards.
The pressure of the tyres has to be checked and, if necessary, resettled before each test to eliminate the influence of the variation of rolling resistance versus pressure [5].

5.3 Battery Preconditioning

To ensure that each test is done with the battery in the same initial conditions, a standard cycle, composed by a standard charge and a standard discharge, both described in the Annex A, should be performed before each test. Every time, during the energy consumption (or range) test, the prescribed sequence is interrupted, the standard cycle must be repeated. The availability of a battery cycler (or at least, a measuring system for battery voltage and current) would surely improve the reliability and reproducibility of the charge/discharge process.
This battery conditioning process only applies to batteries that can be recharged with an on-board or off-board charger from mains.
In case of mechanically rechargeable batteries, such as Zinc-air, a fresh regenerated battery pack must be installed on-board before starting the test sequence.

6 Vehicle testing

The execution of the test sequence is a combination of various parts, which contains measuring aspects, driving cycles and specific vehicle conditions to assure test repeatability (tolerance, shifting modes, control strategy, manual operation selection). Some specific problems related to the behaviour of the battery may be accounted for in the execution of the test sequence, while other aspects may be calculated or considered during data processing. Figure 4 (subroutine 3) sketches the flow diagram of the test sequence for the energy consumption determination of BEVs with electrically rechargeable batteries.

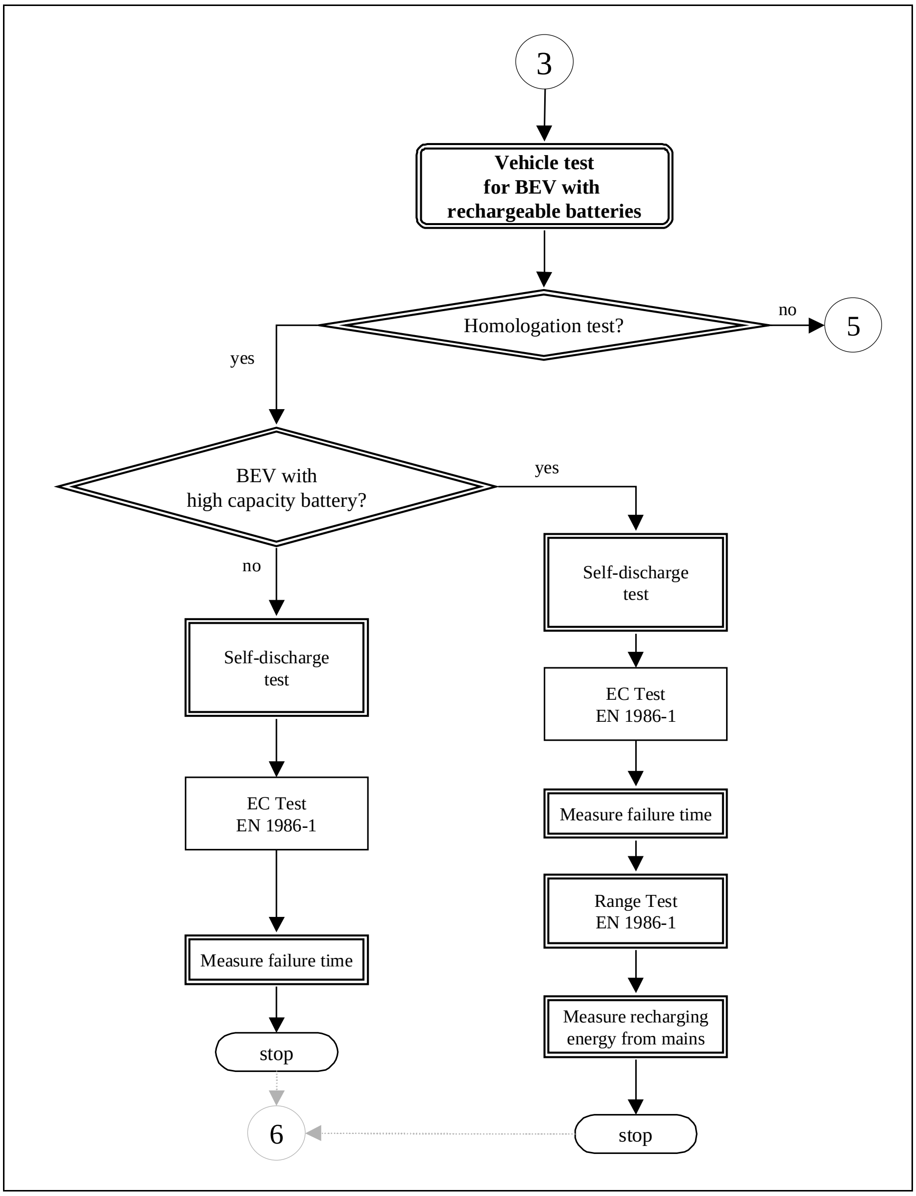

Figure 4: Test sequence flowchart for BEV with rechargeable batteries

6.1 Failure time

The failure time is the amount of time a BEV is unable to follow the driving cycle (within the tolerance band of ± 2 km/h), due to low acceleration value or insufficient maximum speed [4]. In consideration of the dependence of the energy consumption on the failure time (up to 15%) [1][4], the failure time must be recorded (or determined) and mentioned into the test report for both cases, as required in EN1986-1. Vehicles, which are not able to follow the driving cycle, would be operated during the failure time at their power limits. This behaves a reduced efficiency compared to a normal operating usage with middle loads, leading to higher energy consumption compared to a vehicle with the same characteristics (weight, rolling resistance, and so on), but a more powerful electric motor. Testing institute can easily evaluate the failure time by simply comparing during or after a test the actual speed profile with that of the driving cycle.

For BEV with limited maximum speeds (below 80-90 km/h) and intended for urban uses, it is recommended to follow EN-1986-1 test procedure (par. 5.5), using 7 times ECE-15 cycle; while for BEVs with maximum speeds higher than 120 km/h, 2 times of the complete NEDC can be applied. In Annex B, a more complete justification to this approach is shortly described.

6.2 High temperature batteries and self-discharge

Thermal losses of high temperature batteries and self-discharge of any battery may significantly impact the measurement of energy consumption of BEVs. In Annex C the problem is briefly presented.

A recommendation to modify existing standard test procedure (CEN EN1986-1) is to strongly limit the time during which the vehicle is not measured and losses occur. The present flexibility of 4 hours in EN 1986-1 between test starting and vehicle unplugging from mains is not acceptable: 1 h should be a good compromise and is also consistent with SAE J1634.

A correction to EN 1986-1 may be to extend measuring period also to the charging and soaking time and perform a new test: *a specific self-discharge (or initial heating for high temperature batteries) test should be carried out separately from the energy consumption test*. The proposal is to keep separated energy consumption during driving cycles from energy losses before and after driving cycles. In this way, it will be always possible to weigh the contribution of energy losses in any testing procedure (either for homologation or for comparative assessment). SAE J1634 already requires measuring battery capacity, soak and charge duration and energy consumption at the input (AC energy) and the output (DC energy) of the battery charger. The same data can be recorded even in the CEN EN 1986-1.

6.3 High capacity battery

Another source of error in energy consumption determination is the use of high capacity batteries, able to improve up to 4-5 times the present ranges of BEV, which, during standard energy test procedures (SAE and CEN), are shallow discharged. The DOD (depth of discharge) reached at the end of the energy consumption test is below 20% with respect to other BEVs reaching up 40-50% of DOD. In such cases, the measured energy consumption may be affected by the variation of charging efficiency of batteries with DOD. This phenomenon is more significant for high-energy batteries with extremely varying efficiency with DOD, such as alkaline (NiCd, NiMH, NiZn) and lead-acid batteries. Present energy consumption test sequences discharge differently the batteries. For example, EN 1986-1 test sequences apply two difference driving cycles corresponding to an overall driving distances of about 22 km or about 28 km, respectively, but for various batteries these distances corresponds to discharge a varying fraction of the overall available capacity. To take into account the different charging efficiency of the batteries, it is recommended to perform a range test in addition to the energy consumption test and measure the energy consumption from mains also for the range tests.

6.4 Zinc-air BEV

The use of such battery has not been considered in existing standards, which only allows the measurement of electrical energy from mains in the testing station. The need to regenerate the spent zinc electrodes in a dedicated plant, out of the control of the testing institutes, determines some practical and ethical problems:

- the energy consumption for «charging» the battery cannot be directly measured in the test facility;
- the type of measurement and equipment are out of the control of the testing organisation;

- the energy consumption information is still proprietary and hard to obtain in a reliable and reproducible way, even in consideration of the development small-scale stage of the production plants.

Figure 5 (subroutine/action 4) shows the test flow diagram for energy consumption measurements for BEV with non-rechargeable batteries. In Annex D a proposal for a modification to existing standards is described [7].

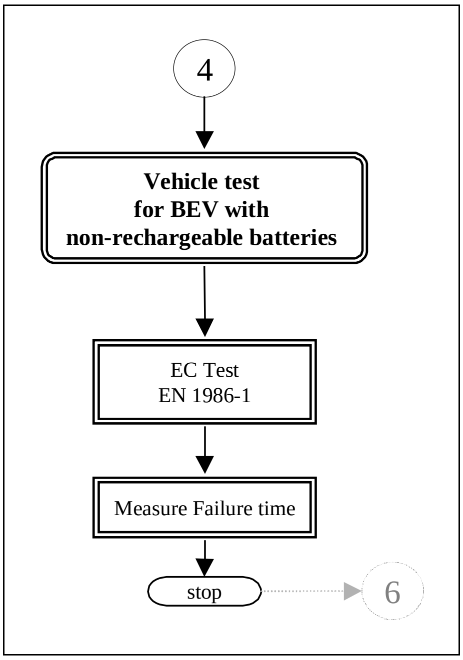

Figure 5: Flow diagram for energy consumption test sequence of a BEV with non-rechargeable battery. The sequence is in the standard, but it is different in the energy measurement

6.5 Regenerative braking

There are BEVs that allows the manual selection of different regenerative braking modes. Old LAREL has three different driving modes (Sport, Normal and Economy) related to regenerative braking, and the VW Electric Bora has an on/off switch for the regenerative braking. EN1986-1, differently from SAE J1634, has not a formal statement for such situation. The possibility to recover energy during braking is one of the main advantages of alternative vehicles with electrical propulsion systems with respect to the conventional ones; it then seems appropriate to state formally the evaluation of the regenerative energy strategy to improve technology comparison. The recommendation is that the energy consumption test must be performed with the regenerative braking option in "on" position.

Furthermore, the effect of actual road regenerative braking, when a 2-WD dynamometer is used, should be accounted for. A combination of simulation, first for estimating the error and, eventually, the «hardware» correction stated in SAE J1634 could be proposed (part of data processing work).

6.6 Driving cycles (homologation versus comparative assessment)

The energy consumption for homologation purposes is based on the measurement during a defined driving cycle, including idle time typical of a continuous service. The discrepancy between CEN and SAE standards most depends on the use of different driving cycles, which also contain different idle times. For technological (comparative) assessment, it is much more representative the real service duties that we can call driving patterns (the entire vehicle duties including, e.g., standstill, driving cycles, off operations stops) in opposition with driving cycles, which try to simulate the real world in a general, simplified manner. In comparative assessment tests, energy losses and performances of the BEVs greatly are objectively part of the overall energy consumption of the specific technology used, including energy losses for self-discharge and heating. The proposal for both test procedures is to assure that all the energy consumption can be selectively and separately measured, and to limit as much as possible the time during which the vehicle behaviour is not recorded. For example, the weight of standstill times in various driving patterns should be determined by measuring independently from the energy test the related losses (alternatively self-discharge or heating data, in W/kWh, for the specific storage systems should be supplied by the vehicle manufacturer). The calculation of the real energy consumption will be then weighed using the results from driving cycles and for standstill tests 0. In Annex E, some justifications of this approach are reported, along with examples of alternative driving cycles. Figure 6 (subroutine 5) presents the routes to be followed for testing BEVs.

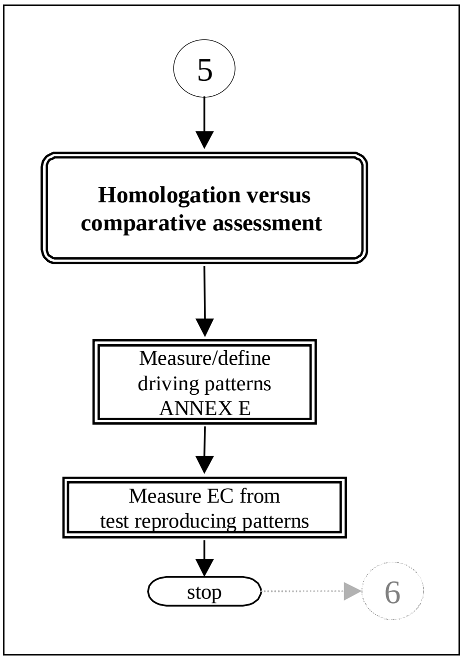

Figure 6: Comparative assessment flow diagram: no standards existing

7 Data input, processing and reporting

The proposed testing procedure may require that various data be supplied from vehicle and battery manufacturers. Existing standards also mention clear inputs from manufacturers about charging procedures, but not clear indications are given about the way this may happen. There are a lot of test results that must be processed to reach final values for energy consumption and emissions (subroutines/actions 4 and 5). The elaboration and testing work will of course depend on the type of vehicle behaviour, the test sequence and the scope of the tests.
For homologation purposes, current (draft) standards already provide (prEN 1986-1 and SAE J 1634) informative lists of technical information to be supplied to the test laboratory and then be reported after the test completion. Figure 7 (subroutines 6 and 7) flowcharts the elaboration process prior to final reporting.

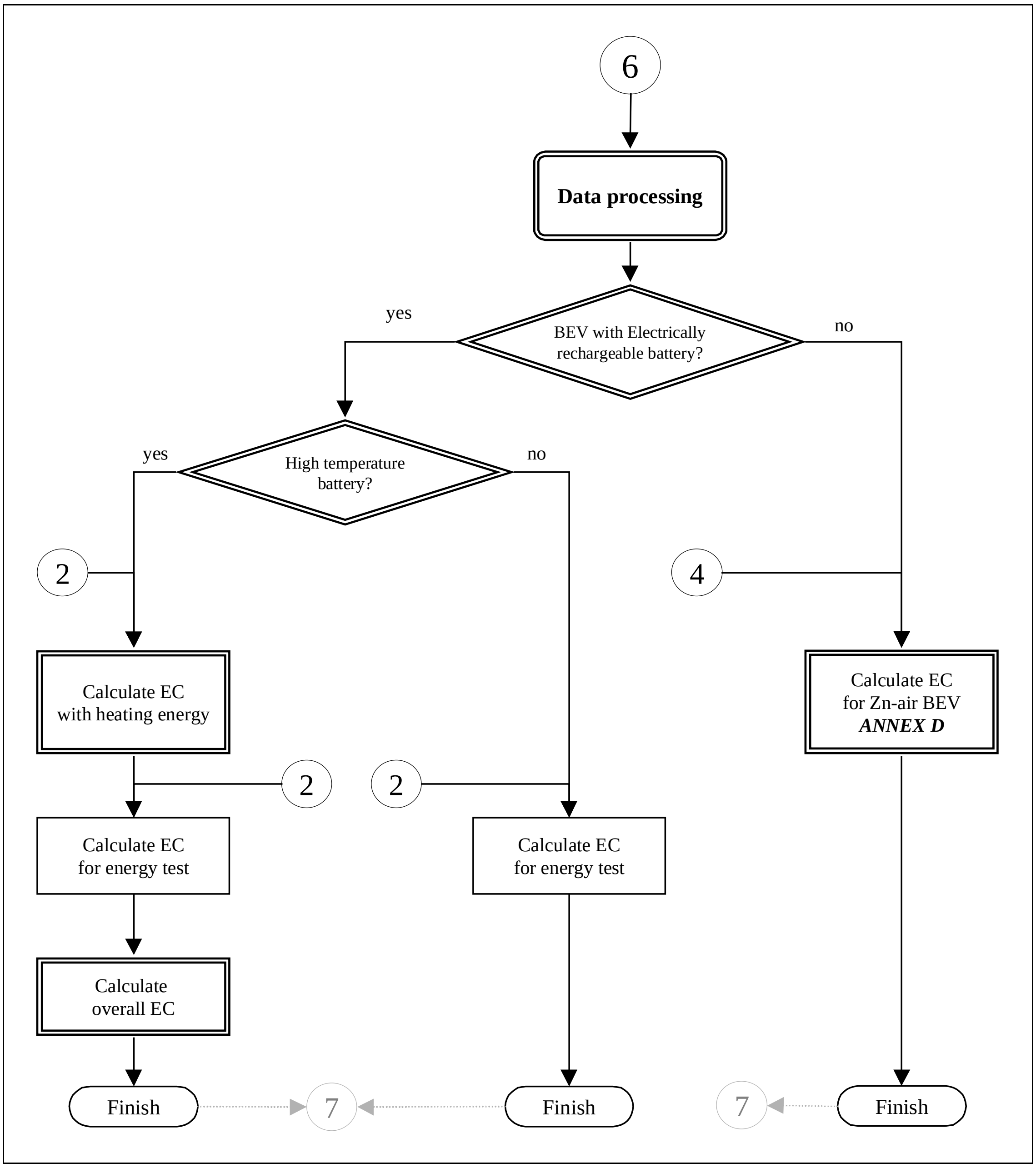

Figure 7: Data processing flowchart with calculation not required in existing standards (boxes with double lines)

8 Remarks for testing HD-BEVs

As stressed in [2], the actual HD test procedure is not representative and useful for alternative drivelines with electrical propulsion systems, because of the impossibility to include in the engine tests the peculiar features of such drivelines of regenerating barking, on/off operation and varying efficiency.

For testing such vehicles two major issues are still unsolved:

a) Whether it is practicable to test these vehicles on dynamometers in terms of availability of powerful transient test benches (requires big investments – and
b) which cycle shall be used or which cycle is representative for the specific use of the given vehicle.

If there is the availability of large dynamometers, the procedure proposed in this framework can be, in general, applied by adapting the driving cycle, which must be more specific for HD-BEVs.
If there is no dynamometer available, a possible testing procedure may be the following: perform a driving cycle on a test track, followed by a laboratory test on the generation and storage components of the driveline. By applying (with a bi-directional electronic device like a battery cycler) an electrical load equal to that measured and recorded during the test track, it is then possible to calculate the energy consumption. This seems to be a viable option for energy consumption measurements.
For the definition of realistic driving cycles, a classification of vehicles is necessary. A first attempt is given below:

- Delivery trucks
- Coaches
- City busses
- Special vehicles (municipal vehicles, road sweepers, garbage trucks)
- Long distance trucks

The real life cycles, reflecting the average use, can only be developed on the basis of intensive measurements on real vehicles of the above mentioned classes.

9 References

[1] C. Renner, S. Ploumen, M. Schüssler, “Evaluation of existing (draft) standards”, Matador Subtask 2.3 Report, Institut für Kraftfahrwesen Aachen (IKA)

[2] E. van den Tillaart, “Driving cycles for LD vehicles”, Matador Subtask 2.8 Report, TNO Automotive

[3] I. Riemersma, “Test methods and driving cycles for HD vehicles”, Matador Subtask 2.9 Report, TNO Automotive

[4] K. Meier Engel, “Failure time and energy consumption of vehicles”, Matador Subtask 2.10 Report, HTA Biel

[5] S. Ploumen, “Accuracy and tolerances”, Matador Subtask 2.11 Report, Institut für Kraftfahrwesen Aachen (IKA)

[6] L. Buning, “ Regenerative Braking on 2 Wheel Dynamometers”, Matador Subtask 2.12 Report, IAE

[7] M. Conte, “Non-rechargeable batteries”, Matador Subtask 2.13 Report, ENEA – Advanced Energy Technology Division

[8] M. Conte, “Self-discharge and Heating Energy”, Matador Subtask 2.14 Report, ENEA – Advanced Energy Technology Division

ANNEX A Battery pre-conditioning

STANDARD DISCHARGE
The battery is discharged, by running at constant speed (see 9.1 EN 1821-1) till the battery voltage will come down to the minimum allowable value (end of discharge voltage). End of discharge criteria fixed in 5.5.1.1 (EN 1986-1) cannot be applied to all battery types or vehicle.

STANDARD CHARGE
The vehicle normally will be charged according to normal charging procedure, as recommended by the manufacturer.

BATTERY VOLTAGE MINIMUM VALUE
The end of discharge (EoD) voltage depends on the battery type, the discharge conditions and the vehicle configuration. The manufacturer of the vehicle must recommend it.

ANNEX B Failure time

For testing purposes, the failure time is part of a more general problem to adapt the driving cycle to the limited performances of BEVs, particularly when they have been produced for exclusively urban use. It is possible to envisage two situations during which the BEV is not able to meet driving cycle characteristics:

- The maximum vehicle speed, as communicated by the manufacturer, is lower than 120 km/h, which is the maximum speed required by the extra-urban cycle of NEDC (or test sequence n° 2 in EN1986-1, par. 4.1).
- The maximum vehicle speed, as communicated by the manufacturer, is higher than 120 km/h.

EN1986-1 already states that:

- *Tolerances on speed (± 2 km/h) and on time (± 1 s) are geometrically combined at each point of the driving profile (speed-time curve).*
- *Below 50 km/h the deviations beyond this tolerance are permitted as follows:*
    - *at gear change for a duration less than 5 s;*
    - *and up to five times per hour at other times, for a duration of less than 5 s each;*
- *The total time out of tolerance* ***(failure time)*** *has to be mentioned in the test report.*
- *Over or equal to 50 km/h, it is accepted to go beyond tolerances provided the accelerator pedal is fully depressed.*

For BEV with limited maximum speeds (below 80-90 km/h) and intended for urban uses, it is recommended to follow EN-1986-1 test procedure (par. 5.5), using 7 times ECE-15 cycle; while for BEVs with maximum speeds higher than 120 km/h, 2 times of the complete NEDC can be applied.
There are not clear justifications for proposing a partial modification of the present standard driving cycles by only reducing the maximum speed [in speed phases with high speeds. Such a problem is not related to the applicability of the standard testing method, but faces the general, vital problem of representativity of the driving cycle for the vehicle under test.

ANNEX C Self discharge and heating energy losses

C.1 The problem

There are various energy losses during battery uses, which may significantly affect energy consumption of BEVs and HEVs. Storage systems (electrochemical batteries, supercapacitors and flywheels) may have high self-discharge and/or may work at high temperature. In all these cases, the amount of energy involved may be high, is strongly dependent on the use of the vehicle (daily travelled distance, km/day, number of chargings per day or per week) and is not always accounted for in existing testing procedures. Furthermore, high temperature batteries require energy to reach the high operating temperature. In general, all the energy losses occur during standstill periods. Three separate phases may be considered during which standstill periods, and related energy losses, may be present:

1. Initial battery heating to have the battery at its working temperature before starting test;
2. Standstill periods before and after driving cycles; (charging, preconditioning and preparation and recharging);
3. Idle times included in driving cycles.

The amount of losses due to self-discharge and heating may significantly impact the energy consumption calculation in BEV and HEV, depending on the measuring conditions and test sequences. Currently, the dimension of such losses may vary from about 50% of the overall vehicle energy consumption (heating energy of $NiCl_2$-Zebra battery for short working time) up to about 45% of the store energy of supercapacitors and 3% for flywheels after 72 h [8].

C.2 Status of standard procedures

Existing standard test procedures do not specifically address the problems of self-discharge and heating energy losses. The amount of losses depends on the duration of standstill in various moments of the test sequence. An analysis of CEN (EN 1986-1) and SAE (J1634) standard procedures for BEVs can be done in relation to the three phases of the test sequence identified: initial battery heating; standstill before and after driving cycles; idle time during driving cycles.

C.2.1 Initial battery heating and charging

Both procedures do not measure the energy spent to warm up the battery at its operating temperature. The heating process is included in the test preparation, also said preconditioning. CEN states that the test operator must follow the procedure recommended by the vehicle manufacturer to maintain the battery temperature in the normal operating range. SAE standard only stipulates that the battery shall remain on charge for the duration of soak and until the full charge of the battery is achieved: there is the obligation to verify the battery capacity (Ah) before starting testing. In SAE J1634 the charging period ranges between 12 and 36 hours before the start of the test, while EN 1986-1 does not state any specific duration for vehicle preconditioning. SAE standard requires that the soak and charging duration be recorded.

C.2.2 Standstill before and after driving cycles

After the vehicle, and the battery, is unplugged from mains and before starting the test, there is no measurement carried out in both existing standards. In addition, the same occurs at the end of the test before recharging the battery. In SAE J1634, there is an interval of 1 h available before the start of the test, whereas EN 1986-1 leaves a maximum of 4 h between the battery disconnection and the start of the test. A minor difference between the two standards after the

end of test cycle and before recharging the battery: SAE has a flexibility of 1 h, whereas CEN has only 30 min.
Combining the energy required during the initial heating with the energy losses due to battery temperature regulation (after unplugging the battery), the difference in charging and standstill times before and after test cycles gives place to high variations of energy consumption between SAE and CEN test procedures. Measurements on the VW Bora with a high temperature battery (Zebra) have shown differences up to 9% (without initial heating energy) and up to 38% (with initial heating energy). This large discrepancy, partially depending on the driving cycles, but most related to test procedure, justifies the recommendation of a unified pre-test (and after test) procedure for both standards.

C.2.3 Idle time during driving cycles

The energy losses occurring during driving cycles are inherently related to the energy economy of the cycles. These losses (self-discharge and heating energy) during BEV tests are normally accounted for in present standards at the end of the test, when the battery is externally recharged from mains. A problem may rise for non-externally rechargeable HEVs: present (draft) standards (CEN 1986-2 and SAE J1711) do not include any method for measuring losses from the storage systems.

ANNEX D Proposal for an Annex F to EN 1986-1

Annex F (normative)
Determination of the energy consumption of an electrically propelled road vehicle powered by a non-electrically rechargeable battery (e.g. zinc-air or aluminum air).

F.1 Introduction

The purpose of this annex is to define the method of measuring the energy consumption of a vehicle powered by non-electrically rechargeable when tested on a chassis dynamometer.

F.2 Reference conditions

Testing shall be performed according to the test sequence described in 4. The step described in There is no modification of the test sequence and vehicle preparation.

F.3 Test procedure modifications

The test procedure for measuring the energy consumption described in 5.5 shall be modified in the following way:

- *Initial charge of the battery (CANCELLED*);
- **Application of the test sequence as defined in 4.1;**
- *Charge of the battery (CANCELLED);*
- Calculation of the energy consumption.

The bold step remains partially unchanged as in 5.5.2. In fact during the test sequence, the current (or the capacity) delivered by the battery shall be measured. This type of measurement is not provided in the procedure for pure electric vehicles. The accuracy of the current (or capacity) measurement should be ± 1%.

F.3.1 Initial charge

The non-electrically rechargeable batteries cannot be recharged by the mains, but are normally mechanically rechargeable, that is, the spent electrodes are substituted by fresh ones. This step of the test sequence is then omitted. Consequently, for the test of these specific vehicles 5.5.1 and 5.5.3 cannot be applied.

F.3.2 Calculation of the energy consumption

The energy consumption E_{NRB} of an electric vehicle with a non-rechargeable battery is defined by the formula:

$$E_{NRB} = \frac{E_C}{d}$$

where E_C is the electric energy consumed at regeneration plant for regenerating the spent electrodes and d is the distance travelled in km recorded during the test. The value E_C does not include the energy consumed for handling the electrodes.

The calculation of the energy consumption from mains E_{NRB} requires various steps:

- The amount of metal (e.g. metallic zinc in zinc-air batteries) consumed can be determined by using the electrochemical equivalent of the discharged capacity. The calculation is based on the following equation:

$$\text{Zinc} \cdot \text{Weight} = \frac{C \times NC}{EE} \qquad (1)$$

where C is the battery capacity measured during the test, NC is the number of cells composing the entire zinc-air battery and EE is the electrochemical equivalent for the zinc (820 Ah/kg_{zinc}).

- The regeneration process of the zinc oxide in zinc-air requires 2,32 kWh/kg (this value only represents the Edison calculation for a defined regeneration plant of zinc oxide). Consequently, the energy consumption from mains is obtained by multiplying the consumed metallic zinc by the regeneration energy consumption:

$$E_C = \text{Zinc.Weight} \times \eta_{Zinc} \qquad (2)$$

where E_C is the energy required for converting the spent zinc in metallic zinc and η_{zinc} is the conversion efficiency to obtain 1 kg of metallic zinc and is plant specific (the value to be used should be certified by the battery manufacturer and indicated in the battery).

ANNEX E Homologation tests versus comparative assessment – Real-life driving patterns

The effect of various representative driving cycles have been thoroughly analysed with experimental and simulation activities [1][2][3][4]. One of the major advantages of BEV and, in general, of most vehicles with electrical propulsion systems is the possibility to recover energy during braking, by converting the electric motor in an electric generator. The amount of recoverable (regenerative braking) energy can be significant and is dependent on the BEV technology but also on the driving cycle. The influence of the driving cycle on energy consumption is relevant with variations for specific BEVs up to 40-50%, as can be seen in Table 1, reporting the test results of a Renault Express Electrique on 6 different cycles.

Table 1 Energy consumption from mains and batteries for a Renault Express Electrique with various driving cycles [6]

	Energy Consumption [MJ/100km]	
Driving cycle	*from battery*	*from mains*
NEDC	57,6	126
Jap1015	46,8	90
USFTP75	57,6	108
Hyzem Urban	57,6	118,8
Hyzem Rural	68,4	126
Hyzem Highway	82,8	158,4

For homologation purposes the test sequence suggested in EN-1986-1 (par. 4) can be applied at this moment until a really representative cycle is defined. Some adaptations to the sequence have, however, to be taken into account in the energy consumption calculation of specific cases: high temperature batteries, charge duration, high capacity batteries, regenerative braking energy and self-discharge.

Results from road experiences [4] confirm that the average daily range in Mendrisio BEV fleet is about 15 km that is consistent with the driving cycle lengths, proposed in EN 1986-1, of about 22 or 28 km (EN1986-1). Moreover, the comparison between bench and field data showed significant differences, indicating that BEV energy consumption (or efficiency) and range depend greatly on operating conditions, because the «real world» driving patterns may include higher or lower speeds and acceleration rates than those found in the standard test cycles. Furthermore, bench tests resulted reproducible and, within the same category, comparable, but their representativity of real vehicle use was limited.

For comparison (both homologation and technology assessment), it is necessary that the driving cycle is representative for the real-life operating conditions. Representativity of the driving cycle implies that the time-speed profile must be:

1. Realistic (dynamic). All transient situations are power demanding for BEV, but may be more favourable for regenerative braking particularly in urban uses, where the number of starts/stops is high.
2. Accurately described in terms of cycle length and duration, average speed, maximum acceleration and deceleration. Statistically determined driving patterns from recorded vehicle usage may greatly help the definition of more realistic driving profiles.

A “real-life driving pattern“, thus, should be selected. Possible cycles that are based on current LD vehicle use, are the Modem cycle (Figure 8) or the three HYZEM cycles (Figure 9 - Figure 11). The three HYZEM cycles are combined in one test, and represent urban, rural, and highway traffic conditions. The outcomes of Subtask 2.8 [2] clearly indicated that stylistic (or "modal") cycles lead to non-representative results for energy consumption (and emissions in case a fuel

converter is present in the vehicle), when the applied cycle is not representative for the actual use of a vehicle in real-life. It has been shown that, for vehicles with alternative drivelines, the driving cycle characteristics have an even more profound influence on the energy consumption (and emissions) than for conventionally powered vehicles. Thus, stylistic cycles as the NEDC with the very narrow and low demanding speed profile would produce unrealistic (often too low) results.
Both the MODEM and HYZEM cycles cover nearly the same operating range in terms of power distribution over vehicle speed, but differ in length. The speed traces are given in the figures below.

As defined before, these cycles are not completely driving patterns, which intend to represent the overall service of the vehicle and not only the running cycles: for electric vehicles there is a significant impact of standstill times, including recharging (partial or complete or fast) on the overall fuel economy.

Within the MATADOR project, it is not the task to determine a cycle nor which existing cycle is most representative for real-life (European) driving conditions. The before mentioned cycles MODEM and HYZEM, therefore, are merely examples of real-life based driving cycles and just give an indication of how a representative cycle might look like and how it might be composed of several specific parts. The definition of this real-life representative cycle is one of the (near-) future tasks to be carried out within the field of vehicle standardisation and legislation research.

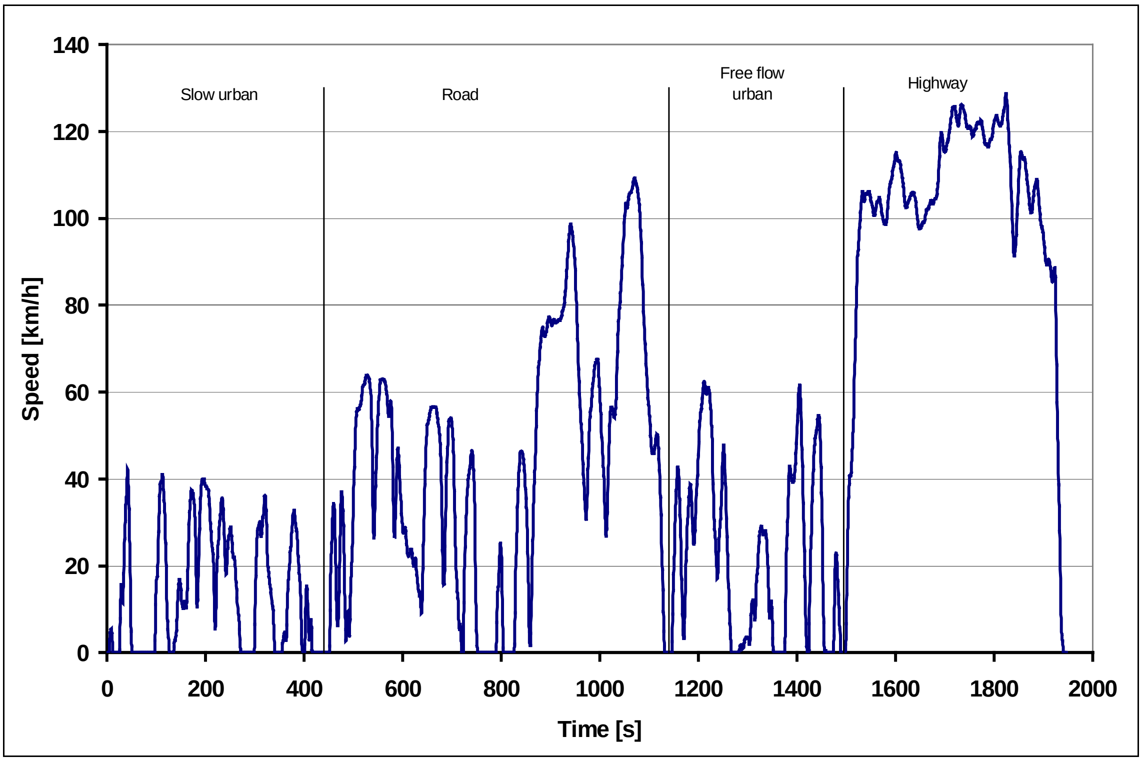

Figure 8: Modem cycle

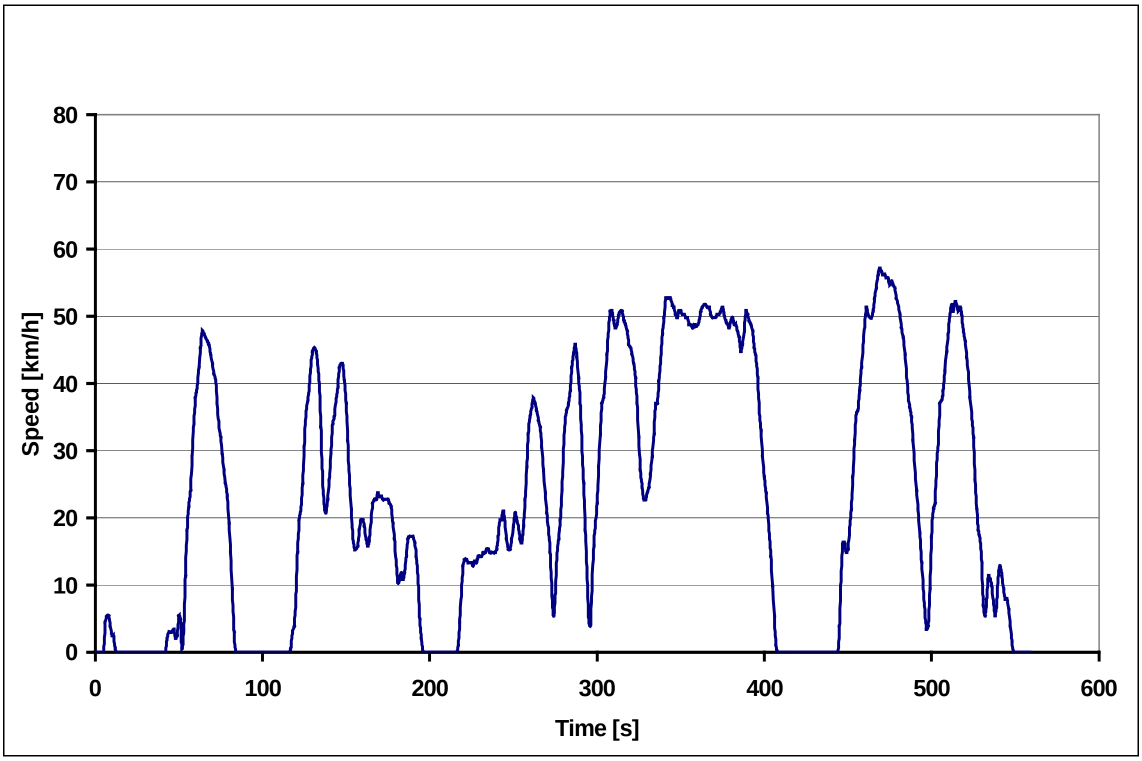

Figure 9: HYZEM urban

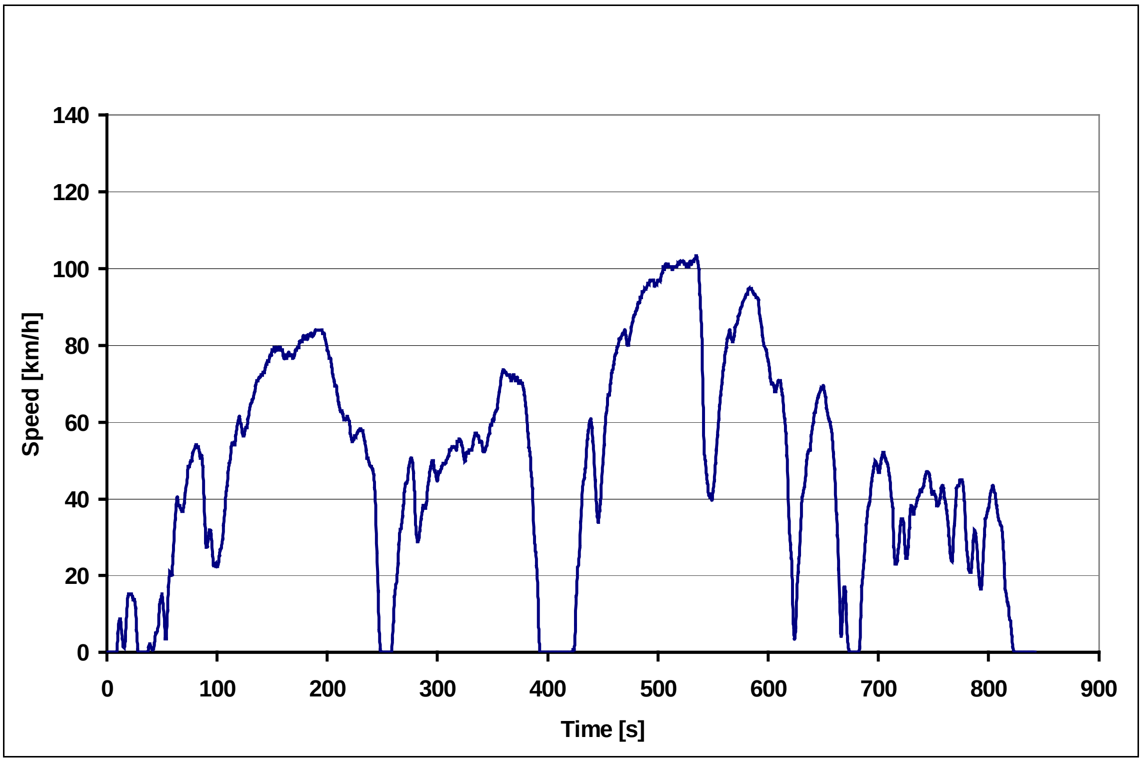

Figure 10: HYZEM rural

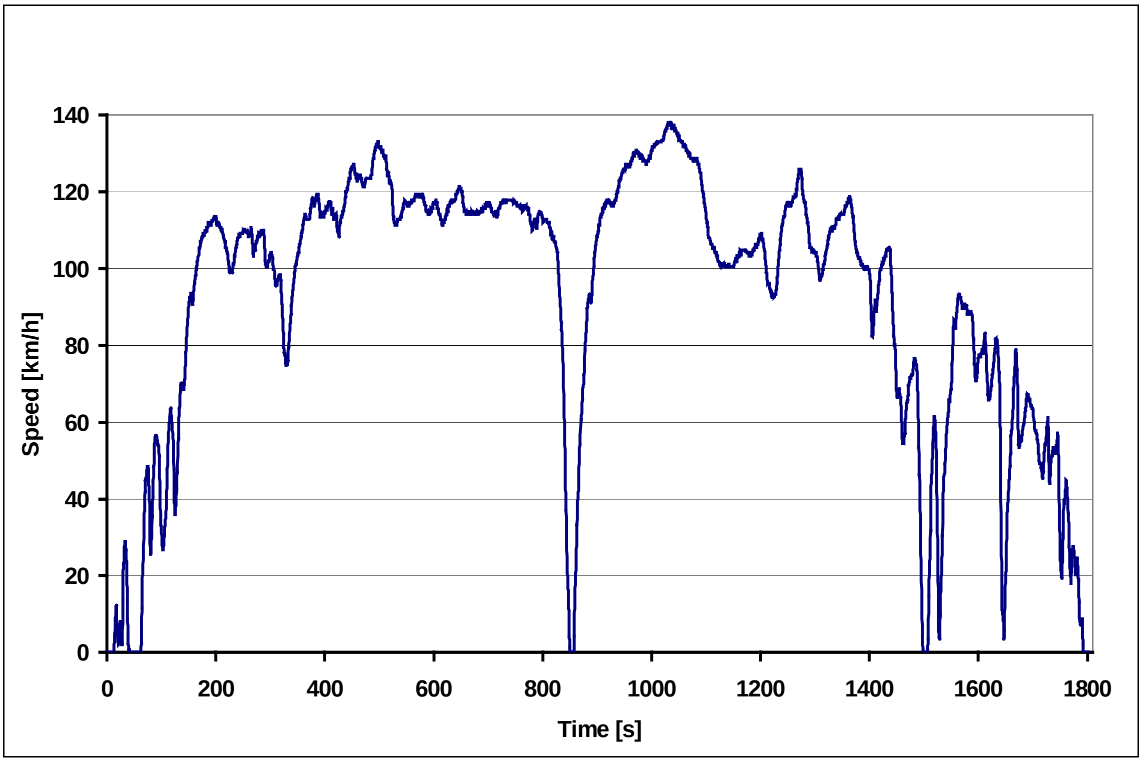

Figure 11: HYZEM highway

MANAGEMENT TOOL for the ASSESSMENT of DRIVELINE TECHNOLOGIES and RESEARCH

MATADOR

Contract JOE3-CT97-0081

Task 2:

Testing methods for vehicles with conventional and alternative drivelines

Framework

Test methods and procedures for Hybrid Electric Vehicles

20 July, 2000

Research funded in part by
THE COMMISSION OF THE EUROPEAN UNION
in the framework of the
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sub-programme
Energy Conservation and Utilisation

Nomenclature

Abbreviations

Ah	change in capacity of the EES over the driving cycle in Ampere-hours
D	distance travelled during test
E	energy
EES	electric energy storage device
EM	emissions
FC	fuel consumption
HD	heavy duty
HEV	hybrid electric vehicle
LD	light duty
MATADOR	Management Tool for the Assessment of Driveline TechnOlogy and Research
SOC	state of charge of the EES

Indices

1,2,3,…	Number of test performed
AC	AC electricity from mains
d	Distance related value
Hyb	Value recorded in hybrid mode
Th	Value recorded in thermal mode
ZEV	Value recorded in electric mode

Contents

1 Introduction

The intention of this paper is to present a framework for a test procedure for light duty thermal hybrid electric vehicles. The content is a synthesis of the results of the subtasks of the MATADOR Task 2 project. The structure of the framework is similar to the structures of existing (European) standards and comprises the following topics:

- Definitions of wording
- Preconditioning
- Measurement issues
- Driver related topics
- Driving cycles
- Test conditions
- Expression of results

As part of the framework, a flowchart is included, which allows for a quick overview of the test cases in the framework. Apart from the framework for LD HEVs, also considerations/recommendations for the testing of Heavy-Duty hybrid electric vehicles as well as for vehicles with alternative propulsion systems other than hybrid electric are made.

2 Scope

This procedure aims at the measurement of energy consumption and emission output of Light-Duty hybrid electric vehicles with thermal engine (carbon based fuels). The testing procedure is primarily meant for homologation purposes. The procedure may be extended [1], or additional measurement signals may have to be recorded, when that is desired for comparative assessments.

3 Definition of wording

- *Charge-depleting EES behaviour*: The state of charge of the Electrical Energy Storage (EES) system on average decreases when a vehicle is driven over a certain driving cycle (driving cycle dependent!). Typically, the operation characteristics of the vehicle may be impaired and performance will become less with decreasing battery charge.

- *Charge-sustaining EES behaviour*: The state of charge of the EES on average is maintained (within defined bounds) when the vehicle is driving over a certain driving cycle (driving cycle dependent!). Typically, the SOC shows a periodic behaviour when the vehicle is driven over (a sequence of) the driving cycle.

- *Driving cycle*: Vehicle speed vs. time pattern; used for determining the energy consumption and emissions. A driving cycle is currently used for LD vehicles. For HD vehicles, currently an engine test is used for type approval and homologation testing.

- *Electric Energy Storage device (EES):* A device in which electrical energy can be stored. Examples are batteries (electro-chemical), electric flywheels (electro-mechanical), (super-) capacitors, or a combination of these.

- *Electric mode (if available):* For hybrid vehicles, this is a user-selectable powertrain mode in which the vehicle is driven by the electric motor only, which in turn is powered from the electric energy storage device alone.

- *Externally rechargeable vehicles*: Vehicles in which the energy storage system can be charged by means of energy from the mains.

- *Hybrid mode (if available):* A powertrain mode in which all energy sources can participate in the propulsion of the vehicle. In case of a thermal engine this yields fuel energy consumption, and by means of an electric motor energy from an electrical energy storage device is used. The operation of the thermal engine and electric motor can be in a combined or alternating way, automated by the vehicle‘s control. The mode may be user-selectable. A hybrid vehicle, which has no user-selectable modes, is considered to have a hybrid mode only.

- *Linear regression method*: Method to determine the fuel consumption and emissions of non-externally rechargeable, charge-sustaining vehicles, that accounts for the difference in energy content of the EES before and after a test [3].

- *Thermal mode (if available):* A user-selectable powertrain mode in which only power from the thermal engine is used to propel the vehicle and/or to charge the electric energy storage device. The electric energy storage device is not discharged for traction purposes at any time during the test.

- *Underpowered vehicles*: Vehicles that do not meet the speed demands of the driving cycle.

- *State of Charge*: Indicates the amount of energy left in a storage system with respect to its maximum energy content.

4 Preconditioning

4.1 Testbench preconditioning

The testbench shall be warmed up without the vehicle according to the recommendations of the supplier of the rollerbench. This way, a proper setting of the road load without affecting a cold start of the vehicle (especially tyres [2]) is represented best.

4.2 Vehicle Preconditioning

Vehicle soak should be for 24 hours (with the EES being charged for externally rechargeable HEVs) at 25±1°C. Thus a cold start of the thermal engine occurs. The narrow limit is defined to eliminate the strong influence of the starting temperature on the driveline behaviour of a HEV. In contrast to conventional vehicles, different starting temperatures can lead to different operating periods due to a strong influence on duration of the warm-up phase of the ICE. This variation can lead to significantly different results for multiple tests [7].

In order to account for the self-discharge effects of the EES during the entire test period, a condition of the currently proposed test procedure [9] has to be specified more strictly. The time interval between battery disconnection from the mains after recharge and start of the test should be minimised. For the same reason, the time period between the end of the driving cycle test and reconnection to the mains for recharge should also be minimised. As guideline, the total amount of time of both periods should not exceed one hour [8].

The pressure of the tyres has to be checked and, if necessary, resettled before each test to eliminate the influence of the variation of rolling resistance versus pressure.

5 Measurement issues

In addition to the signals to be measured and equipment to be used as laid down in the European standards, for some categories of hybrid electric vehicles the state of charge of the EES has to be measured during the driving cycle test:

a) Batteries and combinations of batteries with capacitors and/or electric flywheels: Ah-monitoring by integrating the terminal current of the EES at 10 Hz (may be inductive).
b) Capacitors: internal voltage monitoring (before DC/DC converter; manufacturer has to provide an industrial standard connector bus)
c) Electric flywheels: flywheel speed (manufacturer has to provide an industrial standard connector bus)

In case of user selectable powertrain modes, the current from the EES to the traction system also has to be measured in order to determine the characteristics of the modes in which the thermal engine is used (e.g. thermal mode with/without charging of the battery from fuel).

Note:
Ah-monitoring may not always be a good indicator for the change in state of charge of the EES because of ageing effects, operating temperatures different from the standard values and charge efficiency [4]. However, since the Ah-monitoring is mainly applied on vehicles which rely on high EES efficiency for good overall energy performance, resulting inaccuracies are assumed to be at a level that does not significantly affect the final results of the calculation of the overall energy consumption and emissions. In order to take into account the effect of battery ageing, however, the battery pack has to be in a defined age, accomplished by approximately 300 km of representative use (driving cycle). The vehicle manufacturer may also provide a SOC determination method with which the SOC can be measured at a higher level of accuracy, making use of the measured internal resistance and open circuit voltage at the beginning and the end of the test.

6 Driver related topics in test procedure

6.1 Speed tolerance

The tolerance in vehicle speed is ±2 km/h and ±1 second, as in the existing European standards. The tolerances are not changed, since measurements have shown that human drivers regularly make use of the full tolerance range, especially under transient driving behaviour.

6.2 Shifting points

If the vehicle is equipped with a manual gearbox, predefined shifting points have to be used, similar to the ones used for the New European Driving Cycle. Up- and downshift should occur at the same speeds, no downshifts during braking phases are allowed. If the vehicle manufacturer can verify that the cycle demands cannot be met, than he must provide in a shifting procedure that enables the vehicle to meet the cycle demands. The reason for this is found in the big influence that shifting strategies have on energy consumption [7].

6.3 Driving instructions

The automated driveline control of a vehicle may be forced (for instance by 'nervous' behaviour of the driver) to follow control algorithms that were not intended to be followed at that moment. This might lead to sudden unintended engine starts, which in turn has its influence on the final energy consumption calculated for that test. Problems like these lead to hardly reproducible tests and results, which have to be avoided. Therefore, a manufacturer may have to provide a list with driving instructions, in which it is clearly defined at which times during the driving cycle certain actions are required from the driver. Examples are when:

a) the kickdown has to be applied.
b) the brake pedal has to be applied (which parts of the vehicle deceleration can be met only by releasing the accelerator, and at what parts the use of the braking pedal is necessary).
c) a gearshift (as before mentioned) is necessary.

The results of experiments investigating the reproducibility of energy consumption showed, that reproducibility is only sufficient when the driver is instructed exactly how and when to use powertrain control-critical interfaces [7].

If the vehicle manufacturer specifies (with prove) that the vehicle cannot meet all cycle parts (e.g. rural and/or highway), i.e. it is an underpowered vehicle, the vehicle is to be driven only over the urban part (or urban and rural parts in case only the highway part cannot be met). This way, vehicles dedicated to specific application areas are tested according to their purposes.

6.4 Driving modes

HEV modes: In case of driver-selectable driving modes (hybrid-, electrical-, and/or thermal-mode) the vehicle is to be driven in hybrid mode 0. As an option, the energy consumption in electrical mode and the fuel consumption and emissions in thermal mode can be tested following the procedures for externally rechargeable vehicles without hybrid mode.

For user-selectable regenerative modes with following functionality:

a) regeneration 'on' or 'off'
b) regeneration starts on accelerator release vs. regeneration only at application of brake pedal,

The regeneration has to be enabled in case of a), and the functionality of 'regeneration initiated only by application of braking pedal' chosen in case of b).
In case of driving modes that affect the energy consumption, e.g. sport or economy mode, the economy mode has to be enabled.
The choice of the driving modes should support the aim to exploit the full potential of hybrid electric vehicles in terms of energy saving and emission reduction under representative driving conditions.

7 Driving cycle

For the driving cycle, a "real-life driving pattern" should be selected. Possible cycles that based on current LD vehicle use, are the MODEM cycle (Fig. 7-1) or the three HYZEM cycles (Fig. 7-2 through Fig. 7-4). The three HYZEM cycles are combined in one test, and represent urban, rural, and highway driving. The outcomes of Subtask 2.8 clearly indicate [5], that cycles lead to non-representative results for energy consumption and emissions, when the applied cycle is not representative for the actual use of a vehicle in real-life. It has been shown that, for vehicles with alternative drivelines, the driving cycle characteristics have an even more profound influence on the energy consumption and emissions than for conventionally powered vehicles. Thus, stylistic cycles as the New European Driving Cycle with the very narrow and low demanding speed profile would produce unrealistic (and due to low power demand, too low) results.

Both the MODEM and HYZEM cycles cover nearly the same operating range in terms of power distribution over vehicle speed, but differ in length. The speed traces of these cycles are given in the figures below.

Within the MATADOR project, it is not the task to determine a cycle nor which existing cycle is most representative for real-life (European) driving conditions. The before mentioned cycles MODEM and HYZEM, therefore, are merely examples of real-life based driving cycles and just give an indication on how a representative cycle might look like and how it might be composed of several specific parts. The definition of this real-life representative cycle is one of the (near-) future tasks to be carried out within the field of vehicle standardisation and legislation research.

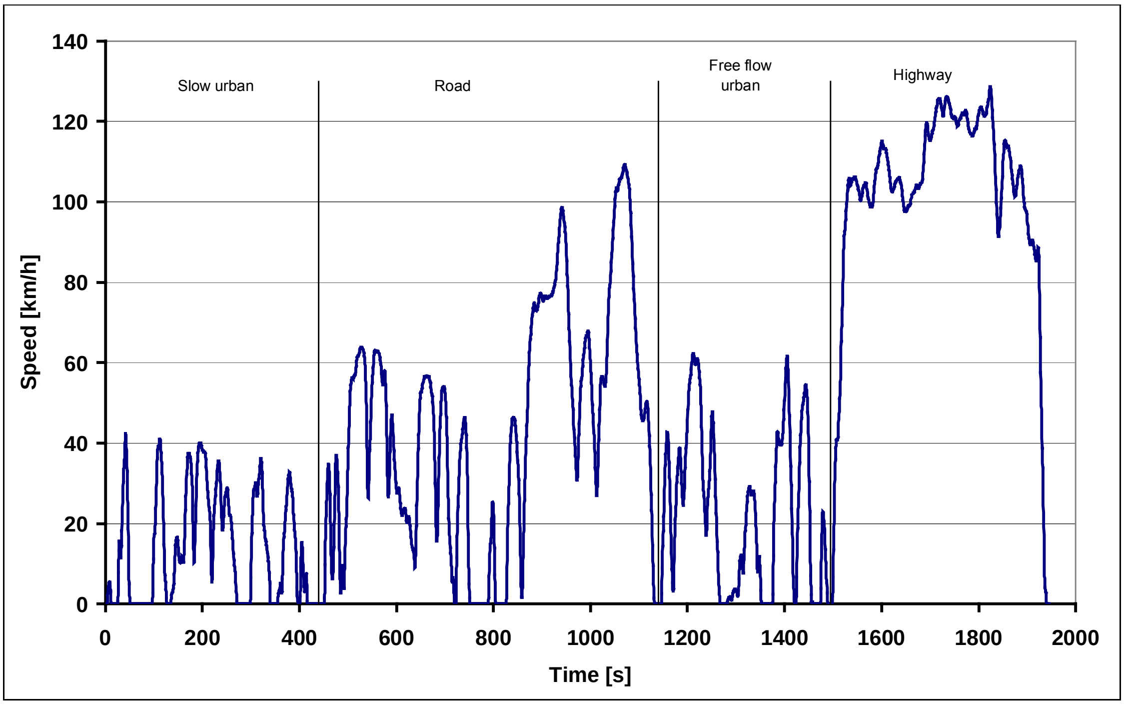


Fig. 7-1: Modem cycle driving cycle

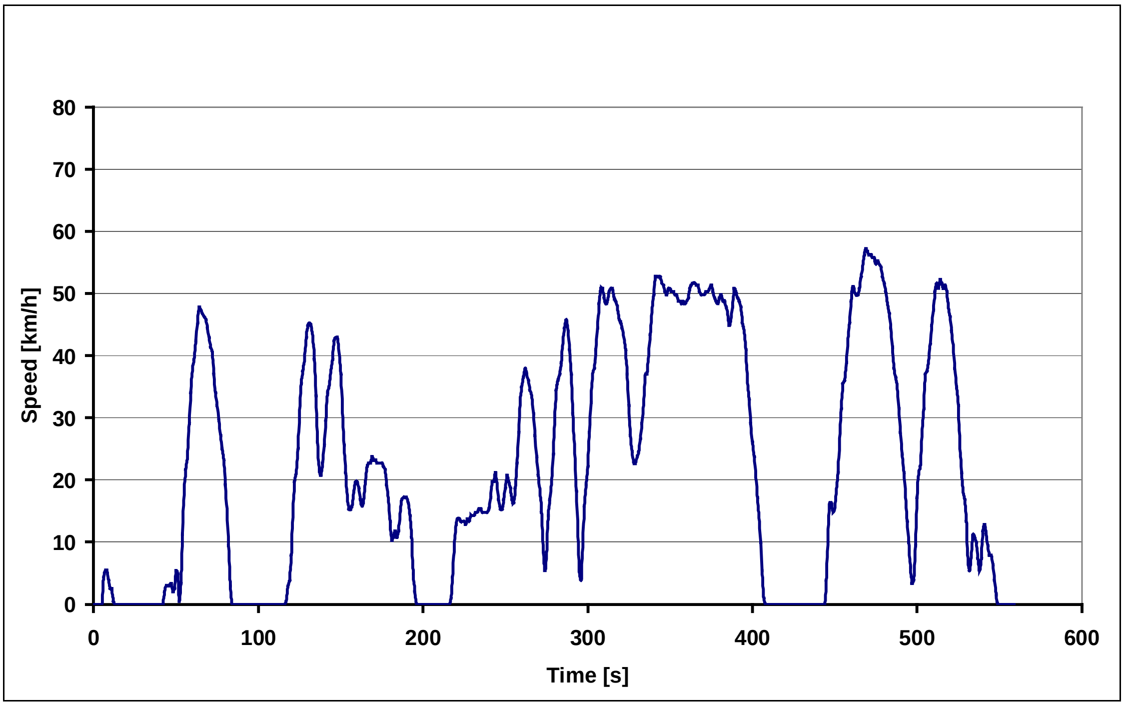


Fig. 7-2: HYZEM urban driving cycle

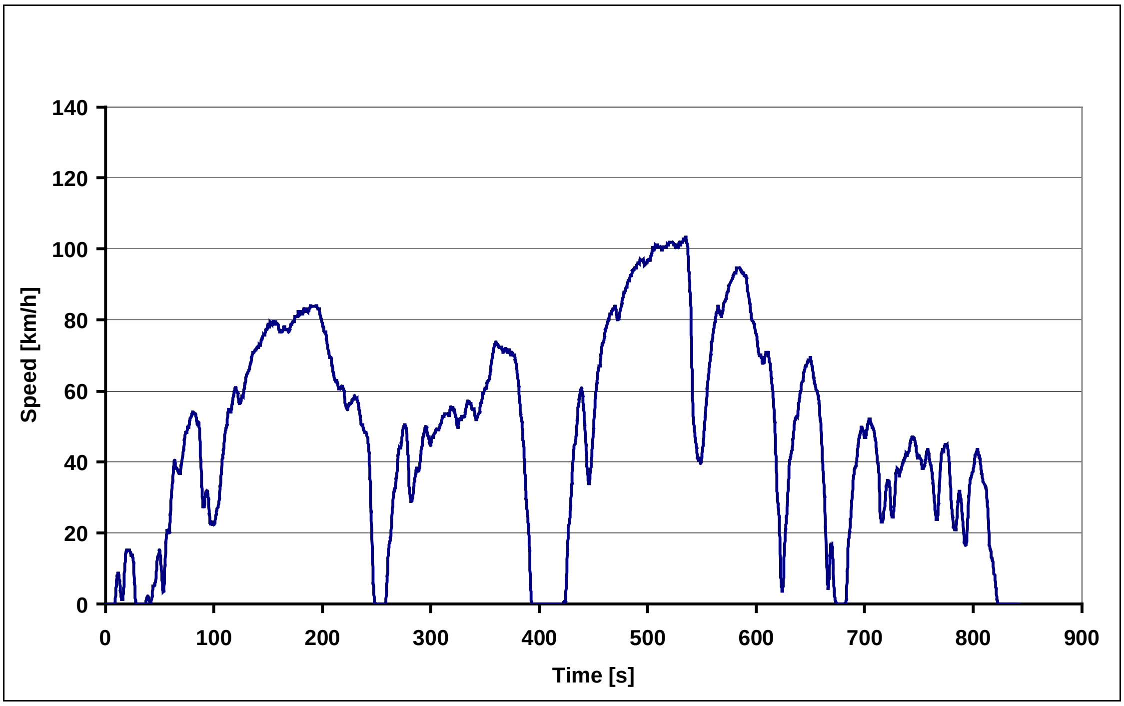


Fig. 7-3: HYZEM rural driving cycle

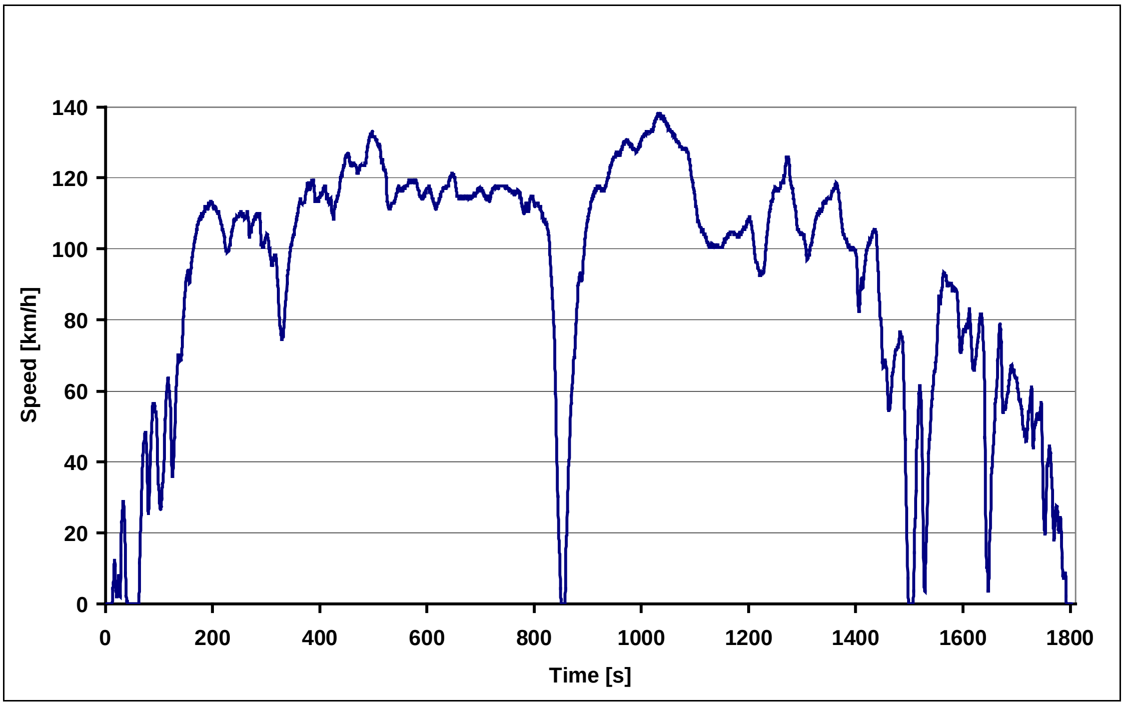


Fig. 7-4: HYZEM highway driving cycle

8 Test procedure

The test procedure distinguishes hybrid vehicles after several aspects. These aspects are:

- Presence of a hybrid mode
- Possibility to (re)charge the EES from outside the vehicle (externally rechargeable vehicles)
- User selectable rechargeability of the EES by on-board fuel energy through the thermal engine (vehicles without hybrid mode)
- Self-discharge behaviour of the EES (slowly or fast, for instance battery vs. flywheel)
- Energetic response character of the EES to the driving cycle (charge-sustaining hybrid vehicles)

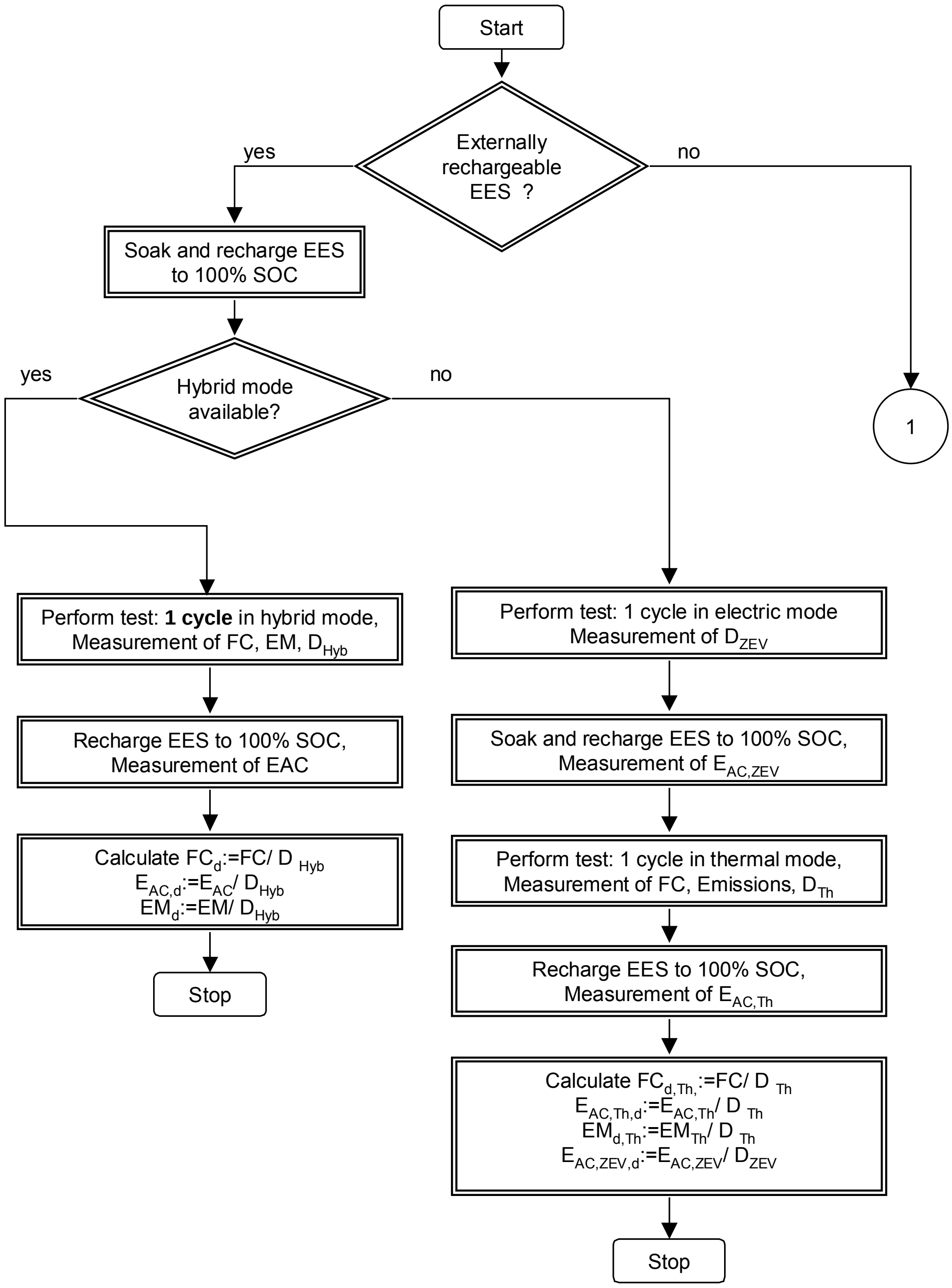
The testing procedures for hybrid electric vehicles are described in the following sections. The signals to be measured for each step in the procedure are written in Italic. The explanations for profound differences between existing European standards [9][10] and the framework are underlined.

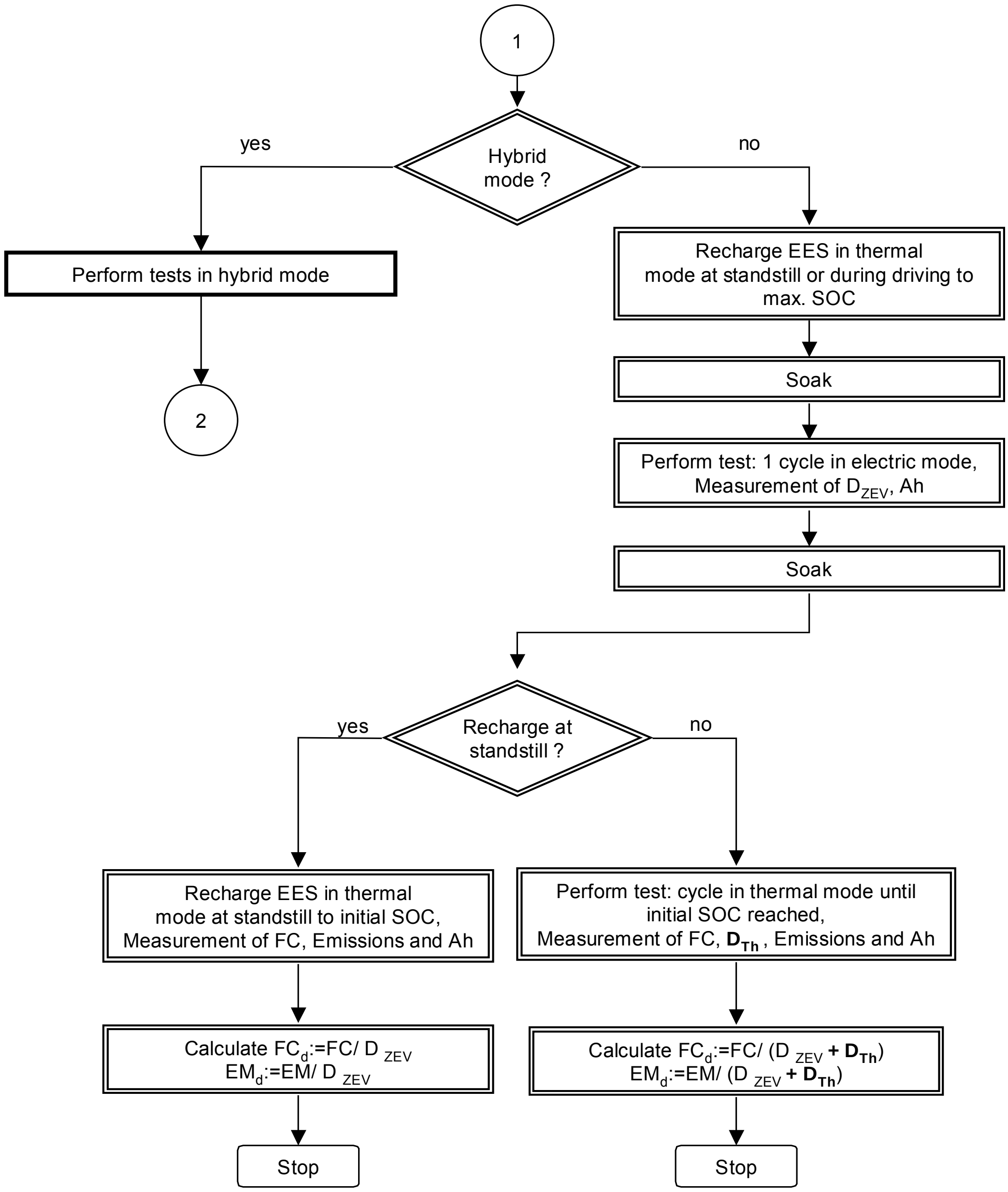
8.1 Test procedure flow chart

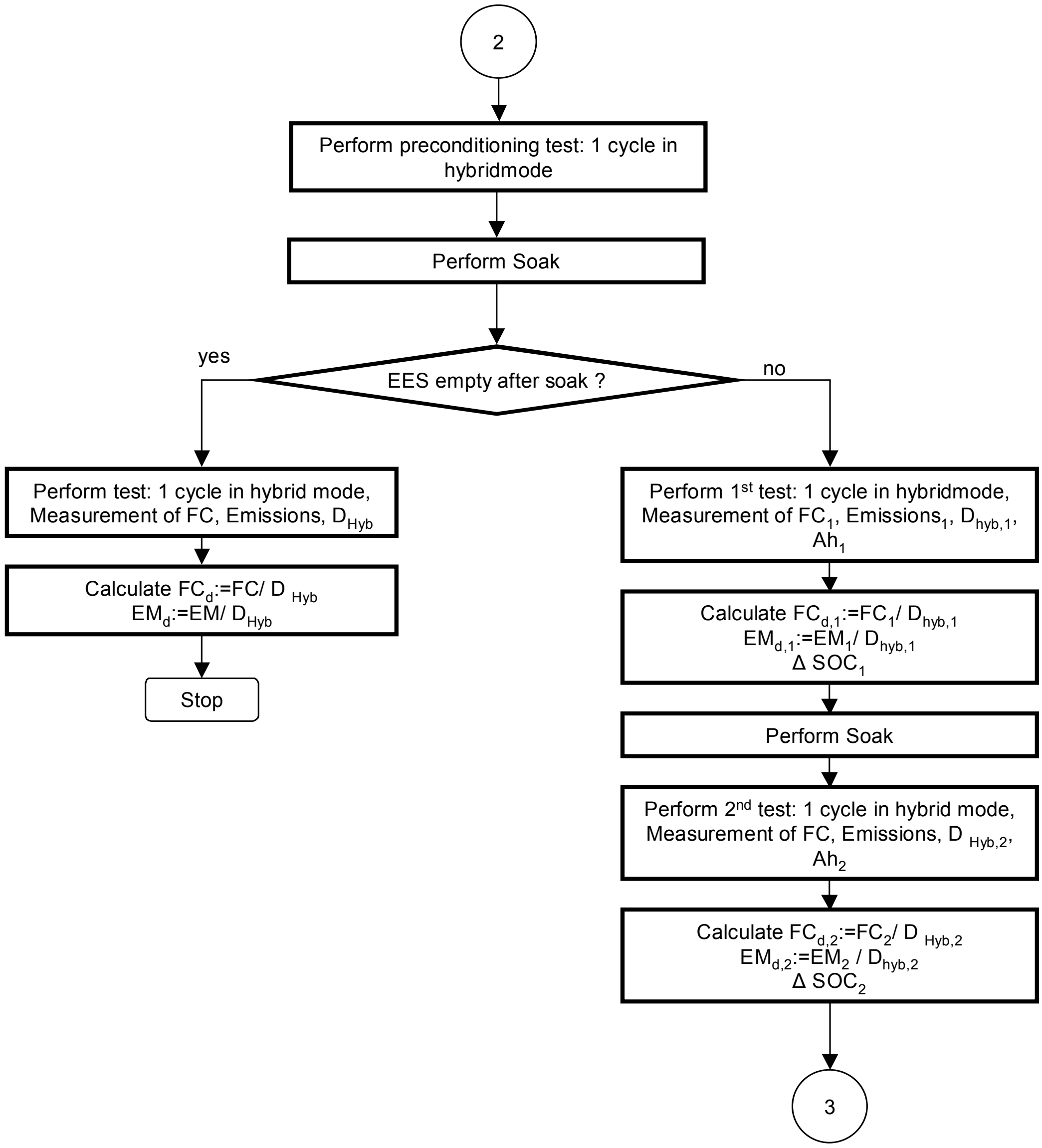
The following flow chart gives a systematic overview of the test procedure structure and can be used to determine which specific actions have to be followed for the testing of Hybrid Electric Vehicles. Sections 8.2 and 8.3 concern the textual completion.

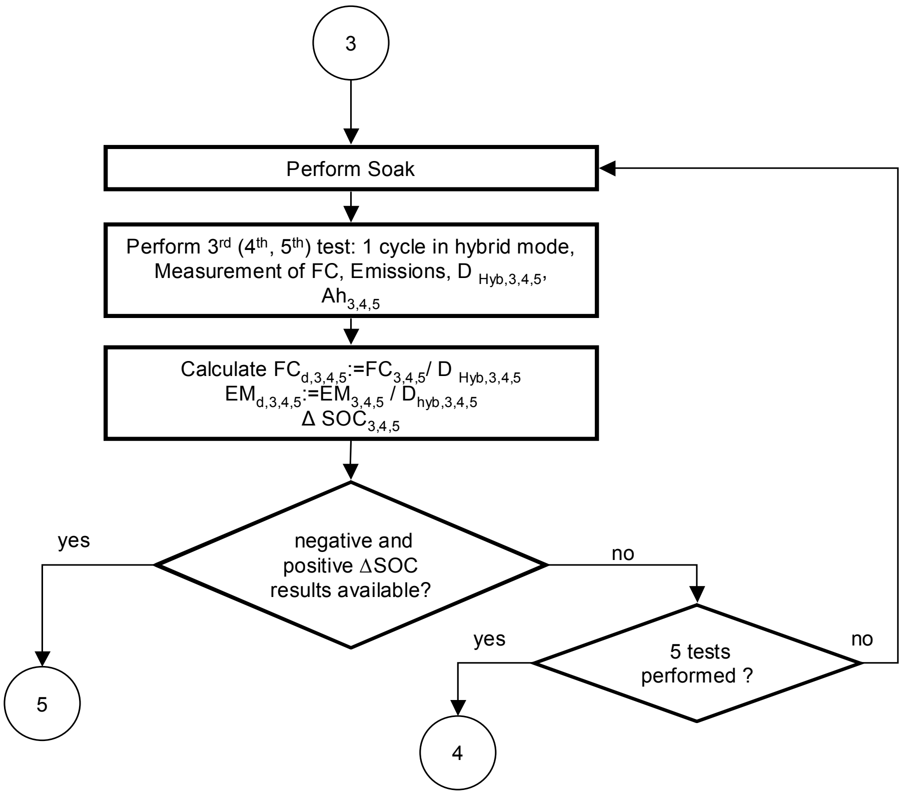
The following sign conventions are used:

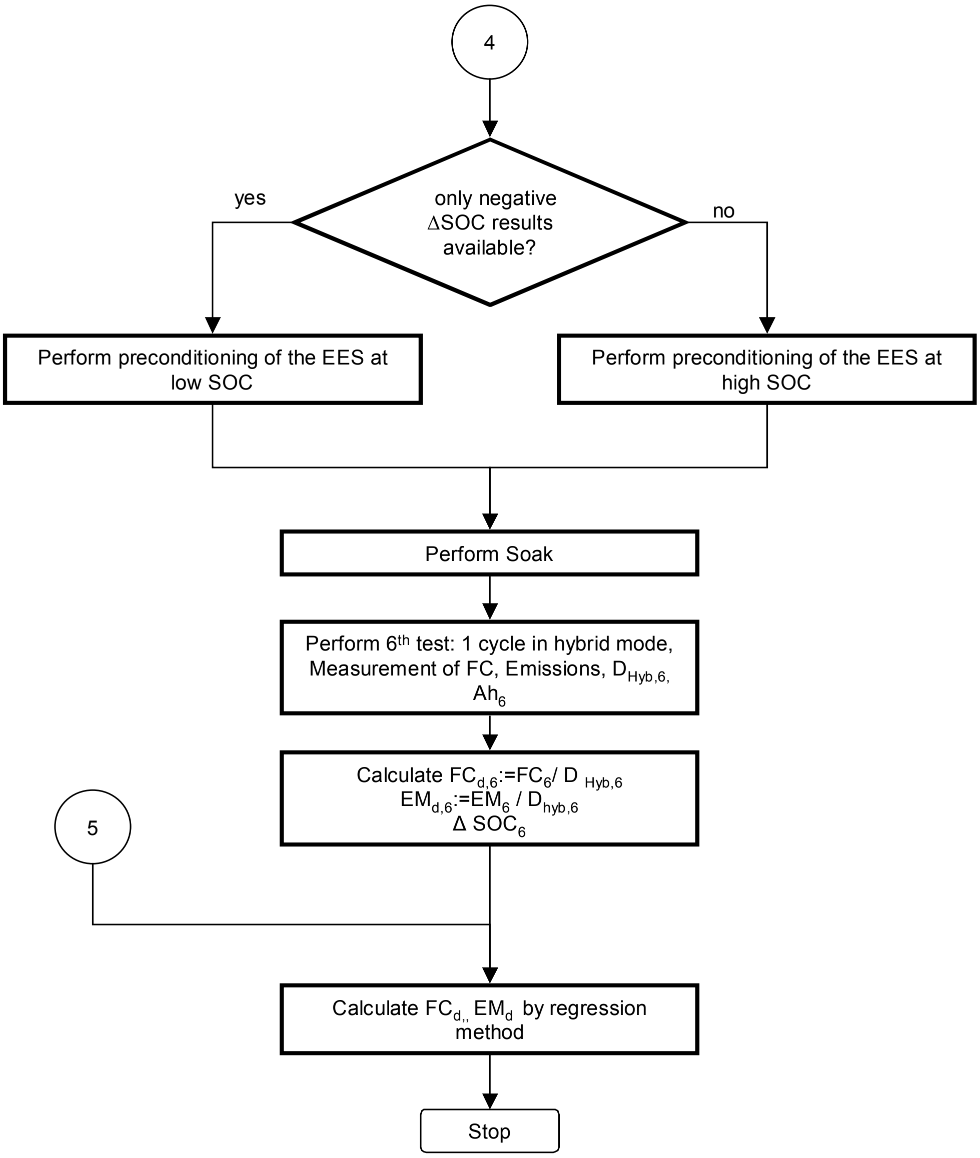
- Bold outlined blocks as well as bold fonts mark test steps that are additional/different to the existing European standard procedures EN 1986-1, EN 1986-2 and EN 13444-1.
- Double outlined blocks mark test steps that are (to a close extend) found in the existing European standard procedures.


Start
Externally rechargeable EES ?
yes
no
Soak and recharge EES to 100% SOC
Hybrid mode available?
yes
no
1
Perform test: **1 cycle** in hybrid mode, Measurement of FC, EM, D_{Hyb}
Recharge EES to 100% SOC, Measurement of EAC
Calculate FC_d:=FC/ D_{Hyb}
$E_{AC,d}$:=E_{AC}/ D_{Hyb}
EM_d:=EM/ D_{Hyb}
Stop
Perform test: 1 cycle in electric mode Measurement of D_{ZEV}
Soak and recharge EES to 100% SOC, Measurement of $E_{AC,ZEV}$
Perform test: 1 cycle in thermal mode, Measurement of FC, Emissions, D_{Th}
Recharge EES to 100% SOC, Measurement of $E_{AC,Th}$
Calculate $FC_{d,Th,}$:=FC/ D_{Th}
$E_{AC,Th,d}$:=$E_{AC,Th}$/ D_{Th}
$EM_{d,Th}$:=EM_{Th}/ D_{Th}
$E_{AC,ZEV,d}$:=$E_{AC,ZEV}$/ D_{ZEV}
Stop


1
Hybrid mode ?
yes
no
Perform tests in hybrid mode
2
Recharge EES in thermal mode at standstill or during driving to max. SOC
Soak
Perform test: 1 cycle in electric mode, Measurement of D_ZEV, Ah
Soak
Recharge at standstill ?
yes
no
Recharge EES in thermal mode at standstill to initial SOC, Measurement of FC, Emissions and Ah
Perform test: cycle in thermal mode until initial SOC reached, Measurement of FC, D_Th , Emissions and Ah
Calculate FC_d:=FC/ D ZEV
EM_d:=EM/ D ZEV
Calculate FC_d:=FC/ (D ZEV + D_Th)
EM_d:=EM/ (D ZEV + D_Th)
Stop
Stop


2
Perform preconditioning test: 1 cycle in hybridmode
Perform Soak
EES empty after soak ?
yes
no
Perform test: 1 cycle in hybrid mode, Measurement of FC, Emissions, D_{Hyb}
Calculate FC_d:=FC/ D_{Hyb}
EM_d:=EM/ D_{Hyb}
Stop
Perform 1st test: 1 cycle in hybridmode, Measurement of FC_1, $Emissions_1$, $D_{hyb,1}$, Ah_1
Calculate $FC_{d,1}$:=FC_1/ $D_{hyb,1}$
$EM_{d,1}$:=EM_1/ $D_{hyb,1}$
Δ SOC_1
Perform Soak
Perform 2nd test: 1 cycle in hybrid mode, Measurement of FC, Emissions, $D_{Hyb,2}$, Ah_2
Calculate $FC_{d,2}$:=FC_2/ $D_{Hyb,2}$
$EM_{d,2}$:=EM_2 / $D_{hyb,2}$
Δ SOC_2
3


3
Perform Soak
Perform 3rd (4th, 5th) test: 1 cycle in hybrid mode, Measurement of FC, Emissions, D Hyb,3,4,5, Ah3,4,5
Calculate FCd,3,4,5:=FC3,4,5/ D Hyb,3,4,5
EMd,3,4,5:=EM3,4,5 / Dhyb,3,4,5
Δ SOC3,4,5
negative and positive ΔSOC results available?
yes
no
5 tests performed ?
yes
no
5
4


4
only negative
ΔSOC results
available?
yes
no
Perform preconditioning of the EES at low SOC
Perform preconditioning of the EES at high SOC
Perform Soak
Perform 6th test: 1 cycle in hybrid mode, Measurement of FC, Emissions, D Hyb,6, Ah6
Calculate FCd,6:=FC6/ D Hyb,6
EMd,6:=EM6 / Dhyb,6
Δ SOC6
5
Calculate FCd,, EMd by regression method
Stop

8.2 Externally rechargeable vehicles

For externally rechargeable vehicles (both charge-depleting and charge-sustaining), following test procedure applies:

1) Soak (for at least 24 hours) at 25±1°C on charge until the EES is fully charged.

8.2.1 With hybrid mode

In case a hybrid mode is available:

2) Perform one driving cycle in hybrid mode. *Measuring of emissions and travelled distance.*

The completion of only one driving cycle is based on the fact that the driving cycle is representative for real-life operation.

3) Fully recharge the EES. *Measuring of the energy taken from the mains*.

4) Determine energy consumption and emissions:
   $FC_d = FC / D_{Hyb}$
   $E_{AC,d} = E_{AC} / D_{Hyb}$
   $EM_d = EM / D_{Hyb}$

8.2.2 Without hybrid mode

In case no hybrid mode is available:

2) Perform one driving cycle in electric mode. *Measuring of travelled distance.*

3) Soak (for at least 24 hours) at 25±1 °C on charge until the EES is fully charged. *Measuring of energy from mains.*

4) Perform one driving cycle in thermal mode. *Measuring of emissions and travelled distance.*

5) Soak (for at least 24 hours) at 25±1 °C on charge until the EES is fully charged. *Measuring of energy from mains.*

6) Determine energy consumption and emissions:

   thermal mode:
   $FC_{d,Th} = FC / D_{Th}$
   $E_{AC,Th,d} = E_{AC,Th} / D_{Th}$
   $EM_{d,Th} = EMTh / D_{Th}$

   electric mode:
   $E_{AC,ZEV,d} = E_{AC,ZEV} / D_{ZEV}$

8.3 Non-externally rechargeable vehicles

When the EES is not externally rechargeable, the following test procedure applies:

8.3.1 With hybrid mode

When there is a hybrid mode available:

1) Perform one driving cycle in hybrid mode (as a means of preconditioning of the EES)

2) Soak 24 hours at 25±1°C

When the EES if fully depleted after the soak:

3) Perform one driving cycle in hybrid mode. *Measuring of emissions and travelled distance.*

4) Determine energy consumption and emissions:
   $FC_d = FC / D_{Hyb}$
   $EM_d = EM / D_{Hyb}$

In case the EES is not fully deplenished after the soak:

1) Perform first test: one driving cycle in hybrid mode. *Measuring of emissions, travelled distance and Amperehours.*

2) Determine energy consumption, emissions and ΔSOC:
   $FC_{d,1} = FC_1 / D_{Hyb,1}$
   $EM_{d,1} = EM_1 / D_{Hyb,1}$
   $\Delta SOC_1 = Ah_1$

3) Soak for 24 hours at 25±1°C

4) Perform second test: one driving cycle in hybrid mode. *Measuring of emissions, travelled distance and Amperehours.*

5) Determine energy consumption, emissions and ΔSOC:
   $FC_{d,2} = FC_1 / D_{Hyb,2}$
   $EM_{d,2} = EM_2 / D_{Hyb,2}$
   $\Delta SOC_2 = Ah_2$

6) Soak for 24 hours at 25±1°C

7) Perform third test: one driving cycle in hybrid mode. *Measuring of emissions, travelled distance and Amperehours.*

8) Determine energy consumption, emissions and ΔSOC:
   $FC_{d,3} = FC_3 / D_{Hyb,3}$
   $EM_{d,3} = EM_3 / D_{Hyb,3}$
   $\Delta SOC_3 = Ah_3$

If there are positive and negative ΔSOC values available:

9) Calculate energy consumption and emissions from results 1 to 3 with linear regression method.

If there are still only positive or negative ΔSOC values available:

9) Soak for 24 hours at 25±1°C

10) Perform fourth test: one driving cycle in hybrid mode. *Measuring of emissions, travelled distance and Amperehours.*

11) Determine energy consumption, emissions and ΔSOC:
$FC_{d,4} = FC_4 / D_{Hyb,4}$
$EM_{d,4} = EM_4 / D_{Hyb,4}$
$\Delta SOC_4 = Ah_4$

If there are positive and negative ΔSOC values available:

12) Calculate energy consumption and emissions from results 1 to 4 with linear regression method.

If there are still only positive or negative ΔSOC values available:

12) Soak for 24 hours at 25±1°C

13) Perform fifth test: one driving cycle in hybrid mode. *Measuring of emissions, travelled distance and Amperehours.*

14) Determine energy consumption, emissions and ΔSOC:
$FC_{d,5} = FC_5 / D_{Hyb,5}$
$EM_{d,5} = EM_5 / D_{Hyb,5}$
$\Delta SOC_5 = Ah_5$

If there are positive and negative ΔSOC values available:

15) Calculate energy consumption and emissions from results 1 to 5 with linear regression method.

If there are still only negative ΔSOC values available:

15) Perform preconditioning test of the EES: Drive the vehicle at a velocity (to be defined by manufacturer, typically about 20 to 30 km/h), at which the thermal engine will stall after warm-up (if any) and the vehicle is driven electrically, until the thermal engine starts (again). *No measurements required.*

If there are still only positive ΔSOC values available:

15) Perform preconditioning test of the EES: Drive the vehicle at 30 km/h under regenerative operation (braking pedal may be applied with a constant, moderate force) until SOC does not increase any more. In order to do so, the dynamometer

should be operated at a set point of 30 km/h. *Measurement/monitoring of Amperehours.*

16) Soak for 24 hours at 25±1°C

17) Perform sixth test: one driving cycle in hybrid mode. *Measuring of emissions, travelled distance and Amperehours.*

18) Determine energy consumption, emissions and ΔSOC:
$FC_{d,6} = FC_6 / D_{Hyb,6}$
$EM_{d,6} = EM_6 / D_{Hyb,6}$
$\Delta SOC_6 = Ah_6$

19) Calculate energy consumption and emissions from results 1 to 6 with linear regression method.

<u>The ΔSOC correction method of linear regression for non-externally rechargeable charge-sustaining vehicles is introduced to determine the fuel consumption and emissions in an exact, representative, and flexible way. Also, there is no procedure from the vehicle manufacturer required which dictates how to ensure that the state of charge of the EES over the test campaign should be balanced, as stated in the European standards, which may not represent real-life use.</u>

8.3.2 Without hybrid mode

If there is no hybrid mode available:

1) Recharge the EES in thermal mode during standstill or during consecutive cycle driving until SOC does not increase anymore. *Measuring/monitoring of Amperehours.*

2) Soak 24 hours at 25±1°C

3) Perform one driving cycle in electric mode. *Measuring of travelled distance and Amperehours.*

4) Soak 24 hours at 25±1°C

If recharge is possible during standstill:

5) Recharge EES in thermal mode at standstill to initial SOC. *Measuring of emissions and Amperehours.*

6) Calculate energy consumption and emissions:
$FC_d = FC / D_{ZEV}$
$EM_d = EM / D_{ZEV}$

If recharge is not possible during standstill:

5) Recharge the EES in thermal mode during consecutive cycle driving to initial SOC. *Measuring of emissions, travelled distance and Amperehours.*

6) Calculate energy consumption and emissions:
   $FC_d = FC / (D_{ZEV} + D_{Th})$
   $EM_d = EM / (D_{ZEV} + D_{Th})$

   The inclusion of the distance driven in thermal mode (during recharge) in the calculation of fuel consumption and emissions is different from the European standards. It is meant to better represent real-life use, since in real life there is an advantage of covering distance while recharging the EES.

8.4 Number of test repetitions

For each kind of hybrid vehicle, the test procedure should be carried out three times. This number of repetitions is necessary to evaluate the reproducibility of the test and to eliminate the influence of random effects.

9 Expression of the results

Fuel consumption should be expressed in l/100 km, pollutant emissions in g/km.
For externally rechargeable vehicles, three results are presented: Fuel consumption in l/100km, pollutant emissions in g/km and electric energy consumption expressed in Wh/km.
The results of the measurements 1 to 3 have to be averaged.

10 Conclusion

The synthesis of the subtasks allows for a reasonable set-up of the testing procedure in terms of feasibility, implementation, and boundary conditions. The selection of a driving schedule itself, which is of prime importance for representativity for real- life conditions, is not part of the MATADOR project.
It has been shown that, for vehicles with alternative drivelines, the driving cycle characteristics have an even more profound influence on the energy consumption and emissions than for conventionally powered vehicles. The used driving cycle has to be representative for real-life vehicle use. Only then the results of different vehicles will be mutually comparable and useful for a decent homologation.

Apart from the wish for a new homologation driving cycle, this framework differs from European standards by defining stricter vehicle preconditioning, vehicle operation during the test, and the inclusion of (selectable) driving modes. Also, differences between the included test sequences are found: in contrast to the European standards, the framework contains definitions how to account for differences in the state of charge of non-rechargeable charge-sustaining hybrid vehicles. In order to account for self-discharge and heating losses for externally rechargeable vehicles, also time duration between disconnection from the charger and the actual use of the vehicle have been defined more strictly. Like the choice of the driving cycle, also these differences are based on the aim to approximate real-life use of the vehicle.

11 Remarks for testing HD-hybrid electric vehicles

For testing HD-HEVs two major issues are still unsolved [6]:

a) Whether it is practicable to test HD-HEVs on dynamometers in terms of availability of powerful transient testbenches (requires large investments) – and
b) which cycle shall be used or which cycle is representative for the given vehicle.

If a) can be answered with yes, the given procedure above for LD-HEVs in general (except the cycle) shall also be applied for HD-HEVs. For b) a classification of vehicles is necessary. A first attempt is given below:

- Long distance trucks
- Delivery trucks
- Coaches
- City busses
- Special vehicles (municipal vehicles, road sweepers, garbage trucks)

12 Remarks for testing vehicles with other alternative drivelines

Hybrid vehicles can be realised in ways different than thermal hybrid electric vehicles. For some of those, the application of the described procedure may therefore not be straightforward or may not even be valid. There are, however, many similarities and basic principles for all hybrid vehicles, which allow an analogous way of testing. For instance, in order to have sufficient range, most hybrid vehicles are equipped with a primary energy carrier and therefore have a thermal engine or fuel cell.

The remaining drivetrain differences are mainly found in the used regenerative secondary energy storage devices and converters. Although regenerative electric energy carriers/converters from today’s point of view show the biggest advantages for this purpose, also other secondary energy systems may be used, such as mechanical flywheels or hydraulic/pneumatic-based systems. In these cases, the way of measuring the in- and outgoing energies of the secondary energy carrier may differ from the measuring methods for the electric systems, the applied procedure and the values of interest in principle however stay the same. Therefore the proposed framework is also valid for these vehicles.

Besides the systems described above, other alternative propulsion systems exist, which cannot be classified as hybrid, since they have only one energy carrier. The energy carrier, however, is not a primary one, but a secondary one. Such propulsion systems therefore belong to the category of single drives, like the conventional propulsion systems. Because of the desired range, in most cases compressed air or nitrogen is used. These vehicles in many cases are similar to pure electric vehicles, since the recharging is done externally (by means of electricity- or thermal engine based compression).

The implications for the energy and emissions measurement of vehicles with alternative propulsion systems other than those fitted with a thermal engine and electric energy storage device are listed below:

- **Hybrid mechanical vehicles (mechanical flywheel)**
  These vehicles can directly be compared with hybrid electric vehicles with electric flywheel. Energy consumption and emissions can therefore be measured according to the proposed framework.

- **Hybrid hydraulic/pneumatic vehicles (hydro- or pressurised gas tank)**
  In order to apply the methods according to the proposed framework, for non-externally rechargeable systems the SOC must be measured by calculating the hydraulic energy content before and after each procedure. This requires the pressure and temperature of the storage medium to be measured. If there is a possibility to recharge the secondary energy carrier externally, the electric energy from the mains is measured.

- **Single alternative drive vehicles (e.g. compressed air/nitrogen)**
  The energy consumption and emissions can be measured by existing drafts (e.g. how much fuel/electric energy is used for the compression of the storage medium at the tank station). The measurement results however are plant-specific instead of vehicle specific, like for pure electric vehicles.

References

[1] R. Bady, C. Renner, M. Schüssler, M. Johannaber, “Classification of EVs”, Matador Subtask 2.1 Report, Institut für Kraftfahrwesen Aachen (IKA)

[2] C. Renner, S. Ploumen, M. Schüssler, “Evaluation of Existing (Draft) Standards“, Matador Subtask 2.3 Report, Institut für Kraftfahrwesen Aachen (IKA)

[3] E. van den Tillaart, “ΔSOC Correction Methods for HEVs”, Matador Subtask 2.4 Report, TNO automotive

[4] L. Cervati, M. Conte, L. De Andreis, G. Pede, “Determination of SOC or ΔSOC in general”, Matador Subtask 2.5 Report, ENEA – Advanced Energy Technology Division

[5] E. van den Tillaart, “Representative Driving Cycles for LD Vehicles”, Matador Subtask 2.8 Report, TNO automotive

[6] I. Riemersma, “Test Methods and Driving Cycles for HD Vehicles”, Matador Subtask 2.9 Report, TNO automotive

[7] S. Ploumen, “Accuracy and Tolerances”, Matador Subtask 2.11 Report, Institut für Kraftfahrwesen Aachen (IKA)

[8] M. Conte, “Self-discharge and Heating Energy”, Matador Subtask 2.14 Report, ENEA – Advanced Energy Technology Division

[9] prEN 1986-2, “Electrically propelled road vehicles - Measurement of energy performances - Part 2: Thermal electric hybrid vehicles”, draft revised by Italy, July 15, 1999

[10] prEN 13444-1, “Electrically propelled road vehicles – Measurement of emissions of hybrid vehicles - Part 1: Thermal electric hybrid vehicles”, draft revised by Italy, July 15, 1999

MANAGEMENT TOOL for the ASSESSMENT of DRIVELINE TECHNOLOGIES and RESEARCH

MATADOR

Contract JOE3-CT97-0081

Task 2:

Testing methods for vehicles with conventional and alternative drivelines

Framework

Test methods and procedures for Fuel Cell Electric Vehicles

20 July, 2000

Research funded in part by
THE COMMISSION OF THE EUROPEAN UNION
in the framework of the
JOULE III Programme
sub-programme
Energy Conservation and Utilisation

Nomenclature

Abbreviations

Ah capacity	the capacity of the EES in ampere hours.
D	distance travelled during test
E	energy
EES	electric energy storage device
EM	emissions
EoC	battery End of Charge
FC	fuel consumption
HD	heavy duty
HEV	hybrid electric vehicle
LD	light duty
MATADOR	Management Tool for the Assessment of Driveline TechnOlogy and Research
SOC	state of charge of the EES
ΔSOC	variation of SOC of the EES during driving cycles.

Indices:

1,2,3,…	Number of test performed
AC	Alternate Current indicating electricity from mains
d	Distance related value
Hyb	Value recorded in hybrid mode
ZEV	Value recorded in electric mode

Contents

1 Introduction

Task 2 of the MATADOR Project (Management Tool for the Assessment of Driveline Technologies and Research, EU-contract JOE3-CT94-0081) is aimed at developing test methods for homologation and evaluating conventional and alternative vehicles and propulsion systems. These testing methods should also allow for a comparative assessment and benchmarking of such technologies. The testing methods, considered in Task 2, are restricted to the determination of energy consumption and emissions of various vehicles and powertrains. The definition of such testing procedures is strongly affected by the vehicle configuration, the required fuels and the specific driving patterns which may be real or simulated on test benches. In addition, the introduction of alternative technologies and fuels may pose measuring problems when compared with conventional vehicles and standardised procedures. Investigation and critical evaluation of technical issues in relation to the various technologies is the main scope of Task 2, from which specific recommendations for modified or new testing and measuring methods are derived.

Fuel Cell Electric Vehicles (FCEV) represents a brand new transport means, which is a typical exemplification of the technical issues encountered in the definition of a specific testing procedure. The starting points for FCEVs considerations about testing methods are the following:

- FCEVs are available only at prototype level with a few pre-series products;
- The configurations investigated until now are various and may present testing problems similar to ICEV, HEV and BEV, depending on the system chosen.
- No standard testing procedure is presently available specifically for FCEVs. Current CEN standards or draft standards only consider BEVs, HEVs with thermal generators and ICEVs.

The use of some aspects of existing testing procedures for ICEV, BEV and HEV may be applied, adapting such testing procedures more specifically to FCEVs.

This document is mainly aimed at establishing a testing framework for measuring energy consumption and emission of electric vehicles (EV), which use fuel cells (FCs) for propulsion and/or for onboard electricity generation, as in a hybrid configuration. The intention is to schematically describe main testing procedure parts, highlighting technical issues/problems (summarising conclusions of specific subtask reports), which are peculiar of the system to be tested and /or have an impact on existing (draft) standards. The test procedure will be fully structured in a pictorial view in order to drive the reader in a simplified manner through the main topics faced during a testing work:

1) Normative reference
2) Definitions
3) Classification of vehicles
4) Test preparation and preconditioning
5) Vehicle testing (test sequence, driving cycles, tolerance and accuracy, measurement issues)
6) Data processing
7) Data reporting

More than defining a complete testing procedure for homologation or other purposes, the framework will refer to existing standards and specific topics by using flow diagrams, showing main test routes and, where possible, recalling test steps of existing (draft) standards. Furthermore, motivations and justifications, with a clear description of the proposed methods and differences with existing ones, will be described in Annexes, outlined in flow charts and in the text. Figure 1 shows how the schematic presentation will look like by showing the main options (numbered subroutines/actions in the main text) in a testing procedure for energy consumption and emissions measurements. Finally, homologation and comparative assessment will be distinguished and some considerations about the testing methods for heavy-duty (HD) vehicles will be presented.

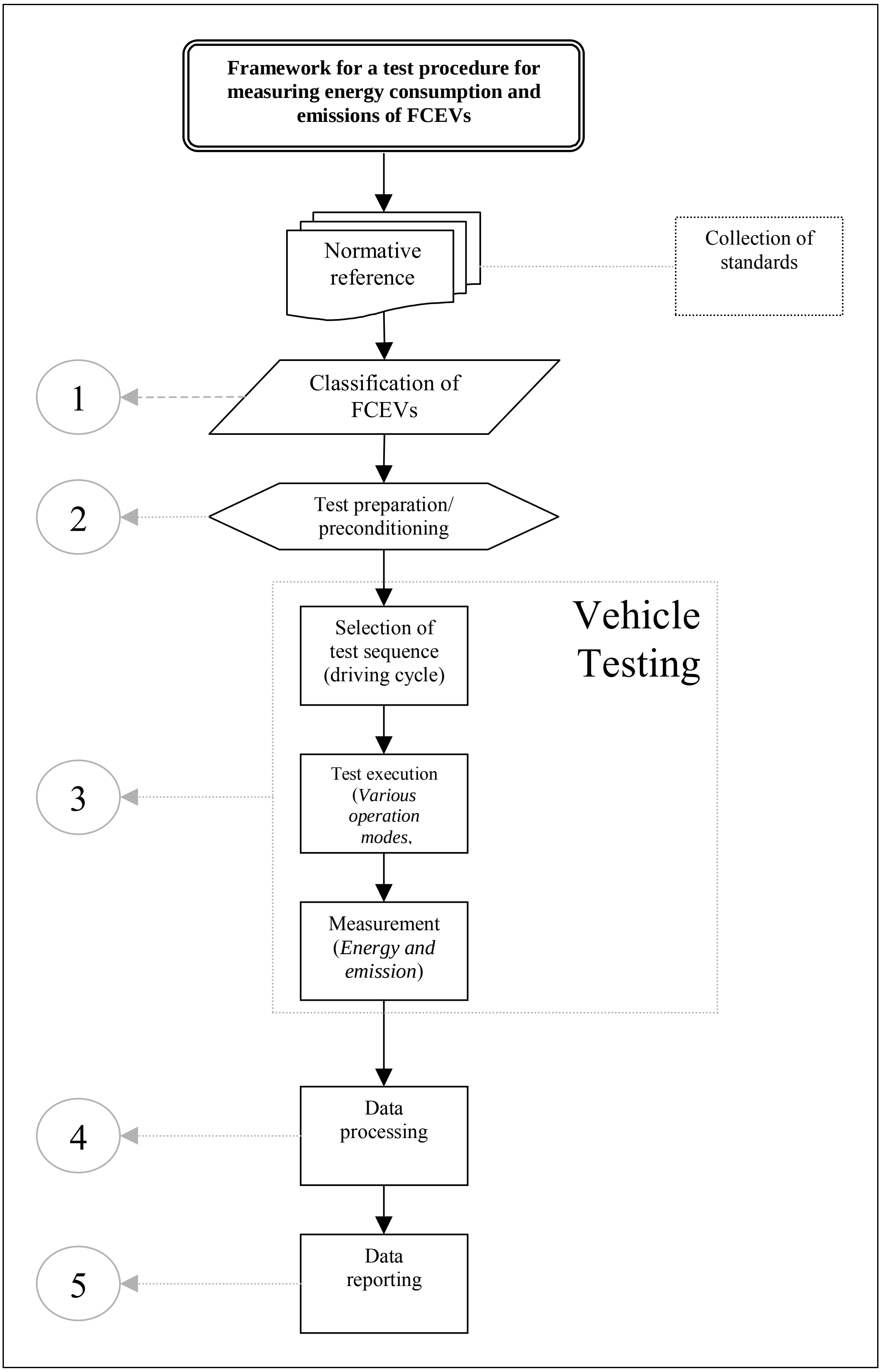


Figure 1: Flowchart of a testing procedure framework

2 Scope

This testing framework aims at measuring the emissions and energy consumption of fuel cell propelled road vehicles (FCEV). The testing procedure schematically summarises the conclusions of subtasks, carried out under the MATADOR project. The structure follows the usual structure of European standards and, similarly, points out to homologation needs. In addition, the needs for comparative assessment (different technologies benchmarking) will be considered. This procedure applies to the light-duty (LD) vehicles (more properly, as mentioned in prEN 1986-2, to categories of vehicles M_1, N_1 and M_2, and for tricycles and quadricycles). This procedure may also apply to hybrid fuel cell propelled road vehicles (FCHEV).
Some considerations/recommendations will be also given for the testing of heavy-duty (HD) vehicles.

3 Normative reference

This procedure incorporates provisions from other publications. These normative references are cited at the appropriate places in the text and the publications are listed hereafter. There are no specific standards for FCEVs. CEN has announced a draft standard prEN 1986-3 aimed at "*Electrically propelled road vehicles- Measurements of energy performances- Part 3: Other hybrid vehicles than those fitted with a thermal machine*": currently, there is no draft available. A first draft document on Fuel Cell Glossary for transportation applications has been prepared by ISO in 1999 [1].

– Directive 70/220/EEC as amended, for exhaust emission measurement.

– Directive 80/1268/EECas amended, for fuel consumption measurement.

– EN1986-1 June 1997
Electrically propelled road vehicles – Measurements of energy performances – Part 1: Pure electric vehicles

– CEN/TC301/WG1, prEN 1986-2 May 2000
Electrically propelled road vehicles – measurements of energy performances – Part 2: Thermal electric hybrid vehicles

– CEN/TC301/WG1, prEN 13444-1 May 2000
Electrically propelled road vehicles – Measurements of emissions of hybrid vehicles – Part 1: Thermal electric hybrid vehicles

– CEN/TC301/WG1, prEN 134447 January 1999
Electrically propelled road vehicles – Terminology

Furthermore, another draft procedure has been considered, as part of the work of evaluating existing (draft) standards: SAE J1711 (Recommended practice for measuring the exhaust emissions and fuel economy of hybrid-electric vehicles). Apart from the large classification of possible hybrid configurations, the main differences are related to the differences in driving cycles [2].

4 Definitions and classifications

4.1 Definitions

This short list of definitions only refers to those applicable along the text of the present document. A more complete summary of definitions for FC in transportation applications in reported in [1].

- *Charge-depleting EES behaviour*: The state of charge of the Electrical Energy Storage (EES) system on average decreases when a vehicle is driven over a certain driving cycle (driving cycle dependent!). Typically, the operation characteristics of the vehicle may be impaired and performance will become less with decreasing battery charge.

- *Charge-sustaining EES behaviour*: The state of charge of the EES on average is maintained (within defined bounds) when the vehicle is driving over a certain driving cycle (driving cycle dependent!). Typically, the SOC shows a periodic behaviour when the vehicle is driven over (a sequence of) the driving cycle.

- *Electric Energy Storage device (EES):* A device in which electrical energy can be stored. Examples are batteries (electro-chemical), electric flywheels (electro-mechanical), (super-) capacitors, or a combination of these.

- *Externally rechargeable vehicles*: Vehicles in which the energy storage system can be charged by means of energy from the mains.

- *Fuel cell electric vehicles (FCEV):* an electrically propelled road vehicle in which the traction system contains a fuel cell, which is the only device providing propulsion power. No energy storage system different from the fuel tank is present.

- *Fuel cell hybrid electric vehicles (FCHEV):* a FCEV with an on-board electrical energy storage system, which participates in the propulsion of the vehicle.

- *Electric mode (if available):* For hybrid vehicles, this is a user-selectable powertrain mode in which the vehicle is driven by the electric motor only, which in turn is powered from the electric energy storage device alone.

- *Hybrid mode (if available):* A powertrain mode in which all energy sources can participate in the propulsion of the vehicle. In case of a thermal engine this yields fuel energy consumption, and by means of an electric motor energy from an electrical energy storage device is used. The operation of the thermal engine and electric motor can be in a combined or alternating way, automated by the vehicle‘s control. The mode may be user-selectable. A hybrid vehicle which has no user-selectable modes is considered to have a hybrid mode only.

- *Linear regression method*: Method to determine the fuel consumption and emissions of non-externally rechargeable, charge-sustaining vehicles, that accounts for the difference in energy content of the EES before and after a test 0.

- *Underpowered vehicles*: Vehicles that do not meet the speed demands of the driving cycle.

4.2 Classification of FCEV

Two large categories of FCEVs have been defined. It seems reasonable to consider two large categories and then subdivide them in other two subcategories, based on fuel types.

1. ***Category 1 as an ICEV*** (FCEV without energy storage system different from the fuel tank)
   1.1. Carbon-based fuel
   1.2. Hydrogen
2. ***Category 2 as an HEV (FCHEV)*** (FCEV with an energy storage system different from the fuel tank)
   2.1. Carbon-based fuel
   2.2. Hydrogen

Both categories include the direct methanol FC systems.

This classification is consistent with that proposed by CEN 301/WG 1. The main difference consists in the elimination of non-carbon based fuels different from H_2, e.g., hydrazine used in space applications. Figure 2 shows a flow diagram of the framework part (subroutine 1) related to the classification and selection of FCEV under test.

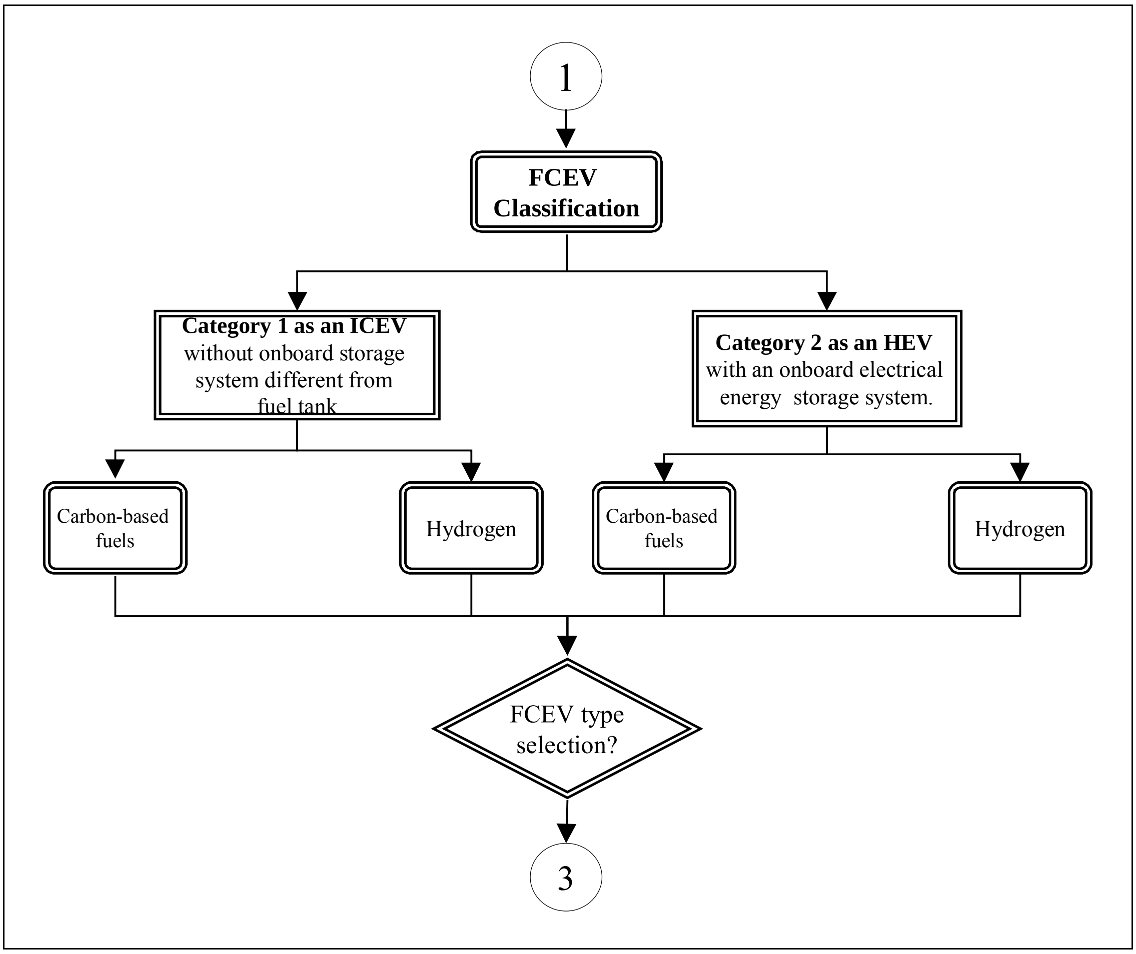


Figure 2: FCEV Classification, based on configuration and fuel type. Double lines mean steps not existing in standards

5 Test preparation and preconditioning

Prior to testing start both vehicle and test bench must be conditioned to have reproducible conditions (mainly temperature) for any test and to make then more comparable the results of different tests on various vehicles. Existing (draft) (EN 1986-1, SAE J1634 and SAE J1711) standards give directions before the test. The indications are not consistent among them and, particularly for FCHEV, may have impact on the overall energy consumption, due to the EES self-discharge 0. Figure 3 is the flowchart (subroutine 2 of the framework) for the test preparation.

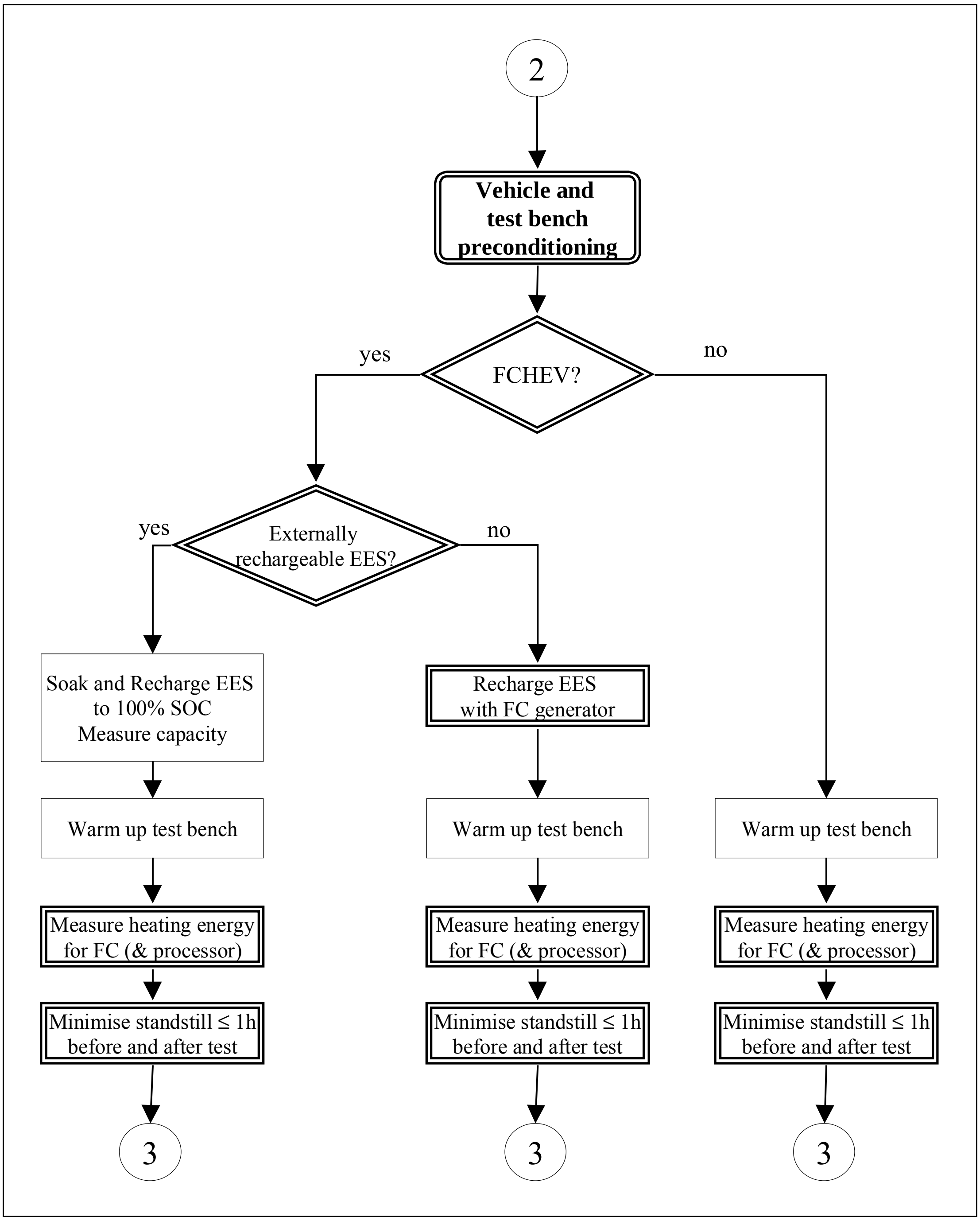


Figure 3: Flowchart for test preconditioning

5.1 Test bench preconditioning

The test bench shall be warmed up without the vehicle according to the recommendations of the supplier of the bench. The procedure allows the reduction of negative effects on the cold start of the vehicle and FC generator (especially tyres [5] and fuel processor, if any [8]) and then facilitates a proper setting of the road load, which is better represented.

5.2 Vehicle preconditioning

Vehicle soak should be for 24 hours (EES on charge for externally rechargeable FCHEVs) at 25±1 °C. Thus a cold start of the FC (and fuel reformer, if any) occurs. The narrow limit is defined to eliminate the strong influence of the starting temperature on the behaviour of a FCHEV compared to conventional vehicles. Different temperatures e.g. have a strong influence on duration of the warm-up phase of the FC (and/or fuel reformer) and therefore small variations can greatly change the result of a test [8].

In order to account for the self-discharge effects of the EES in the test procedure for FCEHVs, the time period between disconnection from mains after recharge and start of the test should be minimised. For the same reason, the time period between end of the test and reconnection to the mains for recharge should be minimised. The sum of both duration should not exceed one hour [9]: this is a compromise between SAE and CEN standards.

The pressure of the tyres has to be checked and, if necessary, resettled before each test to eliminate the influence of the variation of rolling resistance versus pressure [8].

5.3 EES Preconditioning

The EES (battery, supercapacitors, flywheels) should be first charged and discharge (from mains for both cases of externally rechargeable and not externally rechargeable vehicles) and discharged to verify the real capacity and to set the initial SOC of the EES before starting the test, as required in SAE draft standards. Furthermore, during vehicle soak the EES should be adjusted at 100% SOC (or at the value recommended by the vehicle manufacturer for the optimal vehicle operation). Annex D contains a procedure for battery conditioning.

5.4 FC/Fuel reformer start up time and heating energy

The start-up time does not significantly affect the energy losses and emissions, when H_2 is used as fuel. Present goals of major development programs of one-minute start-up time for the FC generator can make negligible this problem for measuring purposes.
The energy losses due to heating/cooling of the FC stacks and reformer are extremely varying and depend on driveline configurations and driving cycles. Specific need for measuring such losses can arise only when long standstill periods are part of the driving patterns. For comparative assessment, rather than for homologation, standstill periods and related heating energy should be recorded to improve accuracy and significance of energy consumption comparisons. For comparison purposes, it is suggested to measure and account separately for the heating energy during the preconditioning phase.

6 Vehicle testing for energy consumption measurements

The execution of the test sequence is a combination of various parts, which contains measuring aspects, driving cycles and specific vehicle conditions to assure test repeatability (tolerance, shifting modes, control strategy, manual operation selection).

6.1 Measurement issues

6.1.1 Data to be measured

There are two main problems in testing vehicles with FC. One is due to the problem of measuring the hydrogen consumption, when it is used as fuel. The second one is in FCHEV (non-externally rechargeable) when the ΔSOC should be measured to take into account the real energy consumption of the EES between the beginning and the end of the test cycles. To improve accuracy in energy consumption determination, it should be necessary to directly measure the SOC of the EES by adding new parameters to be recorded to the list of data already measured in current standards.

Accurate determination of the SOC is a fundamental problem for most battery types and for specific applications, particularly under transient conditions in which charging and discharging modes are involved. This determination can be done by using an Ah-meter, when irreversible phenomena occurring in the battery can be avoided or neglected. For testing purposes, particularly for HEVs and FCHEVs, it seems sufficient to determine the ΔSOC, and, possibly, be sure that ΔSOC=0 at the end of the test sequence. Literature survey and experimental activities showed that is apparent that the Ah-counting is not always a good method for measuring the SOC and ΔSOC in any vehicle working conditions and state of the battery: the combination of internal resistance and open circuit voltage measurements may significantly improve the accuracy [4]. One basic aspect is that the coulombic efficiency of the batteries (and also for other EES) varies at different charging/discharging rates and with battery ageing: Ah-monitoring is well applied when high efficiency EESs are used. The measured values of SOC (or ΔSOC) may be different from the real values up to 20-30%, giving a bad reference for testing purposes.

For testing purposes an SOC determination method with high accuracy (error lower than a few percent) should be supplied by the vehicle manufacturers. The methods may be different for various EES, which imply the use of additional sensors and parameters:

a) Batteries require the measuring of the balance of Ah in and out, including losses due to self-discharge and low charge-discharge efficiency. Where possible, it is strongly recommended to fully recharge the battery at the end of the test sequence to more accurately determine the final SOC.
b) Supercapacitors have the SOC (or the energy content) related to the actual voltage. The working voltage of supercapacitors (before DC/DC converter; manufacturers have to provide an industrial standard connector bus) may be online monitored.
c) Electromechanical flywheels store energy by rotating mass. The rotational speed should be monitored to know the energy content of such EES. Also in this case the manufacturer should provide a dedicated sensor.

Alternatively, in-test and post-test correction methods (interpolation and linear regression) have been proposed as a result of MATADOR activity [3].

6.2 Measurement of the range in pure electric mode

The pr EN 1986-2 applies without modifications. This test is aimed at verifying the applicability of the measurement of the electric energy consumption in pure electric mode.

6.3 Measurement of the electric energy consumption in electric mode

The European standard prEN 1986-2, clause 5, applies without modifications.

6.4 Measurement of the energy consumption and emissions

6.4.1 Principle

For FCEV, the Directive 80/1268/EEC as amended, shall apply.
For FCHEV, if the driver can exclude the EES, the test of the consumption in hybrid mode shall be performed following strictly Directive 80/1268/EEC, as amended. Otherwise, the whole test procedure has to be fulfilled in hybrid mode, see 6.3 of prEN86-2.
Both for FCEV and FCHEV, in order to measure the energy consumption of the vehicle, two fuel-based subcategories have to be considered: carbon-based fuels and hydrogen

6.4.2 Driving Cycles

The prEN 1986-2, 6.2, applies without modifications. Driving cycles have a strong influence on the behaviour and then on the energy consumption and emissions of vehicles. For homologation purposes, the driving cycles used in existing (draft) European standards are low demanding and are valuable only for relative comparison. For comparative assessment, driving patterns, composed of real life driving cycles, are more representative of the real-world operating conditions and then are more suitable for benchmarking alternative drivelines [6]. As an example, some possible real driving cycles are selected and presented in Annex A.

6.4.3 Equipment

The prEN 1986-2, 6.3, applies without modifications.

6.4.4 Fuel

The prEN 1986-2, 6.4, applies without modifications.

6.4.5 Parameters, units and accuracy of measurement

The prEN 1986-2, 6.5, applies without modifications.

6.4.6 Test conditions

The prEN 1986-2 (FCHEV), 6.6.1 and 6.6.2, applies without modifications as regard to vehicle and climatic conditions. Recommended modifications are described in following paragraphs.

6.5 Measurement of energy consumption of FCEV

6.5.1 Carbon-based fuels

For FCEV, the Directive 80/1268/EEC as amended, applies. The FCEV can be then considered as an ICEV.

6.5.2 Hydrogen

For FCEV, the Directive 80/1268/EEC as amended applies with a modification, because the indirect measurement method provided in ICEV standards refers only to carbon-content exhaust gases. In this case, the combustion product that should be measured is water (steam H_2O) and in the exhausts there is also H_2 not derived from the reaction, but from air humidity and the humidification process of the reaction gas inside the stack system.
Therefore, the procedures will be modified with a direct measurement of the H_2 fed to the FC, by means of a mass flow meter (balance or other device) [7].

6.6 Measurement of energy consumption of FCHEV

6.6.1 Externally rechargeable vehicle and non-externally chargeable vehicle with charge-sustaining EES behaviour

The pr EN 1986-2 applies without modifications. To clarify the principle, it is obligatory that during the test the FC switches “on” for the time corresponding to a complete cycle, according to the ratio that is behind point 6.7 of the prEN 1986-2.

6.6.2 Non-externally rechargeable vehicle with charge-depleting EES behaviour

Whenever at the end of the test the storage system cannot reach the initial state of charge (the vehicle is underpowered and a charge-depleting EES behaviour occurred), the linear regression method (see Annex C) has to be applied to the measured results for the calculation of the energy consumption.

In both cases, if the fuel is hydrogen, the measurement method has to be modified, as in clause 6.5.2.

Figure 4 (subroutine 3 for energy consumption) shows the flowchart for energy consumption measurements for all the possible configurations of the EV with FC.

7 Vehicle testing for emission measurement

According to the above classification and considerations, the emission measurements can be differentiated in relation to fuel type as for the ICEV or HEVs. To better identify the type of emissions and set up the measurement equipment, it is necessary to analyse experimentally the real exhaust emissions mainly from the fuel processor, and, generally, from the fuel cell stack.
In case of H_2-fueled EV, there is no need for any regulated emission measurement, since exhaust gases contain only ambient air, water and, in some cases, hydrogen.
Only for benchmarking purposes, real life driving cycles, as those described in Annex A, can be used.
The non-regulated emission problems are accounted for in Annex B. The proposed draft standard prEN 13444-1 will be revised hereafter with some modifications, which are most dependent on the fuel type and the specific vehicle configuration and control strategy.

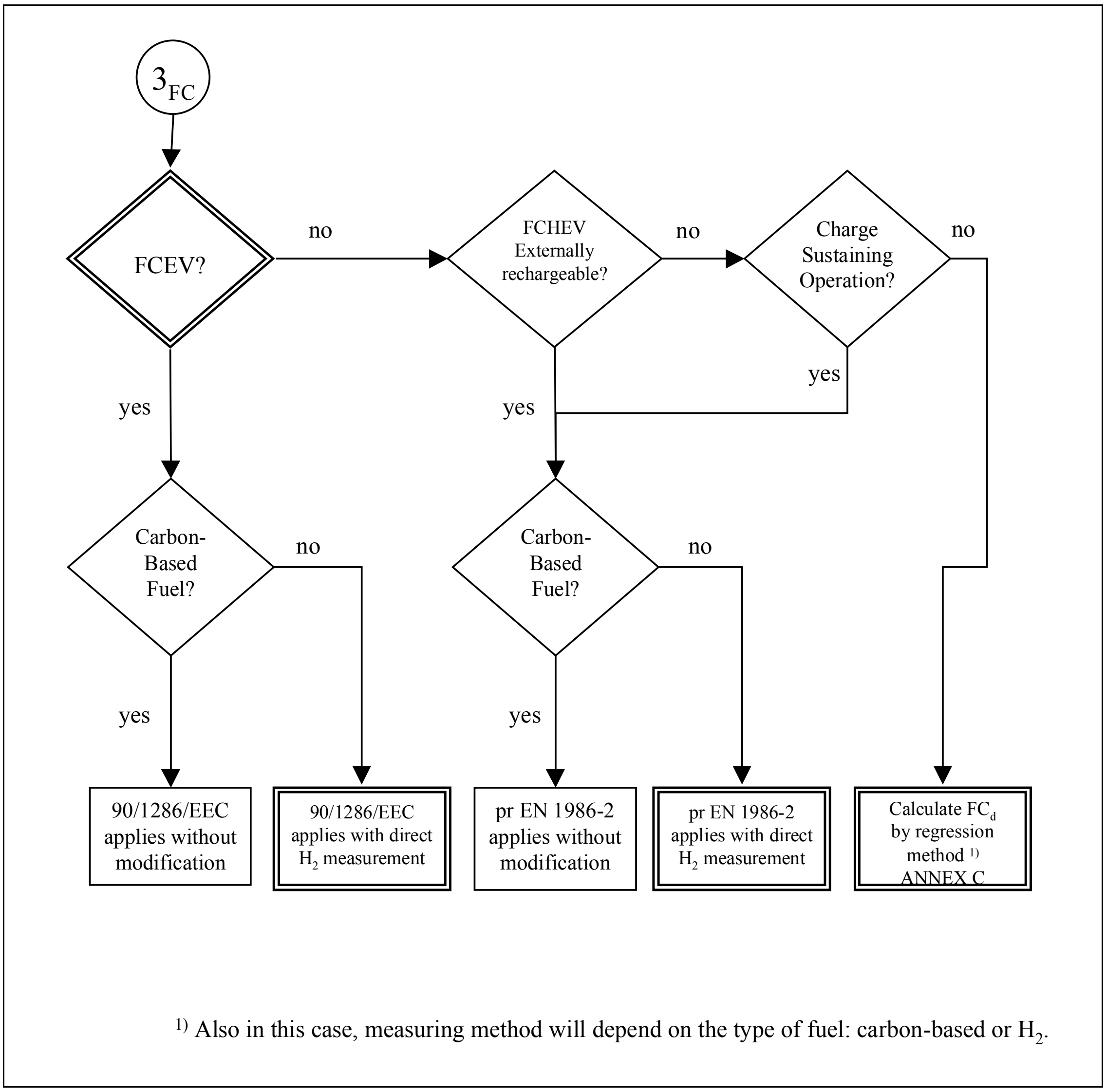


Figure 4: Flow chart for energy consumption test procedure. Double lines mean steps not existing in standards

7.1 Hydrogen

In case of H_2-fueled EV, there is no need for any regulated emission measurement, since exhaust gases contain only ambient air, water and, in some cases, hydrogen.

7.2 Carbon-based fuels

For a FCEV, the Directive 70/220/EEC, as amended applies.
For a FCHEV, if the driver can exclude the EES, the test shall be performed following strictly Directive 70/220/EEC, as amended. Otherwise, two cases have to be considered: EES rechargeable or not rechargeable externally.

7.2.1 Externally rechargeable vehicle and non-externally rechargeable vehicle with charge-sustaining EES behaviour

The whole test procedure has to be fulfilled in hybrid mode, according to the prEN 13444-1, 4.1, 4.2, 4.3, 4.4, 4.5, 4.6, 4.7, 4.8. To clarify the principle, it is obligatory that during the test the FC switches "on" for the time corresponding to a complete cycle, according to the ratio that is behind clause 6.7 of the prEN 1986-2. The test sequence will have to ascertain (or to make possible) that the final SOC of EES is equal to the initial one. This means that the test will continue until such condition is met.

7.2.2 Non-externally rechargeable vehicle with charge-depleting EES behaviour

Whenever at the end of the test the storage system cannot reach the initial state of charge (the vehicle is underpowered and a charge-depleting EES behaviour occurred), the linear regression method (see Annex C) has be applied to the measured results for the calculation of the energy consumption.

Figure 5 (subroutine 3 for emission consumption) shows the flowchart for energy consumption measurements for all the possible configurations of the EV with FC.

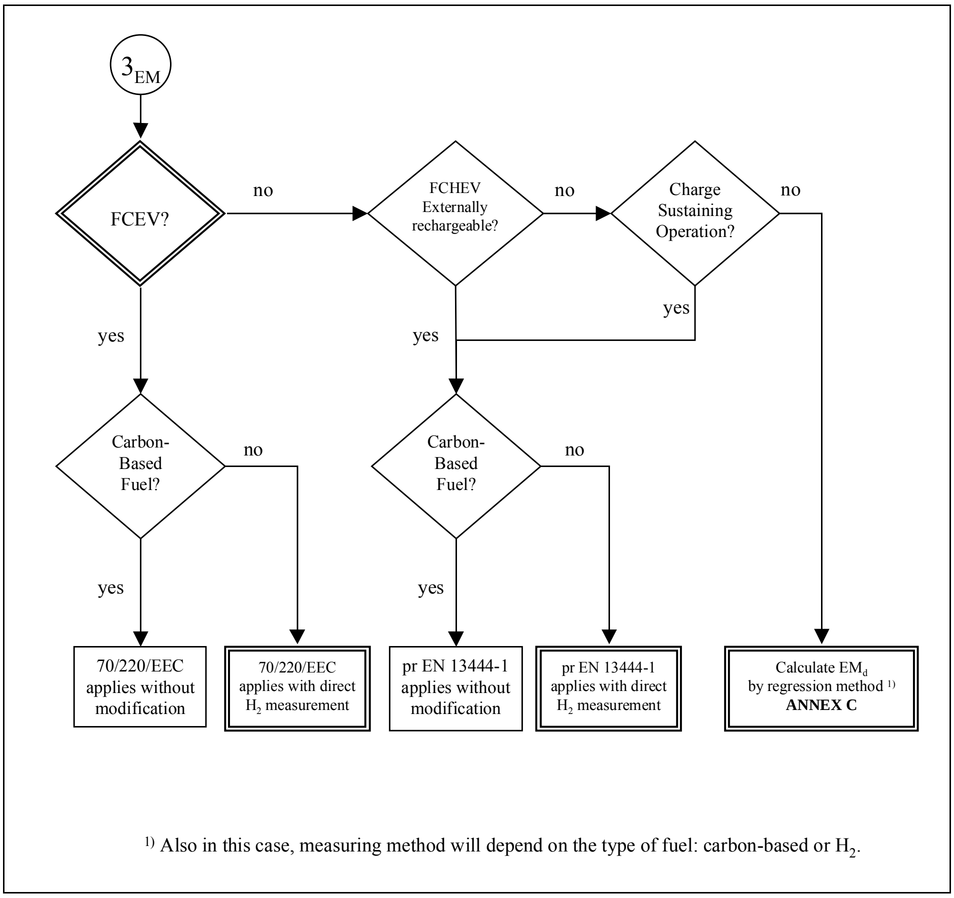


Figure 5: Flow chart for energy consumption test procedure. Double lines mean steps not existing in standards

8 Data processing and reporting

There are a lot of test results that must be processed to reach final values for energy consumption and emissions (subroutines/actions 4 and 5). The elaboration and testing work will of course depend on the type of vehicle behaviour, the test sequence and the scope of the tests (see Annex C).
For homologation purposes, current (draft) standards already provide (prEN 1986-2 and prEN 13444-1) informative lists of technical information to be supplied to the test laboratory and then be reported after the test completion. According to the considerations reported in paragraphs 5 and 6, more information is needed to improve test accuracy, data reliability and test repeatability.
In addition, for comparative assessments in real world conditions, a realistic driving cycle (more properly a driving pattern, which includes not only the driving cycle, but also the complete duty conditions with standstills) should be supplied to test laboratory. It should be preferable to develop realistic driving patterns to have a more extensive technological benchmarking of different drivelines.

9 Remarks for testing HD-Fuel Cell electric vehicles

For testing HD-FCEVs and HD-FCHEVs two major issues are still unsolved [7]:
a) Whether it is practicable to test these vehicles on dynamometers in terms of availability of powerful transient test benches (requires large investments) – and
b) which cycle shall be used or which cycle is representative for the specific use of the given vehicle.

If a) can be answered with yes, the given procedure above for LD-FC powered vehicles in general (except the cycle) shall also be applied to HD- FC powered vehicles.
If the answer is negative, a driving cycle on a test track, followed by a laboratory test on the generation and storage components of the drive line, applying (by a bi-directional electronic device like a battery cycler) an electrical load equal to that measured and recorded during the test track, could be a viable option for energy consumption and emission measurements.
For b) a classification of vehicles is necessary. A first attempt is given below:
- Delivery trucks
- Coaches
- City busses
- Special vehicles (municipal vehicles, road sweepers, garbage trucks)
- Long distance trucks

The real life cycles, reflecting the average use, can only be developed on the basis of intensive measurements on real vehicles of the above mentioned classes.

References

[1] N 284 E/N55 E, “Fuel Cell Glossary”, U.S. Fuel Cell Council for ISO/TC22/SC21, November 1999.

[2] C. Renner, S. Ploumen, M. Schüssler, “Evaluation of existing (draft) standards”, Matador Subtask 2.3 Report, Institut für Kraftfahrwesen Aachen (IKA)

[3] E. van den Tillaart, “ΔSOC correction methods for HEVs”, Matador Subtask 2.4 Report, TNO Automotive

[4] L. Cervati, M. Conte, L. De Andreis, G. Pede, "Determination of SOC and ΔSOC in general", Matador Subtask 2.5 Report, ENEA – Advanced Energy Technology Division

[5] M. Conte, A. Iacobazzi, G. Pede, "FCEV Test Procedures", Matador Subtask 2.7 Report, ENEA – Advanced Energy Technology Division

[6] E. van den Tillaart, "Driving cycles for LD vehicles", Matador Subtask 2.8 Report, TNO Automotive

[7] I. Riemersma, "Test methods and driving cycles for HD vehicles", Matador Subtask 2.9 Report, TNO Automotive

[8] S. Ploumen, "Accuracy and tolerances", Matador Subtask 2.11 Report, Institut für Kraftfahrwesen Aachen (IKA)

[9] M. Conte, "Self-discharge and Heating Energy", Matador Subtask 2.14 Report, ENEA – Advanced Energy Technology Division

ANNEX A: Real-life driving pattern

"Real-life driving pattern" should be selected for a consistent and comparable determination of the energy consumption (and emissions) of vehicles. Possible cycles that are based on current LD vehicle use, are the Modem cycle (Figure 6) or the three HYZEM cycles (Figure 7 - Figure 9). The three HYZEM cycles are combined in one test, and represent urban, rural, and highway traffic conditions. The outcomes of Subtask 2.8 [6]clearly indicated that stylistic (or "modal") cycles lead to non-representative results for energy consumption (and emissions in case a fuel converter is present in the vehicle), when the applied cycle is not representative for the actual use of a vehicle in real-life. It has been shown that, for vehicles with alternative drivelines, the driving cycle characteristics have an even more profound influence on the energy consumption (and emissions) than for conventionally powered vehicles. Thus, stylistic cycles as the NEDC with the very narrow and low demanding speed profile would produce unrealistic (often too low) results.
Both the MODEM and HYZEM cycles cover nearly the same operating range in terms of power distribution over vehicle speed, but differ in length. The speed traces are given in the figures below.

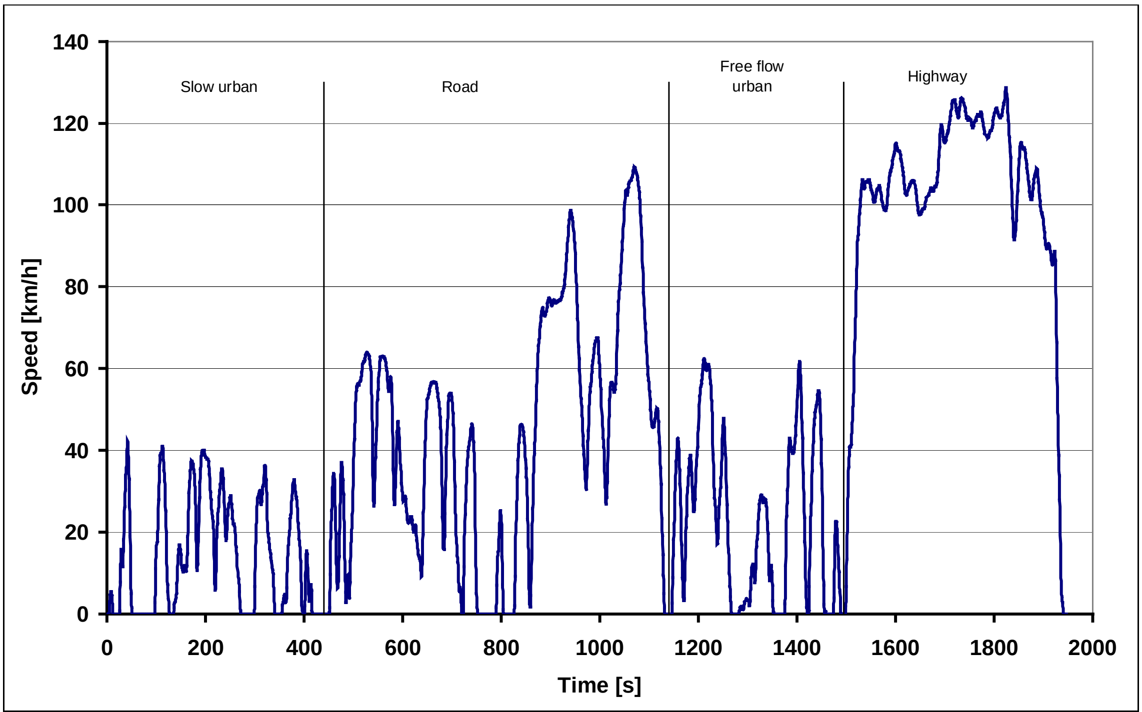


Figure 6: Modem cycle

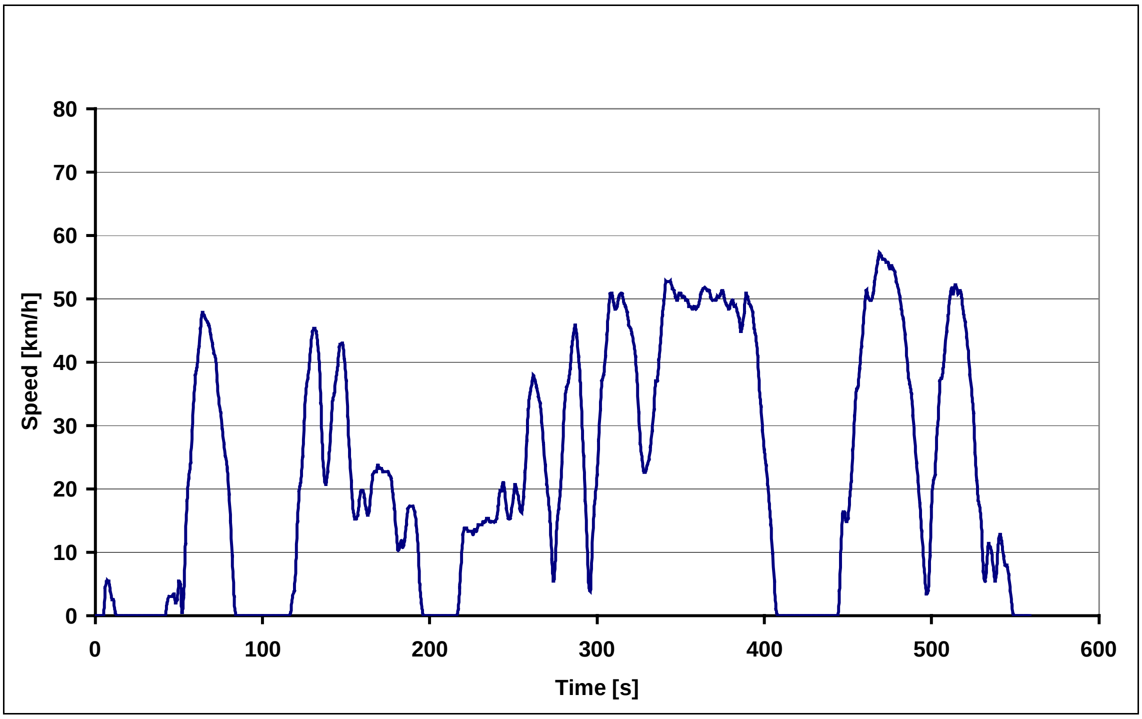


Figure 7: HYZEM urban

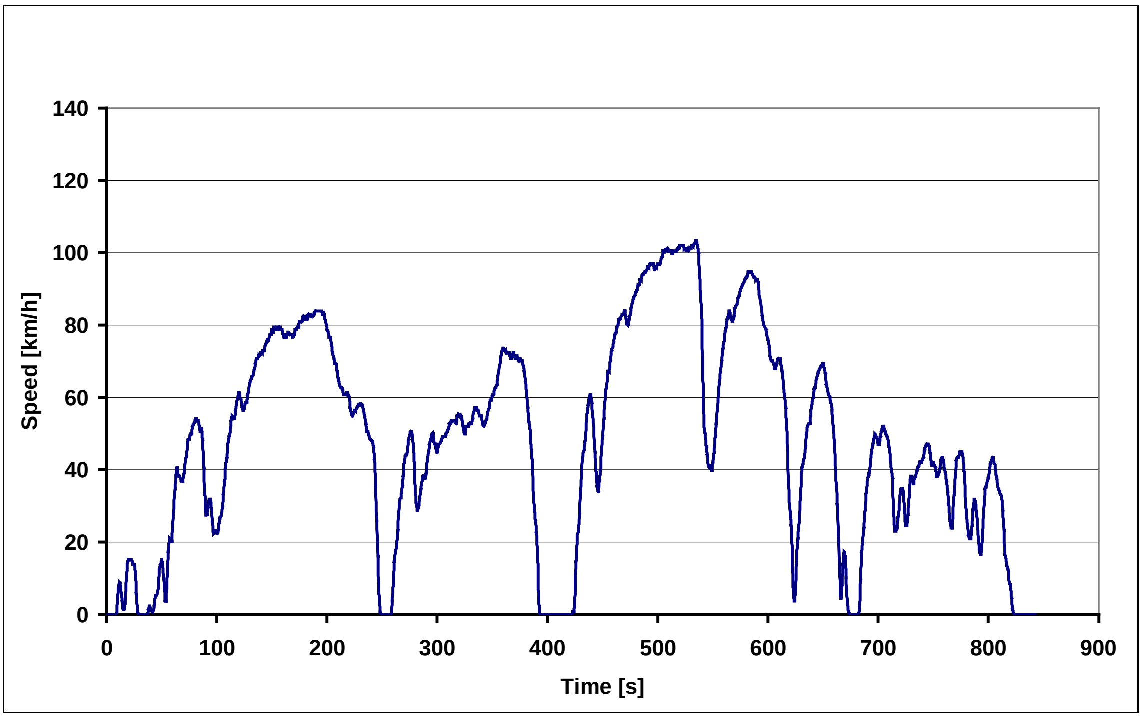


Figure 8: HYZEM rural

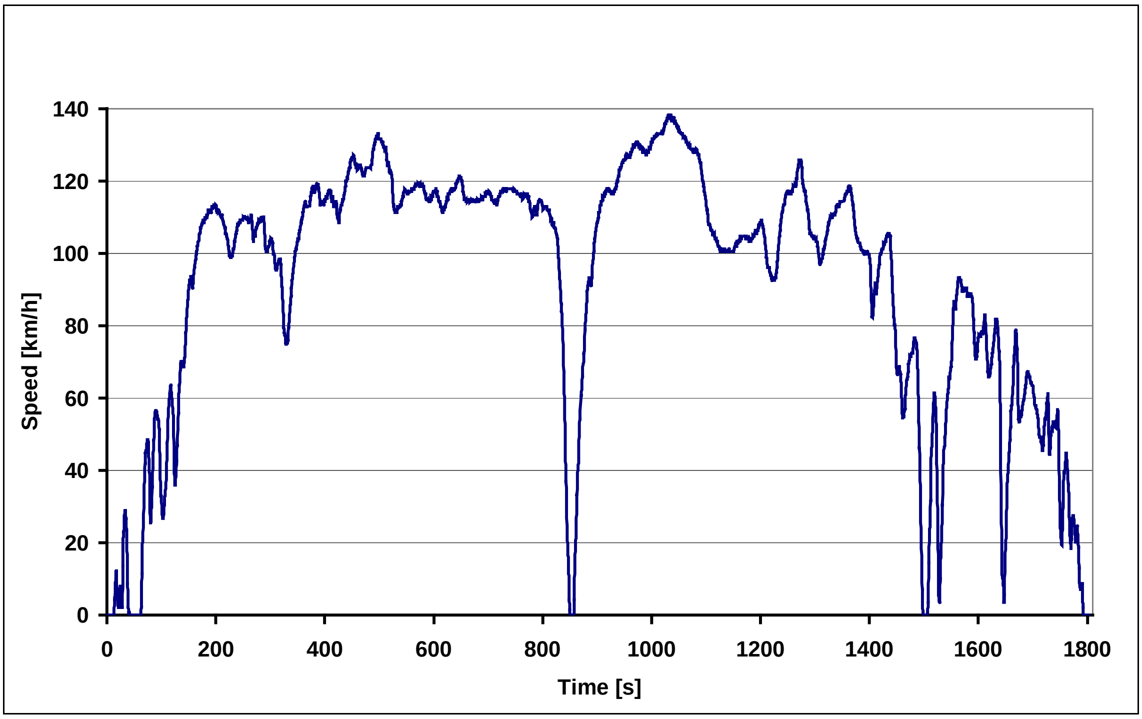


Figure 9: HYZEM highway

ANNEX B: Non regulated emission measurement

To better identify the type of emissions and set up the measurement equipment, it is necessary to analyse experimentally the real exhaust emissions mainly from the fuel processor, and, generally, from the fuel cell stack.

B.1 Carbon-based fuel: METHANOL

Table 1 reports the hydrogen-rich gas composition measured (ENEA and CNR-TAE) [5] at the outlet of a fuel processor (steam reforming or autothermal reforming= POX+steam reforming).

Table 1: Outlet gas composition from fuel processor using methanol

Gas	**Range (%)**
Hydrogen	65 - 75
Carbon Dioxide	20 - 24
Carbon monoxide	ppm
Nitrogen*	Balance
Methanol (non converted)	ppm - 5 %
Formic Acid	ppm
Formaldehyde	ppm
Methyl formate	ppm
Water	0.5 – 2

*In case of autothermal process

Another source (Johnson Matthey) claims a different dry composition:
H_2: 75 %
CO_2: 25 %
CO: < 5 ppm

The overall noxious emissions of a methanol powered FCEV have been measured by DaimlerChrysler in the NECAR3 prototype vehicle. The measured values are 30% lower than the more stringent EU regulations EURO 4, which will be in place in 2005. This vehicle emits extremely low (near zero) polluting exhausts: 0 CO, 0 NO_x and 0,004 HC [5].

B.2 Carbon-based fuel: GASOLINE

The emissions of a fuel processor, using gasoline as a fuel, depend on the composition of the gasoline: commercial gasoline, synthetic gasoline, virgin naphtha, and so on. In practical operations, it is possible to have in the reformed gases all the components contained in the starting gasoline (conversion factor of each component lower than 100%), along with the secondary reaction products, which are strongly dependent on the operating conditions (such as, temperature, type of catalyst and so on).
Nevertheless, Epyx Corporation claims for its processor, fed with gasoline (with no specified composition), the following emissions:
CO < 5 ppm
HC < 4 ppm
NO_x < 1 ppm

Moreover, Epyx declares that SULEV standards are fully met.

According to preliminary tests (CNR-TAE) with a simulated gasoline (a compound of n-octane, benzene), the dry composition (the water content varies between 2 and 5 %) of the hydrogen-rich gas produced by a fuel processor is listed in Table 2.

Table 2: Outlet gas composition from fuel processor using gasoline

Gas	**Range (%)**
Hydrogen	14-25
Carbon Dioxide	4-9
Carbon monoxide	15-22
Nitrogen*	Balance
NH_3	0-10 ppm
CH_4, methane	0.05-2
C_2H_4, ethylene	0.01-2
C_2H_6, ethane	0.02-0.3
C_3H_6, propylene	0.05-1
C_3H_8, propane	0.01-0.02
C4-C5-C6	0.01-0.6
C_8H_{18}, n-octane	5-15
C_6H_6, benzene	0.01-1

*In case of autothermal process

ANNEX C: Test procedure for the application of the linear regression method

The ΔSOC correction method of linear regression for non-externally rechargeable, charge-depleting vehicles is introduced to determine the fuel consumption and emissions when it is not possible to balance the state of charge of the EES over the test campaign, as stated in the European standards.
In this case (if the EES is not externally rechargeable, and the vehicle behaviour during the driving cycle is of charge-depleting type), the following test procedure applies:

1) Perform one driving cycle in hybrid mode (as a means of preconditioning of the EES)

2) Soak 24 hours at 25±1°C

When the EES if fully depleted after the soak:

3) Perform one driving cycle in hybrid mode. *Measuring of emissions and travelled distance.*

4) Determine energy consumption and emissions:
   $FC_d = FC / D_{Hyb}$
   $EM_d = EM / D_{Hyb}$

In case the EES is not fully deplenished after the soak:

1) Perform first test: one driving cycle in hybrid mode. *Measuring of emissions, travelled distance and Amperehours.*

2) Determine energy consumption, emissions and ΔSOC:
   $FC_{d,1} = FC_1 / D_{Hyb,1}$
   $EM_{d,1} = EM_1 / D_{Hyb,1}$
   $\Delta SOC_1 = Ah_1$

3) Soak for 24 hours at 25±1°C

4) Perform second test: one driving cycle in hybrid mode. *Measuring of emissions, travelled distance and Amperehours.*

5) Determine energy consumption, emissions and ΔSOC:
   $FC_{d,2} = FC_1 / D_{Hyb,2}$
   $EM_{d,2} = EM_2 / D_{Hyb,2}$
   $\Delta SOC_2 = Ah_2$

6) Soak for 24 hours at 25±1°C

7) Perform third test: one driving cycle in hybrid mode. *Measuring of emissions, travelled distance and Amperehours.*

8) Determine energy consumption, emissions and ΔSOC:
   $FC_{d,3} = FC_3 / D_{Hyb,3}$
   $EM_{d,3} = EM_3 / D_{Hyb,3}$
   $\Delta SOC_3 = Ah_3$

If there are positive and negative ΔSOC values available:

9) Calculate energy consumption and emissions from results 1 to 3 with linear regression method.

If there are still only positive or negative ΔSOC values available:

9) Soak for 24 hours at 25±1°C

10) Perform fourth test: one driving cycle in hybrid mode. *Measuring of emissions, travelled distance and Amperehours.*

11) Determine energy consumption, emissions and ΔSOC:
   $FC_{d,4} = FC_4 / D_{Hyb,4}$
   $EM_{d,4} = EM_4 / D_{Hyb,4}$
   $\Delta SOC_4 = Ah_4$

If there are positive and negative ΔSOC values available:

12) Calculate energy consumption and emissions from results 1 to 4 with linear regression method.

If there are still only positive or negative ΔSOC values available:

12) Soak for 24 hours at 25±1°C

13) Perform fifth test: one driving cycle in hybrid mode. *Measuring of emissions, travelled distance and Amperehours.*

14) Determine energy consumption, emissions and ΔSOC:
   $FC_{d,5} = FC_5 / D_{Hyb,5}$
   $EM_{d,5} = EM_5 / D_{Hyb,5}$
   $\Delta SOC_5 = Ah_5$

If there are positive and negative ΔSOC values available:

15) Calculate energy consumption and emissions from results 1 to 5 with linear regression method.

If there are still only negative ΔSOC values available:

15) Perform preconditioning test of the EES: Drive the vehicle at a velocity (to be defined by manufacturer, typically about 20 to 30 km/h), at which the thermal engine will stall after warm-up (if any) and the vehicle is driven electrically, until the thermal engine starts (again). *No measurements required.*

If there are still only positive ΔSOC values available:

15) Perform preconditioning test of the EES: Drive the vehicle at 30 km/h under regenerative operation (braking pedal may be applied with a constant, moderate force) until SOC does not increase any more. In order to do so, the dynamometer should be operated at a set point of 30 km/h. *Measurement/monitoring of Amperehours.*

16) Soak for 24 hours at 25±1°C

17) Perform sixth test: one driving cycle in hybrid mode. *Measuring of emissions, travelled distance and Amperehours.*

18) Determine energy consumption, emissions and ΔSOC:
$FC_{d,6} = FC_6 / D_{Hyb,6}$
$EM_{d,6} = EM_6 / D_{Hyb,6}$
$\Delta SOC_6 = Ah_6$

19) Calculate energy consumption and emissions from results 1 to 6 with linear regression method

ANNEX D: Battery preconditioning

STANDARD DISCHARGE
The battery is discharged, by running at 60 km/h till the battery voltage will come down to the minimum allowable value (end of discharge voltage).

STANDARD CHARGE
The vehicle normally will be charged according to normal charging procedure, as recommended by the manufacturer.

BATTERY VOLTAGE MINIMUM VALUE
The end of discharge (EoD) voltage depends on the battery type, the discharge conditions and the vehicle configuration. The manufacturer of the vehicle must recommend it.

Overall conclusions and recommendations

In this section first of all a number of general recommendations is formulated that are relevant to the EU, standard setting bodies and the automotive industry. As a more detailed specification of the recommendations concerning the structure and contents of test procedures for battery-electric, hybrid and fuel cell vehicles the main conclusions and recommendations of the various Subtasks are also summarised.

1 General conclusions and recommendations

1. With hybrid vehicles coming on the market in Europe in the year 2000, it is of paramount importance that standardised test and homologation procedures are developed and implemented as soon as possible. EU emission legislation and related directives for vehicle homologation need to be revised to include hybrid vehicles. In view of the announced introduction of fuel cell vehicles around 2003 or 2004 it is necessary to include fuel cell vehicles at the same time.
2. The exact definition of regulations and test procedures, in combination with the associated legislative emission limits, is critical as this definition in itself influences the relative performance of different technologies subjected to a test procedure. Wrong definitions of the structure of the procedure and the laboratory test conditions may induce manufacturers to develop and market sub-optimal technical solutions.
3. Development of adequate test procedures is hindered by technology specific test problems associated with the complexity of these new technologies and uncertainty about the types of configurations that will be introduced on the market. The work of standard setting bodies and the EU legislators therefore needs to be supported by technical research of the type that has been performed in Task 2 of MATADOR.
4. Due to their technical complexity especially hybrid-electric vehicles pose a challenge for the definition of measurement methods and test procedures. A crucial characteristic of hybrid vehicles is the fact that the instantaneous fuel consumption and emissions are decoupled from the instantaneous road load. In combination with the complex and sometimes discrete nature of the powertrain control strategy this leads to a highly non-linear response of the energy consumption and emissions of hybrid vehicles to changes in the test circumstances.
5. At the start of the MATADOR-project the work of CEN TC301/WG on test procedures for hybrid vehicles (prEN 1986-2 and prEN 13444-1) was already nearing completion. Currently these procedures are in the process of being approved by CEN. Given the incompatible time-frame there was little opportunity for the results of MATADOR to influence the procedures developed by CEN TC301/WG. However, based upon the insights gained in MATADOR several choices and definitions made in the proposed procedures could have been made differently. Also for battery electric vehicles MATADOR has produced results and insights that would motivate a revision of the already adopted procedure (EN 1986-1). It is recommended that the CEN organises an evaluation of its electric and hybrid vehicle procedures within 3 to 5 years from now. Based on the results of research in MATADOR and other projects, knowledge of new technologies coming to the market and experience with the use of the present procedures, proposals can be formulated for improvements of the present procedures.

6. The results of Task 2 of MATADOR, together with the knowledge already reflected in the CEN and SAE procedures, provide a thorough –albeit not yet complete– basis for dealing with measurements of the energy consumption of battery-electric, hybrid and fuel cell vehicles in an appropriate way, both in the context of homologation procedures and for technology evaluations. The applicability of various procedures and test methods to the measurement of the exhaust emissions of hybrid and fuel cell vehicles, however, remains questionable. Within MATADOR this aspect could only be studied to a limited extent due to the limited availability of hybrid vehicles for testing and the impossibility to include emissions in computer simulations in a meaningful way. More theoretical and experimental research is necessary to provide a solid basis for the definition of test procedures for emission measurements.
7. An important aspect of the European emission legislation is durability. Vehicles do not only have to meet standards when they are new, but also after a significant time or mileage of use on the road. There is no information available yet concerning the durability of hybrid and fuel cell vehicles. Besides durability aspects that also play a role in conventional vehicles (e.g. related to exhaust aftertreatment technology and engine management systems) also technology specific aspects can be identified. These include e.g. the ageing of batteries and the way the powertrain control system is able to deal with this.
8. In view of conclusions 1 to 7 it is recommended that the EU sets up a project with active participation of the European automotive industry, standard setting bodies and relevant legislative bodies and advisory groups to systematically co-ordinate the process of establishing standardised test procedures for battery-electric, hybrid and fuel cell vehicles. Research services in this project should be provided by independent research organisations and advanced vehicle test laboratories.
9. After the implementation of complete homologation procedures for hybrid and fuel cell vehicles the results of tests on new vehicles need to be analysed in order to assess to what extent these procedures are able to deal correctly with the vehicle configurations coming on the market.
10. Experience in MATADOR, the UTOPIA-project and other policy-oriented projects evaluating new propulsion systems and transport technologies has taught that the availability of objective, complete and reliable data on the energy consumption and emissions of hybrid and fuel cell vehicles is extremely limited. This is seriously hindering the formulation of a clear policy vision on the potential of these new technologies and on the requirements for successful development and market implementation. The latter includes R&D policies for advanced components such as batteries, power electronics and fuel cells.
11. To act on the conclusions 9 and 10 it is recommended that the EU establishes a network of independent vehicle test laboratories in Europe to perform objective evaluations of battery-electric, hybrid and fuel cell vehicles and of components for these vehicles. Vehicles and components should at least include products are (to be) introduced in European countries in demonstration projects or on a commercial basis. In analogy to the PNGV programme in the USA contractors of EU-sponsored or financed R&D projects could be obliged to provide vehicles and components developed in these projects to the EU for independent testing. This would give the EU an instrument to monitor the technical progress that is established through EU-sponsoring of R&D projects. Obviously such a procedure would have to respect the proprietary rights of the involved companies. The network of test laboratories should preferably also be coupled to the activity proposed under conclusion 8.
12. In the present European situation, with a non-representative modal test cycle for LD-vehicles, the emissions of vehicles with modern engine technology and advanced motor management systems, as measured with the standard homologation procedure, strongly deviate from the emissions produced in real-life traffic. In the near future homologation test

procedures will have to become more representative for real-life driving in order to make sure that manufacturers apply technologies in their vehicles that do not just make the vehicle meet legislated emission limits under laboratory test conditions, but that have a minimal impact on the environment when the vehicle is in actual use.

13. The development of test procedures that are representative for actual use of the vehicles, as proposed in conclusion 12, is not only relevant to governments but is also in the interest of the automotive manufacturers. Their main concern is to develop vehicles that meet the expectations of customers. Design criteria and development targets can only be formulated in a consistent way when the performance demands of homologation procedures and emission legislation are in correspondence with the performance demands set by customer expectations and the actual applications for which vehicles are designed.
14. Although there are a lot of activities in progress aimed at making homologation test procedures more representative for actual vehicle use, it will take a decade or more before these procedures will be in effect. Still, by virtue of their purpose, homologation test procedures will always be more general than test procedures required for the detailed evaluation of vehicles in specific applications (technology assessment or evaluation). Therefore, also for the purpose of product evaluations and technology assessment the development of more or less standardised laboratory test methods is required. These would:
    - make the results of different R&D projects more understandable and comparable;
    - enable a realistic comparisons between different propulsion technologies;
    - produce energy consumption and emission results which are representative for actual use of the vehicles.

2 Technical conclusions and recommendations related to the structure and contents of test procedures

Below the main conclusions and recommendations of the various Subtasks in Task 2 of MATADOR are summarised. To a large extent these conclusions and recommendations have been integrated into the frameworks for test procedures described in this document.

Categorisation of EV configurations

15. The categorisation proposed by SAE J1711 is considered too complex for homologation purposes, but is applicable for technology assessment.
16. For homologation purposes a categorisation is proposed that strongly resembles the scheme that is used in prEN1986-2.

Development of simulation tools

17. Computer simulation of advanced vehicles and powertrains is a powerful tool for developing and analysing test methods and procedures for future vehicle technologies. This, however, is limited to the aspect of energy consumption. It is at present extremely difficult to model the production of exhaust gas emissions in computer simulation models of both conventional vehicles and e.g. hybrid and fuel cell vehicles. The computer simulations carried out in Task 2 therefore only provide results with respect to the energy consumption of the vehicles under study.

Evaluation of existing (draft) standards

18. Test procedures for LD vehicles with battery-electric, hybrid or fuel cell powertrains can closely follow the structure of existing test procedures for conventional LD vehicles, with modifications and additions to deal with categorisation of different types of propulsions systems and technology specific aspects such as ΔSOC correction and regenerative braking.
19. The SAE 1711 procedure is unable to deal with the characteristics of a typical "European" parallel hybrid vehicle where the electric performance is only orientated on urban conditions.
20. The length of a test, in terms of the number of cycles driven, should not be dependent on vehicle-specific criteria, such as the distance that can be driven in pure electric mode.
21. Many of the technology specific test problems identified and studied in MATADOR are not dealt with explicitly in the procedures developed by CEN. The SAE procedure is more complete in this respect. For concrete recommendations on specific test problems the reader is referred to the results of the various Subtasks as summarised in this section and the Subtask Reports.

ΔSOC correction methods for hybrid-electric vehicles

22. For a correct measurement of energy consumption and emissions of charge sustaining HEVs the SOC (state-of-charge) at the end of the test should be the same as at the beginning. If this can not be realised, then the occurring ΔSOC has to be determined and accounted for in a calculation of energy consumption and emissions.
23. A graphical ΔSOC correction method is proposed for which fuel consumption and ΔSOC over a given driving cycle need to be measured several times, with different values for the initial state of charge. By plotting fuel consumption against ΔSOC for each cycle driven the fuel consumption at ΔSOC = 0 can be estimated by interpolation or linear regression. As an indicator for ΔSOC it generally suffices to integrate the battery current during the cycle, yielding a ΔQ in Ah.
24. Within the project two variations of the graphical correction method have been identified, which have been named:
    - the linear regression method;
    - the linear interpolation method.

    Both methods are applicable but require different vehicle conditioning.
25. Both graphical methods assume that the relation between ΔSOC and fuel consumption is (approximately) linear. From measurements and simulations it is found that this is the case in all realistic circumstances. Simulations, however, proved that the relation is not fundamentally linear.
26. The experimental validation of the graphical ΔSOC correction method for measuring fuel consumption of charge-sustaining hybrids has been very limited, as a result of the limited availability of charge-sustaining vehicles. Further research on this subject is required.
27. The applicability of the graphical ΔSOC correction method, and of other methods as well, to emissions seems to be problematic. Measurements on the Toyota Prius revealed a large random spread in measured emission values as a function of ΔSOC, resulting in unfavourable correlation factors. So far we have not been able to come up with a more appropriate method for the ΔSOC correction of emission measurements. For vehicles with larger ΔSOC values than the Toyota Prius, the graphical method may, however, work more satisfactorily. To resolve this issue experimental research on hybrid vehicles with a wide range of powertrain configurations is necessary.

28. In view of the above two points, it is recommended to set-up a project in close collaboration with the automotive industry, in which prototypes and (pre-)commercial hybrid vehicles (especially charge-sustaining vehicles) are made available by the industry for energy and emission testing by independent research institutes to further research the applicability of the graphical methods for ΔSOC correction.

Determination of SOC or ΔSOC in general

29. For determining energy consumption of charge sustaining hybrid vehicles it suffices to accurately determine the ΔSOC in combination with the fuel consumed over a cycle. This in principle is possible by Ah-monitoring, as long as the battery is in a reversible regime (e.g. no hydrogen formation, or Coulombic efficiency =1). For vehicles with (relatively) new batteries it may be assumed that the hybrid control system does maintain the battery within this regime.
30. When vehicles with older batteries are tested, it is therefore recommended that the effective capacity of the battery is measured prior to testing the vehicle and to assess whether the battery's SOC-monitor or the hybrid controller are able to keep the battery's SOC stays within the reversible regime. If this is not the case, Ah-measurement can not be considered an accurate indication for the ΔSOC.
31. The use of simulation models for batteries may help to correct the Ah-counting and improve accuracy in energy consumption determination. The advantage of using models is twofold: increased accuracy in SOC and □SOC assessment and better determination of other parameters (current and voltage) needed to calculate energy consumption, if not directly measured.
32. There are significant variations of battery behaviour with the operating conditions (temperature, ageing, and discharge current), easily detectable with the monitoring of the internal resistance at low current pulse. In addition to Ah-counting, therefore, internal resistance monitoring is proposed as useful technique for SOC- and ΔSOC-measurement.

Comparing electricity and fuel consumption

33. For comparing energy and emission performance of vehicles with different propulsion systems fuel consumption and electricity consumption must be brought on a comparable basis. This is also necessary to evaluate the performance of charge depleting hybrids that consume both fuel and electricity.
34. It is recommended to the EU that a practical common methodology should be formulated for calculating indirect emissions and energy consumption on the basis of final electricity and fuel consumption at vehicle level. Conversion factors should preferably be based on average efficiencies and average indirect emissions of electricity production and fuel refining in Europe.
35. The EU should establish a formal body (organisation or network) that collects all data necessary for applying the common methodology, and that generates conversion factors on the EU level for all energy carriers that are currently used on a significantly large scale (gasoline, diesel, LPG, electricity, and maybe a few more). This body should periodically update the conversion factors to account for changes in the energy supply and demand systems.
36. Based on these conversion factors appropriate emission legislation and associated test procedures for vehicles with alternative power trains can be defined.
37. Each country should be allowed to define national conversion factors based on the same methodology and data set for use in a national policy context.

Fuel cell vehicle test procedures

38. FCEVs are currently available only at prototype level with a few pre-series products. The configurations developed until now are various and may present testing problems similar to ICEV, HEV and BEV, depending on the system chosen.
39. No standard testing procedure is presently available specifically for FCEVs. Current or draft CEN standards only consider BEVs, HEVs with thermal generators and ICEVs.
40. Light duty non-hybrid FCEVs with a reformer running on a carbon-based fuel can be tested according to the same procedures as are applicable to conventional LD vehicles (ICEVs). These procedures can also be applied to vehicles running on hydrogen, provided that a standardised method is defined for measuring the consumption of hydrogen. With similar provisions light duty FCHEVs can be tested using the procedures that are to be defined for hybrid vehicles with a thermal energy source.
41. Heavy-duty fuel cell vehicles should also be tested over a transient driving cycle, similar to LD vehicles.
42. The heating energy and the start up time of FC propulsion systems are expected to have a limited influence on energy consumption measurement. Nevertheless it seems useful to analyse this aspect to verify if there are specific features impacting the testing method. Due to the limited availability of experimental results and products, an analysis has been carried out at a very general level only. More research is needed to formulate adequate proposals for including these aspects in FCEV test procedures.
43. A remaining uncertainty is the possible presence of an intermediate hydrogen or reformate storage tank in vehicles with a fuel processor. This could cause similar problems as with the ΔSOC in hybrid vehicles. Obviously a similar solution could be applied. Given the uncertainty about future fuel cell vehicle configurations this problem has not been studied for the moment.

Driving cycles for LD vehicles

44. Current standard driving cycles bear relatively little resemblance to the conditions of actual vehicle use. Especially the modal cycles used in Europe and Japan (NEDC and Japanese 10-15) are much less demanding than cycles based on real-life driving.
45. More demanding cycles generally require more energy. It is possible, though, that with increasing demands at the wheels the overall driveline efficiency increases to such an extent that the energy consumption decreases (the relation between energy consumption and wheel energy then would be parabolic).
46. The influence of different driving cycle characteristics is different for different drivelines.
47. A representative test value for honest ranking of vehicles with different propulsion technologies can only be found when a representative cycle is used.
48. It is our strong belief that in the near future homologation test procedures will have to become more representative for real-life driving in order to make sure that manufacturers apply technologies in their vehicles that do not just make the vehicle meet legislated emission limits under laboratory test conditions, but that have a minimal impact on the environment when the vehicle is in actual use. The development and use of representative driving cycles is an essential step in this process.
49. Selecting a cycle that is representative for actual use not only requires that the cycle has representative average dynamics. It also requires that the cycle has a representative mix of road types (urban, rural and highway) and that the cycle has a representative length. This assures a representative weighting of e.g. the steep acceleration and deceleration associated with the highway part of the cycle. It may also help to solve problems that are more specific

to hybrids and battery-electric vehicles, e.g. to assure that the thermal engine does actually switch on during the test and that the energy consumed and the emissions produced with the engine on are weighted in the final results in a representative way.

Test methods and driving cycles for HD vehicles

50. A meaningful translation of the current engine-based test procedures for HD vehicles to alternative propulsion systems is not possible. The driveline or vehicle as a whole needs to be tested on a transient driving cycle. In order to obtain a meaningful test result, the test conditions need to represent average driving conditions of the vehicle type in which the propulsion system is applied. Each HD vehicle category (e.g. heavy truck, urban bus, refuse collection vehicle) that has a distinctive type of use therefore needs its own dedicated driving cycle.
51. The best way to obtain a representative test result for HD vehicles is to test the vehicle using a driving cycle on a HD transient rollerbench. However, also more pragmatic (and less expensive) ways of testing are possible, e.g. using measurements on a test track in combination with laboratory tests on the powertrain or its components.

Dealing with vehicles not meeting the demands of the driving cycle

52. The test cycle should be split in a low power and a high power part (e.g. urban and extra-urban) so that most vehicles will at least meet the requirements of the low power driving cycle.
53. When a vehicle is unable to meet the prescribed speed profile of the cycle (failure time) the vehicle should be operated at maximum power ("full throttle") until the vehicle speed coincides again with the prescribed speed.
54. Energy consumption and emissions should be measured separately for both cycles, together with the failure time. The failure time should be presented together with test results on energy consumption and emissions for both cycles.

Accuracy and tolerances

55. For hybrid vehicles, with their discrete switching actions (e.g. ICE on or off) in response to external parameters (e.g. road load) or internal parameters (e.g. battery SOC), the response to small variations in the test conditions may be strongly non-linear. An important aspect is the smoothness with which the test driver is able to follow the prescribed speed-time pattern. Also for conventional vehicles it is known that the allowed tolerances in the execution of the test cause significant variations in the test results. To improve the repeatability of laboratory testing recommendations have been formulated regarding vehicle operating procedures (e.g. concerning clutch and gear shifting), the allowed variations in soak temperature and the number of tests to be performed.
56. Human drivers should be able to perform the driving cycles as stated in standard procedures. Therefore, the speed tolerances should be maintained. The manufacturer should provide a list of operation procedures however. On this list, the driver would be informed at what times/operating points which pedals/pedal positions (e.g. kickdown) should be applied. For conventional vehicles with manual transmission this is already done for the clutch pedal at standstill in the European procedures.
57. Also, the shifting points should be defined for hybrid vehicles with manual transmission. The use of the existing points for conventional vehicles seems obvious. Since hybrid vehicles are often designed for many different applications which may influence the normal use of the transmission, manufacturers may provide a list of shifting points themselves, if can be shown that the vehicle is not able to follow the speed track within the specified tolerances when driving by the default shifting points.

58. In order to keep the influence of ambient temperature as low as possible, the starting temperature of the internal combustion engine should be defined at 25 ± 1°C, measuring the temperature with a thermal sensor at the outside of the engine cylinder head. As an alternative, the temperature tolerances for the conditioning room could be tightened at this value.
59. As a means of minimising the influence of remaining inaccuracies on energy consumption and emissions, the driving test should be performed several times (e.g. thrice). The results to be displayed would then be determined by calculating the mean values of the separate tests.

Regenerative braking on 2WD chassis dynamometers

60. Depending on the vehicle's braking strategy the yield of regenerative braking may be measured too high on two-wheel drive (2WD) dynamometers, as all braking energy is taken up through the driven wheels and none is dissipated by braking the non-driven wheels. Ideally the test should be performed on a 4WD chassis dynamometer. As this would greatly increase the costs of test facilities a correction procedure for use on 2WD dynamometers is preferred. However, no completely satisfactory solution has been found so far. On the other hand the size of the problem has also been difficult to assess due to limited availability of state-of-the-art vehicles with sophisticated braking strategies. When more (especially hybrid) vehicles have come to the market additional experimental assessments are necessary to determine whether or not provisions for dealing with this problem have to be incorporated in the test procedures.

Non-rechargeable batteries

61. A practical method has been developed for measuring the energy consumption of vehicles with non-rechargeable batteries such as Zn-air. The amount of Zn spent can be calculated on the basis of a measurement of delivered Ahs. Independently certified data for the energy consumption of the recycling process should be included in the evaluation to yield energy consumption data that can be compared with those of battery-electric vehicles charged from the grid.

Dealing with high-temperature batteries and self discharge

62. Batteries with high self-discharge and high-temperature batteries loose energy also during standstill. In order to provide input for an assessment of the impact of battery heating and self-discharge in relation to the vehicle use pattern it is recommended to specify a standstill test in addition to the energy consumption test over a test cycle. For high-temperature batteries the energy consumption over the range test should be measured. Furthermore it is proposed that the allowed time intervals between disconnecting the vehicle from the grid and commencing the energy consumption test as well as between the end of the test and connecting the vehicle to the grid for charging should be shorter and more precisely defined. Similarly the prescribed time for connecting the battery to the grid for charging should be reconsidered. In most cases this period is too long.

References

[1] *Programme for Collaboration between CEU and National Programmes on Electric Vehicles in Europe*, JOULE2 CT94-0291.

[2] *EN 1986-1: Electrically propelled road vehicles -Measurement of energy performances; Part 1: Pure electric vehicles*, 1997.

[3] *prEN 1986-2: Electrically propelled road vehicles -Measurement of energy performances; Part 2: Thermal electric hybrid vehicles*, July 1999.

[4] *SAE J1634: Surface vehicle recommended practice; Electric vehicle energy consumption and range test procedure*, June 1995.

[5] *SAE J1711: Recommended practice for measuring the exhaust emissions and fuel economy of hybrid-electric vehicles*, 1999.

[6] *ISO/DIS 8714-1: Electrically road vehicles - Reference energy consumption and range; Part 1: Test procedures for passenger cars and light commercial vehicles*, 1994.

[7] *prEN 13444-1: Electrically propelled road vehicles – Measurement of emissions of hybrid vehicles; Part 1: Thermal electric hybrid vehicles*.

[8] C.J.T. van de Weijer, Heavy-Duty Emission Factors - *Development of Representative Driving Cycles and Prediction of Emissions in Real-Life*, PhD-thesis, Technical University of Graz, October 1997.

[9] Richard Smokers, Ralf Bady, Mario Conte, Leo Buning and Karl Meier-Engel, D*evelopment of test procedures for the evaluation of vehicles with electric, hybrid and fuel ell power trains*, 1998, EVS-15, paper nr. 95.

[10] Richard Smokers, Servé Ploumen, Mario Conte, Leo Buning and Karl Meier-Engel, *Solving measurement and evaluation problems in the development of test procedures for vehicles with electric, hybrid and fuel cell power trains*, 1999, EVS-16, paper E10.

[11] Richard Smokers, Servé Ploumen, Mario Conte, Leo Buning and Karl Meier-Engel, *Test methods for evaluating energy consumption and emissions of vehicles with electric, hybrid and fuel cell power trains*, 2000, EVS-17.

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MANAGEMENT TOOL for the ASSESSMENT of DRIVELINE TECHNOLOGIES and RESEARCH

Contract JOE3-CT97-0081

Task 2:
Testing methods for vehicles with conventional and alternative drivelines

Final Report – Part II

Research funded in part by THE COMMISSION OF THE EUROPEAN UNION in the framework of the JOULE III Programme sub-programme

MANAGEMENT TOOL for the ASSESSMENT of DRIVELINE TECHNOLOGIES and RESEARCH

MATADOR

Contract JOE3-CT97-0081

Task 2:

Testing methods for vehicles with conventional and alternative drivelines

Subtask 2.1

Categorisation of EV configurations

Institut für Kraftfahrwesen Aachen

20 July, 2000

by
Ralph Bady (IKA)
Christian Renner (IKA)
Martin Schüssler (IKA)
Martin Johannaber (IKA)

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Energy Conservation and Utilisation

Nomenclature

Abbreviations

APU	Auxiliary Power Unit (generally an ICE with generator)
EV	Vehicle with (Hybrid) Electric Drive System (including BEVs and HEVs)
BEV	Battery Electric Vehicle
HV	Hybrid Vehicle
HEV	Hybrid Electric Vehicle
SHEV	Series Hybrid Electric Vehicle
PHEV	Parallel Hybrid Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
FCHEV	Fuel Cell Hybrid Electric Vehicle
ICE	Internal Combustion Engine
SOC	State Of Charge (of the electric energy storage device)
OVC	Off Vehicle Charge Capable
LPG	Liquified Petroleum Gas
RME	Rape Methyl Ester
CVT	Continuously Variable Transmission

Contents

1 Introduction

In Task 2 of the MATADOR-project, test methods (Management Tool for the Assessment of Driveline Technologies and Research, EU-contract JOE3-CT97-0081) for battery-electric, hybrid-electric, and fuel cell vehicles are analysed in order to support the development of new test procedures for these vehicles with alternative drivelines. The development and definition of test procedures with alternative drivelines for determining the fuel consumption and emissions requires a detailed work on the technical aspects, which depend strongly on the vehicle's technology. This is obviously more complicated for the development of procedures for a comparative assessment of technologies, which must cover many different aspects, than for the development of procedures needed for homologation, where only values for the fuel consumption and the emissions are mostly relevant. As a basis for the development of new procedures, classification schemes are developed and analysed compared to existing schemes in this subtask report.

Thus, this report deals with the classification of vehicles with (hybrid) electric drivelines (EVs). Despite other definitions commonly used, in the scope of the MATADOR research project, EV is used for vehicles, which incorporate electric components, including hybrid electric and pure electric vehicles. This general and theoretical framework is necessary as a basis and an instrument for the evaluation and visualisation of simplified categorisation schemes to be developed for practical test procedures in other subtasks. Therefore the classifications introduced and discussed in this subtask cover different purposes:

- Classification of vehicles in terms of research and development
- Classification for comparative/technology assessments
- Classification for homologation inside of test procedures

Depending on the scope of the classification, it can be very detailed and cover many aspects of the vehicle, or very simple with only two or three classes. For example, a classification for homologation shall make use of a simple classification scheme in order to have a straightforward procedure with a small number of classes. On the other hand, for R&D purposes, a classification can go into the details of the vehicle and its operation, covering for example the vehicle's behaviour under special driving conditions.

Classifications can be made due to the following aspects:

- Driveline type and structure
- Power and energy storage device
- (driver selectable) Driving modes (hybrid, thermal, pure electric mode, …)
- Operation strategy
- Charging strategy
- "Fuel" (Gasoline, Diesel, Natural Gas, Hydrogen, Electricity, …)

2 Classification of driveline types

The base classification of driveline types is made by dividing the types in conventional vehicles and unconventional or so called alternative vehicles. Conventional vehicles have just a fuel tank, an internal combustion engine (gasoline or diesel) and a gear box (manual or automatic). All other vehicles may be called alternatively driven vehicles.

Vehicles with unconventional liquid or gaseous fuels (e.g. natural gas, LPG, hydrogen, RME, …), which are burned in an (adapted) internal combustion engine, will be classified in the scope of this report as advanced conventional vehicles. The following chapters discuss the classification of alternative vehicles under the aspect of the driveline type. This classification is much more detailed as necessary within a homologation procedure, but it gives an overview of the complex area of possible variants of alternative vehicles. And from this detailed classification, which is useful for research and development purpose, a simple classification for homologation can be derived.

2.1 Electric vehicles

Pure electric vehicles are alternative vehicles, with a simple driveline where the electric motor, which drives the wheels, is powered from energy stored in an electric energy storage device, mainly some kind of electro-chemical device e.g. a battery. Thus the structure of the driveline is quite simple. Sometimes it has been propagated to combine the battery with a set of supercapacitors to cover power peaks during regenerative braking and severe accelerations. Such kind of electric vehicle has a hybrid energy storage, but the basic concept is still an EV.

2.2 Hybrid vehicles

A hybrid vehicle (HV) is a vehicle, where by definition at least two different energy storage (e.g. fuel tank, battery, flywheel, supercapacitor, pressure tank etc.) and two conversion devices (e.g. ICE, gasturbine, stirling engine, electric motor, hydraulic motor, fuel cell) are combined in one driveline.

Additionally at least one of the storage/conversion device combinations should be bi-directional, thus enabling the recharge of the storage device during operation of the vehicle.

2.2.1 Classification by Type of Conversion Device

The type of the energy conversion device used in a HV is a first characteristic to classify different types of HV. The term energy conversion device covers all types of motors and engines. Energy conversion devices convert the stored energy into another type of energy. For example, a thermal engine converts the energy stored in the fuel into mechanical energy, and an electric motor transforms electrical energy into mechanical energy. Energy conversion devices can be mono-directional (all thermal engines, fuel cells) or bi-directional (electric motors, hydraulic machines). The bi-directional devices are used to recover braking energy and are often necessary to recharge for maintaining sufficient state of charge for the secondary, non-fuel storage device.

2.2.2 Classification by Type of Storage Device

The type of the storage device, beside the fuel storage for the thermal engine, allows a categorisation of the vehicle. Today, for storing electric energy, three types of devices are available:

- Electro-chemical batteries
- Super capacitors
- Electric flywheels (a combination of a flywheel with an electric motor/generator)

For storing mechanical energy, flywheels that are mechanically connected via a CVT exist. Hydraulic energy can be stored in pressure accumulators. As this report mainly concentrates on (H)EV, these options are not further regarded in detail.

This categorisation is relevant for all purposes. The type of the storage has a great influence on the operating strategy of the vehicle and is therefore of interest for R&D as well as for technology assessments. For homologation it is relevant, because each type of storage must be handled in a different way to determine the state of charge of the storage device. Also the energy content can have an influence on the fuel consumption. If the change in the energy content of the storage device during a test is so great, that it has a significant influence on the fuel consumption, this effect has to be regarded by a procedure. This effect and how to handle this is discussed in section 2.2.6.

If the storage device has big standstill losses and a small energy content, e.g. a flywheel, it will completely discharge overnight. During normal operation of the vehicle, the storage device will be charged to a certain level first, before it can take part in the supply of power for traction. At the end of the operation of the vehicle, the storage device will have a medium state of charge, but the energy will be lost during long standstill. For a procedure this means, that the storage device will, each time, have a higher final state of charge than at the beginning of the test, but each time a test is performed, it is the same behaviour and therefore approximately the same amount of energy. In such a case, although the final state of charge is higher than the initial, no ΔSOC correction of the fuel consumption is necessary, nor is it possible.

2.2.3 Classification by Structure

Hybrid systems can be roughly divided into two basic structures: the parallel and the series hybrid system. Each of it has its own potentials and problems. Besides these, there are several mixed forms of the parallel and the series structure. An overview of the hybrid classification is given in Figure 2.2-1.

In the parallel hybrid structure (see Figure 2.2-2) the internal combustion engine (ICE) and the electric motor are <u>both</u> linked mechanically to the wheels. Besides to the two driving engines and storage systems these concepts consist of one or even more transmissions, clutches and freewheels. Both systems can be used separately or together to drive the vehicle. During acceleration phases the powers of both engines can be summed. This enables that both can be designed relatively small (in comparison with a conventional vehicle) without harming the acceleration ability and climbing performance of the vehicle. Often, the electric system is dimensioned to meet the requirements of urban traffic (limited operation, zero emissions), while the more powerful combustion engine is used for rural and motorway driving. The delivered power of both engines can be added by means of speed addition (with the aid of a planetary gear), by torque addition (with the aid of a spur gear or chain drive) or traction force addition (combustion engine and electric motor drive different axles). The ratio of the torques in the torque addition solution is free, while the ratio of the speeds is fixed. A decoupling of the combustion and the electric system can be realised with the help of a freewheel or a coupling unit (clutch).

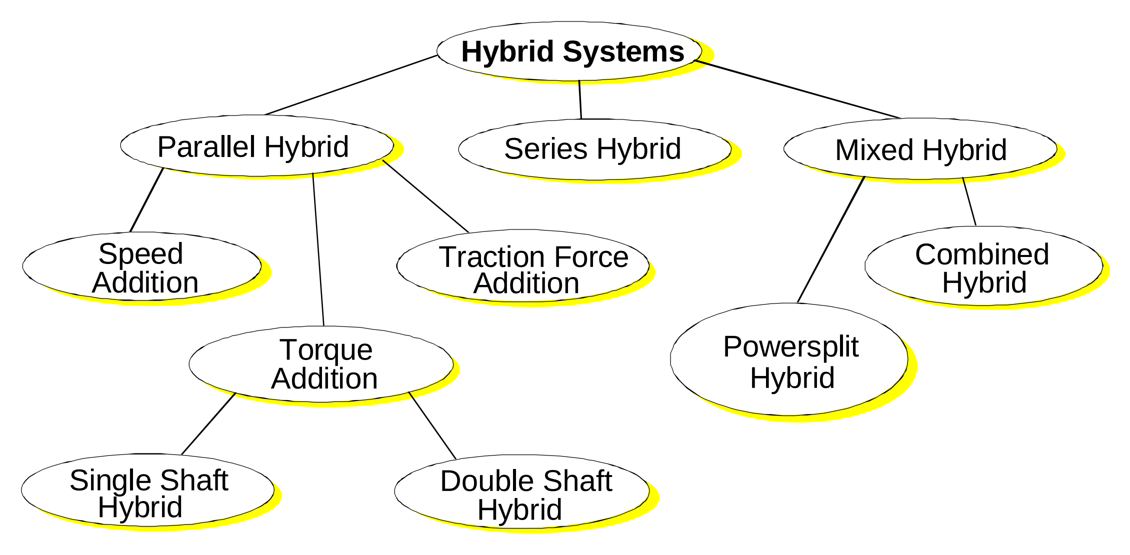

Figure 2.2-1: Classification of Hybrid Systems [1]

In a speed adding system the powers of the energy converters are joined in a planetary transmission, in which the torque ratio is fixed by the gear ratio. The speeds of both engines can be freely chosen. Due to the physical properties the traction force system is a system with torque addition, too. Yet, the two energy converters act on different axles (e.g. the electric motor on the front axle and the internal combustion engine on the rear axle).

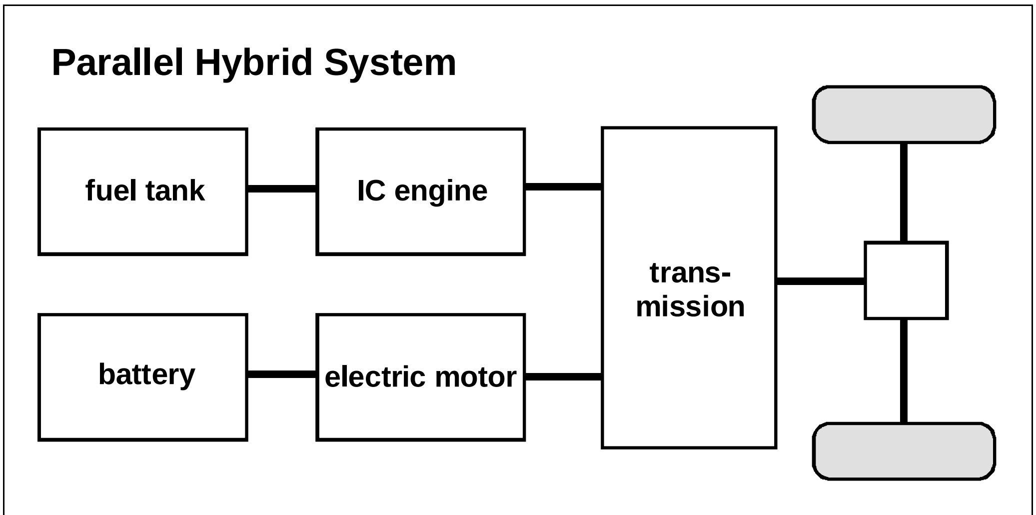

Figure 2.2-2: (Example of) a Parallel Hybrid Drive System [1]

Another possibility for further categorisation of parallel systems is the physical arrangement of the energy converters. A single shaft hybrid is a system in which electric motor and combustion engine work on the input shaft of the transmission. In a double shaft hybrid the two energy converters are arranged on different shafts (input shaft and output shaft respectively).

Distinguishing feature of series hybrid systems (see Figure 2.2-3) is the series connection of the (internal) combustion engine without direct mechanical linking to the electric motor, which in turn drives the wheels. The combustion engine drives an alternator, which supplies the electric driving unit and an accumulator (as a rule a battery) arranged in an intermediate electric circuit.

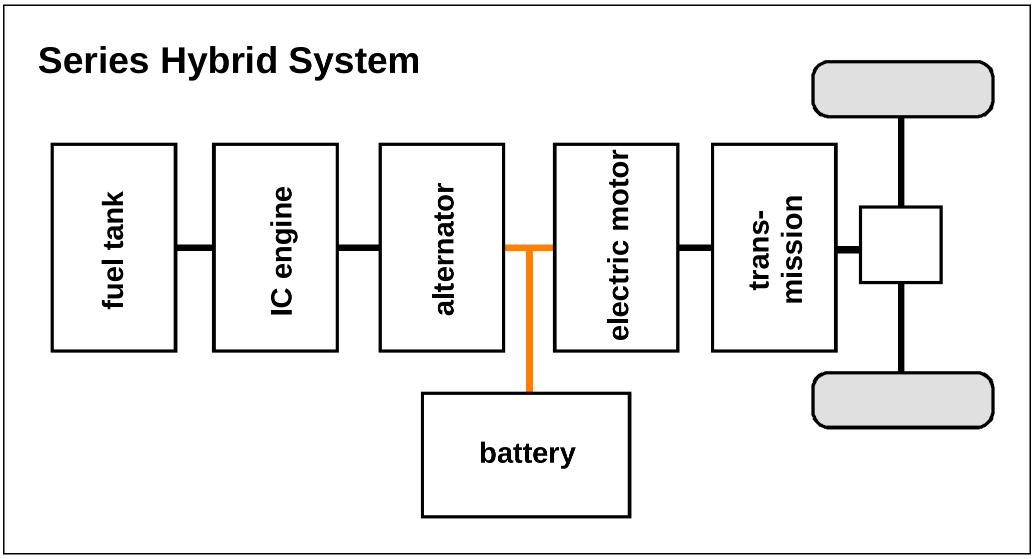

Figure 2.2-3: Series Hybrid System [1]

Systems with one driving motor and a differential, systems with two driving motors on one axle without differential, and systems with wheel-hub motors all (can) exist. The alternator and the accumulator have to be designed under consideration of the operating and charge strategy, a possible desired independence of electric power supply (high charging rate), operating range and driving performance. The higher constructive effort is compensated by the omission of a transmission. Due to the fact that the combustion engine is no longer mechanically linked to the wheels the components can be arranged in the vehicle with high flexibility. In comparison to an electric vehicle the battery can be dimensioned smaller and the availability of the vehicle increases by on-board charging or pure alternator operating. In the dimensioning of the electric driving motor, it has to be considered that it must deliver the whole power for acceleration and climbing performance. Thus it is not astonishing that in the seventies and eighties the realised hybrid systems were exclusively parallel, because electric engines with a necessary power density and efficiency were not available. The mechanical decoupling of the combustion engine provides the possibility to reduce its dynamics and to operate it with an averaged power demand or in an operating point with lowest fuel consumption. It does not have to be dimensioned to maximum power. In extreme cases the combustion engine is operated in only one operating point, which is chosen with regard to low emissions and low fuel consumption. Particularly, the omission of dynamic operating enables the reduction of emissions. The level of comfort is improved by the purely electric propulsion without interruption of the traction force. But the noise level of the operating combustion engine, which is now independent from the operating point of the vehicle, is unfamiliar to the occupants and can be inconvenient.

Unfavourable in a series hybrid system is the double energy conversion from mechanical into electric, and vice versa, maybe in conjunction with storage and the involved long and adverse efficiency chain. The limited capacity of the battery frequently leads to an unavoidable transient operating of the combustion engine to cover power peaks during climbing or acceleration conditions. Due to this the emission and consumption advantage can be reduced and a dimensioning of the engine for stationary operation (simple engine management system and engine design) cannot be realised.

A mixture of the parallel and the series hybrid system are the so called combined and the power split hybrid systems. (See Figure 2.2-4).

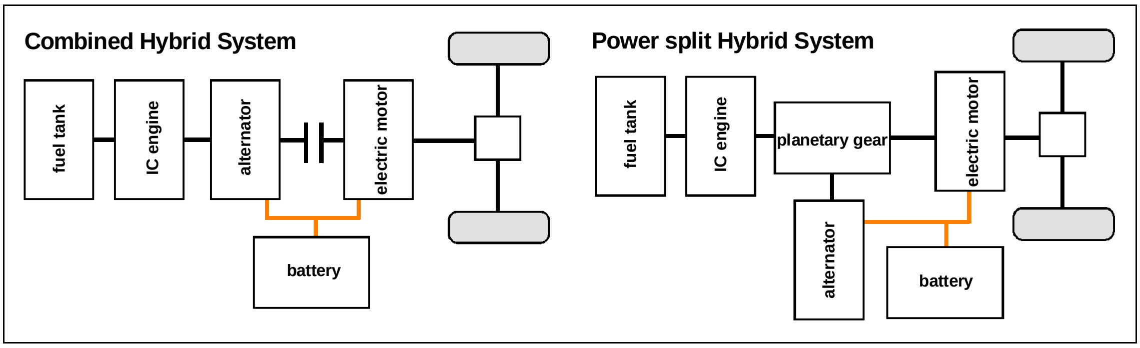

Figure 2.2-4: Combined and Power Split Hybrid Systems

In a combined hybrid system, it is possible to transfer energy from the combustion engine mechanically to the wheels by closing a clutch. With this measure the overall efficiency in some operating point (e.g. high energy demand during motorway drive) can be increased. The two electric motors can simultaneously deliver their power (as in a parallel system) to cover peak power operating points. On the one hand, the combined system increases the efficiency, but on the other hand the constructional effort is increased by the additional clutch and the more complex operating strategy. Furthermore the arrangement of combustion engine and alternator is restricted, because a mechanical coupling to the driveline is present.

Another, solution is a power split hybrid system. In this structure a part of the combustion engine's power is directly transmitted to the wheels. The rest of the power is transmitted to the wheels through a planetary gear and two electric motors. For energy storage a battery is generally used. A system with this arrangement of the electric motors acts like a continuously variable transmission. A separate transmission for the combustion engine is not necessary. This provides the possibility to operate the combustion engine in an operating point that meets the momentaneous driveline requirements best (fuel consumption and emissions). The efficiency can be higher than in the series hybrid systems due to the partly direct mechanical transmission of the power. At this moment, the Toyota Prius (first mass series produced hybrid electric vehicle) is equipped with such a power split hybrid system.

2.2.4 Classification by Power and Energy Storage Capacity

Besides these categorisations of the structure, the hybrid systems can be classified by their electrical driving power as well as their electrical storage capacity.

Parallel hybrid systems with low installed electrical power and low electrical storage capacity are characterised as starter/alternator hybrid system. With higher installed electrical power it is named power assist hybrid or, referring to the storage capacity, low storage hybrid.

A series hybrid system with a high battery capacity and a small alternator unit (auxiliary power unit, APU), is referred to as range extender. If the battery capacity is small, consequently the zero emission range low, it is again referred to as a low storage hybrid. The result of a total omission of a electrical storage is an electrical IVT (infinitely variable transmission).

Fuel cell vehicles with an additional electrical energy storage system belong to the hybrid systems, too.

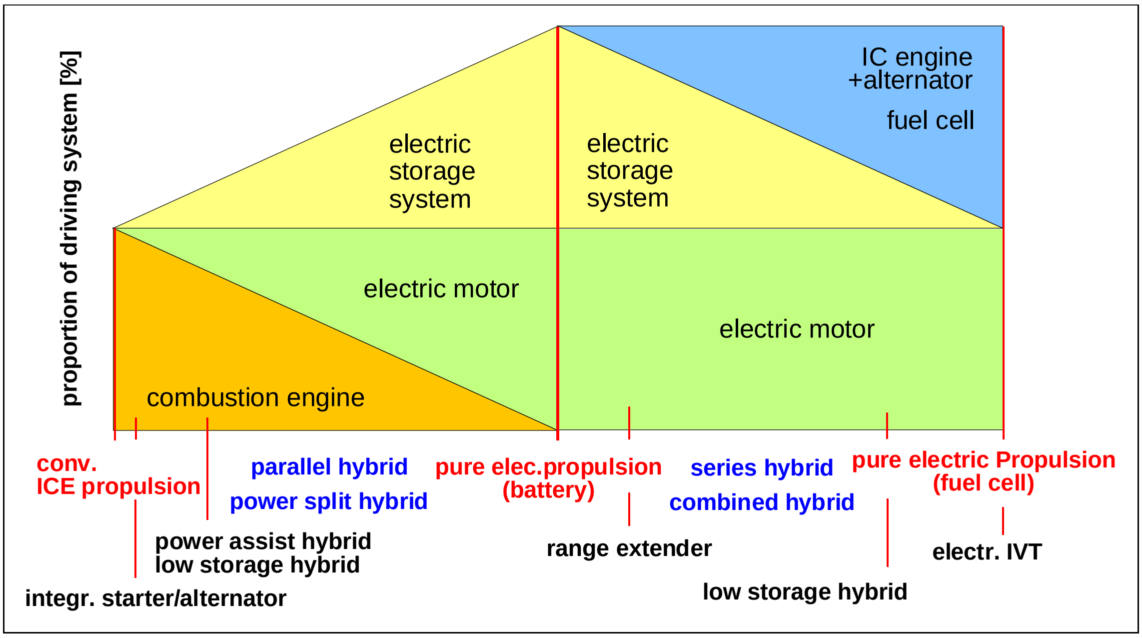

Figure 2.2-5: Classification According to The Proportion of The Driving Systems [2]

The two classifications by structure and by power and energy storage capacity given in the chapters above are mainly relevant for R&D activities and for comparative assessment, because they help to explain the characteristics of a hybrid vehicle. For a homologation process the vehicle's internal driveline structure is preferably handled as a black box. Only the behaviour during a test procedure is of interest for the tester, and with the given behaviour he can apply a corresponding procedure, and not the underlying internal structure.

2.2.5 Classification by Driving Modes

A hybrid vehicle typically has different operating modes, automatically changed by the vehicle's driving strategy implemented in the vehicle's controller, or manually selected by the driver.

In the following analysis, **operating mode** (electric, hybrid, thermal mode, etc.) stands for a user selectable mode. The driver can select a mode by a switch. Of course, a vehicle can have a default mode, which is automatically selected on key-on, and the vehicle controller can override the user's selection (e.g. pure electric mode can be overridden when the battery SOC is too low).

Additionally, a hybrid vehicle has operating states. An **operating state** represents the actual status of the driveline components during a certain driving situation. These states are only determined by the vehicle's controller according to the situation and history, and are not user selectable. For example, a hybrid vehicle in user selected hybrid mode operates at low power demands in electric state. In this electric state, only the electric motor powers the vehicle from the batteries alone. At higher demands it can be in a thermal (or ICE) state, where the thermal engine has been automatically activated and provides the power to drive the vehicle. Additionally, several combined (or hybrid) states are possible (e.g. boosting the vehicle by summing the power of both engines for overtaking and accelerating, or recharging the batteries by increasing the load of the ICE and using the electric motors as a generator). As the definition of a state indicates, it is an internal aspect of the operating strategy. Therefore the term 'state' is only relevant for research and development purposes. For a simple homologation process, the internal states of a operating strategy obviously are not relevant and also not accessible without deep knowledge of the vehicle's internals.

Regarding the purpose, a classification according to modes is necessary for R&D activities as well as homologation. The tester has to know, which modes are present in a test vehicle and the procedure has to prescribe, how they are used in the procedure. But the existence of the classification itself demands not, that the procedure must cover all possibilities of operating modes. For example, a procedure can demand to test the vehicle only in the relevant mode.

The following operating modes often can be found in existing (hybrid) electric vehicles:

- Electric mode (The vehicle is only driven by the electric motor, powered from the batteries)
- Hybrid mode (The thermal engine and the electric motor drive the vehicle, depending on the actual operating state of the vehicle, decided by the vehicle's controller)
- Thermal mode (The vehicle is propelled by the thermal engine only. The electric motor may recharge the battery by recuperation. In case the batteries are empty, it is often combined with a recharge of the battery)

With the (drafts of) test procedures prEN 1986-2 and SAE J1711 (see subtask report 2.3 for detailed description and analysis), two categorisations regarding user selectable modes are already defined. The following part compares these definitions to the definitions made above.

In prEN 1986-2, no difference is made between user selectable modes and states. It defines a pure electric mode, a pure thermal mode and a hybrid mode. prEN 1986-2 defines the pure electric mode the same way as above, but it can be included in the hybrid mode. The definition for hybrid mode is comparable to that given above.

The definition for the "pure thermal mode" given in prEN1986-2 defines this mode in a different way as in the classification presented above. According to this definition, in the pure thermal mode the combustion engine drives the vehicle without any participation of the electric energy storage system. So recuperation is not allowed in this pure thermal mode. (In the understanding and experience of the authors of this subtask report with real hybrid vehicles, such a mode is very unlikely, because if recuperation is possible in a vehicle it is normally used as often as possible).

The SAE J1711 makes also use of three "modes": EV mode, EO mode and hybrid mode.

EV mode is a pure electric mode. EO stands for engine only mode. This EO mode and the hybrid mode are defined the same way as thermal mode and hybrid mode presented above. So apart from the different terms, the classification regarding operating modes of SAE J1711 is the same as the classification presented in this report.

Furthermore, especially in pure EVs, the performance is sometimes user selectable e.g.:

- economy mode,
- normal mode,
- sport mode,

where in economy and normal mode the power is limited to achieve a long range with the limited energy content of the batteries. These different adjustments for the performance become relevant for testing, only if the vehicle is not possible to follow a driving cycle in a low performance mode. prEN 1986-2 stipulates, that the one adjustment, with which the driving schedule can be matched best, shall be selected. If several modes can fulfil the speed demand, the manufacturer has to recommend one. The procedure therefore describes, how to handle this possibility. But the fact of different power adjustments gives no reasonable classification criteria for homologation purpose.

A third user selection, which can be chosen by the driver, is the way how the vehicle makes use of regenerative braking. The possibilities are an on/off switch for regenerative braking at all, and the possibility to influence the coastdown behaviour of the vehicle, if neither the accelerator or the brake pedal are pressed. In this case the driver has often the possibility to chose between a freewheel behaviour, where the vehicles coast down only decelerated by the driving forces, or a braking behaviour, where the electric motor simulates the braking torques of a conventional combustion engine and feeds the power back into the batteries. The later functionality is often intended for more comfortable downhill operation of the car. A test procedure must handle this possibility for an adjustment of the vehicle behaviour, but no explicit classification regarding the homologation procedure can be derived from the fact, that such an adjustment is possible.

2.2.6 Classification by charging strategy

Another point to distinguish an unconventional vehicle, is the charging strategy.

Generally there are two possibilities for this criteria:

- External charge capability
- No external charge capability

If the vehicle is normally recharged from the grid by an on board or external charger, it is externally chargeable. A non regularly charging possibility only for maintenance of the batteries is not regarded here for an externally chargeable vehicle. The terms ‘externally chargeable’ and ‘not externally chargeable’ are also used in the same way in the draft prEN 1986-2. The SAE J1711 uses the terms off-vehicle charge-capable vehicles (OVC capable) and not OVC capable with the same definitions.

If no external recharge possibility exists, there could be the possibility to reload the battery by using the APU in standstill.

Further on, the vehicle could be handled as a:

- charge depleting or
- charge sustaining

hybrid during normal driving.

Per definition, the charge depleting hybrid vehicle will use its complete energy stored in the battery for driving in mainly electric state of a hybrid mode. Once the energy of the battery is totally used, the vehicle can no longer be operated in a way that was intended.

Thus, the correct operation of the vehicle is impaired by the discharged batteries. After that the state/mode can be changed automatically by the control-system or manually by the user. A charge depleting vehicle makes only sense, if it is either OVC capable or has an operation mode in which the batteries are completely recharged or has the possibility to reload the battery by using the APU at standstill.

The charge sustaining vehicle will at least stabilise the state of charge of the battery at a certain level, allowing continuous operation of the vehicle.

If the SOC is higher than this level (e.g. because the batteries are charged by an external charger or regenerative braking, which could reach high levels during prolonged downhill operation of the car), the strategy would operate the vehicle afterwards mainly in electric state to reach the specific SOC. In the other case, which means, that the battery is discharged deeper than intended, the SOC is increased again by operating the vehicle in a recharging state (e.g.

increasing the load of the ICE and using the electric motor as a generator). As a charge sustaining vehicle needs no recharge from the grid, an onboard charger is not necessary; the vehicle can operate autark and independent from any recharging possibility from the grid.

This charge sustaining/depleting characterisation of a driveline depends on the applied driving cycle. Obviously, a vehicle which is normally charge sustaining, can show a charge depleting behaviour under very power demanding conditions. But this problem will be solved by the selection of a representative driving cycle. A vehicle which is not externally chargeable, it must have at least one operation mode, where the state of charge during this representative cycle is stabilised and the vehicle operates charge sustaining or even predominantly charging.

From the point of a simple test procedure, the criteria of externally chargeable and charge sustaining/charge depleting can be handled together. If the vehicle is externally chargeable, the energy consumption of this vehicle consists of a fuel consumption and an electric energy consumption to recharge the battery from the grid. If the vehicle is not externally chargeable, it must have at least one operation mode, where the electric energy storage device is hold at a certain state of charge or even recharged to 100 % state of charge. In this case, either a correction method must be applied to the test fuel consumption in order to regard the change in the state of charge of the batteries or the energy content of the storage device (flywheel, super capacitor) is very small, that a change in the SOC has no big influence on the fuel consumption.

An additional aspect to classify vehicles and which has a close relationship to the recharge strategy, is the type of fuel. Besides the conventional fuels like gasoline or diesel fuel and other fuels for combustions engines as hydrogen, ethanol, methanol, natural gas, or RME, it is of interest if also electricity must be restored. Besides the effect, that each of the fuels has an influence how to measure consumption and emissions, the need to restore electric energy is a similar aspect as the characterisations being externally chargeable or not.

3 Comparison of Classification Schemes

In the preceding chapter several classification aspects were defined and explained. From the point of R&D, all this topics can be relevant, whereas for homologation purpose, the number of characteristics shall be very small. As summarized in Figure 2.2-1, the R&D classification covers all aspects.

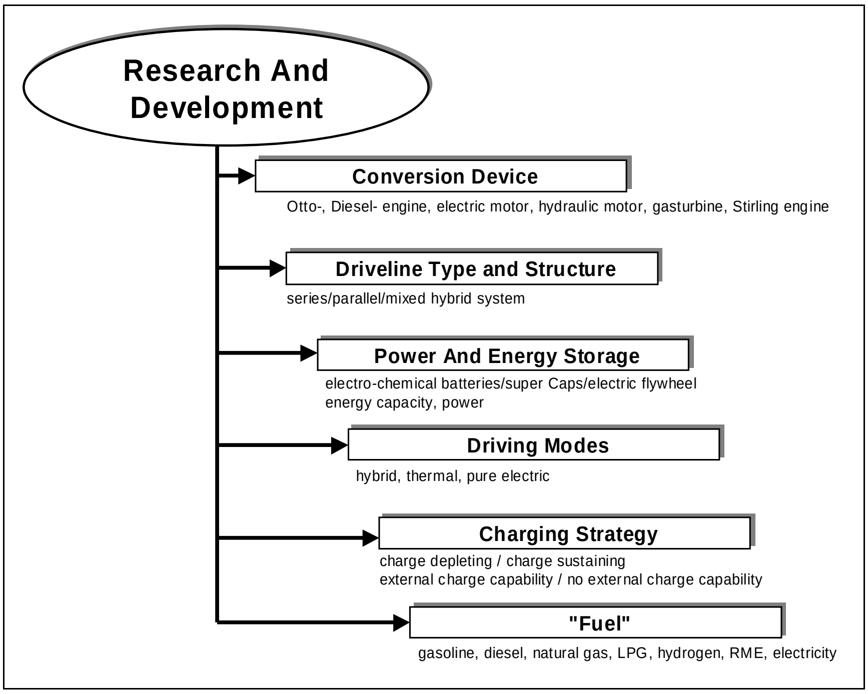

Figure 2.2-1: Classification aspects for research and development

A classification for testing and homologation purpose must only cover the essential aspects (See Figure 2.2-2). From the point of testing HEVs the storage technology for the regenerative storage device is of interest, because the technology determines the method to measure its energy content and has also a big influence on the operational behaviour of the vehicle.

For measuring energy consumptions it is further of interest, if one must supply only fuel – than the car must be at least in one operation mode somehow charge sustaining – or additional electricity must be fed from the grid for normal use of the vehicle.

The existence of different driving modes is for a homologation process is not so relevant (indicated by the hatching). A simple test procedure shall be used to test the vehicle, if possible, in the hybrid mode. (The authors suppose that the hybrid mode is the most probable mode for the use of the hybrid vehicle in real life). Only for hybrid vehicles, which have not such a mode, but for example one pure electric and one thermal mode, this aspect of different modes becomes relevant. Additionally the range and consumption in a pure electric mode can be of interest, but with lower priority.

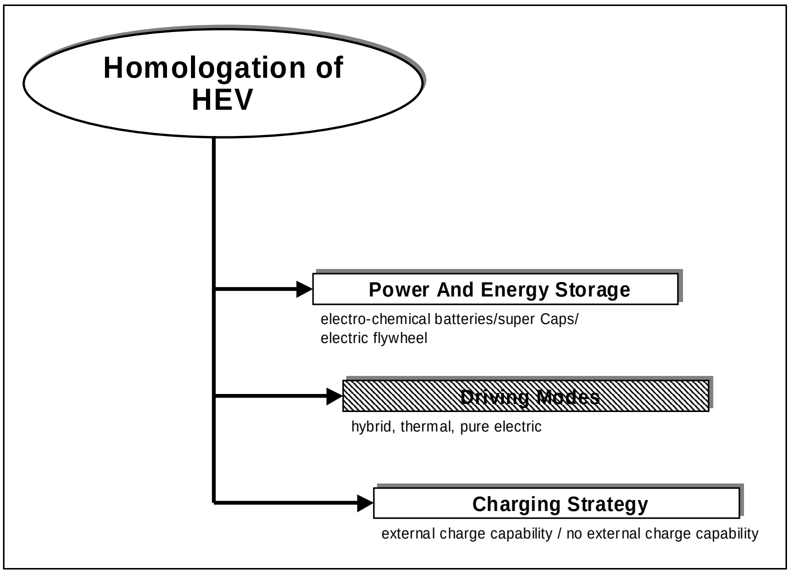

Figure 2.2-2: Classification aspects for homologation

For a comparative assessment, the analysed aspects may vary, starting with that given for homologation and ending at that for R&D purposes.

A comparative assessment would mainly focus on the evaluation of consumption and emissions under real life conditions. This could result in the use of different cycles and driving patterns to represent different user behaviours. But regarding a test procedure, this does not mandatory result in a more complex classification scheme. Only the boundary conditions may vary.

Furthermore an assessment would also cover the different operating modes in detail, whereas a homologation test would use the mode, which is representative for the vehicle (in most cases the hybrid mode).

Looking at the existing drafts for testing hybrids (SAE J1711 and prEN1986-2), some general differences become obvious.

The classifications according the SAE J1711 is given in Figure 2.2-3.

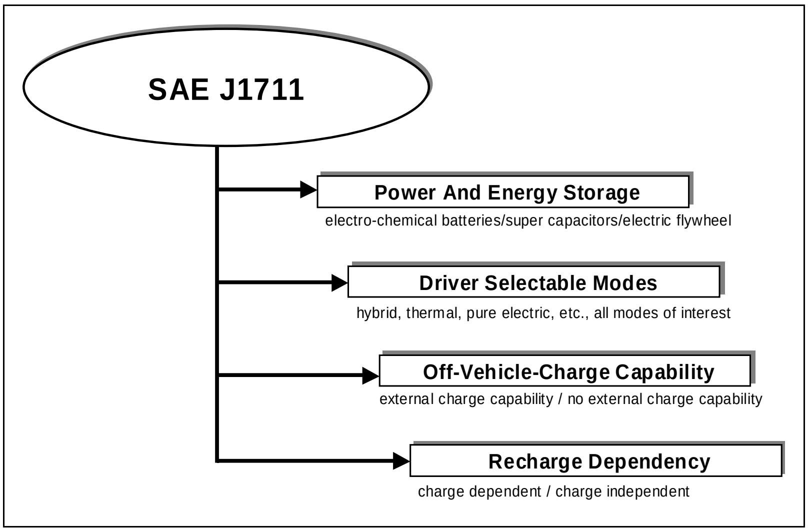

Figure 2.2-3: Classification aspects of HEVs according to SAE J1711

As a result of this classification scheme, a big number of tests has to be performed, as illustrated in Figure 2.2-4.

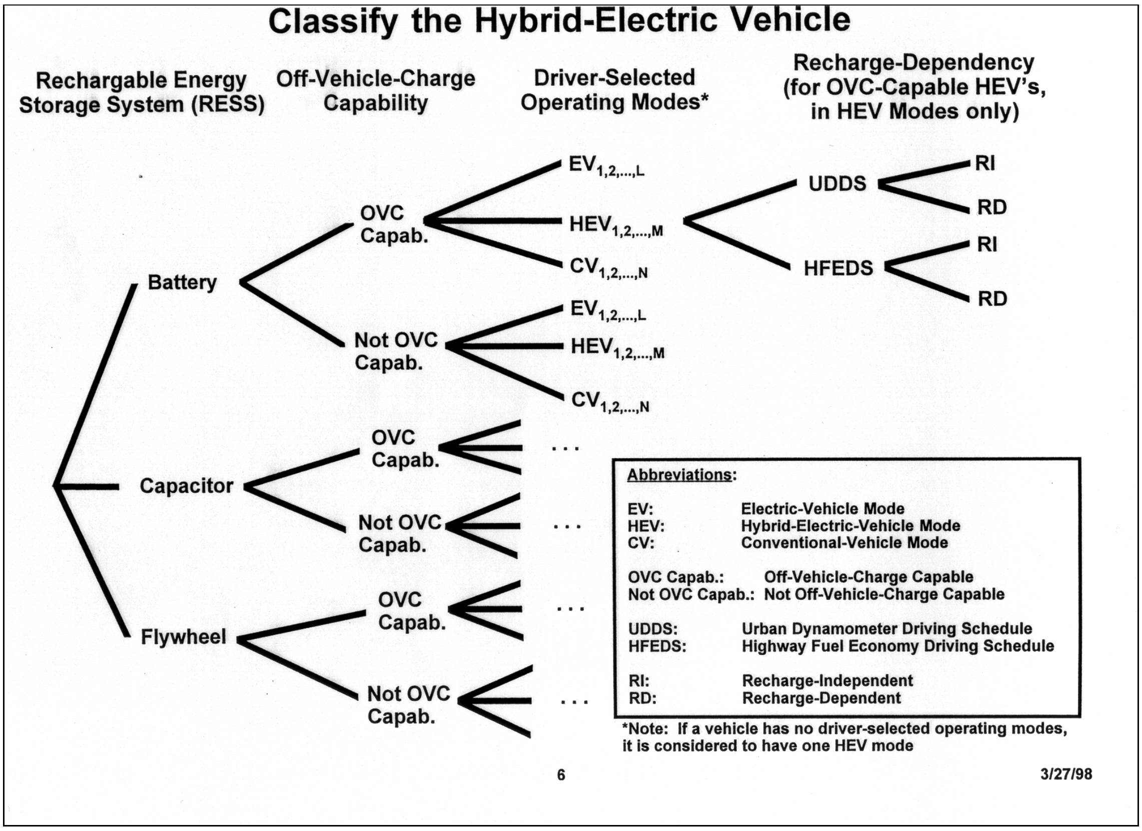

Figure 2.2-4: Classification of HEV (SAE J17711) [3]

According to this procedure, the vehicle is tested in each user selectable mode in different cycles. If the vehicle is OVC-capable, one has to make a difference between RD and RI operation of the car. The performed tests allow a detailed analysis of the vehicles behaviour under different conditions. The analysis end up with much information and measured values more than needed for a homologation of the car and allows a well justified assessment of the vehicles behaviour.

The categorisation aspects of prEN 1986-2 are shown in Figure 2.2-5.

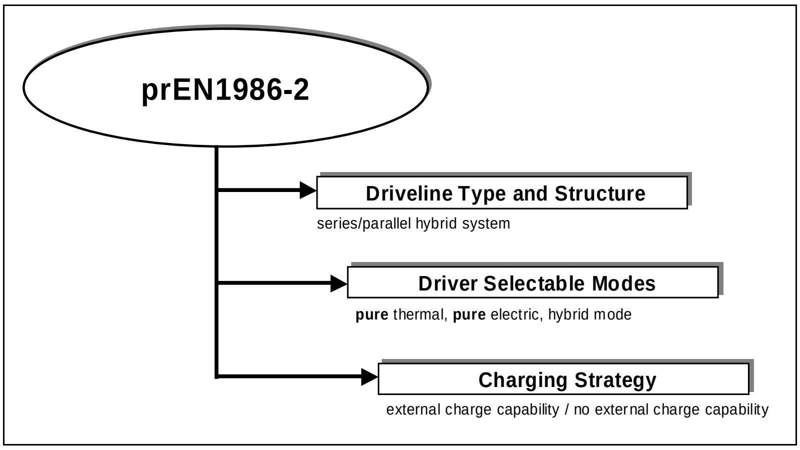

Figure 2.2-5: Classification aspects of HEV prEN 1986-2 [4]

According to prEN1986-2, if the vehicle has a pure thermal mode, the vehicle is tested as a conventional one according to the procedures for conventional cars without regarding the hybrid drivetrain. If the vehicle has no pure thermal mode, the electric range, the energy consumption and the consumption and emissions in the hybrid mode are measured. If the vehicle is externally chargeable, the test in hybrid mode starts with fully charged batteries. If the vehicle is not externally chargeable, the state of charge of the secondary electric storage device (battery, electric flywheel, super capacitor) shall be balanced over the test or can be recharged afterwards by using the thermal engine. The introduced classification aspect structure is not relevant for performing the tests and not necessary in order to define, which tests must be performed according to prEN1986-2. Thus, the procedure is quite simple and focuses more on the purpose of homologation.

Comparing Figure 2.2-2 and Figure 2.2-5, it is evident, that the figures and their content are nearly the same. The main difference is the thermal mode versus pure thermal mode. For a homologation of a hybrid vehicle, the vehicle should at least operate in the typical hybrid mode. Although there may be a mode, in which it behaves completely like a conventional car, testing the vehicle in this mode – for simplicity reasons – misjudges this car completely. It not correspondents to the real world usage of such a vehicle. In this case, the value given would be a worst-case value, where the vehicle is penalised by the weight of the additional hybrid components without being allowed to use them.

4 Summary

In Task 2 of the MATADOR-project test methods (Management Tool for the Assessment of Driveline Technologies and Research, EU-contract JOE3-CT97-0081) for battery-electric, hybrid-electric and fuel cell vehicles are analysed in order to support the development of new test procedures for these vehicles with alternative drivelines. The development and definition of test procedures for vehicles with alternative drivelines in order to determine the fuel consumption and emissions requires a detailed work on the technical aspects, which depend strongly on the vehicle's technology. This is obviously more complicated for the development of procedures for a comparative assessment of technologies, which must cover even more different aspects, than procedures needed for homologation, where values for the fuel consumption and the emissions are most relevant. As a basis for the development of new procedures, in this subtask report classification schemes are developed and analysed compared to existing schemes.

In the scope of this subtask, different classifications of alternative vehicles have been defined. Due to the complexity of hybrid systems and the many different possible structures and energy storage components, it is not easy to assign a system to only one class clearly. Classification can only be done according to special aspects of the hybrid system.

Depending on the purpose, the categorisation scheme is divided in a different number of categories. For homologation it is desirable to have as few classes as possible, while a categorisation for research and development has to cover all the different aspects of the systems internals and therefore may be more extended.

Classification can be made due to the following aspects:

- Charging strategy
- Power and energy storage device
- Driving modes (hybrid, thermal, pure electric modes, …)
- Driveline type and structure (driver selectable)
- Operation strategy
- "Fuel" (Gasoline, Diesel, Natural Gas, Hydrogen, Electricity …)

All these categories are important for research and development, while for homologation it can be reduced to the first two aspects. Only in hybrid vehicles, which have no hybrid mode, but only a pure electrical and a pure thermal mode, the driving mode is of interest.

The aspects of the existing drafts for testing hybrid vehicles (SAE J1711 and prEN1986-2) are discussed in this report. prEN1986-2 provides a categorisation scheme similar to the categorisation scheme for homologation delivered in this report. SAE J1711 additionally considers the aspect of the charge dependency. The complexity of the tests to be performed according SAE J1711 shows that with this procedure a more detailed assessment of vehicles rather than testing only for homologation purposes is conducted.

The different aspects of hybrid systems are described and, beside explanations, examples are given to illustrate the abstract definitions.

In the scope of this subtask, different classifications of alternative vehicles have been defined. The classification criteria are the driveline structure, the power and energy storage capacity, the available driving modes and the charging strategy. Beside explanations, examples are given to illustrate the abstract definitions.

References

[1] B. Harbolla, "Entwicklung eines Bewertungsverfahrens zur Auswahl von Pkw-Hybridantrieben und Realisierung eines seriennahen Antriebskonzeptes", PhD-thesis, Institut für Kraftfahrwesen Aachen, RWTH Aachen, 1993

[2] J.-W. Biermann, R. Bady, "Hybridantriebe - Strukturvarianten, Betriebsstrategien sowie deren Vor-und Nachteile", 5. Symposium „Elektrische Straßenfahrzeuge", Technische Akademie Esslingen, 26./27. März 1998

[3] SAE HEV Test Procedure Task Force, "Recommended Practice for Measuring the Exhaust Emissions and Fuel Economy of Hybrid-Electric Vehicles", SAE J1711 (Draft), 1998

[4] prEn 1986-2, "Electrically propelled road vehicles - Measurement of energy performances - Part 2: Thermal electric hybrid vehicles", draft revised by Italy, July 15, 1999

MANAGEMENT TOOL for the ASSESSMENT of DRIVELINE TECHNOLOGIES and RESEARCH

MATADOR

Contract JOE3-CT97-0081

Task 2:

Testing methods for vehicles with conventional and alternative drivelines

Subtask 2.2

Development of simulation models

Institut für Kraftfahrwesen Aachen
&
TNO Automotive

20 July, 2000

by
Servé Ploumen (IKA)
Erik van den Tillaart (TNO)

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Energy Conservation and Utilisation

Nomenclature

Abbreviations

AC	Alternating Current
APU	Auxiliary Power Unit
AUT.TR.	Automatic Transmission
BAT	Battery
BEV	Battery Electric Vehicle
CHEV	Combined HEV
CNG	Compressed Natural Gas
CS	Control Strategy
DC	Direct Current
DIFF	Differential gear
DUBC	Dutch Urban Bus Cycle
el. Flywheel	Electro mechanical flywheel
EM	Electric Motor
ESS	Energy Storage System
EV	Electric Vehicle
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
FCHEV	Fuel Cell Hybrid Electric Vehicle
FW	Flywheel
FWHV	Flywheel Hybrid Vehicle
GE	Generator
genset	Generator set (APU)
HD	Heavy-Duty
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
ICEV	(Conventional) Internal Combustion Engine Vehicle
IKA	Institut fur Kraftfahrwesen, Aachen
LD	Light-Duty
LPG	Liquefied Petroleum Gas
MATADOR	Management Tool for the Assessment of Driveline TechnOlogies and Research
NiCd	Nickel-Cadmium (battery)
NiMH	Nickel Metal Hydride (battery)
PG	Planetary gear
PHEV	Parallel HEV
PHEVbat	Parallel HEV with battery
PHEVfw	Parallel HEV with flywheel
PM	Permanent Magnet
RED	Reduction gear
SHEV	Series HEV
SHEVbat	SHEV with battery and load-follower strategy
SHEVfw	SHEV with flywheel
THS	Toyota Hybrid System
TNO	(Netherlands) Organisation for Applied Scientific Research
TNO-ADVANCE	TNO Automotive DriVeline Analysis and Concept Evaluation (tool)
TR	Transmission
VEH	Vehicle
WH	Wheels
ZEV	Zero Emission Vehicle

Symbols

SOC	State-of-Charge	[%]
SOChigh	Upper SOC control limit	[%]
SOClow	Lower SOC control limit	[%]
SOCmid	Middle SOC control value	[%]
C_w	Air drag coefficient	[-]
f_r	Rolling resistance coefficient	[-]
i	Gear ratio	[-]
BSFC	Brake Specific Fuel Consumption	[g/kWh]
θ	Moment of inertia	[kgm^2]
P_APU_high	High power APU operating point	[kW]
P_APU_low	Optimum power APU operating point	[kW]
P_APU_opt	Optimum APU power	[kW]
P_BAT_desired_max	Maximum desired battery charge power (signal)	[kW]
P_BAT_desired_min	Maximum desired battery discharge power (signal)	[kW]
$P_{BATsignal}$	Control parameter, battery (dis)charge value	[kW]
P_{driver}	Driver request for wheel power	[kW]
Pel	Electric power	[kW]
$P_{ICE,des}$	Desired ICE power	[kW]
R_{dyn}	Dynamic wheel radius	[m]
A	Frontal area	[m^2]
E	Energy	[MJ] [kWh]
M_opt	Optimum torque	[Nm]
$M_{max, electric\ motor}$	Maximum torque EM	[Nm]
$M_{max,combustion\ engine}$	Maximum torque ICE	[Nm]
$M_{min, electric\ motor}$	Minimum torque EM	[Nm]
$M_{optimum, combustion\ engine}$	Optimum torque ICE	[Nm]
T	Torque	[Nm]
ω	Angular velocity	[rad/s]
N_opt	Optimum speed	[rpm]
P	Power	[W]

Driveline models' abbreviations

IKA models	
PHEVfw	Parallel Hybrid Electric Vehicle with flywheel storage system
PHEVbat	Parallel Hybrid Electric Vehicle with battery storage system
SHEVfw	Series Hybrid Electric Vehicle with flywheel storage system
SHEVbat	Series Hybrid Electric Vehicle with battery storage system and load follower APU operating controls strategy
TNO models	
BEV	(LD) Battery Electric Vehicle
PHEV	(HD) Parallel Hybrid Electric Vehicle
SHEV	(LD or HD) Series Hybrid Electric Vehicle with discrete, SOC based APU control strategy
CHEV	(LD) Combined Hybrid Electric Vehicle
FCEV	(LD) Fuel Cell Electric Vehicle
FCHEV	(LD) Fuel Cell Hybrid Electric Vehicle with discrete, SOC based APU control strategy

Contents

1 Introduction

In the context of Task 2 of the MATADOR-project (Management Tool for the Assessment of Driveline Technologies and Research, EU-contract JOE3-CT97-0081), research is carried out in support of the development of test procedures for electrically propelled road vehicles and vehicles with other alternative drivelines. The definition of testing procedures for determining energy consumption and emissions of vehicles with different drivelines requires the evaluation of technical aspects, specific of each vehicle technology. Furthermore, the development of testing procedures that allow for a comparative technical benchmarking of different vehicle power trains is an even more complicated task, because the performance of each technology could be significantly different from each other (alternative fuels, hybridisation, combined energy sources) asking for various measuring needs. Key issues have been addressed and are evaluated in terms of their impact on testing methods.

The research on the key issues is conducted from several starting-points. One of the methods that can very well be used to study most of the vehicle technology related problems is computer simulation. Simulations give freedom and the possibility to change and investigate all those aspects which seem interesting and of influence on the determination of vehicle's performances, energy consumption, and emissions. A wide range of vehicle concepts can be subjected to a multitude of simulated experiments, test procedures, and driving cycles with very little costs, which is a big advantage. As simulations are unable to cover all of the influences present in experimental situations, they cannot replace actual testing altogether, but they can be used to motivate which experiments are really necessary and which are not. Computer simulations can be used to gain thorough insight into the behaviour of different drivelines under different conditions.

Of course, accurate models of vehicles and power trains as well as reliable simulation program(s) are needed. Various partners in Task 2 of the MATADOR project have simulation programs at their disposal, which are used to build and evaluate a wide variety of driveline models. In general, these models are able to calculate the energy consumption of vehicles quite accurately, since they focuss on the longitudinal behaviour of the vehicle. Prediction of vehicle emissions, however, is in most cases problematic or at least less accurate.

Also, most of the vehicles modelled in this project are generic, which means that they do not exist in reality, but rather are built up from scalable data of existing vehicle components. This way, vehicle characteristics and powertrain performance can be setup as preferred, enabling a consistent comparison of vehicles with different drivelines. The influence of typical real vehicle data, such as the thermodynamic characteristics of the powertrain components, however, is limited or left out of the modelling. This restricts the insight in powertrain (component) temperatures as well as the use of temperature-dependent efficiency characteristics. Consequently, the warm-up behaviour of, especially, the combustion engine is not incorporated in the models. For comparative assessment studies, however, the use of efficiency data under standard operating conditions has proven to be sufficiently accurate to determine a vehicle's energy consumption.

In this Subtask 2.2 report the available simulation tools will be presented and the modelling of a wide set of driveline structures will be discussed. The power train models have been used to support the research in the other subtasks of the MATADOR project.

2 Available simulation tools

Several partners in the MATADOR Task 2 project have simulation tools at their disposal. Especially IKA and TNO have programs which allow them to build a vast set of driveline models to their own insights. This chapter describes the available simulation tools, which are used to build the power train models illustrated in the following chapters.

2.1 IKASIM

At IKA a dynamic driveline simulation tool has been set up in MATLAB/SIMULINK [1]. The tool is referred to with 'IKASIM' and is only available for internal use. The SIMULINK toolbox within the MATLAB programming environment is a software package for modelling, simulating and analysing dynamical system.

Individual modules were established for power train components in order for those to be generally usable and comprehensible. This way, driveline models for a parallel hybrid electric vehicle as well as for a series hybrid vehicle, both with either a NiMH- traction battery or an electric flywheel, were build.

The following picture roughly shows the drive train structures of the IKA series and parallel hybrid electric vehicle models.

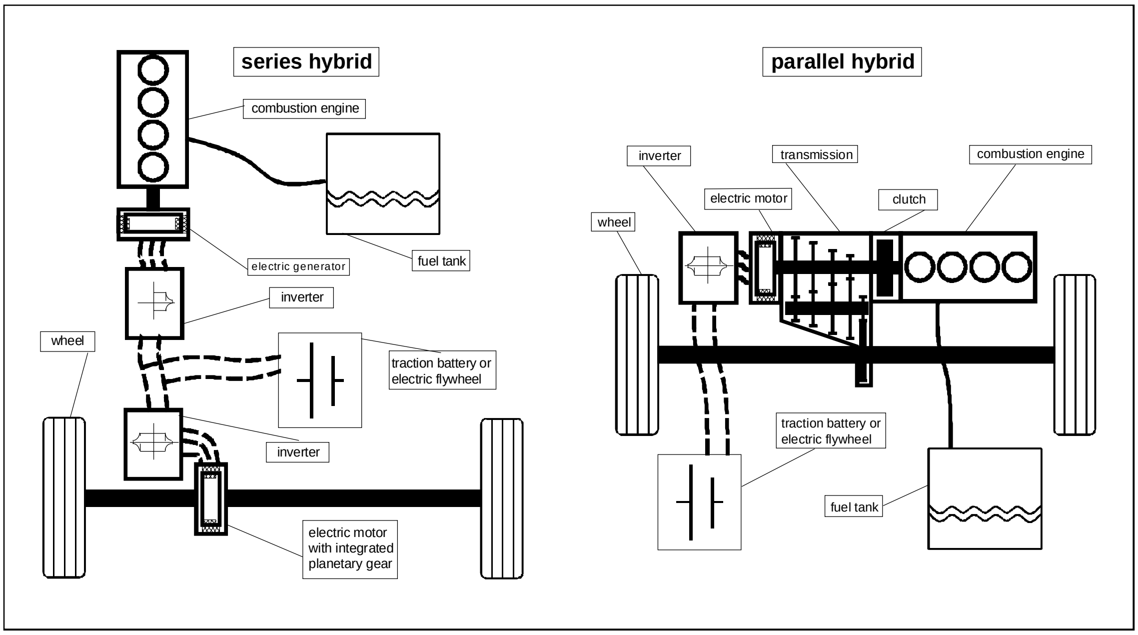


Figure 1: IKA series and parallel hybrid vehicle model structure

The modelling of the driveline and its control is based on the cause to effect principle. This means that the driveline states (the effect) are calculated as a reaction on the driver demands (the cause).

Because of standardised interfaces between the power train components, the modules 'combustion engine', 'generator', 'vehicle', 'flywheel', 'battery' and 'driver' (integrated in the control module) could be used in all hybrid models.

The modules 'clutch', 'transmission' and 'axle ratio' are only needed in the parallel hybrid models, the 'electric motor' module only in the models of the series hybrid.
In the mechanical part of the drive trains, for example the chain consisting of electric motor and vehicle or the chain combustion engine-generator of the series hybrid, the “predecessor” impresses its speed to the “successor”, this successor transfers the entire load torque and moment of inertia of the successors in the remaining chain to its predecessor. Since the electric motor in the parallel hybrid model is locked with the gearbox input shaft, and therefore placed behind the module of the combustion engine and the clutch, the engine speed is imposed by the combustion engine module in the engaged status and in disengaged status by the clutch module. For this electric motor, therefore, the same module as for the generator in the series hybrid model is used.
In the electrical part of the hybrid drive trains, the components are linked by the DC-bus interface. The sum of electrical powers of the electric motor, the auxiliary devices, and in case of the series hybrid driveline also of the electric generator is imposed to the storage device (battery or flywheel), which then is used to calculate state of charge as well as bus voltage and -current.

In order to follow the desired velocity profile (cause-to-effect principle), a driver module is integrated, which calculates the demanded torque at the transmission input on the basis of the desired and actual velocity as well as the currently applied gear ratio. The integrated control strategy splits this demanded torque according to the states of the drive train into demands for the components combustion engine, electric motor, generator (series hybrid), and the mechanical brakes in the vehicle module. From the control strategy, these signals are sent to the appropriate modules.
Additionally, the control module determines the desired gear ratio in the case of the parallel hybrid according to a table with desired gear changing points. If the gear changing points are not listed, then a gear changing strategy selects the correct gear depending on the engine speed, the vehicle velocity and the given speed and velocity limits.
When engaging the combustion engine, the clutch control distinguishes between two states depending on transmission input speed. At transmission input speeds below the starting speed, a starting process is recognized. The strategy regulates the contact pressure of the clutch in such a way that the engine speed cannot rise above the starting speed. If the combustion engine is engaged while driving, then the contact force remains zero until the combustion engine is synchronized to the transmission input speed. After that, the contact pressure is increased to close the clutch completely.

The modules of electric motor and generator represent the electrical machines with their power electronics. The consumed or delivered electrical power, the induced torque acting on the motor shaft and its angular speed are calculated.

Within the torque limitations of the electric machine, the induced shaft torque is set to the value of the demanded torque calculated by the controller. At demanded torques exceeding the maximum machine torque or below the maximum generative torque, the induced torque is set equal to the respective limit value. These limit values are stored as speed dependent lookup tables. At each simulation step the torque limitations are calculated according to these values and compared with the demanded torque.

The total power losses of the combination inverter/machine depend on the absolute value of the torque and on the machine speed. Its sign is independent of the respective operating range, and therefore the power loss map is defined for the motor-quadrant only. The electric power is then calculated by the sum of actual mechanical power and power loss. The power loss map is generated from the standard efficiency map.

In the module of the combustion engine the fuel rate in kg/s, the torque delivered to the crankshaft and its angular speed are calculated. The latter is calculated with the induced torque, the torque load and the reduced moment of inertia with the help of moment of momentum, as in the electric motor module.
Also the induced torque is determined in a similar way as in the electric motor. Instead of the maximum recuperation torque, here the curve of maximum drag forms the lower bound of the torque limitations. The fuel rate is calculated using a two dimensional lookup table, dependent on engine speed and -torque.
Successor of the combustion engine within the driveline of the parallel hybrid model is the take-off clutch. It distinguishes between two states, engaged and slipping. The status is determined on the basis of the clutch contact pressure, the desired transfer torque at the friction surface, and the input and output speed.
In the closed-status (engaged), the combustion engine speed is directly passed on to the clutch and to the transmission input shaft; the load torque and reduced moment of inertia at transmission input shaft is directly passed to the combustion engine. In slipping-status, the output speed (transmission input) is calculated within the clutch module directly, depending on the contact pressure applied by the controller.

In the model of the parallel hybrid, the module of the transmission represents the transmission ratio and the synchronous clutches. The input speed is converted to the output speed and the load torque stamped at the gearbox output is converted to the load torque at the gearbox input on the basis of the currently applied gear ratio.
To enable a gear shift without abrupt hooking in of the transmission input and output, a friction clutch model is integrated, which represents the synchro meshes in real transmission. The clutch is arranged at the gearbox output and corresponds to a large extent to the module of the take-off clutch.

The properties of the traction battery are modelled in the battery module. Battery current, bus voltage, and state of charge are calculated with the combined electrical power from electric motor, generator and auxiliary devices. Both in the calculation of bus voltage and battery current, the open circuit voltage as well as the internal resistance are used. They are integrated in the module as state of charge dependent lookup tables.

Electric flywheels consist of a flywheel rotor and an electric machine. Therefore, electric flywheels can be considered as electric machines, which can be modelled with the appropriate electric formulas and their characteristic values. This is done in the electric flywheel module. Goal of this modelling approach is to determine the 'effect' change of rotational speed with the help of the 'cause' charge/discharge power.

The interfaces of both battery- and electric flywheel modules are identical to the battery module, which allows a quick substitution of either one in a complete vehicle model.

At the end of the drive train chain the vehicle module is arranged. It models the air drag resistant force of the vehicle body work, the rolling resistance of the tyres as well as the inertial force of the vehicle mass on the drive train.

2.2 TNO-ADVANCE

TNO-ADVANCE is a dynamic power train simulation model [2], which has been developed at TNO Automotive. It has first been developed during 1996 and 1997 within the scope of programmes sponsored by the Dutch Ministry of Transport, Public Works and Water Management and the Ministry of Housing, Spatial Planning and the Environment. Since then, TNO-ADVANCE has been used in various projects and has continuously been updated and expanded.

ADVANCE stands for Automotive DriVeline Analysis and Concept Evaluation. Within this universal, modular simulation tool fundamental and operational aspects of the different power train components are combined, making use of the knowledge available within the multi-disciplinary organisation TNO.

TNO-ADVANCE can be used for two distinctly different purposes. On the one hand it is a design tool for the development of present and future advanced power trains. As such TNO-ADVANCE cost-effectively enables a design team to dimension power train components and to design and test control algorithms. On the other hand TNO-ADVANCE can also be employed to assess the potential of future power train concepts. In that case TNO-ADVANCE is, for example, used to estimate the energy use for vehicles that are modelled in such a way that they can fulfil realistic performance requirements.

Based on user requirements, the TNO-ADVANCE simulation tool has the following general properties:

- The model is able to predict fuel consumption, emissions and driving performances of a selected power train on the basis of a driving cycle or an accelerator pedal position,
- The model has a modular design, in the sense that modelled drive trains are composed of individual component modules, each representing a mathematical model of a power train or vehicle component,
- The model is flexible and universal, and can be used for a wide range of vehicles with different power trains,
- The design of a power train can be carried out with a minimum of time and effort,
- The model is user-friendly.

In TNO-ADVANCE longitudinal vehicle movements are evaluated in order to predict fuel consumption, emissions, and driving performance. A mathematical model of power train and driving resistances is used to describe the behaviour of the vehicle. The mathematical representation is represented by a set of differential equations, which can be solved when the driving resistance is defined as a function of time, speed, and place. TNO-ADVANCE solves the set of differential equations by using the cause-to-effect method.
The driving cycle specifies the desired vehicle speed and road slope as a function of time and place. A driver model is used to control the accelerator pedal position in order to let the vehicle follow the required driving cycle as good as possible. The cause-to-effect method enables the TNO-ADVANCE user to create and simulate power trains without any limitations concerning the use of slipping components or power split devices.
TNO-ADVANCE has been implemented in a $Matrix_x$, Systembuild environment [3], which provides a numerical program for simulating dynamic systems. $Matrix_x$ is an object-oriented programming tool, with Systembuild serving as a graphical interface. In the Systembuild environment the individual power train components are represented by blocks. A mathematical model of a power train can easily be created by selecting the power train component modules from the TNO-ADVANCE component library, and connecting these blocks to constitute the power train model.

Driveline components that have a profound influence on the simulation results are described here in short.

The internal combustion engine model consists of engine maps (measured data), rather than a detailed calculation of the combustion process within each cylinder. Engine torque and break-specific fuel consumption (BSFC – g/kWh) are determined from look-up tables, using the throttle position, angular velocity and acceleration as input parameters. The available data originates from a LD Otto-engine with a maximum output of 130 kW and a maximum speed of 6000 rpm. In order to use this engine map for different ICE specifications, the maps are scaled in torque range to deliver the desired output power.

The electric machines are modelled together with the necessary power electronics. Two models are available in TNO-ADVANCE; an asynchronous (or induction) motor, and a permanent magnet motor. In principal both are AC electric machines, but the power electronics provide direct current (DC) power.
They can be used in four-quadrant operation, thus applicable as motor and generator. Operating limitations are determined by defining a nominal power, and an overload factor (set to 1.5). The electric motor module has the torque available to the driveline as an output parameter, calculated from the electrically generated torque, minus the inertia effect due to acceleration of the axle. In the generator module, the electrically generated torque is subtracted from the available (drive) torque, resulting in the axle acceleration. Depending on the configuration and other component blocks, either the motor or generator module is selected (both can operate in four quadrants).

The battery module uses mathematical equations to model the electrochemical characteristics, as well as data from manufacturers (voltage, internal resistance) to describe a certain type of battery. Requested power from- or delivered power to the battery is the input parameter, from which the battery's current, voltage, SOC and internal resistance are calculated.

A simple representation of the hydrogen fuel cell is used, as there is little information available. For the same reason a reformer is left out of the model. On the basis of output power demand the input power is determined with a fuel cell curve, representing the fuel efficiency at a certain power ratio (defined as desired output power divided by maximum output power).

The wheels are simulated by a complex module. A distinction is made between front and rear wheels, to account for the load shift during acceleration and deceleration of the vehicle. Even the wheel-slip, as a result of tyre deformation, is calculated. In the vehicle module, the vehicle acceleration and speed are calculated from available drive force and the air and slope resistances.

A driver model is used to convert the difference in desired speed (resulting from the drivecycle) and actual speed into a driver signal for the driveline control module. The control strategy in this module is of paramount importance to the behaviour of the driveline. From the driver signal, throttle position for the ICE (or desired fuel cell output), torque request for the electric machines, and brake torque are calculated. As each driveline calls for its own specific control strategy, these will separately be discussed in detail.

2.3 Computer models versus actual vehicles

Two driveline simulation tools have been presented and explained in the previous sections. Both tools can be used for detailed modelling of driveline behaviour. Despite a detailed level of modelling, there are limitations to accurate accounting for certain aspects of real-life operating conditions. An example is the influence of temperature (engine, battery, tyres, etc.) on system performance. As a result, these factors are not or only to a certain extent included in the models. Excluding the influence of temperature, for instance, implies that a constant operating temperature is assumed. Warm-up effects then are not represented by the models and it is not possible to make comments based on the computer simulations. For that, knowledge from actual measurements is needed.

Besides modelling difficulties, the reason for not including known effects in simulations can be for practical reasons. Comprehensive engine models capable of predicting emissions with accuracies specified for e.g. standard test procedures are not available and neither is data on transient effects. The dynamic models for the internal combustion engines for instance do (or can) include maps on fuel consumption and emissions, yet the data in these maps is derived from static measurements. Including the transient effects into the models would result in highly complex and therefore slow models, which is unpractical for comparative assessments of several different drivelines with even more parameter variations.

This indicates that computer simulations can never entirely replace measurements, since tests give information on the actual performance of a system. Also, real-life conditions always involve some kind of measurement resolution or other (almost) uncontrollable factors like the influence of small pedal variations (no matter how small), which cannot be included in a simulation. The actual influence of certain factors cannot be determind, yet may be present.

Main effects that are not modelled in IKASIM or TNO-ADVANCE are:

- Temperatures
- Tire pressure
- Effect of transient engine operation on fuel consumption
- Engine emissions
- Limited or simplified use of time constants
- Human driving characteristics (repeatability)

Validation

The driveline models which are used for the MATADOR project are generic models that are very useful for research on driveline behaviour and effects on energy consumption, but that are not capable of predicting emissions nor can they be used for the ranking of technologies. The modals do contain all the essential physics so that the response to changing test conditions is adequately simulated.

3 IKA driveline models

In support of several subtasks of the MATADOR project, vehicle simulations will be conducted to investigate the influence of power train configuration and many parameters. In the Subtask 2.1 report (Categorisation of EV configurations) a categorisation is given to classify different types of vehicles. Several main groups can be identified:

- Conventional Internal Combustion Engine Vehicle (ICEV)
- Battery Electric Vehicle (BEV)
- Parallel Hybrid Electric Vehicle (PHEV)
- Series Hybrid Electric Vehicle (SHEV)
- Combined Hybrid Electric Vehicle (CHEV)
- Fuel Cell Electric Vehicle (FCEV)
- Fuel Cell Hybrid Electric Vehicle (FCHEV)
- Flywheel Hybrid Vehicle (FWHV)

Figure 2 shows these main driveline configurations. In the parallel hybrid configuration the electric motor can be coupled at the input (1) or the output (2) shaft of the transmission.

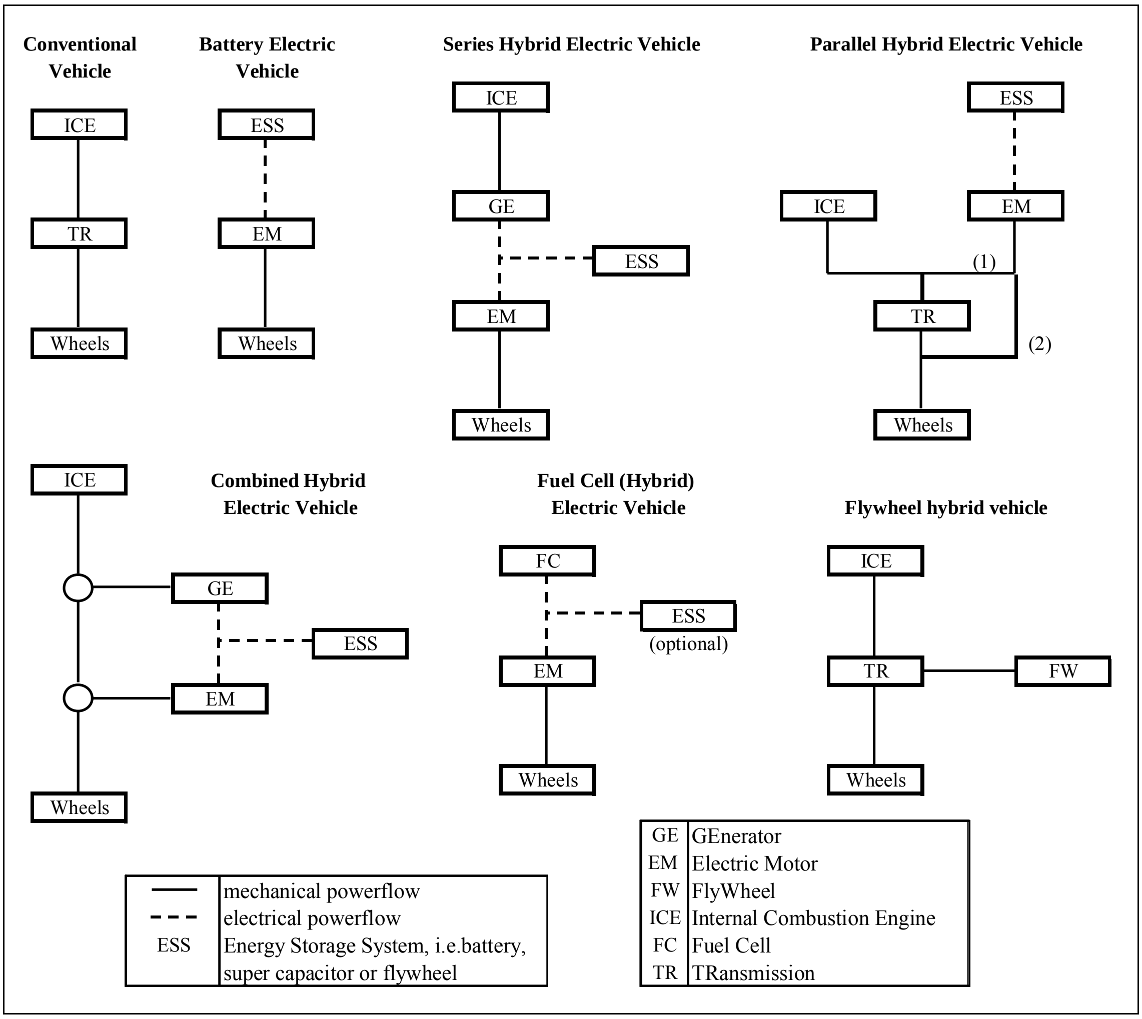


Figure 2: Types of power trains

Conventional vehicles are well known and testing procedures for these types of vehicles are available worldwide. Since the available procedures are likely to pose problems for vehicles with alternative drivelines the influence of advanced drive trains is partly investigated by means of simulation. Both IKA and TNO therefore have set up several models with advanced hybrid electric drivelines. The following sections will discuss the IKA models, and chapter 4 gives a description of the TNO driveline models.

3.1 Control strategies of the hybrid electric vehicles

3.1.1 Charge-sustaining hybrid vehicles

Aim of the series hybrid is to exploit the more flexible operating possibilities of the combustion engine, as a result of the missing mechanical connection to the wheels, in order to reduce the fuel consumption. Thus the hybrid drive train needs a control strategy that uses the high efficiencies of electric motor, storage device and generator to run the combustion engine in the optimum operating state. The control strategy determines with the aid of important state variables e.g. state of charge or demanded power, whether, when and with which charging power the charging device has to be operated.

The aim of the control strategy of the charge-sustaining parallel hybrid is to operate the combustion engine at its minimum specific consumption (see curve II in Figure 8).

In most cases it is not possible to operate the ICE on this control curve exactly, since the (stepwise) fixed ratio of the transmission between combustion engine and wheels does not allow a free choice of operation states. In addition to this, it is aimed to use the possibilities of the electric motor as much as possible, respectively to drive electrically, in case of sufficient energy content and power demands which do not exceed the maximum of the electric motor.

3.1.2 Charge-depleting hybrid vehicles

The most characteristic property of charge-depleting hybrid vehicles is their dependence of external recharging. This means, that when driving the vehicle over sufficient distance under normal driving conditions, the energy of the traction battery is completely used. Eventually, a proper operation of the vehicle is restrained due to insufficient battery power. In case of highway traffic however, an eventual cutback of vehicle operation is not wanted since a sufficient range then is of high importance. This can be achieved by implementing a hybrid control strategy that relieves the battery at higher vehicle speeds and only uses the internal combustion engine (parallel hybrid) or the APU (series hybrid) to deliver the demanded power.

To incorporate these properties into the series and parallel hybrid models, following principles are used defining the control strategy: The demanded power at lower vehicle speeds is always delivered by the traction battery and as a result of that a depletion of the battery occurs. At higher speeds, the internal combustion engine of the charge-depleting hybrid vehicle is used to deliver the traction energy, thus relieving the traction battery and allowing for travelling longer distances.

3.2 Series Hybrid Electric Vehicle

3.2.1 Dimensioning

Charging device and electric motor

The charging device, also called APU (auxiliary power unit), consists of a direct injection diesel engine and an electric generator. Both components have the same mechanical power to avoid operation with low efficiencies. The energy storage devices do not contain enough energy for permanent high velocities. In case of longer periods of high velocities, the electric motor has to take the energy straight from the charging device. So the maximum cruising speed depends on the maximum power of the APU. With the road load, the vehicle data and the desired maximum cruising speed it is possible to calculate the demanded power at the wheels, which in connection with the efficiencies of the electric motor and the generator provides the required mechanical power of the combustion engine and the generator.
Calculating with the vehicle data of a reference mid-sized car (Table 1), the demanded power at the wheels results in 44 kW. The double energy conversion in the electric motor and the generator results in a required power of the combustion engine of about 55 kW. Due to the fact that the vehicle performances should be comparable with those of the reference vehicle, the power of the electric motor is chosen equal to the one of the combustion engine of the conventional vehicle, about 65 kW. In this case there is used a so-called tandem motor with two output flanges. Each output flange is connected with a motor via a planetary gear. The speed and torque levels allow a direct connection to the drive shafts.
For the dimensioning the efficiency map of a permanent magnet synchronous motor with maximum torque curve was available. The power has been scaled from originally 30 kW to 65 kW at unchanged speeds by multiplying the torques by 2.17. This calculation not only considers the conversion of the electrical energy into mechanical, but also the losses of the planetary gear. Thus the power of 65 kW is directly available at the wheels.

Table 1: Reference vehicle data

Road load		**Figures and weight**	
Air drag coefficient (C_w)	0.3	Frontal area (A)	2.0 m^2
Rolling resistance (f_r)	0.010	Dynamic wheel radius (R_{dyn})	0.28 m
		Curb weight + half pay load	1300 kg

Energy storage device

As energy storage devices an electric flywheel and a NiMH-battery are used. For the vehicle acceleration from 0 to 100 km/h under full load, the flywheel or the battery has to be dimensioned for the necessary power and energy. They are primarily dimensioned for maximum electrical power. Therefore the maximum mechanical power of the electric drive train has to be divided by the motor efficiency. One can determine the energy capacity of the storage device primarily from the product of maximum electrical power and desired acceleration duration. After considering the motor efficiencies the energy capacity of the storage device results.
Because the electric motor has a maximum mechanical power of 65 kW and an efficiency of about 90%, a maximum electrical power of the storage device of about 72 kW is sufficient. During full load acceleration, the electric motor does not deliver its maximum power from standstill, at first its power linearly increases with the speed. Therefore, the average demanded power is 52 kW and the minimum energy capacity of the storage device with a desired acceleration duration of 15 seconds and an average motor efficiency of 80% is calculated to 970 kJ, or 270 Wh.

Flywheel
The moment of inertia of the flywheel rotor and its maximum speed is a measure for the energy capacity, which is calculated with the formula $E=0.5 \cdot \theta \cdot \omega^2$.
The moment of inertia then follows from the maximum speed of the flywheel and, after considering the efficiency for the internal transformation of kinetic into electric energy of the electric motor, from the determined minimum energy capacity.
For the flywheel the 72 kW of electrical power leads to a mechanical power of 80 kW, since efficiency at maximum flywheel power is about 90%. With the minimum considered electrical energy capacity of 270 Wh, the kinetic energy capacity results to 300 Wh. Since the maximum flywheel speed is 9000 rpm, the moment of inertia of the flywheel rotor results to 2.43 kgm^2.

Battery
For the dimensioning of the battery, its specifications in terms of energy- and power density are used. The necessary battery mass for the energy demand as well as for the power demand can then be calculated. The maximum value of both is the mass to be considered.
For the NiMH-battery the power density is 4 kg per kW, this means that for an electric power of 72 kW the minimum battery weight is 288 kg. The energy density is 40 Wh/kg, which means that for a minimum electric energy capacity of 270 Wh the minimum battery weight is 7 kg. So the battery's weight results to 288 kg. The resulting energy capacity then is 11.5 kWh.

The results of the simulated driving performance for the series hybrid are shown in Table 2. Comparing the values with the demands shows that the components of the drive train are well dimensioned; only the demanded maximum speed cannot be reached completely.

Table 2: Series hybrid vehicle performances

	0 – 80 km/h [s]	0 – 100 km/h [s]	$v_{max, continuous}$ [km/h]
el. flywheel	8.7	12.7	164
battery	9.7	14.2	164

3.2.2 Charge sustaining control strategy (flywheel and battery version)

The electric motor takes the energy from the charging device until this reaches a predefined minimum state of charge. At this point the APU is turned on for charging. It is operated most favourably in the operating state in which its overall efficiency is at its maximum. The power that is given in this operating state will not be used completely in the lower partial-load range of the electric motor. Therefore, additional charging power is supplied until the upper state of charge limit is reached. In city traffic and at low constant driving speed, when the average demanded power is lower than the power of the optimum operating state, a cycle operating results, in which the storage device repeatedly is discharged and charged.
In case of higher constant power demands, when the APU is in the optimum operating state and cannot provide excess power for charging, or when the power of the optimum operating state even is not sufficient for the demands of the drive train, the APU power is set to exactly provide the demanded power of the electric motor.
The demanded electric power can be provided by the APU in different operating points. For each power demand there is one operating state where the overall efficiency is maximum. Therefore this one is chosen by the control strategy. During this power coverage the storage device delivers no power and the charging and discharging losses are avoided. Thus the APU will be run in the operating states of the control line shown in Figure 3, which corresponds to the optimum power or higher.

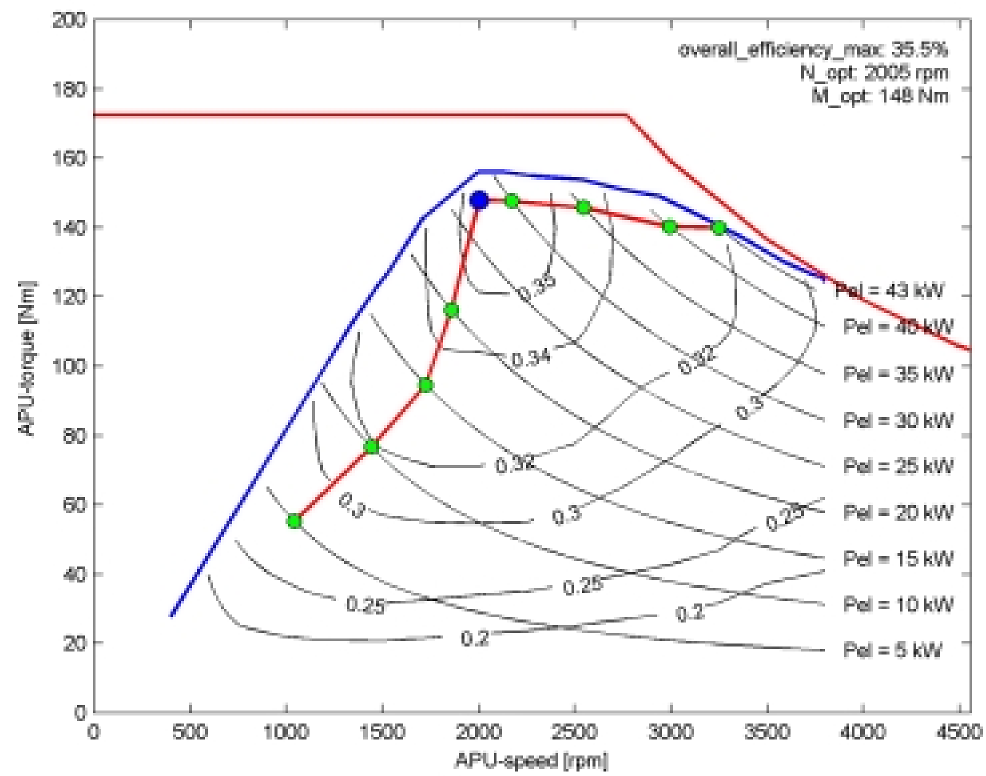


Figure 3: Overall efficiency map of the APU and control line

Consequently there are two operating modes: on the one hand power coverage (direct drive), in which the state of charge is kept constant by the APU, if the demanded power exceeds the power of the charging device's optimum operation state, and on the other hand cycle operating, in which the energy demanded for a longer period of time is covered by operating the charging device at its highest efficiency.
Battery and flywheel storage device have principle-cause differences concerning the power density, the energy density, the charging and the discharging efficiency, which call for different control strategies.

<u>Strategy of the series hybrid with battery storage device</u>
The battery is charged in different ways by the APU depending on the state of charge and the power demand of the electric motor.
Depending on the state of charge it is decided, when the battery will be charged. When the state of charge drops below its lower limit of 70%, the APU starts into charging mode. When the state of charge reaches its upper limit of 90%, the charging procedure is stopped. This kind of operating avoids turning on and off the combustion engine too often. Additionally this ensures the possibility of regenerative braking at any time, that the battery always contains a defined residual energy content for emission-free driving and that it operates within a range of maximum efficiency. The on/off-characteristic of the APU is shown in Figure 4.

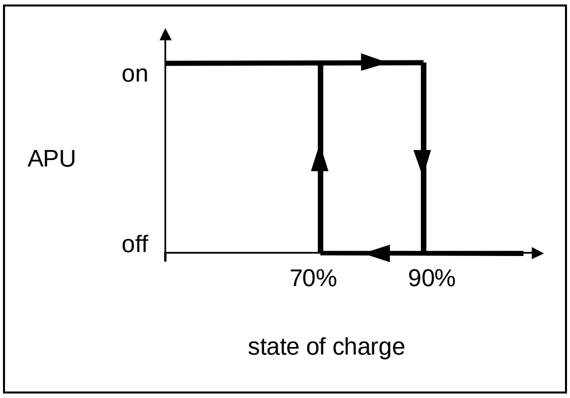


Figure 4: On/off-characteristic of the APU

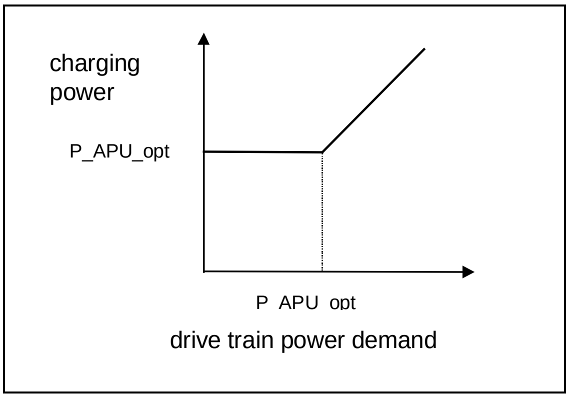


Figure 5: Relation between power demand and charging power

After determining the on/off-criterions of the APU in dependence of the state of charge, the charging power of the APU has to be determined. In case the power demand of the drive train becomes smaller than the power in APU-optimum, the charging power is set equal to this APU-optimum power. In case the power demand of the drive train exceeds the APU-optimum power, the charging device supplies the same power as the drive train requirement. The dependence of the charging power on the power demand is shown in Figure 5.

<u>Strategy of the series hybrid with electric flywheel storage device</u>

The flywheel storage device has two differences compared to the battery storage device that influence the charging strategy. First, the energy capacity is smaller when having the same maximum power, which leads to the fact that the storage device must be recharged more frequently. Secondly, the range of best charge- and discharge efficiencies of the examined flywheel is at lower speeds that are at lower states of charge.

Because of its low energy capacity, the strategy provides in using a wide range of state of charge. At low power demands the state of charge is controlled between 0.25 and 0.9. At the same time the flywheel is charged by the APU with constant power according to its optimum efficiency. If the power demand of the drive train exceeds the APU-optimum power, the state of charge further decreases. If the state of charge in that case drops below 0.25, the charging power increases linearly with the decrease of state of charge, until the maximum value is reached at 0.05 state of charge. By using this strategy, a covering between power demand of the drive train and the charging power of the APU at states of charge between 0.05 and 0.25 is reached. In contradiction to the strategy with battery storage device, the demanded power of the drive train is not used to determine the charging power (Figure 6).

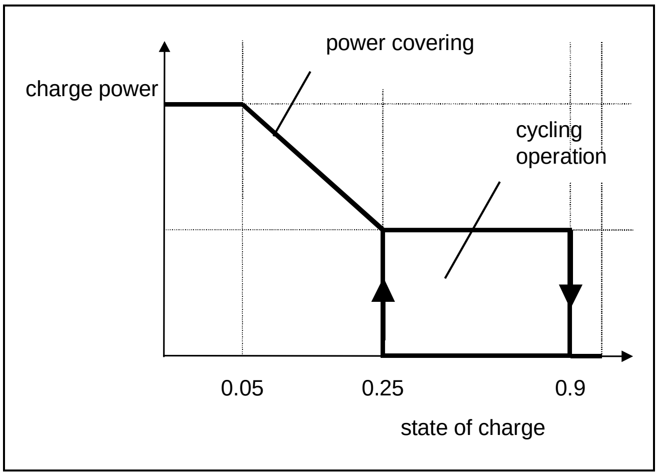


Figure 6: Control strategy of the series hybrid vehicle with electric flywheel

3.2.3 Charge depleting control strategy (battery version)

<u>Series hybrid with NiMH battery</u>

The control strategy of the series hybrid vehicle is as follows: up to 55 km/h, the APU is not operated, since the battery has sufficient power for a pure electric mode. As soon as the vehicle exceeds this speed, the APU is started.

In this case, the APU is controlled over its best-efficiency control line in direct operation. This means that the power demand of the electric motor is directly delivered by the APU, thus relieving the battery and enabling a recharge independent operation.

As soon as the vehicle speed drops below 45 km/h however, the APU is switched off and the pure electric mode is entered again. This way too frequent start/stop behaviour of the internal combustion engine is prevented.

In Figure 7, the stateflow logic of the control strategy is shown. An explanation of the stateflow symbols is given in Table 3. Also an all-electric mode is possible by setting the simulation parameter "edrive_only" at the beginning of the simulation to 1.

Table 3: Legend for Figure 7 and Figure 9

Symbol	Explanation
&	Logical AND operator
|	Logical OR operator
~	Logical NOT operator
(initial transition arrow)	Initial state parameter
◯	Knot of (different) signals

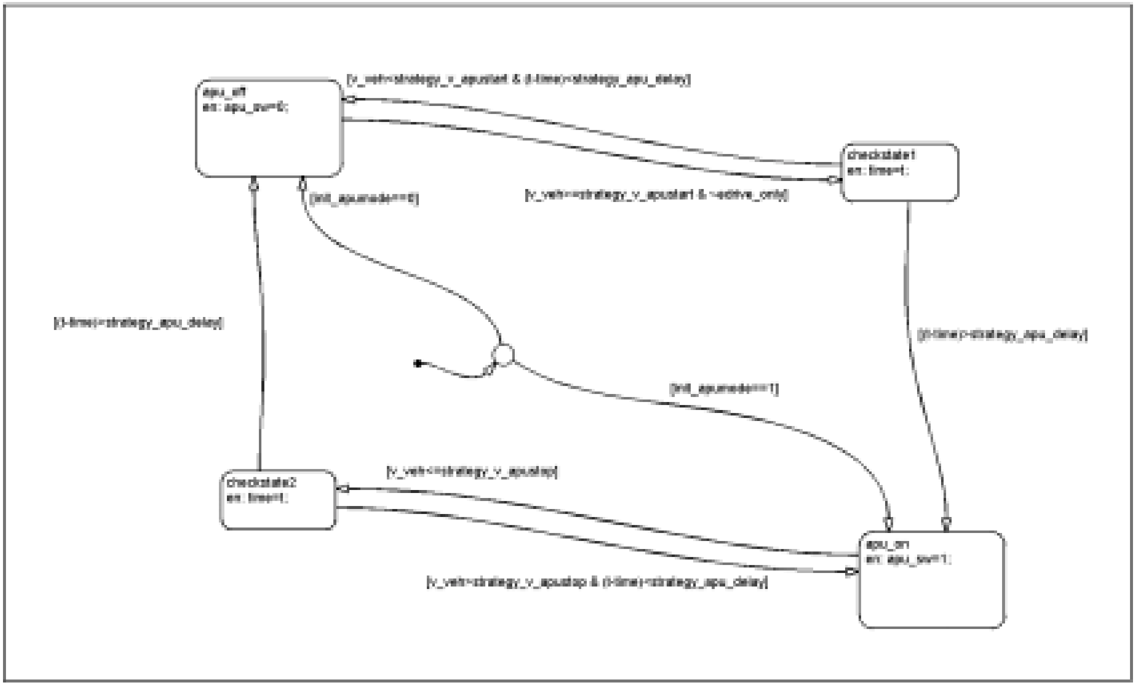


Figure 7: Stateflow diagram of the charge-depleting series hybrid vehicle control strategy

3.3 Parallel Hybrid Electric Vehicle

3.3.1 Dimensioning

Combustion engine and electric motor

For the dimensioning of this drive train regarding acceleration performance, the traction interruption during shifting up has to be considered. Up-shifts during full load acceleration up to 100 km/h might cause an increase in acceleration time of about 2 or 3 seconds. In the lower gears the mass factor has a large influence. An overall drive train power of 80 kW therefore is chosen.

The driving performance of the parallel hybrid depends on the possibility to use the electric motor as a booster during full load acceleration. This again depends on whether the momentary energy content of the storage device is sufficient for acceleration. So an influence on the driving performance by a boost operation should be kept low and therefore the electric motor should not be to big, and the energy capacity of the storage device should not be to small.

As with the series hybrid, the maximum power of the combustion engine for the parallel hybrid is calculated with the desired maximum cruising speed also. After considering the efficiencies of gearbox and drive axle, this maximum ICE power is calculated to be 50 kW. The power of the electric motor, which should be installed in that case, is 30 kW. Since the acceleration performance of this ratio (30/50), especially in combination with a flywheel storage device, too much depends on the momentary energy content, the combustion engine is dimensioned for 60 kW and the electric motor for 20 kW.

Storage device

Analogous to the series hybrid the maximum power of the storage device complies with the power of the electric motor. Considering the motor efficiency the maximum electric power of the storage device is 22 kW.
The minimum energy capacity is determined by the desired acceleration performance. The energy reserve should suffice for accelerations to higher speeds to avoid a change from electric acceleration to acceleration with the combustion engine only. The content of the storage device is dimensioned for an acceleration time of 30 seconds. In that case the average power demand of the motor is to be set to its maximum power, since the electric motor can be driven also at maximum power in the lower speed range because of the transmission. Thus the moment of inertia of the flywheel storage device is calculated to 1.62 kgm^2 and the energy capacity of the NiMH battery (with a weight of 88 kg) is calculated to 3.6 kWh.
The results of the driving performance for the parallel hybrid are shown in Table 4. If compared with the objectives, it shows that the components of the drive train are well dimensioned. Also the continuous maximum speed is reached, in contradiction to that of the series hybrid, which is actually a little less than the demands.

Table 4: Parallel hybrid vehicle performances

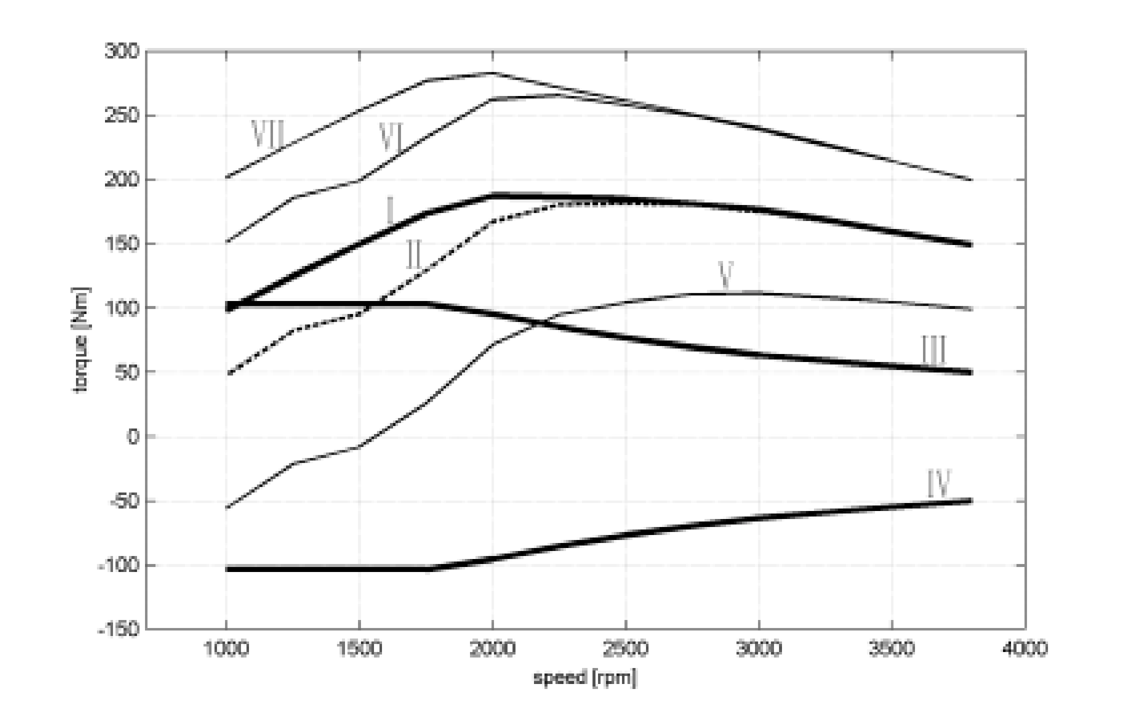
	0 – 80 km/h [s]	0 – 100 km/h [s]	$v_{max, continuous}$ [km/h]
el. flywheel	9.9	14.0	170
battery	10.8	14.4	170

3.3.2 Charge sustaining control strategy (flywheel and battery version)

At high state of charge, the drive train operates in electric mode, if possible in terms of power demand. If the power of the electric motor is not sufficient (above curve III in Figure 8), the combustion engine is switched on and provides the driving power until the power demand again

allows an operation in electric mode. If even the maximum power of the combustion engine is not enough (above curve I), the electric motor has to support the combustion engine and provide the missing torque. Starting the combustion engine because of a higher demanded power for a short time after shifting as well as switching off because of a short decrease of the demanded power has to be avoided.
If the state of charge drops below a defined minimum level while driving in electric mode, the combustion engine is switched on and the electric motor is operated in generating mode in order to charging the storage device (load levelling operation). In this charging mode the combustion engine is kept as close as possible to the optimum control curve. Low power demands (below curve IV) can only be realized by reducing the power of the combustion engine and maximising generating power. Power demands above the optimum control curve (up to curve VI) are provided by running the combustion engine on the control curve while providing the missing power by the electric motor. If even this maximum power does suffice, the combustion engine is operated up to maximum power. During standstill, the combustion engine is not used to charge the storage device. Achieving a defined upper state of charge the control strategy switches again into electric mode.
The electric mode and the charging mode both have the possibility of regenerative braking. In charging mode and in combustion engine operation during the electric mode, the combustion engine will be declutched and switched off after a delay period to avoid switching on and off too often.

Similar to the charge-sustaining series hybrid there are two main modes in the parallel hybrid. The switch between these modes is defined by upper and lower limits of the state of charge. In the first mode there will be driven mainly electrically, in the second mode the engine is operated and the storage device is loaded. The state of charge limits orientate on the values used for the series hybrid. Because of a lower energy capacity of the flywheel storage device the lower limit here is defined at 10%.



Curve	Explanation
I	$M_{max,\ combustion\ engine}$
II	$M_{optimum,\ combustion\ engine}$
III	$M_{max,\ electric\ motor}$
IV	$M_{min,\ electric\ motor}$
V	$M_{optimum,\ combustion\ engine} + M_{min,\ electric\ motor}$
VI	$M_{optimum,\ combustion\ engine} + M_{max,\ electric\ motor}$
VII	$M_{max,\ combustion\ engine} + M_{max,\ electric\ motor}$

Figure 8: Operating ranges of the combination combustion engine/electric motor for parallel hybrid

Figure 9 shows the stateflow diagram implemented in the simulation model of the control strategy, Table 3 explains the symbols used in the stateflow diagram. In this diagram the variable „init_emode" (0 or 1) gives the possibility to either choose the electric or the charging mode at the beginning of the simulation.

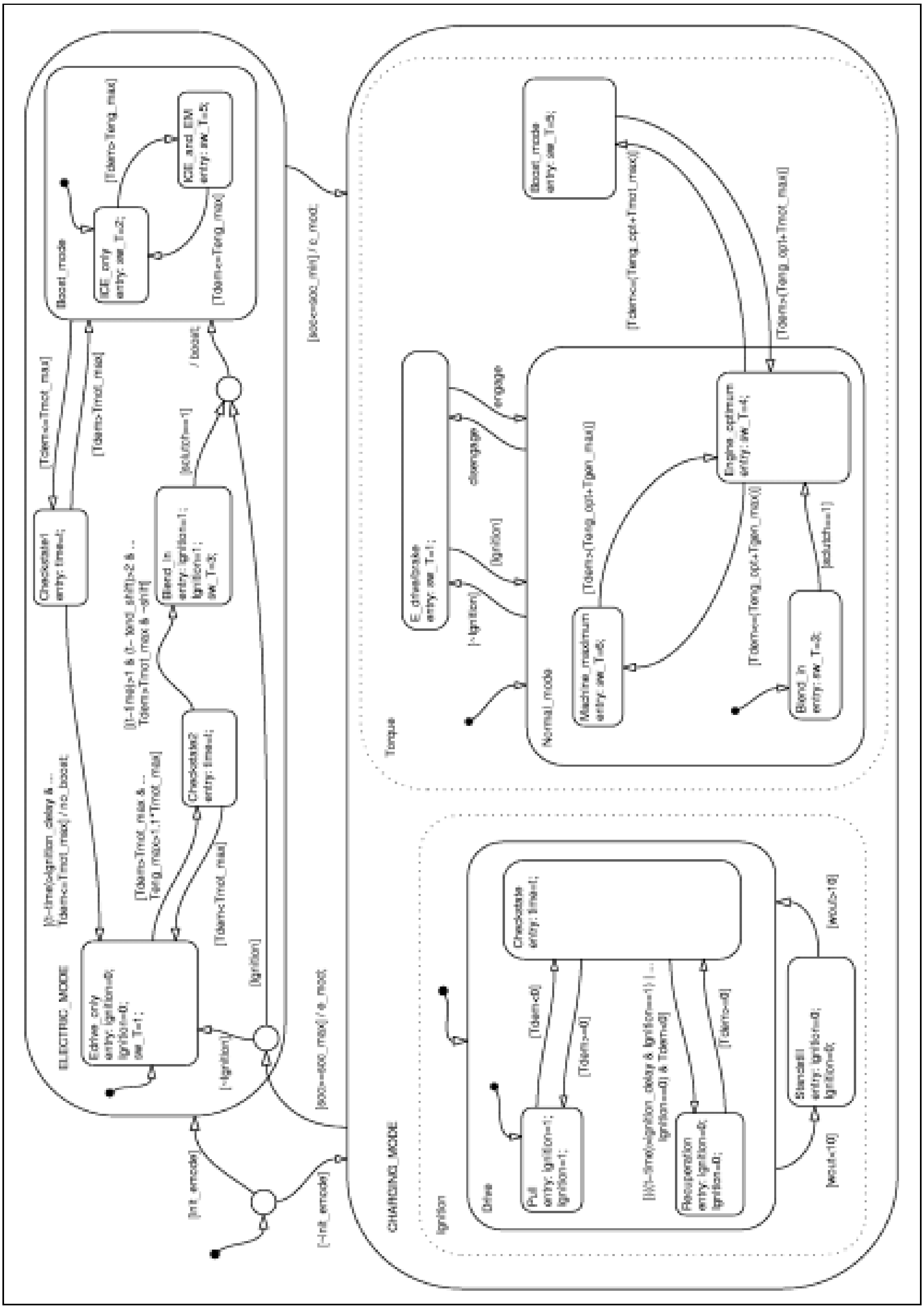


Figure 9: Stateflow diagram of the parallel hybrid control strategy

3.3.3 Charge depleting control strategy (battery version)

For the parallel hybrid, a similar control strategy has been implemented as for the charge depleting-series hybrid. This means that the vehicle will be driven electrically as long as the velocity stays below 55 km/h. Because of the low-power electric motor (20 kW) however, a boost operation of the internal combustion engine is required: If the demanded torque cannot be delivered by the electric motor (if kickdown is applied), the ICE is started and takes over the propulsion task. As with the series hybrid, a hybrid operation is again only possible if the “edrive_only” parameter is set to 0.
During ICE-operation, recuperation of braking energy by the electric motor is possible. In that case, the combustion engine is operated at zero torque level.
If the vehicle speeds drops below 45 km/h and the power demand can be delivered by the electric motor, the control strategy again switches into the pure electric mode. The stateflow diagram of the CD parallel hybrid control strategy is shown in Figure 10.

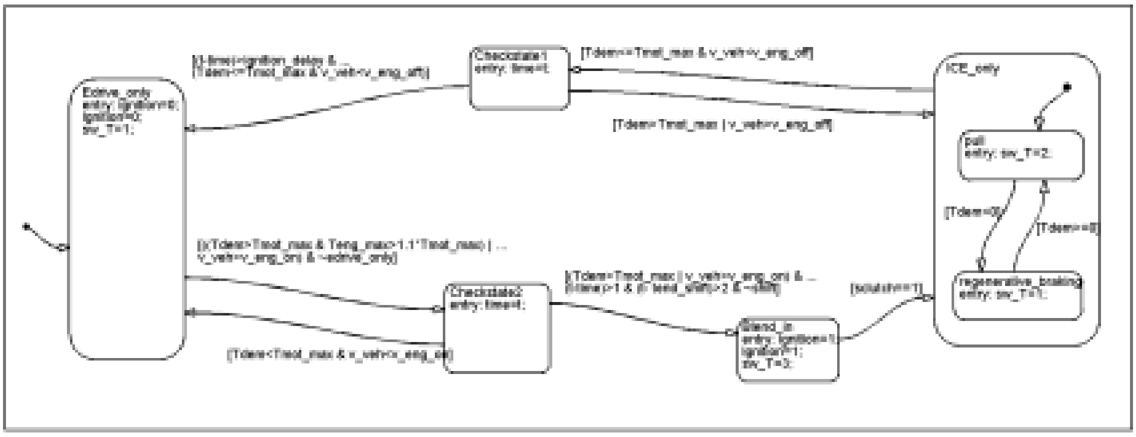


Figure 10: Stateflow diagram of the charge-depleting parallel hybrid vehicle control strategy

<u>Charging characteristics for charge depleting vehicles</u>
In order to determine the charged energy from the grid, after each simulation a charging procedure has been carried out, in which the NiMH battery is charged to its initial SOC.
In common use, a charging power of 3500 Watt (16A at 220V) taken from the mains is possible. Based on the experiences with electric and hybrid electric cars at IKA, an average charger efficiency of 83% has been used.

4 TNO driveline models

The TNO models are built in TNO-ADVANCE. For the specific components (e.g. ICE, EM, BAT, WH, VEH, etc.) the same component modules (block diagrams) are used in each vehicle. Different drivelines can be built by connecting blocks in different ways. Like this, the power trains described in this chapter have been obtained.

4.1 Battery Electric Vehicle

In a Battery Electric Vehicle (BEV) the wheels are driven by one (or more) electric motor(s), often coupled to the wheels by a reduction gear. The electric motor (EM) is powered by a battery. Figure 11 shows the powertrain structure of a BEV. The electric motor and battery enable regenerative braking, i.e. during braking the EM operates as generator, energy is regenerated and stored in the battery. The following components are used in the Battery Electric Vehicle model:

- Vehicle (VEH)
- Wheels (WH)
- Reduction gear (RED)
- Electric Motor (EM)
- Battery (BAT)

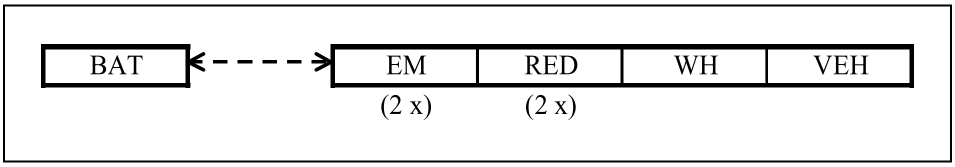


Figure 11: Battery Electric Vehicle drivetrain

Battery Electric Vehicles can be Heavy-Duty as well as Light-Duty. At this moment only a LD BEV has been dimensioned, since those are seen more often than HD applications.

The light-duty vehicle models represent hybrid versions of regular mid-sized passenger cars like the Opel Vectra, Ford Mondeo, and Peugeot 406. The vehicle frontal area (A) and the air drag coefficient (C_w) are set to 2.0 m^2 and 0.3 respectively for all LD vehicle models built by TNO. A (hybrid) electric vehicle generally is heavier than a conventional vehicle, because the driveline consists of more components and/or components with a lower power density. The vehicle weight for the (hybrid) electric vehicles is set to 1350 kg, representing the empty vehicle with additional payload.
In order to have an acceptable performance, the 0-100 km/h acceleration should be below 15 seconds.

All vehicle models have been given approximately the same drive power of 75 kW maximum. As a result the Battery Electric Vehicle is equipped with two EMs that each deliver 25 kW nominal and 37.5 kW maximum power. These powers can, however, be easily changed.
A system voltage of 300 V has been chosen for the LD vehicles. For this, 240 cells of a NiCd battery are connected in series, and in combination with a capacity of 65 Ah, the battery then has an energy content of approximately 20 kWh.
The main parameters for the Battery Electric Vehicle are listed in Table 5.

Table 5: Battery Electric Vehicle component parameters

Battery		**Reduction gear**	
Type	NiCd	i [-]	5.25
Capacity [Ah]	65	**Wheels**	
Cell voltage [V]	1.2	$R_{dynamic}$ [m]	0.295
Number of cells [-]	240	Number of wheels (front/rear)	2 / 2
Cell internal resistance [mΩ]	0.72	**Vehicle**	
Electric motor		Mass [kg]	1350
Type	Permanent magnet	C_w [-]	0.3
Power (nom/max) [kW]	(2 x) 25 / 37.5	A [m^2]	2
Base speed [rpm]	3000		

4.2 HD Parallel Hybrid Electric Vehicle

Many different types of Heavy-Duty vehicles currently exist on the market. Several examples are long distance distribution trucks, delivery trucks, (urban) buses, excavators, buldozers, tractors, etc. Hence, a wide variety. Not all of these machines are also used for road traffic however, yet primarily serve a different purpose. Main interest of the MATADOR project concerns road vehicles like trucks and (urban) buses. In literature, urban buses are often used as demostrator projects for HD Hybrid Electric Vehicles. Therefore the HD PHEV model is built as if it where a hybrid electric city bus. Figure 12 shows the power train layout with the following component modules:

- Vehicle (VEH)
- Wheels (WH)
- Differential gear (DIFF)
- Automatic Transmission (AUT.TR.)
- Internal Combustion Engine (ICE) + additional reduction gear (RED)
- Electric Motor (EM)
- Battery (BAT)

The applied engine data in all TNO models is available from a Light-Duty Otto engine, which has a much higher maximum engine speed than a regular HD diesel engine. The automatic transmission, however, contains data from a heavy-duty urban bus automatic transmission. Therefore, the ICE is coupled to the automatic transmission through an additional (loss-less) reduction gear in order to match the engine speed to the gearbox speed. The use of an Otto engine in hybrid vehicles is not new. For reasons of exhaust emissions (no/lower particles), an Otto engine fuelled by LPG or CNG is often applied in hybrids, even though a diesel engine is generally more energy efficient.

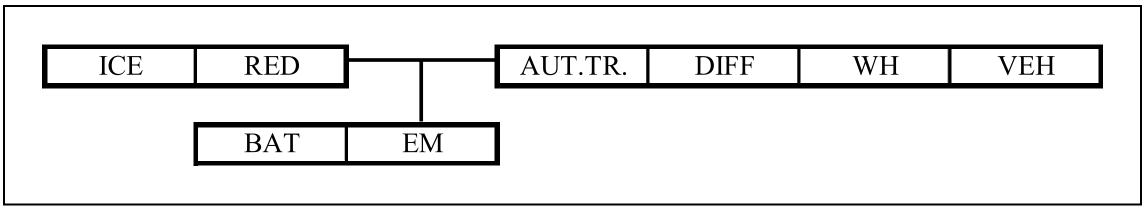


Figure 12: HD Parallel Hybrid Electric Vehicle configuration

In a parallel hybrid the internal combustion engine is directly connected to the wheels. Its speed therefore is linearly dependent on the vehicle speed. The speed of the electrical machine also is directly linked to this speed. This has its reflection on the control for the parallel hybrid.

Most preferable would be to operate the ICE in its sweet-spot (most energy efficient operating point) in case the engine is turned on. Since the speed is imposed from the vehicle speed, the engine will be operated at different speeds and out of its sweet-spot. Next best solution is to operate the engine at the most energy efficiency operating point at each engine speed. Since these points lie at high loads of the engine (Figure 13), this might result in a surplus of mechanically generated power, causing the electric motor to overload the battery (in case the requested propulsion power is less than the optimum engine power!).

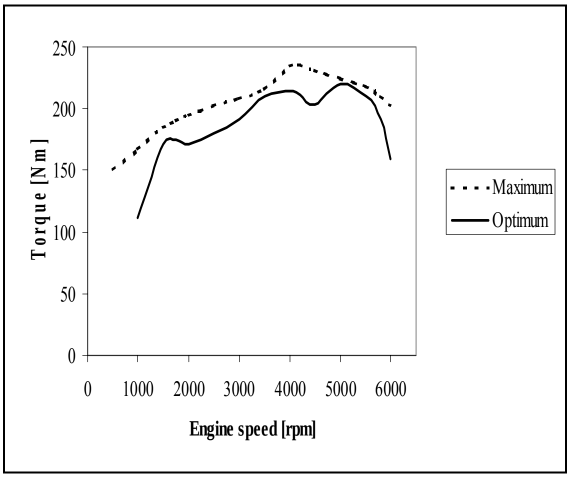


Figure 13: Torque-speed map Otto engine

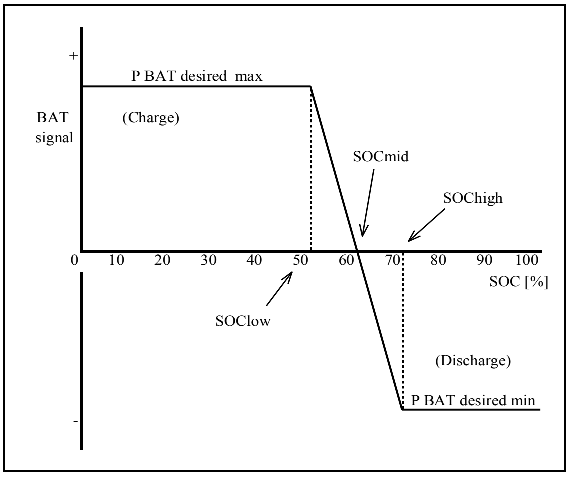


Figure 14: Battery signal (kW) as function of SOC

In order to prevent the battery from being overcharged, the requested engine operating point is made dependent on the SOC of the battery according to Figure 14. This additional battery signal will, in general, try to maintain a SOC at the value of SOCmid.

From the battery signal ($P_{BATsignal}$) together with the driver signal (P_{Driver}, from the driver module, representing the request at the wheels), the actual request for the engine ($P_{ICE,des}$) is generated with Equation 1.

$$P_{ICE,des} = P_{Driver} + P_{BATsignal} \qquad \{0 \le P_{ICE,des} \le P_{ICE,opt}\} \qquad \textit{Equation 1}$$

The desired engine output is limited between zero (engine off) and the momentaneous optimum operating point (speed dependent). When the desired engine power is determined, this value is used to select the corresponding throttle position.

The ICE and the Electric Motor (EM) together have to provide the requested power at the wheels. Now that the ICE power has been determined the EM power can easily be determined to be the net difference of engine power and driver request; motor operation in case engine output is lower than the total request, and generator operating in case engine output is higher than requested. Although it might seem that the desired EM power equals the battery signal, this is not always true, since additional limitations are incorporated along the way which might force other energy distributions. The torque control signal for the EM is generated by dividing the desired EM power by the EM speed (which is equal to the transmission input speecd). In case of braking the electric machine also operates in generator mode, when not limited by a high battery SOC. Braking energy thus is regenerated.

Previously it has already been mentioned that the model represents a large city bus. Table 6 lists the main data which are used for the simulations with the Parallel Hybrid Electric Vehicle model. The vehicle mass has been chosen at 15000 kg, an average for (hybrid) electric buses. The performance demand that has been defined, is that the acceleration and top speed should at least be equal to those in the Dutch Urban Bus Cycle [5]. The actual demand set, thus is that the vehicle has to be able to be driven over the Dutch Urban Bus Cycle.

Table 6: HD Parallel Hybrid Electric Vehicle component parameters

Internal combustion engine		**Reduction gear (engine)**	
Type	Otto	i [-]	2.75
Max. power [kW]	130	**Differential gear**	
Max. speed [rpm]	6000	i [-]	4.64
Max. torque [Nm]	240		
Transmission		**Battery**	
Type	Automatic	Type	NiCd
i (1st gear) [-]	3.429	Capacity [Ah]	50
i (2nd gear) [-]	2.007	Cell voltage [V]	1.2
i (3rd gear) [-]	1.416	Number of cells [-]	500
i (4th gear) [-]	1.000	Cell internal resistance [mΩ]	0.72
Vehicle		**Electric motor**	
Mass [kg]	15000	Type	Permanent magnet
C_w [-]	0.6	Power (nom/max) [kW]	80 / 120
A [m^2]	7.0	Base speed [rpm]	500
Wheels		i = gear ratio	
$R_{dynamic}$ [m]	0.507		
Number of wheels (front/rear)	2 / 4		

4.3 Series Hybrid Electric Vehicle

In a Series Hybrid Electric Vehicle the wheels are driven by an Electric Motor only. Basically it is a Battery Electric Vehicle to which an APU (Auxiliary Power Unit, engine-generator set) has been added. The APU converts fuel into electricity. Since the configuration is more complex than that of a BEV the control strategies, of course, are different.

The difference between Heavy-Duty and Light-Duty series hybrid electric vehicles lies more in the dimensioning of components than in the applied components. Nevertheless, two series HEVs have been modelled, of which one has been given a HD dimensioning and the other a LD one. The applied components in the SHEV models (Figure 15) are:

- Vehicle (VEH)
- Wheels (WH)
- Differential (DIFF) or Reduction gear (RED)
- Electric Motor (EM)
- Battery (BAT)
- Internal Combustion Engine (ICE)
- Generator (GE)

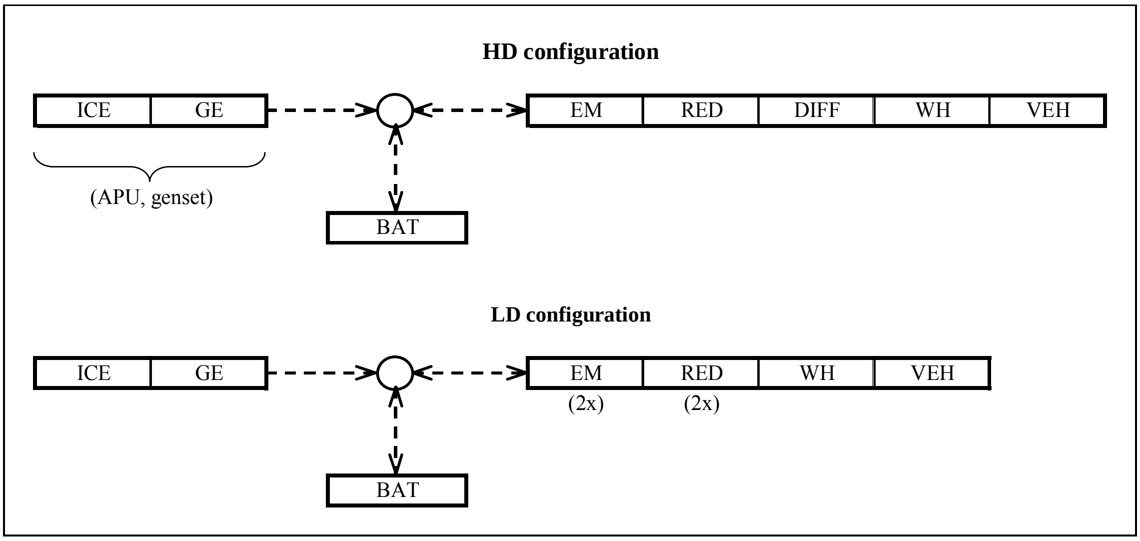


Figure 15: Series Hybrid Electric Vehicle models

In a series HEV, one or more Electric Motors drive the wheels through reduction and/or differential gears. The EM is powered from the APU and the battery. The APU is not mechanically connected to the wheels and thus can operate independently from the road-load.

The main powerflows through the drivetrain are the same for both the LD and HD model (APU and BAT power the EM). Therefore the control strategies can be alike too. The EM provides propulsion power and can be used for regenerative braking. The control signal for the electric motor is linearly dependent on the driver signal, which represents the requested wheel power.

Many control strategies (CS) are possible for the APU. Often the CS is highly dependent on the application of the vehicle. Here it is chosen to use an arbitrary State-of-Charge (SOC) control. This means that the APU operating point is selected on the bases of SOC and the previous APU condition (on/off) alone. Three different control strategies (Figure 16) have been selected to investigate the resulting effects in the simulations.

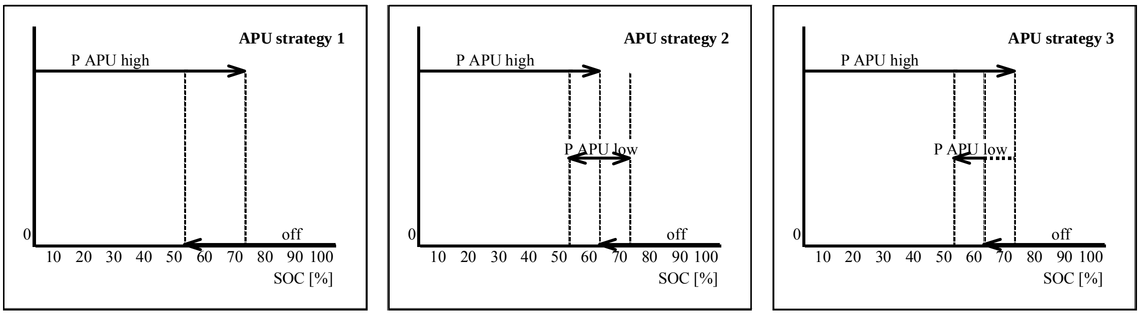


Figure 16: APU control strategies for SHEV vehicle models

The control strategies either use two or three operating points (off/low/high). In the low power point the engine operates at its optimum BSFC, thus at the highest energy efficiency for this specific engine. The high output point is selected at higher engine speed (in its most efficient point at that speed) to ensure that the APU delivers sufficient power for the vehicle to be charg sustaining, i.e. on average the APU can deliver more power than requested for driving.
It is important to incorporate hysteresis in this control, to prevent the APU from frequently switching between operating points. Frequent switching would only result in higher fuel consumption, emissions, and other undesired dynamics (e.g. electric power peaks from the generator).

In the LD version only the second APU control strategy is applied, while all three are used in the simulations with the HD vehicle.

The dimensioning of the HD SHEV vehicle is done according to that of the HD PHEV. Again the Dutch Urban Bus Cycle sets the demands for acceleration and top speed, this time to be delivered by the EM only. The engine is used unscaled in the HD SHEV model. In the selected operating points it, therefore, delivers 27.5 and 69.2 kW for the low and high point respectively.

Just like the BEV, the LD Series Hybrid Electric Vehicle has two electric motors with a maximum mechanical power output of 37.5 kW each. Since the EMs are powered from the APU too, the battery capacity has been decreased. The engine is scaled down so much that it still provides sufficient power for the vehicle to maintain a continuous top speed of circa 150 km/h in its maximum operating point without depleting the battery. The second operating point lies at its sweet spot.

The main component parameters for both the LD and HD Series Hybrid Electric Vehicle model are presented in Table 7.

4.4 Combined Hybrid Electric Vehicle

Combined Hybrid Electric Vehicles (CHEV) are even more complex than parallel or series hybrids. The first mass produced hybrid vehicle nevertheless has a combined hybrid structure. Toyota has put their Prius (with the Toyota Hybrid System – THS [4]) to the market in Japan at the end of 1997, and in the summer of 2000 it will also become available in America and Europe.

The combined hybrid structure actually is a combination of the series and parallel configuration, i.e. the engine is routed mechanically as well as electrically to the wheels. In the THS the connection is made through a planetary gear. The ICE and GE are coupled to the sun and planet carrier axles respectively, while the ring gear axle is connected to the reduction gear, where the electric motor is coupled. Several other combined hybrid systems with clutches also exist as research or demonstrator projects.

The CHEV model is primarily based on the Toyota Prius and therefore has the same power train layout (Figure 17). The following components have been used in the model:

- Vehicle (VEH)
- Wheels (WH)
- Reduction gear (RED)
- Planetary gear (PG)
- Internal Combustion Engine (ICE)
- Electric Motor (EM)
- Generator (GE)
- Battery (BAT)

Table 7: Series Hybrid Electric Vehicle component parameters

		Heavy-Duty	Light-Duty
Internal combustion engine			
Type		Otto	Otto
Max power [kW]		130	65
Max speed [rpm]		6000	6000
Max torque [Nm]		240	120
Operating points [kW]	low	27.0 @ 1500 rpm	13.5 @ 1500 rpm
	high	69.2 @ 3500 rpm	38.0 @ 3500 rpm
Generator			
Type		Permanent magnet	Permanent magnet
Power (nom/max) [kW]		60 / 90	50 / 75
Base speed [rpm]		3500	4000
Battery			
Type		NiCd	NiCd
Capacity [Ah]		50	6.5
Cell voltage [V]		1.2	1.2
Number of cells [-]		500	240
Cell internal resistance [mΩ]		0.72	0.72
Electric motor			
Type		Permanent magnet	Permanent magnet
Power (nom/max) [kW]		165 / 247.5	(2 x) 25 / 37.5
Base speed [rpm]		2500	3000
Gear			
Type		Reduction	Reduction
i [-]		5.5	5.25
Type		Differential	
i [-]		4.64	
Wheels			
$R_{dynamic}$ [m]		0.507	0.295
Number of wheels (front/rear)		2 / 4	2 / 2
Vehicle			
Mass [kg]		15000	1350
C_w [-]		0.6	0.3
A [m^2]		7	2

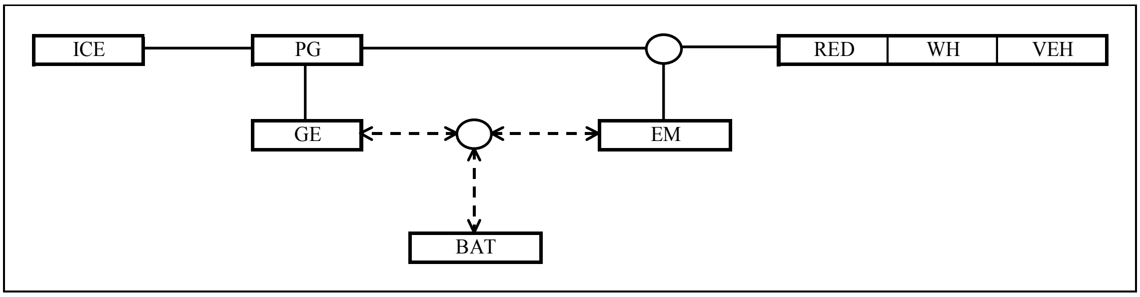


Figure 17: Combined Hybrid Electric Vehicle structure (based on Toyota Hybrid System)

In this system the planetary gear is one of the most important components, since it enables continuously variable operation of the ICE, in order that it can be operated at its most energy efficient points at all times. The generator is used to control the engine speed over the planetery gear (torque distribution fixed, speeds have linear dependency of one another) and the electric motor functions as torque assist or is used for regenerative braking.

The idea of this combined hybrid structure is that propulsion power directly comes from the ICE as much as possible. The system control (control strategy) itself determines which is the optimum route for the requested power. At higher speeds power will flow directly through the mechanical connection to th wheels (parallel path), while at low speeds the electrical path through GE and EM will be used (series route), or the engine might be shut off at all.

The actually delivered ICE output is determined from the wheel request and the battery State-of-Charge, just like it is in the Parallel Hybrid Electric Vehicle model described before. Each requested power corresponds to an operating point (torque and speed). Through the planetary gear relations the desired GE power and speed then are determined. Dependent on the delivered engine power which is directly routed to the reduction gear and requested wheel power, the electric motor operates as torque assist or as electric brake.

The previously defined vehicle data (mass, C_w, A) are used for this model again. The electric motors are given the same power as those in the Toyota Prius, and the available engine map is scaled down. The final component data for the Combined Hybrid Electric Vehicle is listed in Table 8.

Table 8: Combined Hybrid Electric Vehicle component parameters

Internal combustion engine		**Generator**	
Type	Otto	Type	Permanent magnet
Max power map/limited [kW]	65 / 41	Power (nom/max) [kW]	15 / 22.5
Max speed map/limited [rpm]	6000 / 4100	Base speed [rpm]	4000
Max torque [Nm]	240	**Planetary gear**	
Battery		i [-]	3
Type	NiCd	**Reduction gear (engine)**	
Capacity [Ah]	80	i [-]	3.927
Cell voltage [V]	1.2	**Wheels**	
Number of cells [-]	240	$R_{dynamic}$ [m]	0.295
Cell internal resistance [mΩ]	0.72	Number of wheels (front/rear)	2 / 2
Electric motor		**Vehicle**	
Type	Permanent magnet	Mass [kg]	1350
Power (nom/max) [kW]	20 / 30	C_w [-]	0.3
Base speed [rpm]	940	A [m^2]	2

4.5 Fuel Cell Electric Vehicle

Currently many vehicle manufacturers conduct research on the application of fuel cells in vehicles. The fuel cell then converts the fuel into electricity, which is used to directly power the electric motor(s). The driveline structure (Figure 18) is similar to that of the Battery Electric Vehicle, yet with a fuel cell instead of the battery. As a result of lacking an energy storage system, no energy can be regenerated in a Fuel Cell Electric Vehicle (FCEV). At the same time, the fuel cell also operates like a conventional engine, i.e. transient since it is the only power source for the EM. In TNO-ADVANCE a model of a FCEV has also been built.

The following components have been used:

- Vehicle (VEH)
- Wheels (WH)
- Reduction gear (RED)
- Electric Motor (EM)
- Fuel Cell (FC)

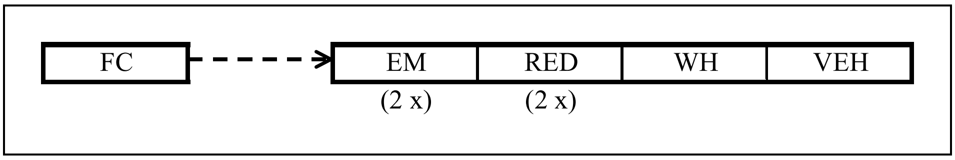


Figure 18: Fuel Cell Electric Vehicle configuration

A Light-Duty vehicle has been dimensioned. In fact, only the fuel cell is dimensioned to meet the electric motor specifications as they were set for the BEV. Using an 85% efficiency of the EM at maximum power (2x 37.5 kW mechanical) and some power for the auxiliaries, then the fuel cell has to have a maximum electrical power output of approximately 90 kW. The data for the FCEV is presented in Table 9.

4.6 Fuel Cell Hybrid Electric Vehicle

Instead of a pure fuel cell electric vehicle, it is also possible to create a hybrid fuel cell vehicle. The power train configuration (Figure 19) then is equal to that of the Series Hybrid Electric Vehicle. Instead of the engine-generator set, a fuel cell is applied. The main power train control for the Fuel Cell Hybrid Electric Vehicle can actually be kept the same as that for the SHEV. Since a battery is present in the system, regenerative braking is possible. With respect to the FCEV, main differences are the steady-state operation of the fuel cell (the same control strategy is applied, Figure 16) and that it is a less powerful fuel cell.

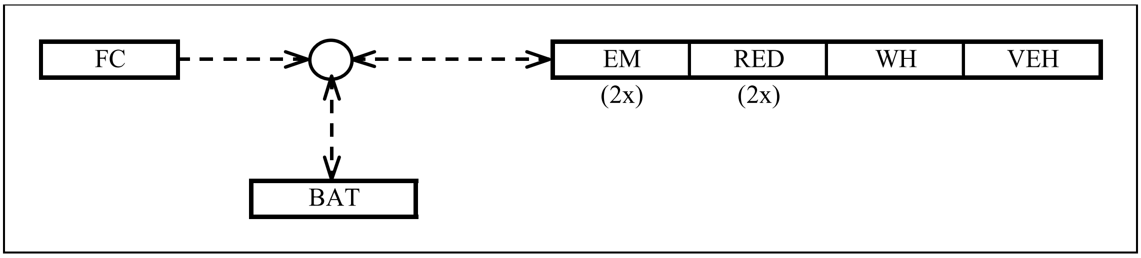


Figure 19: Fuel Cell Hybrid Electric configuration

In general, all component data has been directly copied from the other LD vehicle models. The fuel cell power and its operating points are determined from the electrical output of the generator in the Series Hybrid Electric Vehicle. All data is listed in Table 9.

Table 9: Fuel Cell (Hybrid) Electric Vehicle component parameters

	FCEV	FCHEV
Fuel Cell		
Type	Hydrogen	Hydrogen
Max power [kW]	90	36.5
Operating points low/high [kW]	transient	10.95 / 36.5
Electric motor		
Type	Permanent magnet	Permanent magnet
Power (nom/max) [kW]	(2x) 25 / 37.5	(2x) 25 / 37.5
Base speed [rpm]	3000	3000
Battery		
Type	-	NiCd
Capacity [Ah]	-	6.5
Cell voltage [V]	-	1.2
Number of cells [-]	-	240
Cell internal resistance [mΩ]	-	0.72
Reduction gear		
i [-]	5.25	5.25
Wheels		
$R_{dynamic}$ [m]	0.295	0.295
Number of wheels (front/rear)	2 / 2	2 / 2
Vehicle		
Mass [kg]	1350	1350
C_w [-]	0.3	0.3
A [m^2]	2	2

4.7 Vehicle models performances

Many performance criteria can be used to dimension a vehicle. For the LD vehicle models a performance demand was set in order to create vehicles that are mutually comparable. For this research only one demand has been set: 0-100 km/h within 15 seconds. This is a moderate demand. For each vehicle model, several performances have been determined. Since all vehicles have been given the same weight and drive power, different figures are only found for drivelines with (completely) different control strategies. In case of comparable control strategies (e.g. SHEV, FCHEV), differences occur due to slightly different dimensioning.

Table 10: LD vehicle model performances

	LD vehicle model				
Acceleration [s]	**BEV**	**SHEV**	**CHEV**	**FCEV**	**FCHEV**
0-60 km/h	6.7	6.7	6.9	6.7	6.7
0-100 km/h	12.7	12.7	14.6	12.7	12.7
80-120 km/h	7.9	7.9	9.3	7.9	7.9
Continuous speed [km/h]	189	164	154	189	163

5 Conclusions

The goal of Subtask 2.2 was the '*Development of simulation models'* that could be used to investigate many aspects which were defined as key issues in the MATADOR Task 2 project. Both IKA and TNO already had tools for dynamic driveline simulation at their disposal, called IKASIM and TNO-ADVANCE respectively.

Both partners have built an extensive set of driveline models, together comprising many of the possible powertrain configurations. Main functionality for the models is showing representative driveline behaviour. The working of components therefore has to be similar to real-life operation. Many components have not actually been validated however. The results of the simulation, therefore, may only be compared qualitatively. Ranking the different powertrain configurations is also not allowed due to the lack of actual validation. All models are meant to give insight into the differences in driveline behaviour for various types of powertrains, not to rank them in terms of energy efficiency.

At IKA the following Light-Duty driveline models have been set up:

- 3 x Parallel Hybrid Electric Vehicle
  - Battery storage system (Charge sustaining & depleting)
  - Flywheel storage system (Charge sustaining)
- 3 x Series Hybrid Electric Vehicle
  - Battery storage system (Charge sustaining & depleting)
  - Flywheel storage system (Charge sustaining)

At TNO the following (charge sustaining) driveline models now are available:

- 1 x Battery Electric Vehicle (Light-Duty)
- 1 x Parallel Hybrid Electric Vehicle (Heavy-Duty)
- 2 x Series Hybrid Electric Vehicle (Light-Duty & Heavy-Duty)
- 1 x Combined Hybrid Electric Vehicle (LD)
- 1 x Fuel Cell Electric Vehicle (LD)
- 1 x Fuel Cell Hybrid Electric Vehicle (LD)

All of these models are used to support the research conducted in other subtasks of the MATADOR Task 2 project and have proven to be very useful for this purpose. Quite often in the Subtask Reports, the models are referenced to with an abbreviation, which will be included in the list of abbreviations. Detailed information on the models, however, is only presented in this subtask report.

Simulations can never fully replace actual measurements. A computer model's representativity is always limited by factors like the influence of temperatures or tyre pressure, that can hardly be modelled. Practical reasons can also be the cause for not modelling known effects. Detailed models can result in time-consuming simulations and also obtaining necessary, meaningful data can be a problem (e.g. which and how do you measure transient effects on for instance fuel use and emissions of combustion engines). Well-known effects then are not included into the models.
The models described in this document are generic models, which can very well be used to research driveline behaviour and energy consumption, yet that cannot produce useful information on the emission of a certain driveline type. The models do contain all the essential physics so that the response to changing test conditions is adequately simulated.

References

[1] Using Simulink, reference manual, The MathWorks, Inc., 1996

[2] Hendriksen, P. et al. (1998). "TNO-ADVANCE, A modular Power Train Simulation, Design and Assessment Tool", TNO report 98.OR.VM.037.1/PHE

[3] Integrated Systems Inc., $Matrix_x$ Product Family Technical Specifications, 1995.

[4] Toyota Press Information 1997

[5] Weijer, C.J.T. van de, Graaf, R. van der (1993). "Urban Bus Driving Cycle", Proceedings 4th International EAEC Conference, 16-18 June, 1993, Strasbourg, page 513-528

MANAGEMENT TOOL for the ASSESSMENT of DRIVELINE TECHNOLOGIES and RESEARCH

MATADOR

Contract JOE3-CT97-0081

Task 2:

Testing methods for vehicles with conventional and alternative drivelines

Subtask 2.3

Evaluation of existing (draft) standards

Institut für Kraftfahrwesen Aachen

20 July, 2000

by

Christian Renner (IKA)

Servé Ploumen (IKA)

Martin Schüssler (IKA)

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Energy Conservation and Utilisation

Nomenclature

Abbreviations

APU	Auxiliary Power Unit (generally an ICE with generator)
BEV	Battery Electric Vehicle
HEV	Hybrid Electric Vehicle
SHEV	Series Hybrid Electric Vehicle
PHEV	Parallel Hybrid Electric Vehicle
ICE	Internal Combustion Engine
NiMH	Nickel Metal Hydrid battery
SOC	State Of Charge (of the electric energy storage device)
UDDS	Urban Dynamometer Driving Schedule
HWFET	Highway Fuel Economy Test
SC03	Supplemental Federal Test Procedure Start Control Cycle
US06	Supplemental Federal Test Procedure High Load Cycle
NEDC	New European Driving Cycle
ECE	City Cycle, Urban Part of NEDC
FT	Failure Time
FTP	Federal Test Procedure
IFT	Independent Full Charge Test
IPT	Independent Partial Charge Test
DFT	Dependent Full Charge Test
DPT	Dependent Partial Charge Test
EVT	Electric Vehicle Test
EOT	Engine Only Test
RI	Recharge Independent
RD	Recharge Dependent
OVC	Off Vehicle Charge Capable

Contents

1 Introduction

In Task 2 of the MATADOR-project test methods (Management Tool for the Assessment of Driveline Technologies and Research, EU-contract JOE3-CT97-0081) for battery-electric, hybrid-electric and fuel cell vehicles are analysed in order to support the development of new test procedures for these vehicles with alternative drivelines. The development and definition of test procedures with alternative drivelines for determining the fuel consumption and emissions requires a detailed work on the technical aspects, which depend strongly on the vehicle's technology. This is obviously more complicated for the development of procedures for a comparative assessment of technologies, which must cover many different aspects, than for the development of procedures needed for homologation, where only values for the fuel consumption and the emissions are mostly relevant. As a basis for the development of new procedures, existing standards for battery electric and hybrid vehicles are analysed in this subtask report.

This report deals with the evaluation of existing standards for battery electric vehicles and hybrid vehicles. Currently a number of already adopted or draft standards exist. Additionally, various institutes have developed their own procedures.

Concerning vehicle test procedures a general conflict exists between the following aspects:

Simple application with regard to time and equipment needed for the test and correlation to the real conditions under which these vehicles are used in reality.

Especially for hybrid vehicles this problem becomes evident, for three reasons:

- The variety of realised propulsion systems to be covered is much more higher than for conventional or also electric vehicles.
- Different types of storage and transfer devices (batteries, flywheels, capacitor etc.) have to be considered.
- Driver or automatic selected driving modes change the behaviour of the vehicles in terms of emissions and energy consumption and therefore have to be taken into account.

So the main issue of the work reported here was to asses these standards in terms of applicability, accuracy and suitability for different vehicle types and propulsion system configurations, regarding the above problems.

This work is performed in two ways, theoretic analysis on basis of simulations and practical experience by doing real measurements with available vehicles. The experience and possible problems encountered during the test allows a deep understanding of the problems of applying and defining test procedures.

Because of the fact, that there is no great number of hybrid vehicles available for testing, the simulations were made to make an analysis of configurations possible, which cannot be done on prototypes.

2 Standards for electric and hybrid vehicles

2.1 Introduction in the compared standards

The standards which are discussed here for electric vehicles are:

- EN 1986-1: Electrically propelled road vehicles – Measurement of energy performances – Part 1: Pure electric vehicles
- SAE J 1634: Electric vehicle energy consumption and range test procedure

Additionally, two testing procedures, which have been established for internal use in the regarding institutes, have been discussed too.

- HTA-Biel: Mendrisio BEV Test Procedure
- ENEA: BEV Test Procedure

For hybrid vehicles the following procedures are investigated:

- prEN 1986-2: Electrically propelled road vehicles – Measurement of energy performances – Part 2: Thermal electric hybrid vehicles (Draft)
- SAE J 1711: Recommended practice for measuring the exhaust emissions and fuel economy of hybrid vehicles (Draft)
- California Air Resources Board (CARB): California exhaust emission standards and test procedures for 2003 and subsequent model zero-emissions vehicles, and 2001 and subsequent model hybrid electric vehicles, in the passenger car, light-duty truck and medium-duty vehicle class (adopted 5.8.1999)

2.2 EN 1986-1: Electrically propelled road vehicles – Measurement of energy performances – Part 1: Pure electric vehicles

This standard is used for vehicles for passenger transportation with a maximum weight of 5000 kg and for vehicles for freight transportation with a maximum weight of 3500 kg (classes M_1, M_2, N_1 and N_2 according to directive 92/53/EWG) and for motor tricycles and quadricycles (as defined in directive 92/61/EWG). The standard intends to test the range and energy consumption of pure electric vehicles with batteries as energy storage. Other energy storage systems are not regarded. The driving schedule used is based on the NEDC, which is defined in 91/441/EWG, but without the steps for the gear changes.

For Equipment, accuracy, tolerances and units the standards given in 91/441/EWG and EN 1821 are used. Thus, the vehicle weight for testing is the curb weight plus 100 kg. (The curb weight is the total weight of the vehicle with all standard equipment and including batteries and lubricants at nominal capacity.)

A coast down test determines the road load for the dynamometer simulation.

Before the test, an initial charging procedure is prescribed, in which the battery is being discharged by driving a constant velocity of 70% of the 30 minutes maximum speed as describes in EN 1821-1. After the initial discharge, the battery is charged according to the usual charging procedure, which should be used also before all subsequent tests. After disconnecting from the grid, this time t_0 has to notified, the driving test must start within 4 hours.

For the range test, the modified NED-cycle is used. The range test ends, if the vehicle is not able to follow the reference speed at speeds below 50 km/h or a signal from on-board instrumentation signals to stop. At higher speeds, the driver has to drive with the accelerator pedal fully depressed, until the vehicle meets the reference speed.

For measuring the energy consumption one can choose driving a modified ECE-cycle 7*4 times resulting in about 28.4 km or driving in a modified NED-Cycle 2 times resulting in a distance of 22.044 km. In the later case it is also allowed, to miss the reference speed at speeds equal or higher 50 km/h., if then the accelerator if fully depressed.

After performing the range test, the vehicle is charged normally. The charge has to be started within 30 minutes and stopped if 24 h since t_0 are elapsed. Due to the fact of possible waiting period of 4 hours, the charging time can vary about 4 hours, starting with minimal 17.98 hours up to max 23.3 hours.

The energy consumption is calculated from the AC-energy divided by the real driven distance.

2.3 SAE J 1634: Electric vehicle energy consumption and range test procedure

The adopted procedure addresses to electric vehicles (passenger cars and trucks) with batteries. This standard intends to test the range and energy consumption of pure electric vehicles with batteries as energy storage. The driving cycles are the Urban Dynamometer Driving Schedule (UDDS) and the Highway Fuel Economy Driving Schedule (HWFET).

A coast down test determines the road load for the dynamometer simulation.

The vehicle weight is the curb weight plus 136 kg. Trucks heavier than 6000 lbs (~= 2700 kg) may be tested at curb weight plus one-half vehicle payload.

The test can either be run in the UDDS and or HWFET or in a combined cycle consisting of both cycles. The speed tolerances are +/- 3.2 km/h and +/- 1 s. For energy consumption tests, speeds lower than prescribed are allowable provided the vehicle is operated with maximum available power. For the range test a set of termination criteria exists.

For measuring the energy consumption, after a soak period on charge of about 12 to 36 h the vehicle shall be operated over two successive UDDS cycles, separated with 10-min pause with the key switch in off-position. If the HWFET is used, the vehicle is driven two cycles with a 15s pause at zero speed with key on. If the combined cycle is used, two UDDS with 10 min pause and two HWFET with 15 s key on between shall be driven. The HWFET have to be performed within 3h after the end of the UDDS without the benefit of intermediate charge.

Afterwards within 1 h the battery charge shall start. The minimum duration is 12 h. Charging is complete when the manufacture’s end of charge criteria are met within a minimum of 12 h and with a maximum allowed time, calculated as follows:

Max. time = 2x battery energy capacity (kWh)/ Main power supply (kW)

For measuring the range of the vehicle, the above driving schedules are repeatedly driven, until one of the termination criteria is met:

The test termination criterion for the range test is defined as when the vehicle is unable to accelerate fast enough to meet the +/- 3.2 km/h and +/- 1 s tolerances with the following exceptions:

- Exception for the high-speed portion of the UDDS: The test may continue, if the vehicle is no longer able to achieve speeds greater than 72 km/h. However, the UDDS test cycle shall be terminated if the vehicle speed falls below 72 km/h between the 217-s mark and the 305-mark.

- Exception for the high-speed portion of the HWFET: The test may continue, if the vehicle is no longer able to achieve speeds greater than 72 km/h. However, the HWFET test cycle shall be terminated if the vehicle cannot maintain a minimum speed of 72 km/h within 15 s of when the driving schedule speed is 72 km/h or above.
- Exception for reduced performance: the range test may continue even though the vehicle speed falls below the normal tolerance of +/- 3.2 km/h and +/- 1s. However, the test shall be terminated if the vehicle cannot maintain the driving schedule within the lower limit of 8.0 km/h lower than the lowest point on the trace within 2 s of given time.
- Other manufacturer specified test termination: The manufacturer can specify other termination criteria, for example a lowest allowable battery terminal voltage to prevent damage to the battery.

The termination criteria are rather complex, because two speed tolerance, depending of the schedule speed and time, have to be regarded. For example, with the existing control software at the dynamometer at the ika, this is not possible.

2.4 HTA-Biel: Mendrisio BEV Test Procedure

During the field tests in Mendrisio, HTA-Biel has established a testing procedure to measure the energy consumption of electric vehicles. This procedure has been developed in 1994. At this time only some drafts of standards were available. Because already at this time a pure urban vehicle was absolutely not the goal for the development of electric vehicles HTA Biel decided to use the new European cycle with the extra urban part, but with a reduced the maximum speed from 120 to 80 km/h.

The intention to limit the speed at 80 km/h was not to test BEV at speeds they are not designed for. With the EN 1986-1 a standard exists, where one can choose for measuring the energy consumption between the ECE cycle with top speeds of 50 km/h or the NEDC with speeds up to 120 km/h. So this issue is handled in the European standard, without creating a modified special speed profile for BEV.

A second difference is the recharge time of 8 hours, which has been assumed to be representative for electric vehicle usage.

2.5 ENEA: BEV Test Procedure

The ENEA BEV test procedure refers in many topics to the EN 1986-1 standard. The main difference is a method for preconditioning the vehicle. ENEA introduced a warm-up of the vehicle and of the driveline on the rollerbench. During this warm-up of the vehicle, the bench drives the vehicle with the motor in neutral, to warm up the tires. During the driveline warm-up, the motor drives the vehicle at a speed of 15 km/h with the load of the rollerbench set to zero. Thus the motor has to overcome only the losses in the drivetrain and the rolling resistance of the driven wheels. By this method, the starting temperature of the tires is stabilized at warmed up conditions, artificially lowering the load to propel the vehicle. The influence of this preconditioning is discussed in chapter 2.9.1.

2.6 prEN 1986-2: Electrically propelled road vehicles – Measurement of energy performances – Part 2: Thermal electric hybrid vehicles (Draft)

The part two of EN1986 addresses to thermal electric hybrid vehicles. The procedure covers also other secondary energy storages as batteries, e.g. flywheels or capacitors, but only very roughly without any detailed description. For reference, this draft is given in the appendix.
The main issue of this draft are, that if the hybrid vehicle has an operation mode, where it acts as a conventional vehicle (operation of the ICE only, no participation of the electric components in particularly no recuperation), it shall be handled as a conventional vehicle according to the correspondent standards.

For other hybrid vehicles, the fuel and energy consumption is measured in the modified NEDC (according to EN1986-1).

The measurement of energy consumption and range in pure electric mode is performed according to EN 1986-1. The test starts with the range test in pure electric mode in the modified NEDC. For measuring the consumption, the ECE or NEDC may be chosen. If the hybrid vehicle is not able to drive the distances given in EN 1986-1 , about 28 km in the ECE or 22 km in the NEDC, the test shall be performed with the highest possible whole number of cycles (ECE about a multiple of 4 km, NEDC about 11 km) compatible with the range in pure electric mode. If the range is shorter than 4 km, the energy consumption procedure is not applicable.

The measurement of the energy consumption and range in pure electric mode according to EN 1986-1 is only applicable to externally chargeable hybrid vehicles. If it is necessary and if, how to measure the pure electric range or even consumption for a not externally chargeable hybrid vehicle, which could have nevertheless a pure electric user selectable mode, is not mentioned. The test in hybrid mode is performed in the NEDC. The vehicle is driven continuously over the cycle, until the distance travelled has reached the distance from the range test, then completing the actual cycle and driving a further complete cycle. If different hybrid operating modes are available, the manufacturer can recommend one.

For a hybrid vehicle with no pure electric range, this results in driving one NEDC, as for a conventional car, but this is not explicit stated in this draft.

For externally chargeable vehicles, the secondary energy source shall be initially fully charged. After the test, the secondary energy storage is charged to the initial value from the grid, measuring the AC-energy. The energy consumption is than given as a combination of fuel consumption in l/100 km and electricity from the grid in Wh/km.

For not externally chargeable vehicles, the initially state shall be set to a value recommended by the manufacturer to balance the state of charge over the test. The manufacturer, according to technology, must define this procedure. Otherwise the manufacturer shall provide a procedure to recharge the secondary energy storage by using the thermal engine, measuring the additional emissions and fuel consumption, but taken into account, that a potential distance driven to recharge the storage device is not regarded for calculating the fuel consumption and emissions.

The actual draft defines not, what balanced means ore gives a tolerance for the change of the energy content or state of charge for a not externally rechargeable hybrid vehicle. This way of recharging the battery seems more to be addressed to serial hybrid drives, where the APU can recharge the energy storage at standstill. For parallel hybrid drives, the vehicle may be driven a certain distance, which is not regarded, thus increasing the values.

It also give no indicating of the benefit of the hybrid vehicle, if a pure thermal mode is available, because than such a vehicle is tested as a conventional one, which would normally not correspondent to the real world usage of such a vehicle. In this case, the value given would be a worst-case value, where the vehicle is penalised by the weight of the additional hybrid components without being allowed to use them.

2.7 SAE J 1711: Recommended practice for measuring the exhaust emissions and fuel economy of hybrid-electric vehicles (Draft)

This SAE test procedure is addressed to the testing of hybrid vehicles. (See the appendix for a reproduction of the complete draft). It shall provide representative test results for any type of hybrid vehicle (series, parallel etc.), with or without significant all-electric range, with and without available/required off-vehicle charging and having multiple driver-selected operating modes. Beside batteries also flywheels and supercapacitors as secondary energy storage are covered. The test procedure also prescribes a method to weight the emissions and consumptions in different cycles and operating modes to get a representative, to real world usage comparable, result.

This test procedure provides a detailed classification of hybrid vehicles, according to different tests shall be performed. The criteria used are:

- Secondary energy storage system: Battery, capacitor, flywheel
- Off-vehicle recharge capability (OVC): Required, Available, not available
- Recharge dependency (only for off-vehicle rechargeable vehicles): The operating strategy of the vehicle stabilize the state of charge of the secondary energy storage on a certain level by recharging to permit continuously operation of the car (recharge independent RI), or the during the operation of the car the energy storage is discharged, impairing the correct operation of the car. In that case the car is recharge dependent (RD) and must be off-vehicle recharged after a certain distance. This classification is related to the cycle, so it is possible, that a vehicle, which operates recharge independent over the UDDS, is recharge dependent in the high power US06.
- The availability of different, driver-selectable operating modes: Pure electric mode (electric vehicle mode EV), hybrid electrical vehicle mode (HEV) and engine only mode (EO).

The test procedure provides tests in each driver-selected operating mode. Combined with a possibility for off-vehicle charging and recharge dependent or independent operation, this lead to a great number of tests, which must be performed:

- Tests in EV-mode: EVT (only for OVC-capable vehicles)
- Tests in EO-mode: EOT
- Tests HEV mode in recharge dependent and independent mode starting with fully charged energy storage (for OVC-capable vehicles): DFT and IFT
- Tests HEV mode in recharge dependent and independent mode starting with partial charged energy storage (for both OVC-capable vehicles and not OVC-capable vehicles): DPT and IPT. For the IPT the initial state of charge must be set in such a way, that the final state of charge is equal or higher than the initial.

All the tests shall be performed in four cycles, the Urban Dynamometer Driving Schedule (UDDS), the Highway Fuel Economy Driving Schedule (HWFET) and the supplemental tests US06 and SC03. The SC03 is performed with A/C on under higher temperatures. It is only performed for not diesel engine driven vehicles with A/C.

For the EVT, the DFT and IFT the UDDS shall be repeated five times, the HWFET and US06 four times and the short SC03 eleven times.

For the test with partial charge IPT and DPT and the EOT, the driving schedules are repeated twice.

Given a hybrid vehicle with three operating modes (electric, hybrid, engine only), which is off-vehicle charge-capable this results in not less than 4 tests, each of them performed in four cycles, with the needed soak time in between.

In case of off-vehicle charging the energy needed to recharge the energy storage device to the initial state is converted to a value of equivalent fuel consumption using a fuel conversion factor and divided by the driven distance. Finally, this fuel consumption is added to the measured fuel consumption, giving the total fuel consumption.

All the tests in recharge dependent hybrid mode and the recharge independent full test are started with a cold vehicle and no cold start/ hot start weighting takes place. The weighting is implicit done by consecutive driving several cycles, where the cold emissions are measured together with the hot emissions.

Compared to conventional vehicles, where the UDDS is started cold and driven only ones with the first phase repeated, and the other cycles hot, this gives an underestimation of emissions for the UDDS and an overestimation for the other cycles. This problem is caused by the fact, that for a vehicle, which is externally charged, no warm-up before testing is possible. Performing a warm-up would change the state of charge of the batteries. So the energy recharged afterwards a test would not only result from the energy used during the test itself, but also during the warm-up phase.

The emissions and fuel consumption within one operating mode is weighted according to the following figures. In these figures the probability of off-vehicle charging for the recharge independent hybrid mode is 50%. The daily usage of the car, with is reflected by the daily distance, is regarded by weighting the fully charged results with the partial charged results. It is assumed, that distances shorter than 38 miles in the UDDS or 41 miles in the HWFET have a probability of 71% or 74%. Longer distances are covered in partial modes, but have a lower probability. Pure EV-mode is assumed only for the shorter trips, longer distances are covered in hybrid mode.

Afterwards the results of the different modes are weighted equally according to Figure 2.7-3.

Mode	Test	0-38 mi (71% Utility)*	38+ mi (29% Utility)	Weighting for Probability of OVC
RI HEV	IFT	IFT	IPT	x 0.5
	IPT	IPT	IPT	x 0.5
RD HEV	DFT / DPT	DFT	Avg. of (IPT, EOT), or DPT**	x 1.0
EV	EVT	EVT	Avg. of (IPT, EOT), or DPT**	x 1.0
EO	EOT	EOT	EOT	x 1.0

* For RD HEV and EV modes that cannot complete DFT and EVT schedules respectively, use utility value corresponding to actual mileage at which driving trace could not be followed for the first time
** Use DPT results only if driver cannot select a RI HEV or EO mode after RD HEV or EV capability is exceeded

Figure 2.7-1: Calculation of daily travel results for each type of mode from individual test results (urban)

Mode	Test	0-41 mi (74% Utility)*	41+ mi (26% Utility)	Weighting for Probability of OVC
RI HEV	IFT	IFT	IPT	x 0.5
	IPT	IPT	IPT	x 0.5
RD HEV	DFT / DPT	DFT	Avg. of (IPT, EOT), or DPT**	x 1.0
EV	EVT	EVT	Avg. of (IPT, EOT), or DPT**	x 1.0
EO	EOT	EOT	EOT	x 1.0

* For RD HEV and EV modes that cannot complete DFT and EVT schedules respectively, use utility value corresponding to actual mileage at which driving trace could not be followed for the first time
** Use DPT results only if driver cannot select a RI HEV or EO mode after RD HEV or EV capability is exceeded

Figure 2.7-2: Calculation of daily travel results for each type of mode from individual test results (highway)

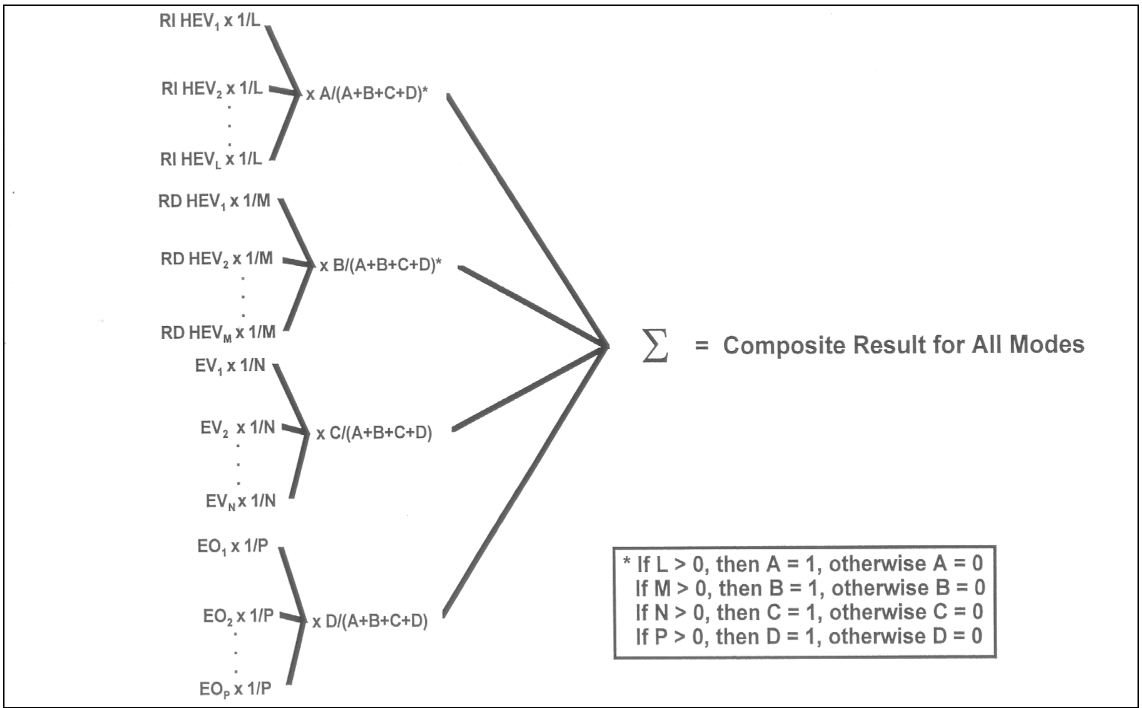

Figure 2.7-3: Weighting of driver–selected operating modes

The result is a composite emission factor and a fuel consumption for each driving schedule, which regards by the weighting the daily usage and the different operating modes.

Afterwards the emissions are weighted by cycle, depending on whether air-conditioning is available or not. For A/C vehicles the weighting is:

FTP: 35 %
US06: 28 %
SC03: 37 %

For non A/C-vehicles:

FTP: 72 %
US06: 28 %

The composite fuel consumption is calculated as follows:

$$\text{Composite fuel economy} = \frac{1}{\dfrac{0.55}{\text{MPG}_{\text{Urban}}} + \dfrac{0.45}{\text{MPG}_{\text{Highway}}}}$$

2.8 California Air Resources Board (CARB): California exhaust emission standards and test procedures for 2003...

The standard “California Air Resources Board (CARB): California exhaust emission standards and test procedures for 2003 and subsequent model zero-emissions vehicles, and 2001 and subsequent model hybrid electric vehicles, in the passenger car, light-duty truck and medium-duty vehicle class (adopted 5.8.1999)” was created for the Californian certification process and to develop procedures to determinate the credit for electric and hybrid vehicles. In this procedure, hybrid-vehicles are classified according the following criteria:

- Technology for secondary energy storage: Battery, super-capacitor or flywheel

- Manual or automatic activation of APU
- Off-vehicle charging capability available or not available
- Charge sustaining or charge depleting operation

Charge depleting means that the battery of a hybrid vehicle ultimately fully discharges and impairs vehicle operation as the vehicle continuously operates over a given driving cycle when no off-vehicle charging is performed and the consumable fuel is regularly replenished. Hybrid vehicles are required to be classified as charge depleting or charge sustaining over each driving cycle (i.e. UDDS, HWFET, US06 or SC03).

Charge sustaining means that the battery of a hybrid electric vehicle ultimately does not fully discharge and impair vehicle operation as the vehicle continuously operates over a given driving cycle.

For electric vehicles and hybrid vehicles in electric mode the all-electric range is tested in the UDDS and HWFET cycles after a full charge of 12 h up to 36 h. The cycles are repeated, until the vehicle is not longer able to stay within the tolerances. A 10 min soak shall follow each UDDS. For testing the range in the HWFET two successive HWFET are separated by a 10 min soak. This pure electric range test is only applicable for hybrid vehicles with off-vehicle charging. Although not off-vehicle charge capable vehicles may have a pure electric range, it is not regarded here, because the all-electric range is counted for a partial zero-emission-vehicle credit. So only electric ranges where the electric energy comes from an off-vehicle source are valid according to the definition of the CARB. The electric energy consumption is measured in the same test, so no extra test is done to measure consumption.

Hybrid vehicles are also tested in hybrid operation in the UDDS, the HWFET, the US06 and SC03 cycles. Before each test run, the vehicle is operated through the same cycle for preconditioning. Only for the UDDS test, there is a soak of 12 up to 36 hours and within the test the UDDS is driven twice, the first one with a cold start and the second drive as a hot test, which is separated by a 10 min key off period. The cold emissions are weighted with 43% and the hot with 57% and added afterwards.

For all other tests, which are hot tests, the emissions are measured in a second cycle immediately after a preconditioning cycle.

For the preconditioning cycles, the APU should work for the maximum possible amount of time. If the APU can manually be activated, it shall be activated over the full preconditioning cycle. For charge sustaining vehicles, the initial state of charge shall be set to the lowest by the manufacturer allowable level. For charge depleting hybrid, the initial state of charge shall be set at the level, at which the manufacturer recommends the driver to change from ZEV to hybrid mode by activating the APU.

If the APU can not manually activated, the state of charge shall be set at a level, which causes the hybrid electric vehicle to operate the APU for the maximum possible cumulative amount of time during the preconditioning drive.

Only after the preconditioning for the UDDS the state of charge may be corrected in the following way (the other tests are driven with the state of charge as a result of the preconditioning cycle):
If the vehicle does not allow manual activation of the APU and is charge sustaining over the UDDS, the state of charge shall be set at a level, that the SOC-criterion would be satisfied for the dynamometer procedure. If off-vehicle charge is required for proper setting, then it shall occur during the 12 to 36 h soak period.

If the vehicle does not allow manual activation of the APU and is charge depleting over the UDDS, then no battery adjustment is allowed.
If the APU can manually be activated, the initial state of charge shall be set at the level, at which the manufacturer recommends the driver to change from ZEV to hybrid mode by activating the APU.

For charge sustaining hybrids, it always must be checked, if the SOC-criterion is satisfied. This criterion defines a tolerance for the change of state of charge in Amp-hours during the test drive depending on the consumed fuel.

$$(Amp - hr_{final})_{max} = (Amp - hr_{initial}) + 0.01 * \frac{(NHV_{fuel} * m_{fuel)}}{(V_{system} * K_{1)}}$$

$$(Amp - hr_{final})_{min} = (Amp - hr_{initial}) - 0.01 * \frac{(NHV_{fuel} * m_{fuel)}}{(V_{system} * K_{1)}}$$

If the change of state of charge is greater than allowed by this tolerances, the test must repeated up to three times.

This test procedure handles a hybrid vehicle in general more as an electric vehicle with an auxiliary power unit. Obviously, by specifying the combustion engine as an APU, the vehicle is supposed to be basically an electric vehicle, which is additionally equipped with a thermal engine. As this classification may be valid for series configurations, it is not appropriate for most of the parallel structures. In such structure, the thermal engine normally has more power than the electric motor.

2.9 Analysis of standards

Comparing the different standards, the major differences are the driving cycles used for the tests. In European standards, the ECE-cycle and the NEDC are used, whereas in the American procedures the UDDS, HWFET, SC03 and US06 cycles are prescribed. Both of the European ones are artificial, consisting out of periods with constant velocity and slope with constant acceleration and are so called modal cycles.

However, the American cycles are derived from real world driving patterns, giving second by second values for the speed with no constant phases for velocity or acceleration and are so called transient cycles. There are also more power demanding, especially the US06 test. An overview of the speed traces is given in the following figures. Additionally, the matrices as a result of a classification of acceleration over speed and specific power as the product of speed multiplied with acceleration over speed are shown. Looking at the classification results, the artificial character of the European cycles becomes obvious. Only very narrow parts of the matrices are used, but if, then the relative amount of time spend at this values is very high.

Contrary to that, the American cycles show more spread matrices, whereas the relative frequency in one class is lower. Regarding the applicability of the test procedure, especially the matrices for the specific power are of interest. Looking at these figures, a first suggestion of the power needed to follow the cycle can be made, and with that, one can decide, if the vehicle would be able to follow the driving cycle.

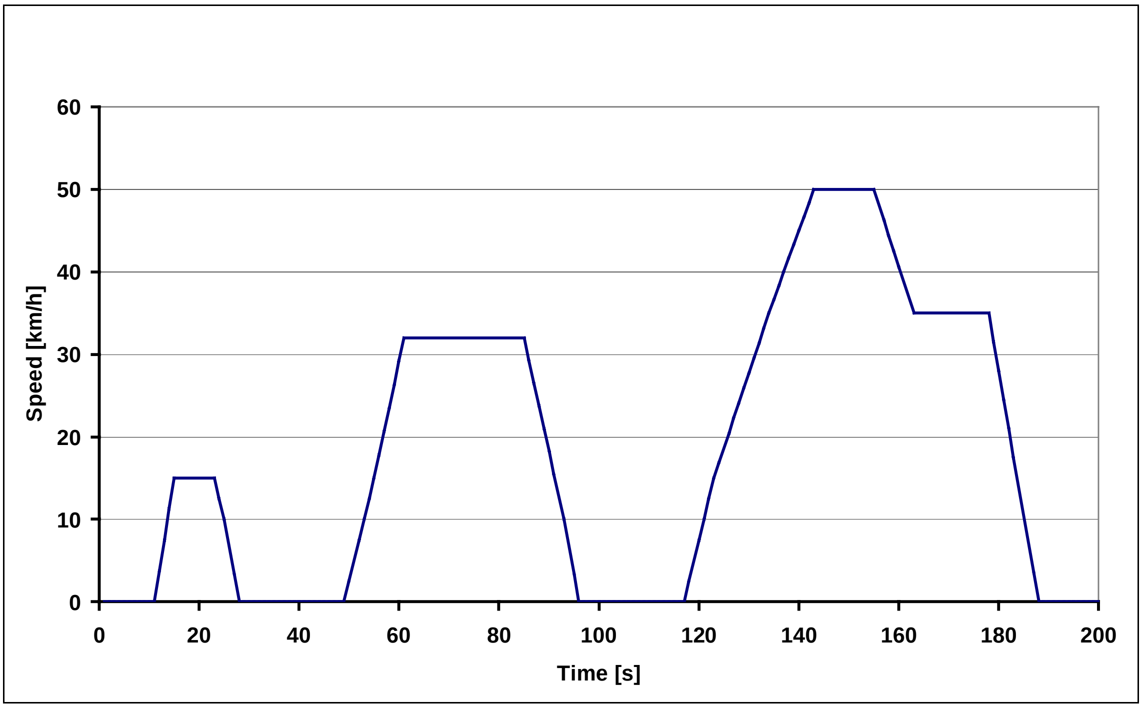

Figure 2.9-1: Speed profile of modified the modified ECE-cycle (EN 1986-1)

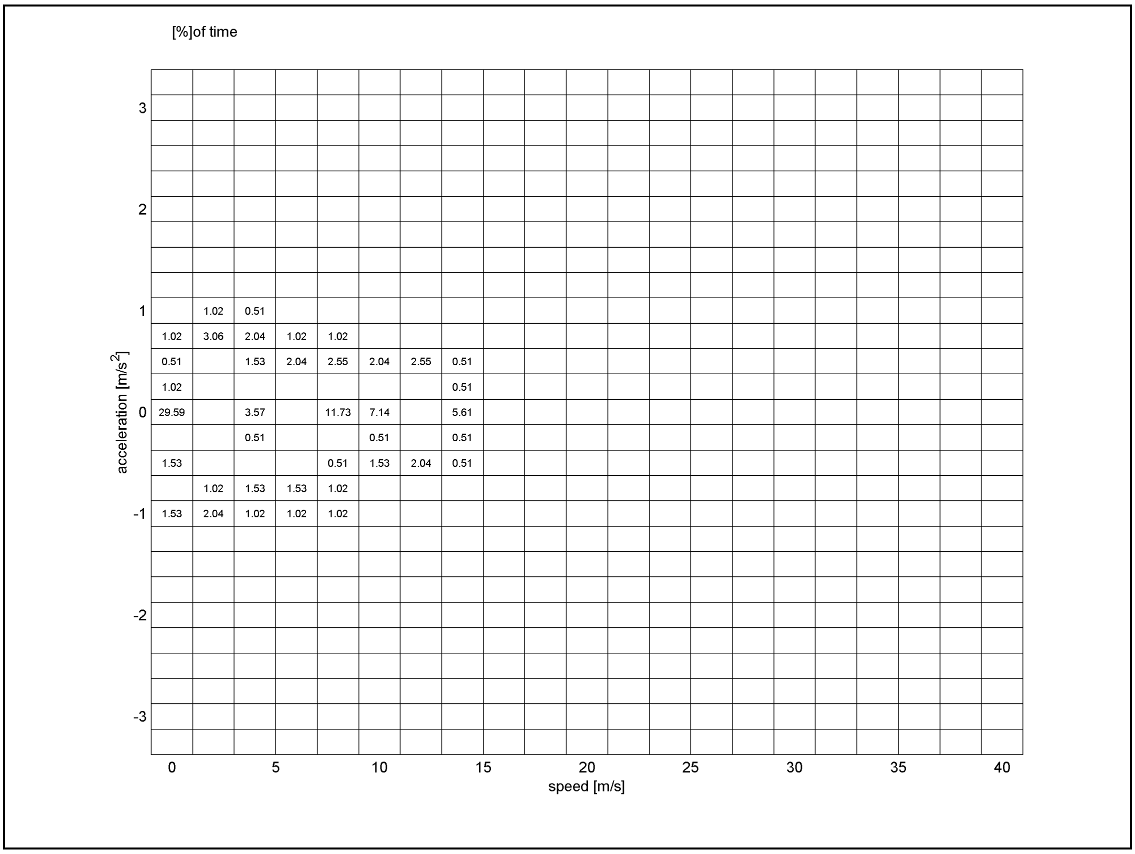

Figure 2.9-2: Relative frequency of acceleration over speed for the modified ECE-cycle (EN 1986-1)

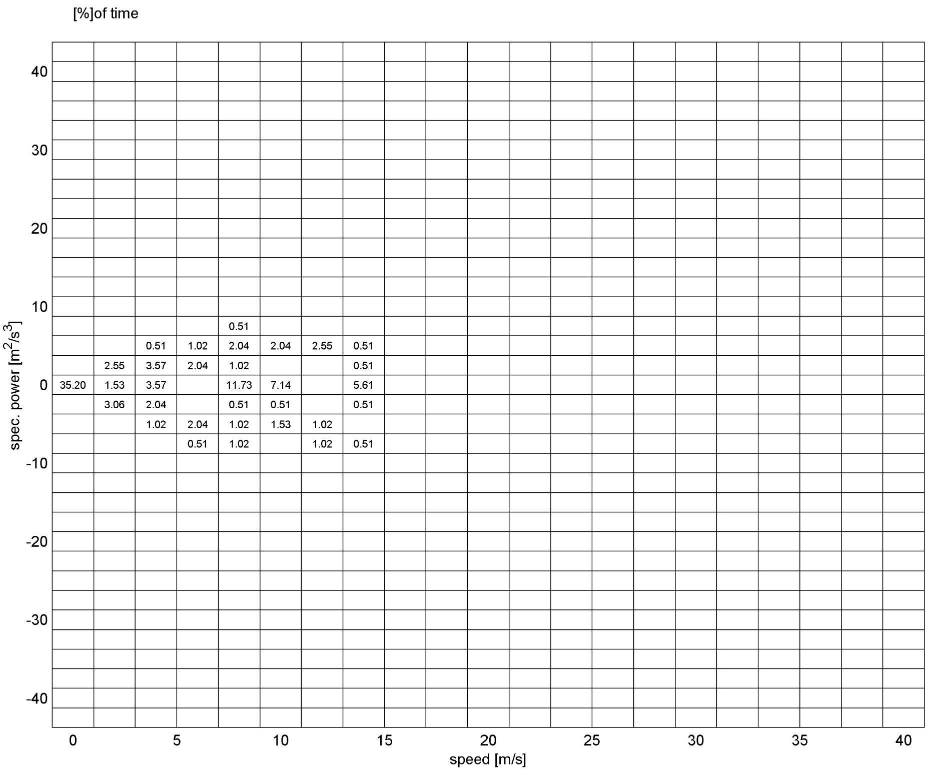

Figure 2.9-3: Relative frequency of specific power over speed for modified ECE-cycle (EN 1986-1)

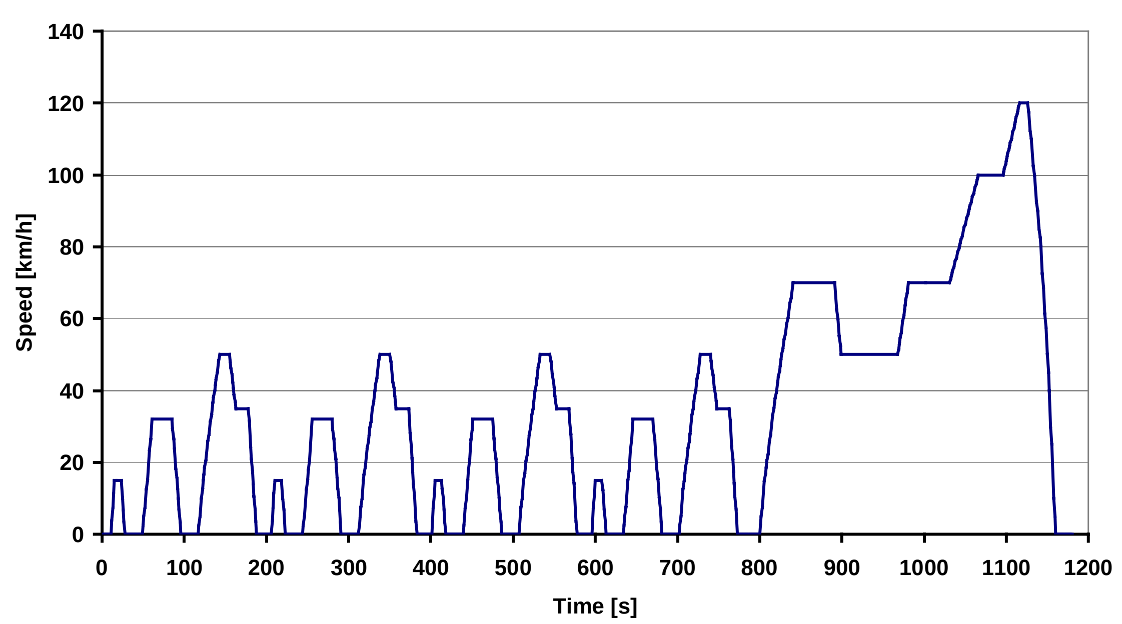

Figure 2.9-4: Speed profile of the modified NEDC (EN 1986-1)

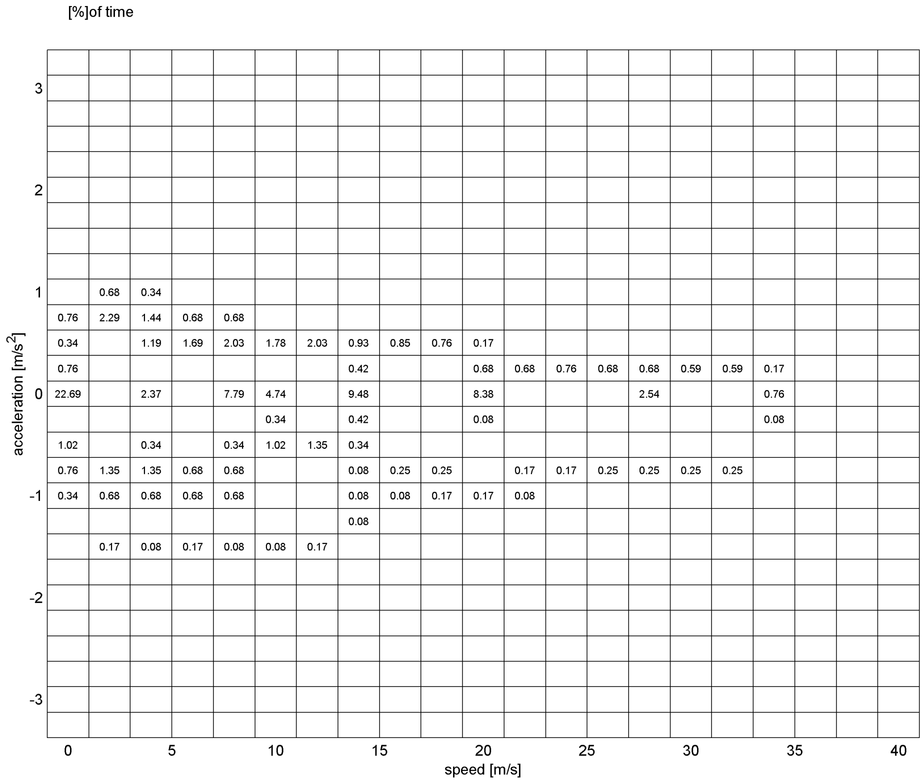

Figure 2.9-5: Relative frequency of acceleration over speed for the modified NEDC (EN 1986-1)

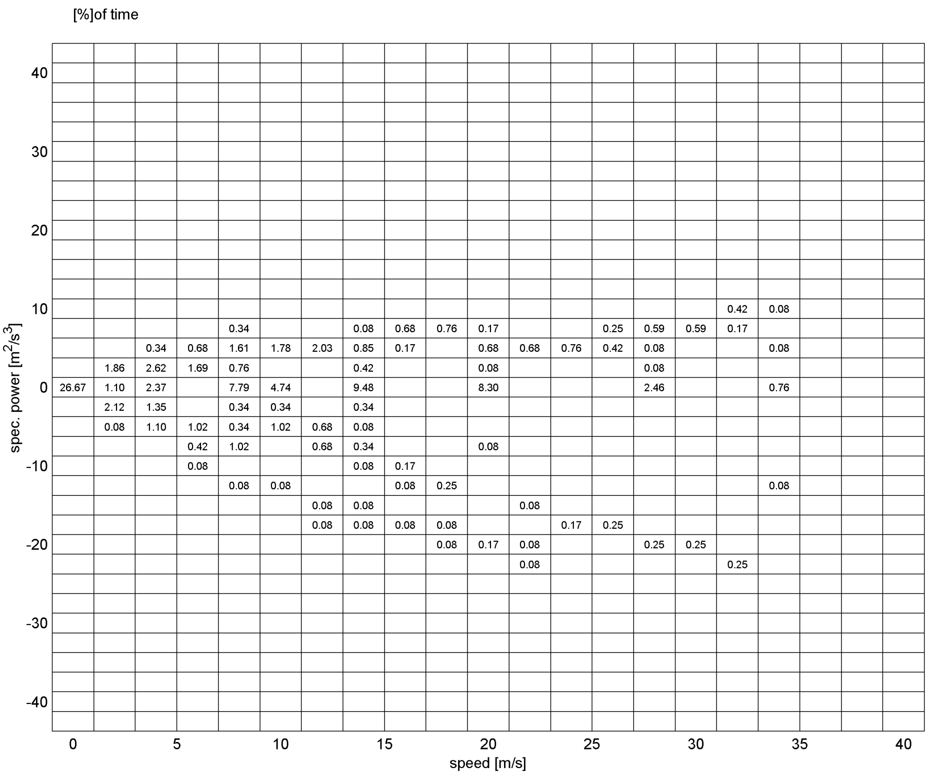

Figure 2.9-6: Relative frequency of specific power over speed for modified NEDC (EN 1986-1)

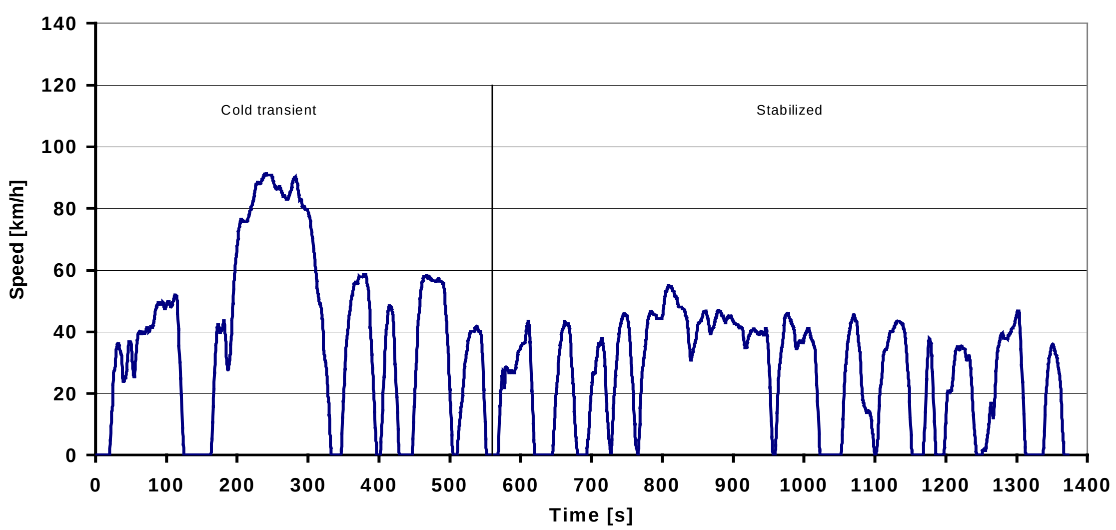

Figure 2.9-7: Speed profile of the UDDS

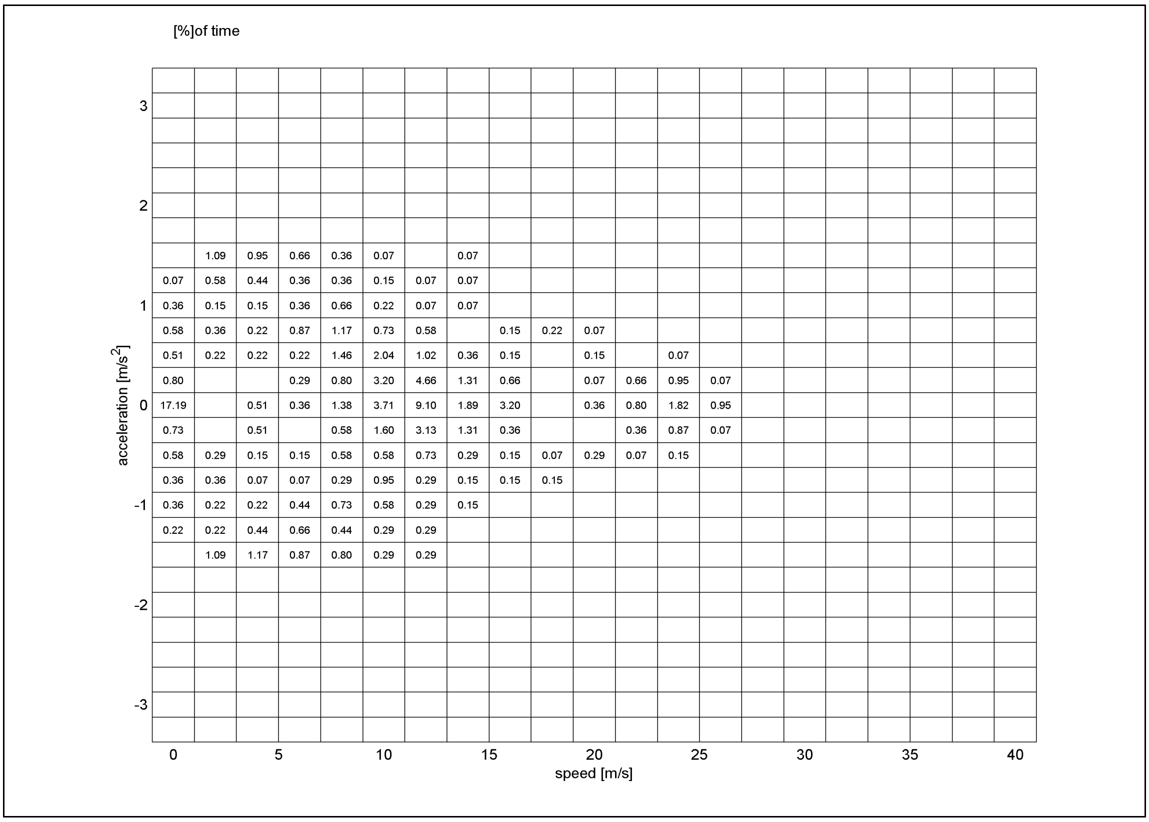

Figure 2.9-8: Relative frequency of acceleration over speed for the UDDS

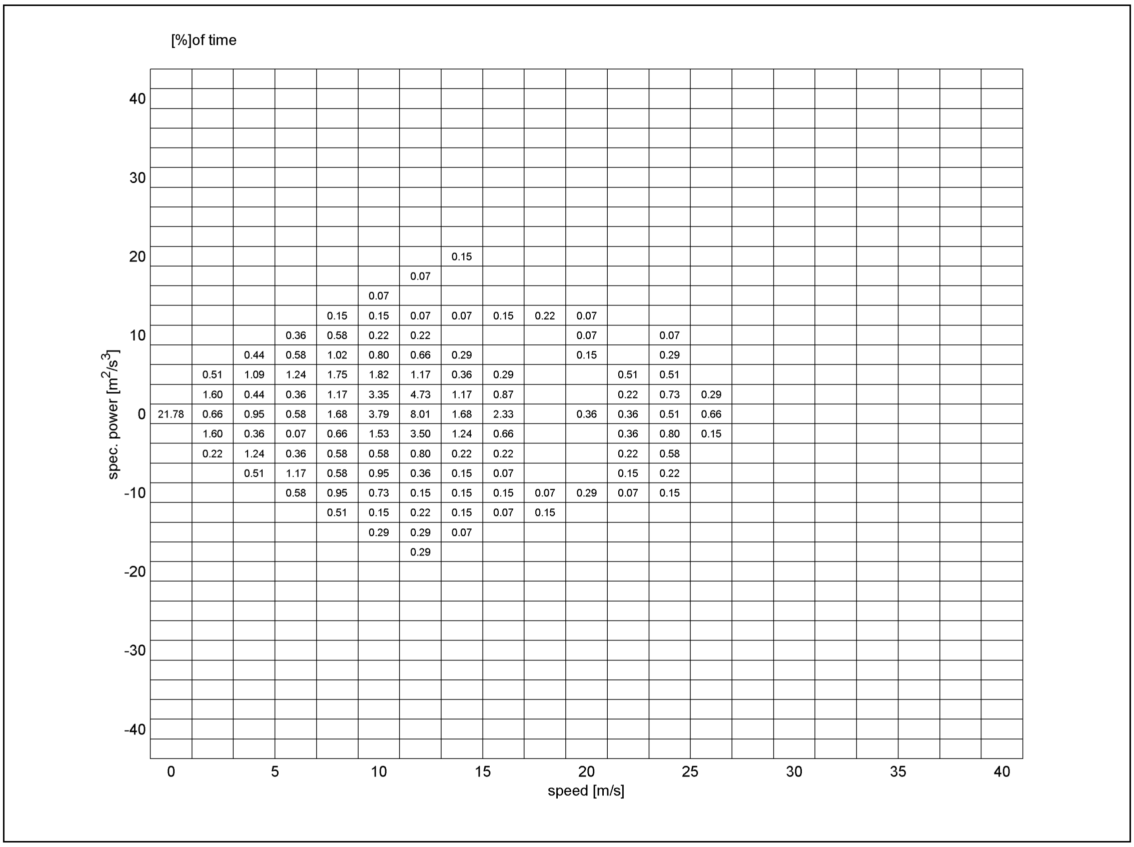

Figure 2.9-9: Relative frequency of specific power over speed for the UDDS

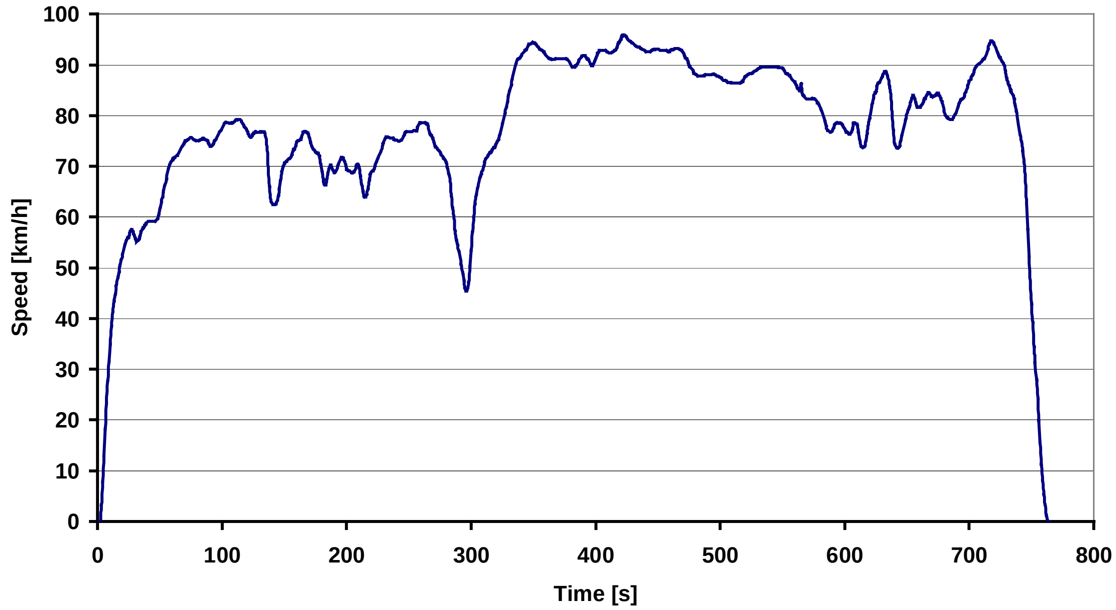

Figure 2.9-10: Speed profile of the HWFET-cycle

[%]of time

acceleration [m/s²] \ speed [m/s]	0		5			10		15			20		25			30		35			40
3																					
2																					
			0.13	0.13																	
		0.13		0.13	0.13																
1	0.13				0.13	0.26		0.13	0.13												
							0.13	0.26	0.13												
	0.13						0.39	0.13		0.59	0.13	0.39									
							0.13	0.65	1.18	2.02	5.68	4.11	3.79	2.02							
0	0.46						0.13		2.09	0.65	9.67	13.46	13.06	20.18							
	0.13						0.13	0.26	0.52	0.52	1.96	2.87	2.35	1.70							
	0.26							0.39	0.26	0.52	0.78	0.91	0.13								
		0.26							0.13	0.26	0.13	0.13	0.13								
-1			0.13	0.13	0.26	0.13	0.13				0.39	0.13									
			0.13	0.13		0.13		0.13													
								0.13	0.13	0.13											
-2																					
-3																					

Figure 2.9-11: Relative frequency of acceleration over speed for the HWFET-cycle

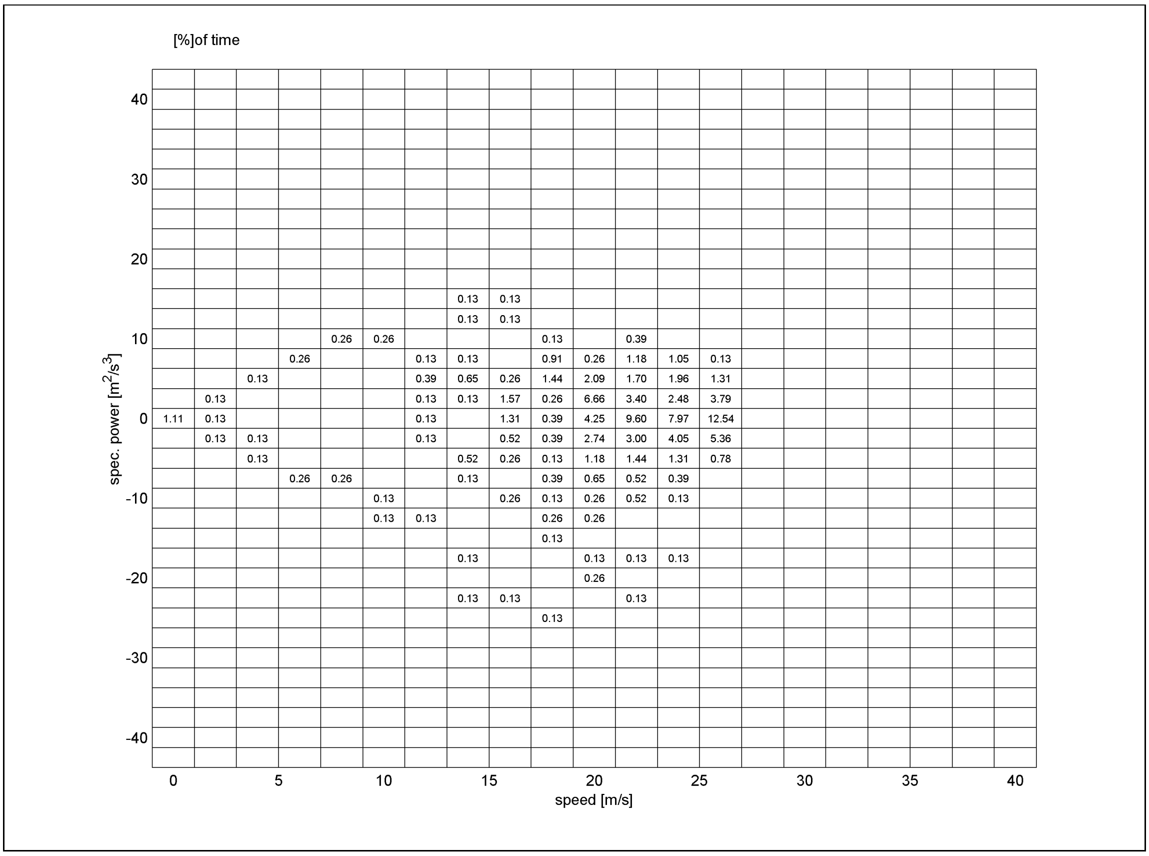

Figure 2.9-12: Relative frequency of specific power over speed for the HWFET-cycle

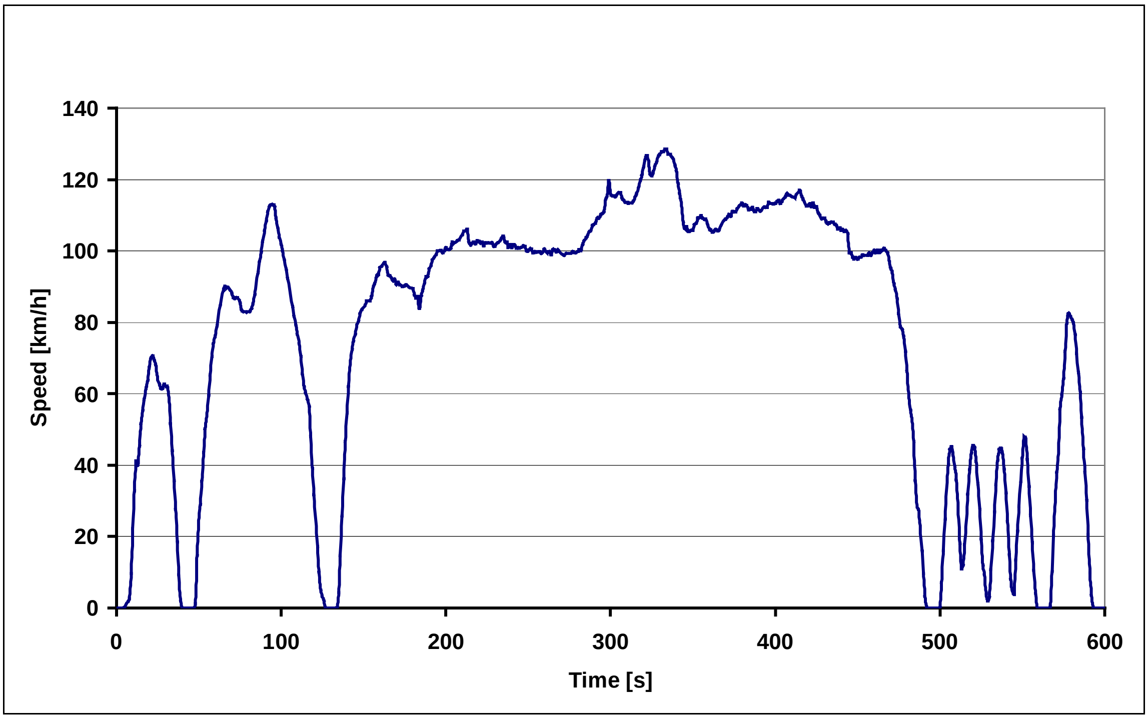

Figure 2.9-13: Speed profile of the US06-cycle

[%]of time

acceleration [m/s^2]

			0.17	0.17																	
3			0.17		0.17	0.17															
		0.33		0.17		0.17															
			0.33	0.17	0.17		0.17	0.17													
		0.33		0.17	0.17				0.17		0.17										
2	0.17	0.17		0.50	0.33	0.83	0.17		0.17	0.17											
			0.17		0.17		0.33			0.17											
	0.17					0.17	0.17	0.33	0.17	0.17	0.17	0.17									
	0.17	0.17					0.17		0.33		0.17										
1	0.33		0.17				0.33		0.17												
							0.17	0.17	0.17	0.50	0.33	0.50	0.50	0.33	0.50	0.33	0.17				
	0.17						0.33				0.33	0.50	1.00	0.67	0.17		0.67	0.67	0.17		
	0.67						0.17			0.17			1.33	1.33	3.00	3.66	3.00	0.33	0.33		
0	6.49									0.33	0.17		1.50	2.50	13.31	4.49	6.82	0.33	0.83		
	0.33						0.33			0.17	0.17	0.50	1.00	0.50	2.00	2.33	1.66		0.67		
	0.83	0.17							0.33	0.33		0.17	0.67	0.50	0.50	0.17	0.50	0.33			
			0.17		0.17		0.50			0.33	0.17	0.83	0.33	0.67	0.50	0.67	0.17	0.50			
-1		0.33			0.17		0.17	0.17	0.17		0.17		0.33			0.17	0.17				
	0.33	0.17						0.17		0.17	0.33	0.17									
	0.17	0.33	0.17			0.17	0.17		0.50	0.17	0.17										
		0.33	0.17	0.17		0.33			0.17	0.17											
-2		0.17	0.17	0.17	0.17	0.33	0.17	0.17													
		0.17	0.17	0.50	0.33	0.50	0.33	0.17													
		0.17		0.33	0.50	0.17		0.33													
				0.17																	
-3																					

0 5 10 15 20 25 30 35 40

speed [m/s]

Figure 2.9-14: Relative frequency of acceleration over speed for the US06-cycle

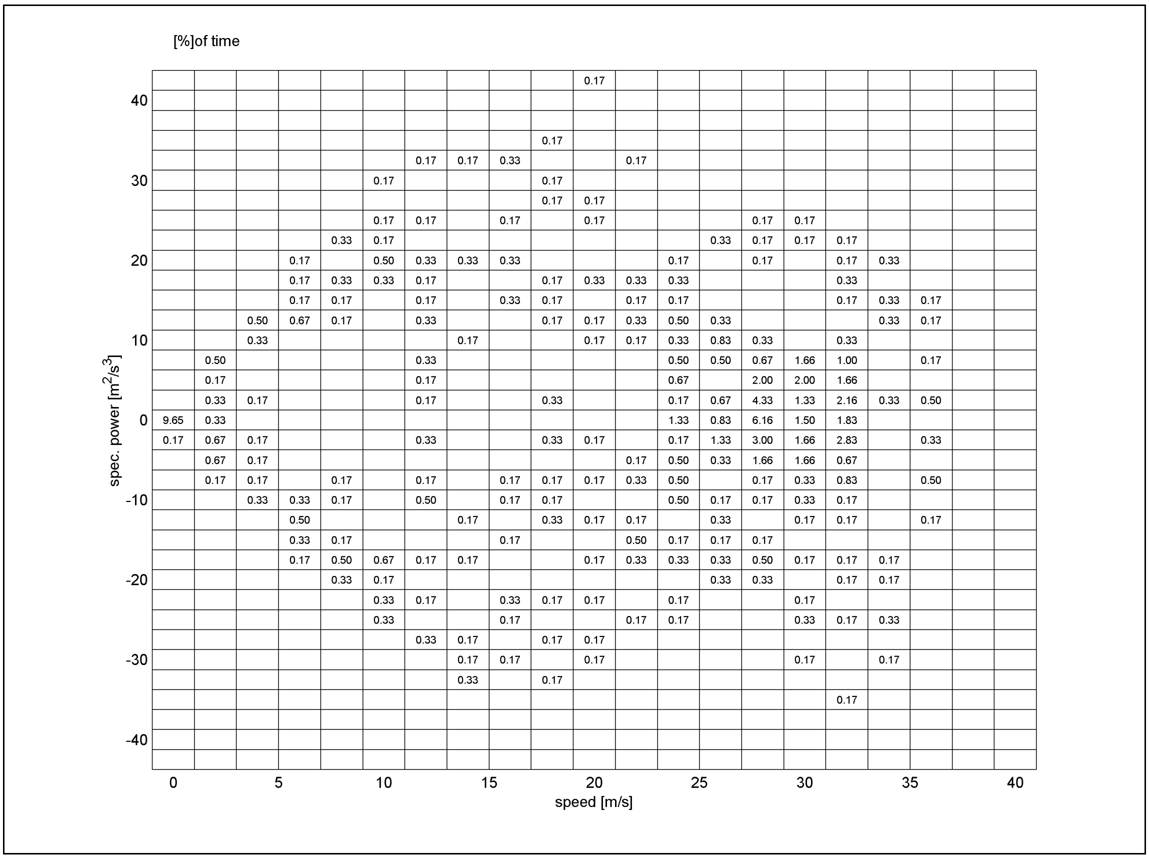

Figure 2.9-15: Relative frequency of specific power over speed for the US06-cycle

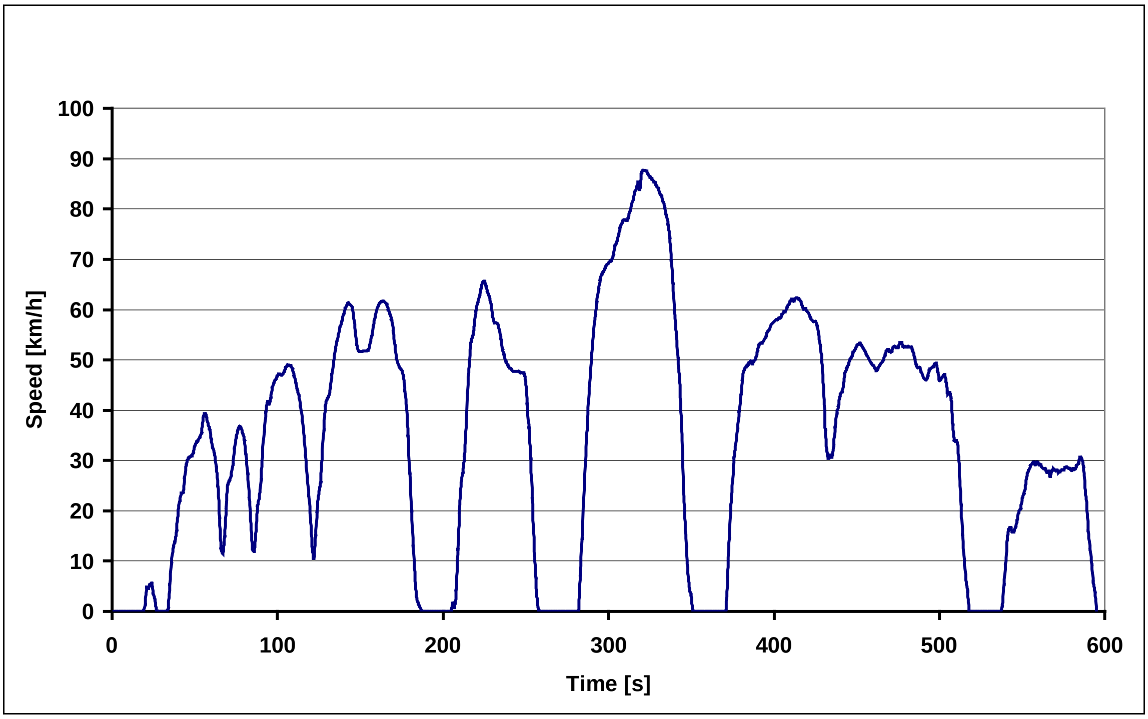

Figure 2.9-16: Speed profile of the SC03-cycle

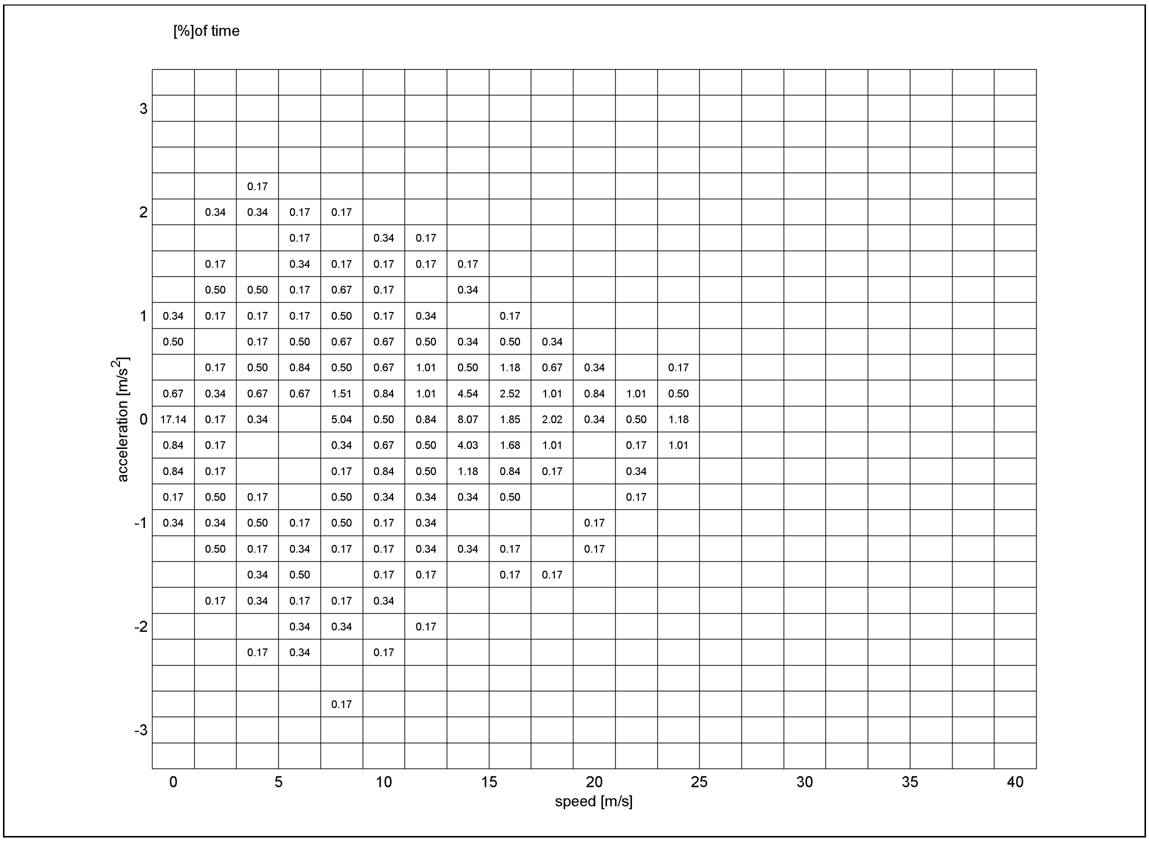

Figure 2.9-17: Relative frequency of acceleration over speed for the SC03-cycle

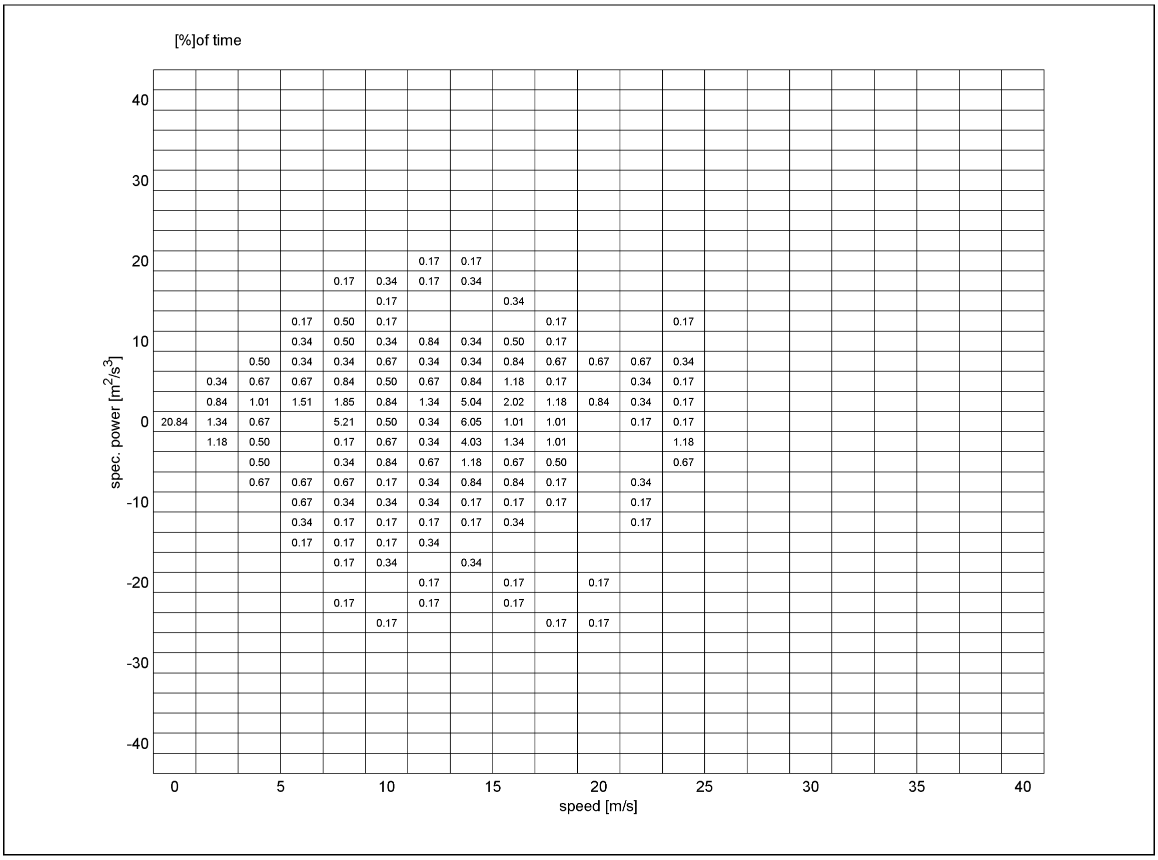

Figure 2.9-18: Relative frequency of specific power over speed for the SC03-cycle

Depending on the structure of a hybrid vehicle, the power in electric mode can be relatively low, compared to conventional vehicles. Especially with parallel hybrid drives, the installed electric power is often significant lower than the power of the thermal engine. Looking at the US06 cycle, the needed power increases up to 40 W/kg, meaning that for a hybrid vehicle of example 1500 kg the electric motor must deliver about 60 kW power to the wheels. The maximum specific power needed in the NEDC or ECE is about 10 W/kg, which is also significant lower than the power needed to follow the UDDS or HWFET with about 20 W/kg respectively 15 W/kg. So it is obvious, that most of the parallel hybrid vehicles in pure electric mode will fail to follow the US06 within the tolerances from the beginning despite the fact of possible fully charged batteries. Thus the recommended test in the US06 in pure EV-mode, as foreseen in SAE J1711, may not be applicable for most of the (parallel) hybrid vehicles. Also for series configurations, where the electric motor is much more powerful, because it is the only motor which delivers power to the wheels, this can be the case. The limiting factor in a series hybrid vehicle in pure EV-mode is often the power available from the batteries. To get the full performance to follow such high dynamic cycles as the US06, the APU must be started, which is not allowed in EV-mode.

This problems concern not only the applicability of the procedure but also the question of how representative for real life are the given cycles.

Another difference is the used test weight. In EN1986 it is curb weight plus 100 kg, whereas SAE J1711 and CARB use a test weight equal to the curb weight plus 136 kg. The resulting influence on energy consumption of 36 kg weight difference may negligible compared to other uncertainties resulting of the complexity of hybrid drives with different operating modes.

Of more significance is the influence of different recharge times. In the EN1986 the recharge time is at minimum about 18 hours, where SAE states 12 hours. For battery systems with high standby losses, as with high temperature batteries are systems which needs a permanent sustaining charge, there is a difference of 6 hours in time, during such losses occurs. An example for this influence can be found in chapter 3.1, where the tests with an electric vehicle with a high temperature battery are described.

2.9.1 Vehicle preconditioning

The vehicle preconditioning has an influence on the energy consumption and the reproducibility of the measurements. Besides establishing a specific state of charge prior to the test, which is a specific task for electric and hybrid vehicles, the preconditioning foreseen in the procedures is equal to that of conventional vehicles. Thus by storing the vehicle during the charge (longer than 12 hours) at ambient temperatures, all components as tyres, gearbox and the engines reach at least the ambient temperature. During the tests, the components warm up and the losses, which are often some effect of friction and lubrication, decrease due to the fact that the lubricants become more viscous with rising temperatures. For the tyres it can be said, that the rolling resistance of the tyres decrease also with rising temperatures.

ENEA has investigated the influence of tyre temperatures and pressure on the rolling resistance. The results are shown in the following chapters 2.9.1.2 and 2.9.1.2.

For these tests, the vehicle has been positioned on a roller bench, with the motor in neutral. Then the roller bench has been started, in a constant speed running mode. The considered resistance components are therefore:

– Bearings friction and transmission load coefficient of the rolls mechanics
– Rolling resistance coefficient of the tyres on the rolls

– Vehicle transmission load coefficient

The rolling resistance of the bench dynamo (brushes, bearings) has not been accounted for. The tests have been performed on January 1999, on the electric vehicle FIAT 500, with GOOD YEAR tyres, GT Electric 145/80 R 13 79 Q model, the curb-weight was 1290 kg.

2.9.1.1 Tyre temperature dependence

The working pressure in the temperature tests was established at 2.9 atm. The test results, rolling resistance in Newton, are reported below and in the related figures.

Table 2.9-1: Rolling resistance at various speeds

				Rolling resistance in Newton at various speeds					
Time (min)	**T in °C, Sidewall**	**T in °C, Tread**	**T in°C, Ambient**	**10 km/h**	**20 km/h**	**30 km/h**	**40 km/h**	**50 km/h**	**60 km/h**
0	8.4	8.4	11	165.5	180.5	186.5	192.5	196.5	200.5
25	19.3	25.2	12	149.5	163.5	172.5	179.5	182.5	186.5
40	20	26.7	13	149.5	161.5	169.5	179.5	182.5	186.5
60	20.4	26.2	14	143.5	155.5	165.5	171.5	177.5	180.5
80	20.5	27	14	147.6	159.6	167.6	173.6	177.6	182.6
100	21.6	26.6	14.5	141.6	151.6	161.6	167.6	171.6	176.6
120	22.7	28	14.5	141.7	153.7	161.7	167.7	171.7	174.7
130	22.5	28.8	14.2	141.8	151.8	159.8	167.8	171.8	174.8

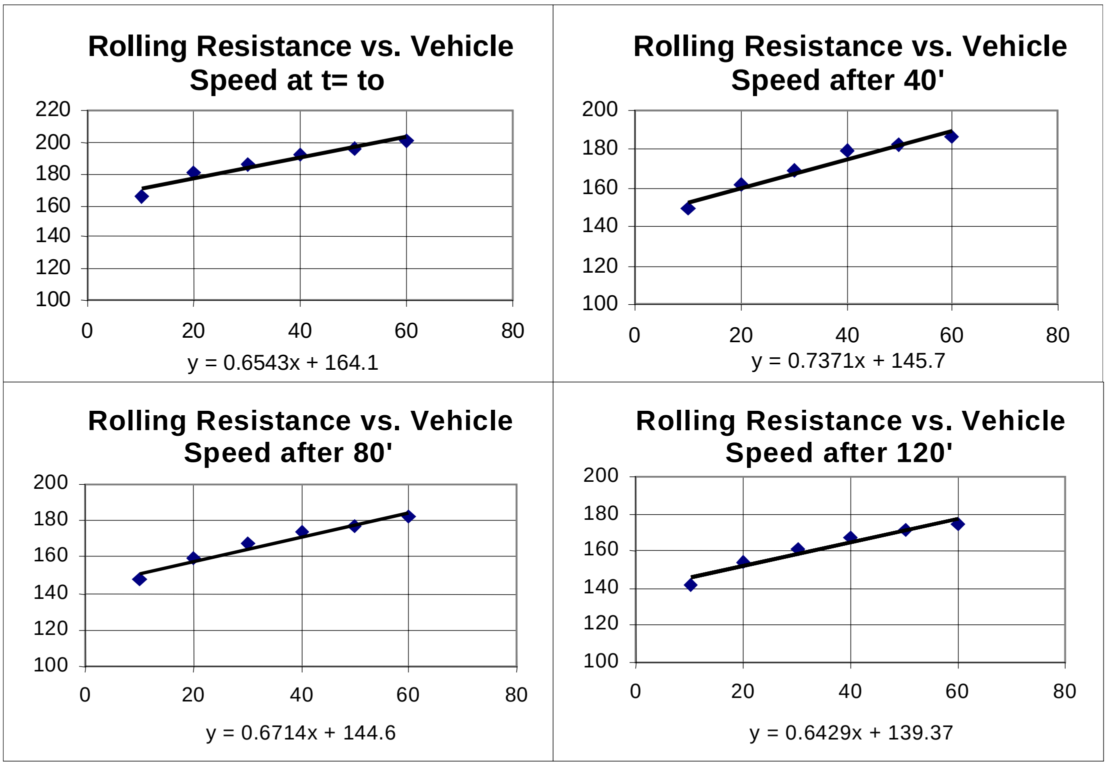

Figure 2.9-19: Rolling resistance vs. time

The rolling resistance parameter is subjected during the warming time to variations of about 13÷14%, then the values become quite constant, with differences remaining in the range of 3÷4%. To assure repeatability of the test, the sidewall tyre temperature and the tread temperature should be stabilised, exceeding the ambient temperature of 7÷8 °C and 14 ÷15 °C respectively, as shown in the figure below.

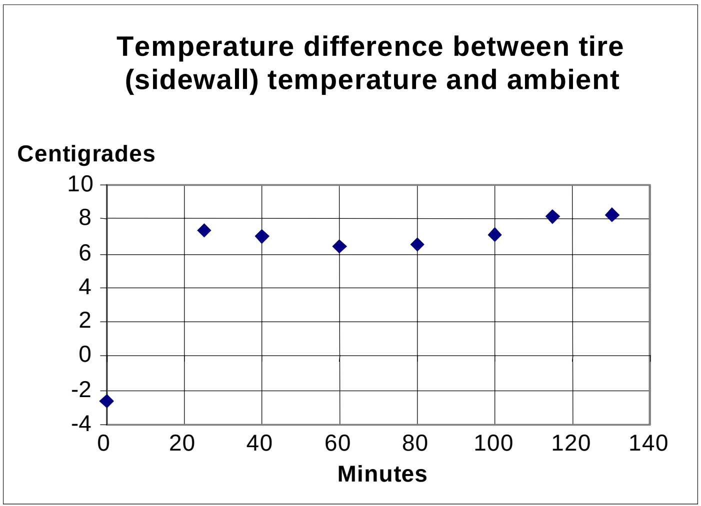

Figure 2.9-20: Temperature difference between tire (sidewall) temperature and ambient

2.9.1.2 Tyre pressure dependence

The second test block has been performed recording periodically the losses at different speeds, then changing the tyre pressure. During such tests the ambient temperature increased from 9.8 °C to 13.8 °C; the tyre (sidewall) temperature increased from 17.4 °C to 27.4 °C; the tread temperature increased from 23.7 °C to 30.7 °C.

Table 2.9-2: Rolling resistance in Newton at various speeds

	Rolling resistance in Newton at various speeds					
Pressure	**10 km/h**	**20 km/h**	**30 km/h**	**40 km/h**	**50 km/h**	**60 km/h**
3.2	148.6	161.6	169.6	177.6	178.6	180.6
3.0	150.6	163.6	172.6	177.6	180.6	182.6
2.8	150.7	164.7	170.7	175.7	180.7	182.7
2.6	150.9	162.9	170.9	176.9	178.9	182.9
2.4	155.7	168.7	176.7	180.7	186.7	188.9
2.2	153.9	167.9	174.9	178.9	182.9	186.9
2.0	162.9	174.9	184.9	188.9	194.9	194.9
1.8	165.9	178.8	186.9	194.9	198.9	200.9
1.6	176.8	190.8	199.8	205.8	208.8	210.8
1.4	179	193	204	211	213	214
1.2	198.8	213.8	222.8	228.8	231.8	233.8

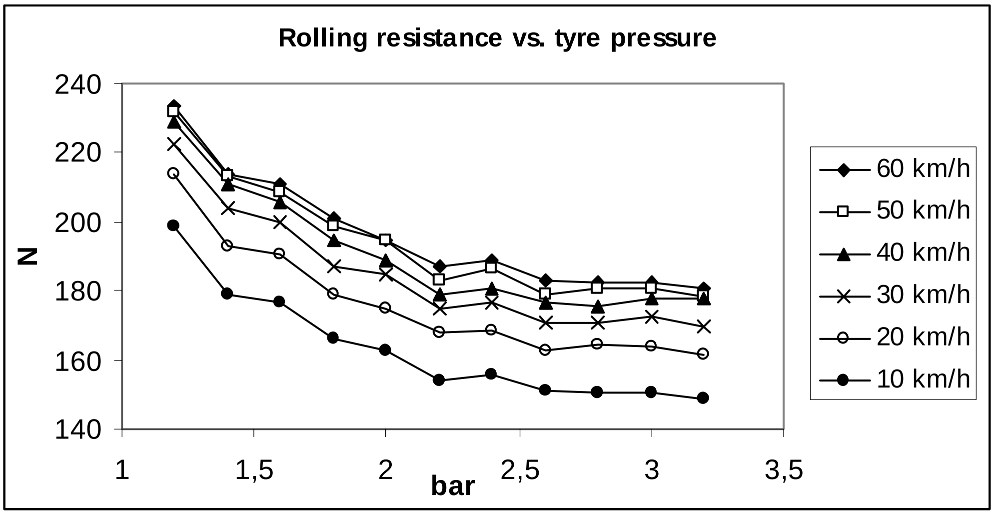

Figure 2.9-21: Rolling resistance vs. tyre pressure

As expected, the tests pointed out that the tyre pressure sensibly affects rolling resistance. Changing it, 34 % variations have been obtained. The strongest variation was in the range 1.2÷2.4 bar; then the latter value is suggested as the minimum pressure value allowed.
To reach the required temperature stabilisation, a warming time of about 30 minutes is sufficient; for this reason, a vehicle warming-up procedure has been introduced in the ENEA procedure for roller bench testing.

As expected and this is common to conventional vehicle, the rolling resistance decrease with temperature and pressure. During running a test, the tires heat up thus reducing the rolling resistance of about 13 – 14 %.

To achieve a good reproducibility the pressure of the tires before testing should be carefully monitored and settled to the given value to perform the test on a dynamometer. The temperature should be the same before every test by storing the vehicle at controlled constant ambient temperatures. The existing standards ensure this already, because the vehicle has to be stored at least for the required recharge duration at ambient temperatures.

In the point of view of the authors of this report, in contrary to the recommendation by ENEA, a vehicle warm-up is not necessary. If the pressure and temperature of the tyres is the same before each test, the influence of the warming up processes of the tires is the same every time a test is performed.

Additionally, in case of a warm-up of the vehicle is performed prior testing, this falsifies the result in comparison to conventional vehicles, which are tested without any warm-up, by lowering artificial the load. So an energy consumption measured with a warm-up procedure performed prior to testing would be lower than doing the same test without, extenuating the result.

2.9.2 Influence of failure time

An additional effect, which could have a major influence on the test results, is how to handle the procedure, if the vehicle is not able to follow the speed given in the prescribed driving schedule. One method to analyse the influence of the problem, that the performance of the car is lower than desired, is the method of measuring the failure time (FT). This is the amount of time, for which the vehicle was not able to follow the driving cycle.

Investigations on this topic have been performed by HTA Biel by tests and TNO by simulation (See Subtask 2.10). The investigations performed show, that the failure time has an influence on the energy consumption. Vehicles which are not able to follow the demand, would be operated during the failure time at their power limits with normally reduced efficiency compared to the normal operating range with middle loads, leading to higher energy consumption compared to a vehicle, which has the same characteristics (weight, rolling resistance etc.) but higher power. So, the lower the power of the electric motor is, the greater FT becomes and the longer the electric motor operates with low efficiency leading to higher consumption.

Nevertheless, with a given vehicle, the behaviour of the vehicle in a cycle is fixed, thus the testing institute has no influence, if FT occurs or not. Regarding the applicability of test procedures it is easy to evaluate the failure time afterwards of a test by simple comparing the actual speed profile with that of the driving cycle, considering that also a shifting process could be the reason for a speed deviation. Therefore this method is easy to apply for the testing institute.

The existing and draft standards only demand, that the times, when the vehicle cannot follow the cycle, are recorded. But they make no difference between normal deviations from the desired speed profile during shifting and deviations caused by lack of power. Additionally, prEN 1986-1 allows deviations of each maximum 5 s for five times during one hour. So a detailed definition of FT should include a clear statement how to handle deviations caused by shifting. In the understanding of the authors FT should not include the times caused by shifting.

Additionally, if FT occurs for a specific vehicle, it gives a hint, that the energy consumption may be relatively high.

To overcome this effect, and as mentioned before, the EN 1986-1 provides for the measurement of the energy consumption two possibilities: Measurement in the ECE cycle with speeds up to 50 km/h and measurement in the NEDC-cycle with speeds up to 120 km/h. So the existing standard EN 1986-1 allows to use a cycle, which fits better to the characteristic of a BEV intended for urban use. In the SAE standards, one can not chose between different cycles for measuring the energy consumption. The foreseen cycles partly consist of sections with high speeds exceeding 80 km/h. In the case of a BEV with low power or a hybrid vehicle in EV-mode one must expect the occurrence of failure time. The effect would be an increase of energy consumption. If this is a falsification of the result, which worsens the judgement of such a vehicle, is not a question of the applicability of the testing method, but a question how representative is the used driving schedule for such a vehicle.

3 Investigation of applicability by tests

To investigate the applicability of the different test procedures tests with a pure electric vehicle (VW Bora with ZEBRA battery) and with a hybrid vehicle (Audi DUO) have been performed at the ika. The results are given in the following chapters.

3.1 VW Bora with ZEBRA-battery

At the ika in Aachen, a Volkswagen Bora electric vehicle with ZEBRA-battery was tested for MATADOR on the dynamic rollerbench test facility (see Figure 3.1-1). All necessary data were measured with appropriate acquisition equipment.

Vehicle data:

Vehicle type:	Volkswagen Bora EVENT
Vehicle weight:	1530 kg
Electric motor:	Bosch asynchronous, 50 kW, 190 Nm
Battery:	ZEBRA Z10 ml3 115 cells of 96 Ah in series, three branches in total nominal voltage 297V weight: 318 kg

Performance:

0 - 50 km/h:	5.7 s
0 - 80 km/h:	12.4 s
0 - 100 km/h:	21.3 s
vmax:	123 km/h

Figure 3.1-1: Volkswagen Bora electric vehicle on the dynamic rollerbench of the ika

Since ZEBRA batteries for traction applications have system-inherent high self-discharge losses, this topic had to be examined in particular.

3.1.1 Testing procedures

For vehicles with electric propulsion and battery energy storage device, in the United States of America the SAE standard J1634 is used. This procedure uses the highway fuel economy test (HWFET) and the Urban Dynamometer Driving Schedule (UDDS) as driving cycles. In Europe, the testing and homologation procedure for such vehicles is layed down in EN 1986-1, which enables the testing engineer either to use the European urban driving cycle (ECE) of the New European Driving Cycle, which is a combination of the ECE and the Extra Urban Driving Cycle (EUDC). The first one can be used for typical city vehicles with low maximum speed; the latter can be used for vehicles with higher maximum speeds.

3.1.2 Vehicle coast down

In both standards a coastdown of the vehicle has to be performed in order to determine the road load of the vehicle, which serves as an important input for vehicle installation on the testbench. The standards both provide a procedure, which describes how to determine the road load power, which then is entered together with the test weight into the rollerbench. For each velocity interval, the power of the electric motor of the rollerbench has to be adjusted in order to reach the same average deceleration value on the bench as on the road.

At ika, a type of rollerbench is used, which enables the testing engineer to enter the coast down curve directly into the test bench computer by defining the speed intervals and the according duration of deceleration. With these values and the vehicle weight, the computer calculates an initial polynom for the road load. After that, an automated multi-coastdown iteration process can be started, in which the initial polynomial values are adjusted in order to match the road measured coast down curve accurately. The coastdown curve of the electric Bora is shown in Figure 3.1-2.

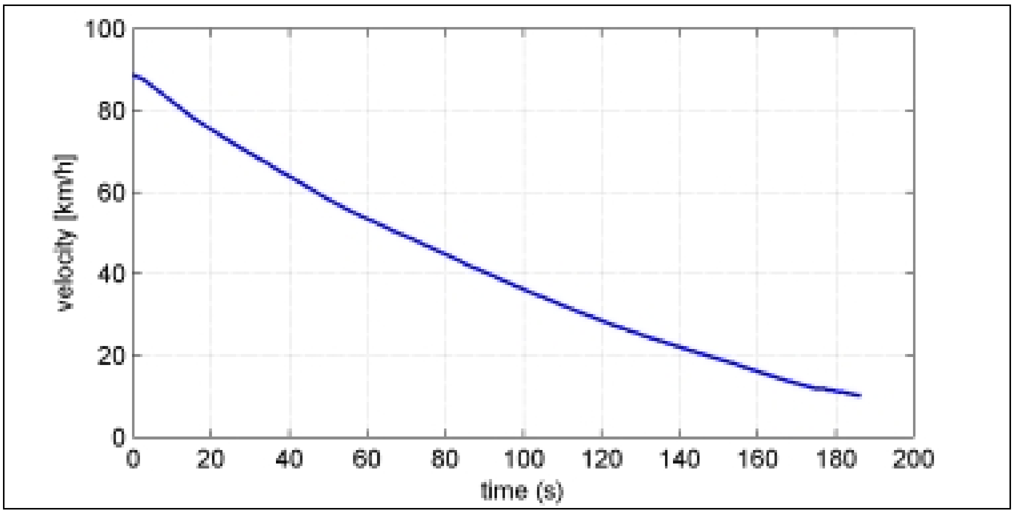

Figure 3.1-2: Coast-down curve of the VW Bora electric vehicle

3.1.3 Energy measurements

After the installation of the vehicle on the test bench, the vehicle is prepared for the measurement procedure. In SAE J1634, the vehicle has to be soaked before each test at ambient temperature for at least 12h and a maximum of 36h while having the battery charger connected to the mains, until the state of charge of the battery has reached 100%. In EN 1986-1, no such soak period is part of the test. Instead, at the arrival of the vehicle an initial charging procedure is prescribed, in which the battery is being discharged by driving a constant velocity of 70% of the 30 minutes maximum speed as describes in EN 1821-1. After the initial discharge, the battery is charged according to the usual charging procedure, which should be used also before all subsequent tests.

In Table 3.1-1 the values of energy consumption are shown. All tests are driven with the motor recuperation switched on, except for one measurement of the NEDC. In SAE J1634, the procedure defines recuperation possibilities to be enabled. In EN 1986-1, this is not defined. Therefore a difference in the measured energy consumption can occur. As can be seen, the distance related DC energy consumptions of the battery differ about 12% (HWFET vs. NEDC).

Without including the recuperative energy, the differences among the cycles amount to a maximum of 20% (HWFET vs. UDDS), which derives from the few deceleration phases in the HWFET. The NEDC and UDDS instead have a typical start-stop characteristic (more recuperative energy), which leads to bigger differences if comparing energy consumption with and without recuperation possibility.

Table 3.1-1: Energy consumption of the VW Bora electric vehicle

cycle/procedure	HWFET/SAE J1634	UDDS/SAE J1634	NEDC/EN 1986-1	NEDC/EN 1986-1 recup. switch off	NEDC/EN 1986-1 range test
driven distance [km]	33.992	24.054	22.129	22.049	177.458
DC battery energy during test [Wh/km]	123	138	140	163	133
DC battery en. without recuperation during test [Wh/km]	132	165	161	163	156
AC charging energy (without heating) [Wh/km]	163	187	172	212	174
total AC energy from mains [Wh]	7390	6663	7710	8690	31990
AC energy consumption according to procedure [Wh/km]	217	277	348	394	180
remarks to charging procedure	12 h connected to mains	12 h connected to mains	24h between charge-plug disconnection before and after test	24h between charge-plug disconnection before and after test	24h between charge-plug disconnection before and after test
HWFET: Highway Fuel Economy Test; UDDS: Urban Dynamometer Driving Schedule; NEDC: New European Driving Cycle					

This start-stop characteristic inevitably leads to a difference in energy consumption, if the recuperation-switch on the electric Bora is on or off. This can be seen in Figure 3.1-3, where the DC battery energy consumption for the NEDC is displayed. In the European standard, the resulting difference in AC charging energy amounts to 23% (without heating); the difference when including heating energy drops to 13% (charging according to standard). Therefore it would be appropriate, if the European standard would stipulate the use of any recuperation possibilities.

When comparing the differences between AC charging energy consumptions (without heating energy) measured from the mains and the corresponding DC consumptions measured at the Battery terminals, it is noticed that the values for the SAE cycles are bigger than the one of the NEDC. This can be explained by the fact that the transient SAE cycles are more battery-demanding than the modal NEDC.

Another important aspect is the total energy consumption (which includes also the energy for battery heating) from the mains when applying the charging procedures defined by the standards.

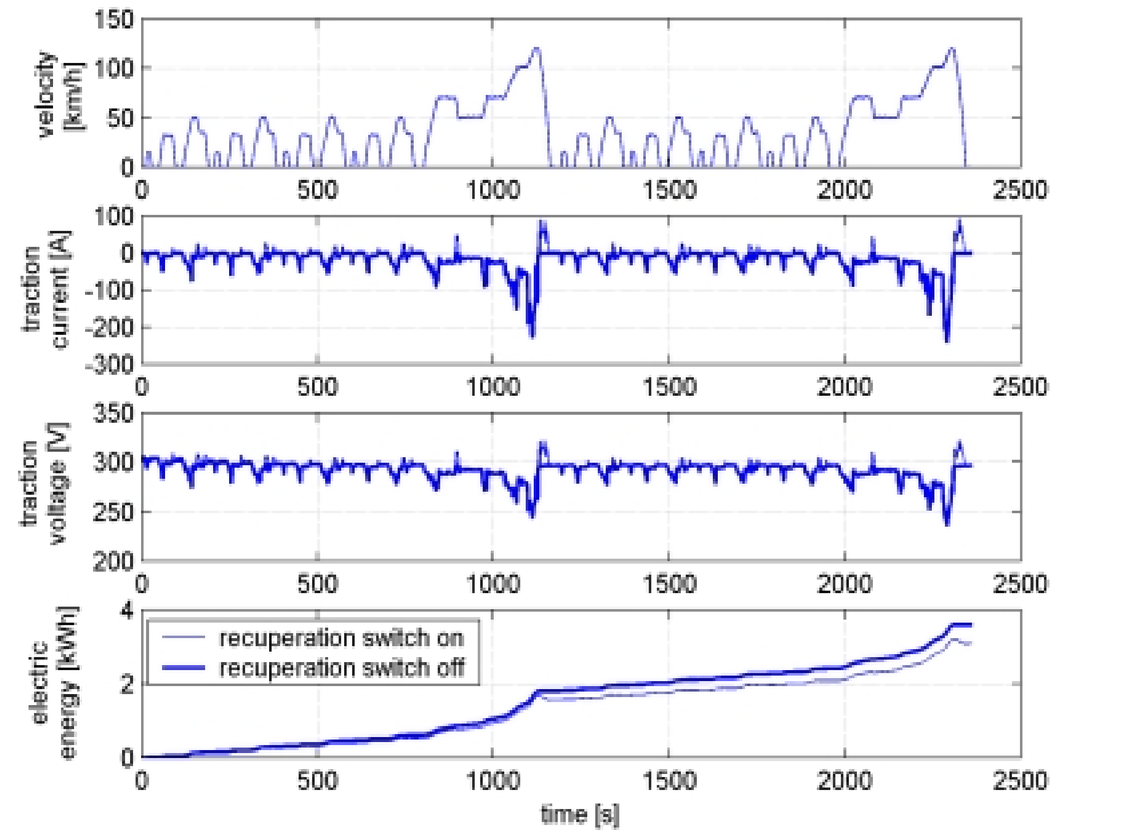

Figure 3.1-3: Time histories of velocity, current, voltage and battery DC energy for the NEDC with and without recuperation

In SAE J1634, a charging period of minimum 12 and maximum 36 hours, stopping the charge if the vehicle indicates fully charged batteries, is stipulated, whereas in EN 1986-1 the period between the charge-plug disconnection before the cycle test and the charge-plug disconnection at the end of the charging period has to be 24 hours. In order to define a minimum charging duration, in the latter the maximum delay between first disconnection and beginning of the driving cycle (4 hours) as well as the maximum delay between the end of the cycle and the charge-plug connection at the beginning of the charge (30 minutes) are stipulated. So the minimum charging period in this standard is 18 hours and 51 minutes in case of the NEDC (39 minutes) and 17 hours and 59 minutes in case of the ECE (91 minutes). For the measurements on the Volkswagen Bora, the charging period was about 22 hours and 45 minutes. In Figure 3.1-4 the charging power and charging energy of the ZEBRA battery are displayed which were measured after three different driving cycles.

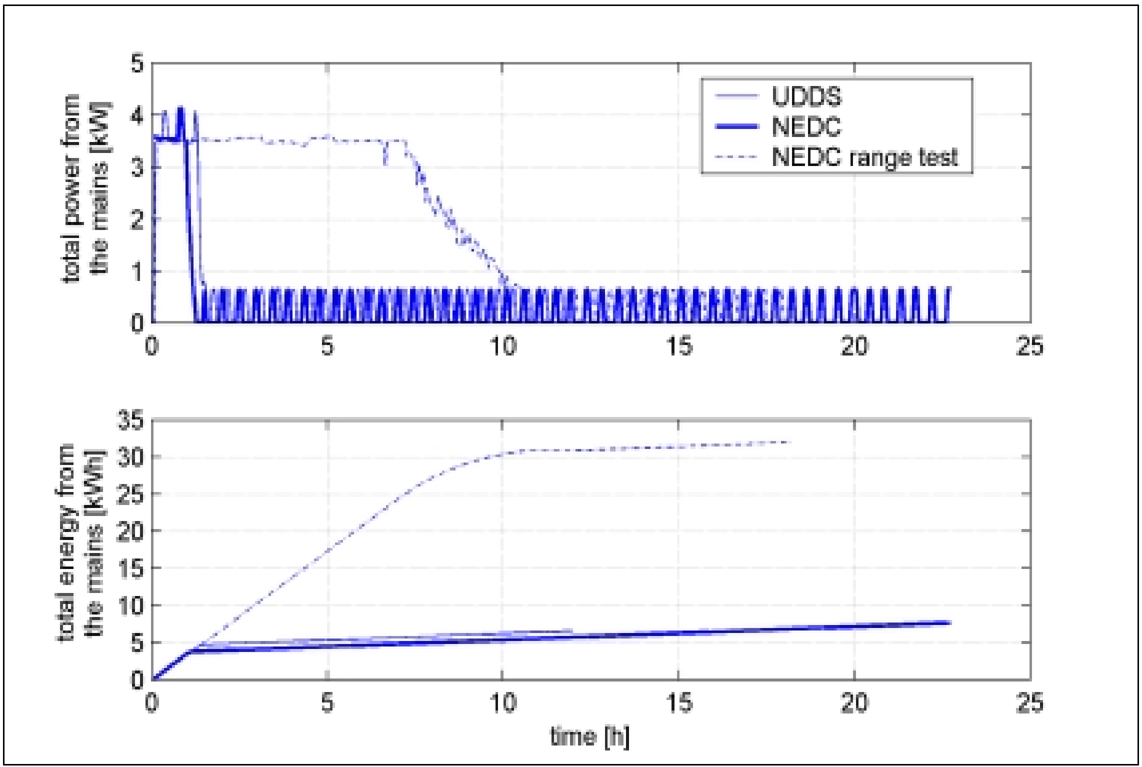

Figure 3.1-4: Time histories of charging power and -energy for UDDS (SAE J1634), NEDC (EN 1986-1) and NEDC range test (EN 1986-1)

Due to these differences in charging time, differences for batteries with high self-discharge losses can be considerably high when comparing energy consumption for SAE J1634 and EN 1986-1. The average of the self-discharge losses of the Z10 Zebra Battery amounts to 180 W, which is either taken from the battery's energy content itself (if not connected to the mains), or from the mains during charging. As can be seen in Figure 3.1-5, the difference in energy consumption between SAE and EN is very high if the heating energy is taken into account, in contrast to the energy consumptions without heating energy. If excluding heating energy, the difference between HWFET and NEDC amounts to 5%, the difference between UDDS and NEDC to 9%. If heating energy is included these differences are respective 38% and 20%. Only for range tests, where the complete energy content of the battery has to be recharged afterwards, the heating part on the total amount of used AC energy has a minor influence on energy consumption. In this respect, the resulting discrepancy between SAE and EN can be considered as (too) high. For comparison reasons it therefore would be recommendable to unify the charging procedure for both standards.

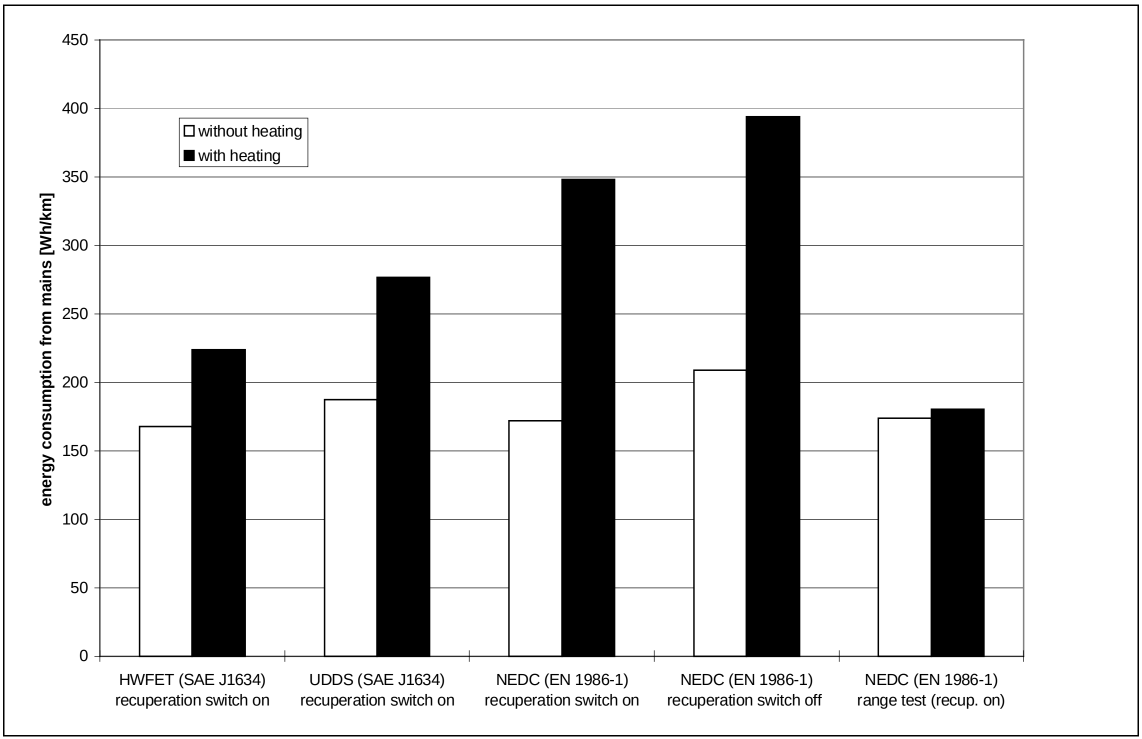

Figure 3.1-5: Comparison of the energy consumption with and without energy for battery heating

3.1.4 Conclusions for testing BEV

The measurement results of the Volkswagen Bora with ZEBRA battery lead to the following conclusions:

EN 1986-1 does not stipulate the use of any recuperation modes. In case of the electric Bora, which has an on/off-switch for the recuperation, this results in a difference in energy consumption of 13% when the vehicle is driven with or without recuperation. Therefore it would be appropriate if the European standard would stipulate the use of any recuperation possibilities, as in SAE J1634. Also, a discrepancy between SAE and EN occurs when comparing their charging durations. In SAE, a charging period of 12 hours to 36 hours is recommended, in the European standard the charging time varies from 18 hours to 23 hours and 20 minutes. For vehicles with high self-discharge losses (as with ZEBRA batteries), this difference results in a difference in energy consumption from 20% (UDDS vs. NEDC) to 38% (HWFET vs. NEDC). If energy consumptions of electric vehicles in a broader sense should be comparable to each other, the charging procedures of SAE J1634 and EN 1986-1 should be unified, using a realistic and representative charging duration. Additionally, an extra measurement of the standstill losses should be introduced into the standards.

3.2 Investigation of the applicability by measurements with the Audi Duo

The Audi Duo was tested at the ika on the dynamometer. As no emission measurement equipment is available at the ika, the tests performed are addressed only to electric energy and fuel consumption.

Figure 3.2-1: Audi Duo on the dynamic roller testbench of the ika

The vehicle data is given below:

Vehicle type:	Audi Duo, based on a conventional A4 Avant
Curb Weight:	1710 kg
Combustion Engine:	1.9 l direct injection turbo charged Diesel engine 66 kW 202 Nm @1900 1/min
Electric motor:	Siemens water cooled synchronous motor 21 kW, 20 Nm, max speed 10000 1/min
Battery:	Sonnenschein Sealed Pb-Gel batteries 22 Modules á 12 V in series nominal Voltage 264 V 7 kWh, weight 320 kg
Transmission	manual 5-speed gearbox with automated clutch, electric motor working on inputshaft of gearbox with an additional gearing of 2.36

Performance:

	Electric	Hybrid
0 - 50 km/h:	10.5 s	
0 - 100 km/h:	-	16.0 s
vmax:	80 km/h	170 km/h

The vehicle has three operating modes: Pure electric, hybrid (default) and thermal mode. The default mode is hybrid mode. This mode is automatically activated at the time the driver starts the vehicle by turning the key switch to on.

In hybrid mode, the battery is depleted during driving. The combustion engine is started at speeds above 80 km/h or at high power demands by the driver. Once the battery is fully discharged, the operational behaviour of the car is badly influenced. Although driving is still possible, the power of the electric motor is to low to accelerate the vehicle adequate. No automatic shifting to ICE mode occurs.

In pure electric mode, once the battery is completely discharged, thermal mode is activated automatically.

In thermal mode, the combustion engine drives the vehicle. But in case the batteries are discharged, charging occurs. Thus this mode is no pure thermal mode as defined in EN1986-2. According to that, the vehicle must be tested in electric und hybrid mode.

3.2.1 Vehicle coast down

Before testing the vehicle on the roller testbench, coast down tests have been performed. The procedure of setting up the dynamometer is the same as described for the VW Bora. The coastdown curve of the Audi Duo is shown in Figure 3.1-2. This curve results from the averaging of several coast down manoeuvres and is taken as input for the dynamic rollerbench.

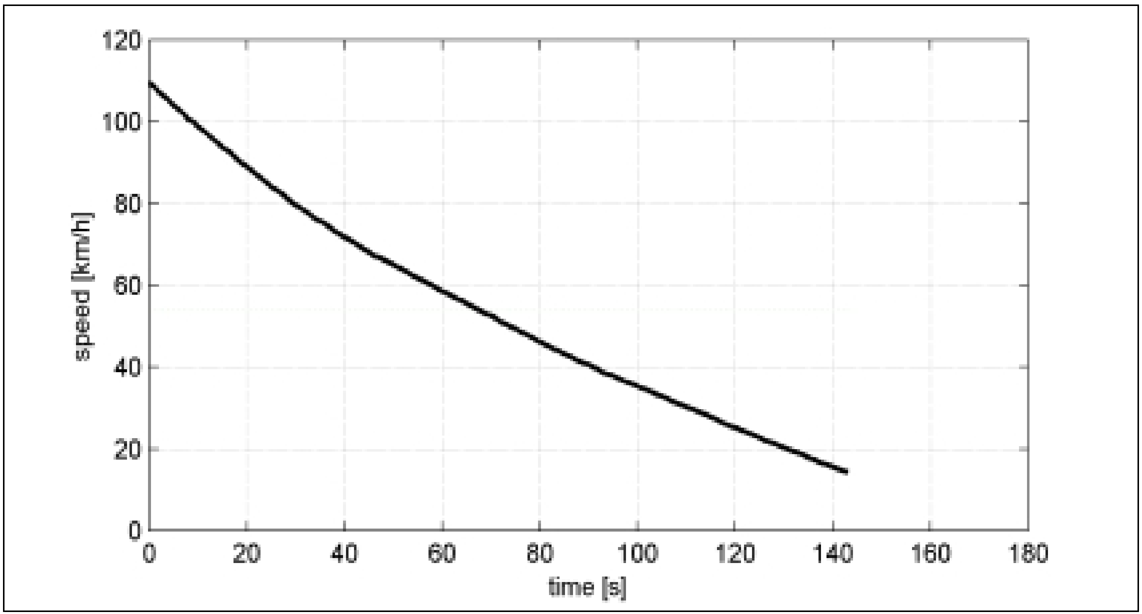

Figure 3.2-2: Coast-down curve of the Audi Duo

3.2.2 Measurement according to prEN 1986-2

The vehicle was tested according to prEN 1986-2 to evaluate the suitability and applicability of this test procedure on the Audi Duo. According to prEN 1986-2 the Audi Duo is a parallel thermal electric hybrid vehicle. The following tests have been performed:

- NEDC range test in electric mode
- NEDC consumption test in electric mode
- NEDC consumption test in hybrid mode
- NEDC test in ICE mode (to verify, that this is no pure thermal mode)

On the following pages, plots for the essential data of the drive system are shown.

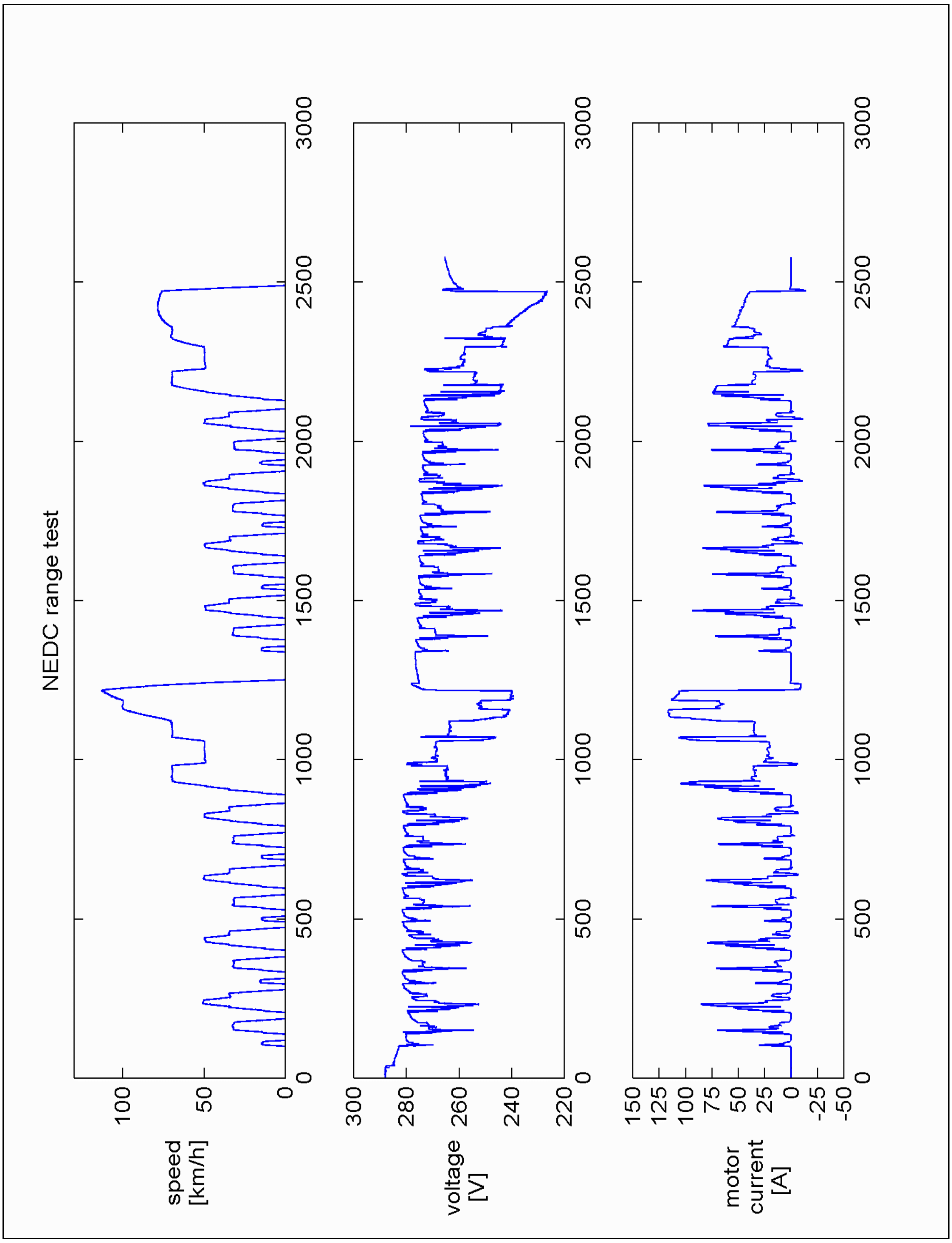

Figure 3.2-3: *NEDC range test in electric mode*

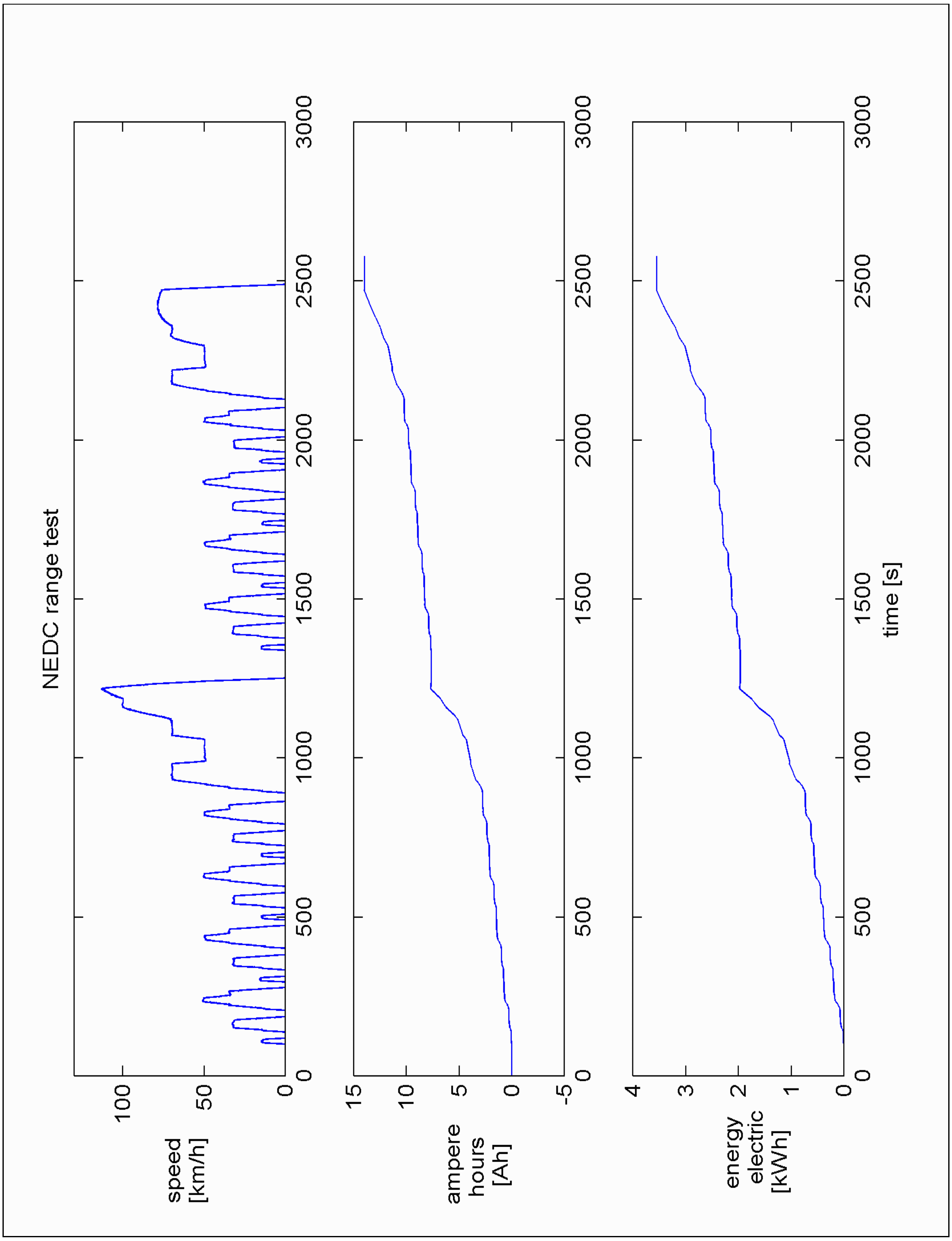

Figure 3.2-4: NEDC range test in electric mode

Since the power of the electric motor compared to the weight of the vehicle is low, the vehicle cannot follow the NEDC cycle at higher speeds. After about 20 km, the vehicle was no longer able to follow the driving cycle. At this time the analogue meter for the state of charge showed 0%.

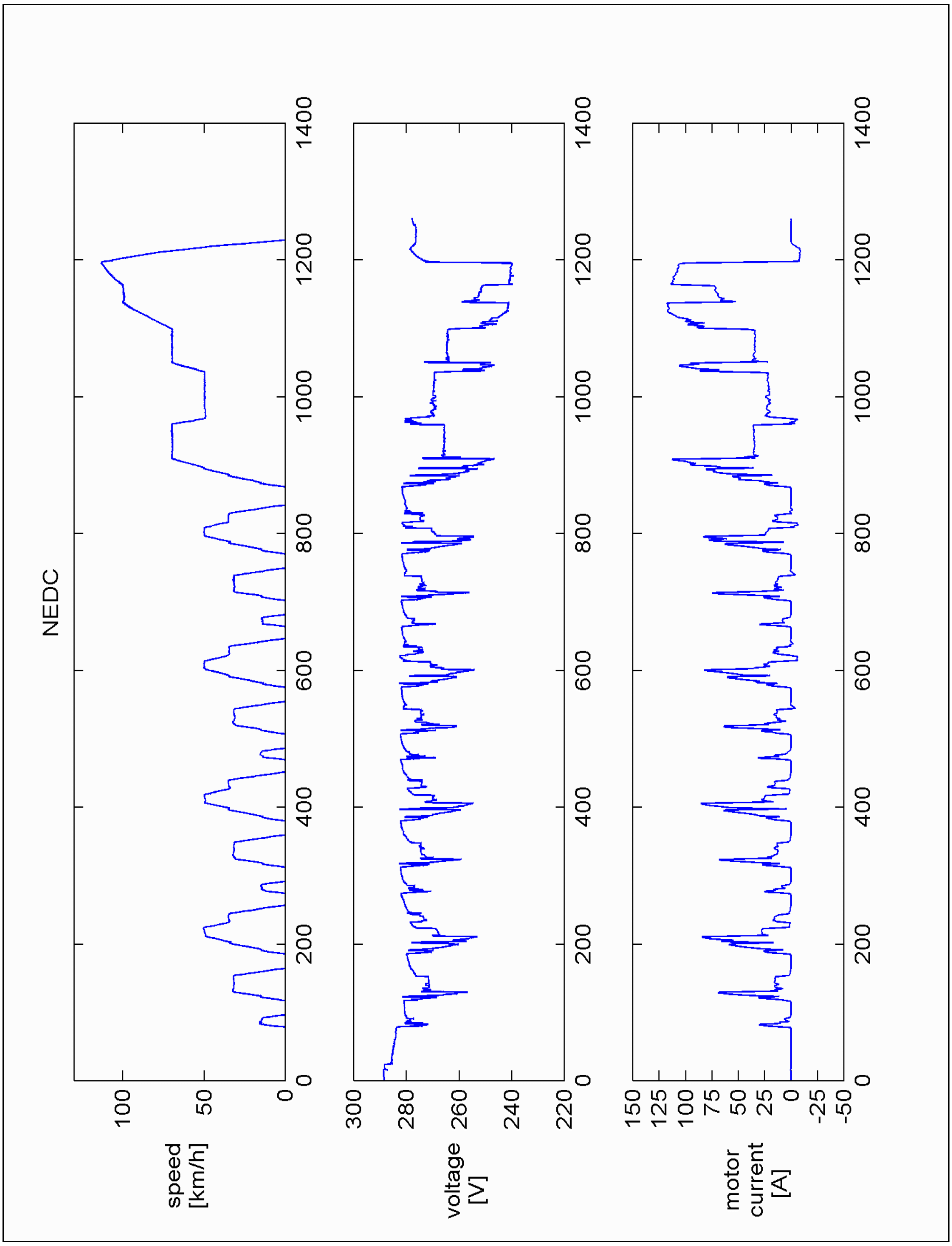

Figure 3.2-5: NEDC energy consumption test in electric mode

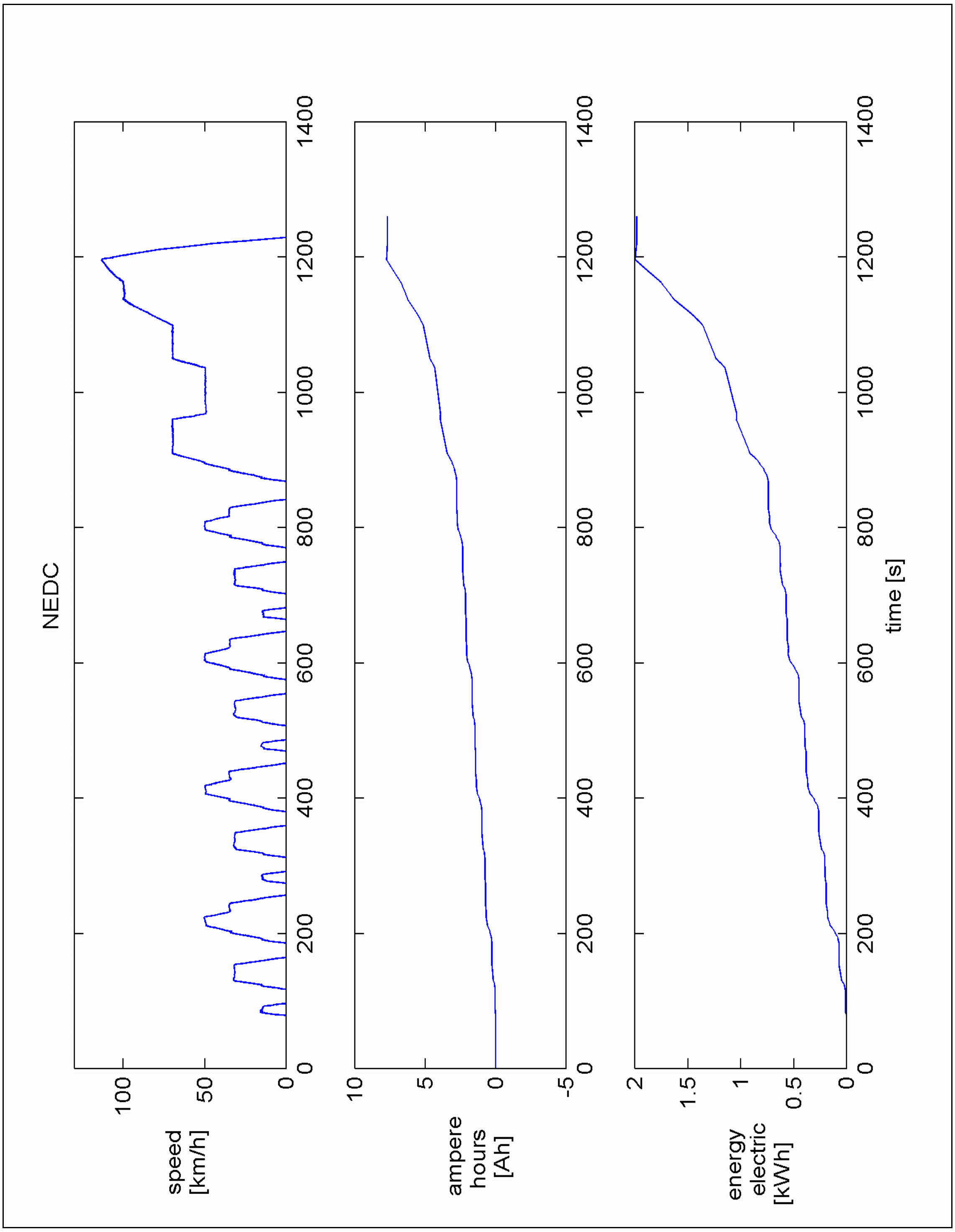

Figure 3.2-6: NEDC energy consumption test in electric mode

As the range in pure electric mode was about 20 km, the measurement of energy consumption in electric mode was performed over one NEDC cycle.

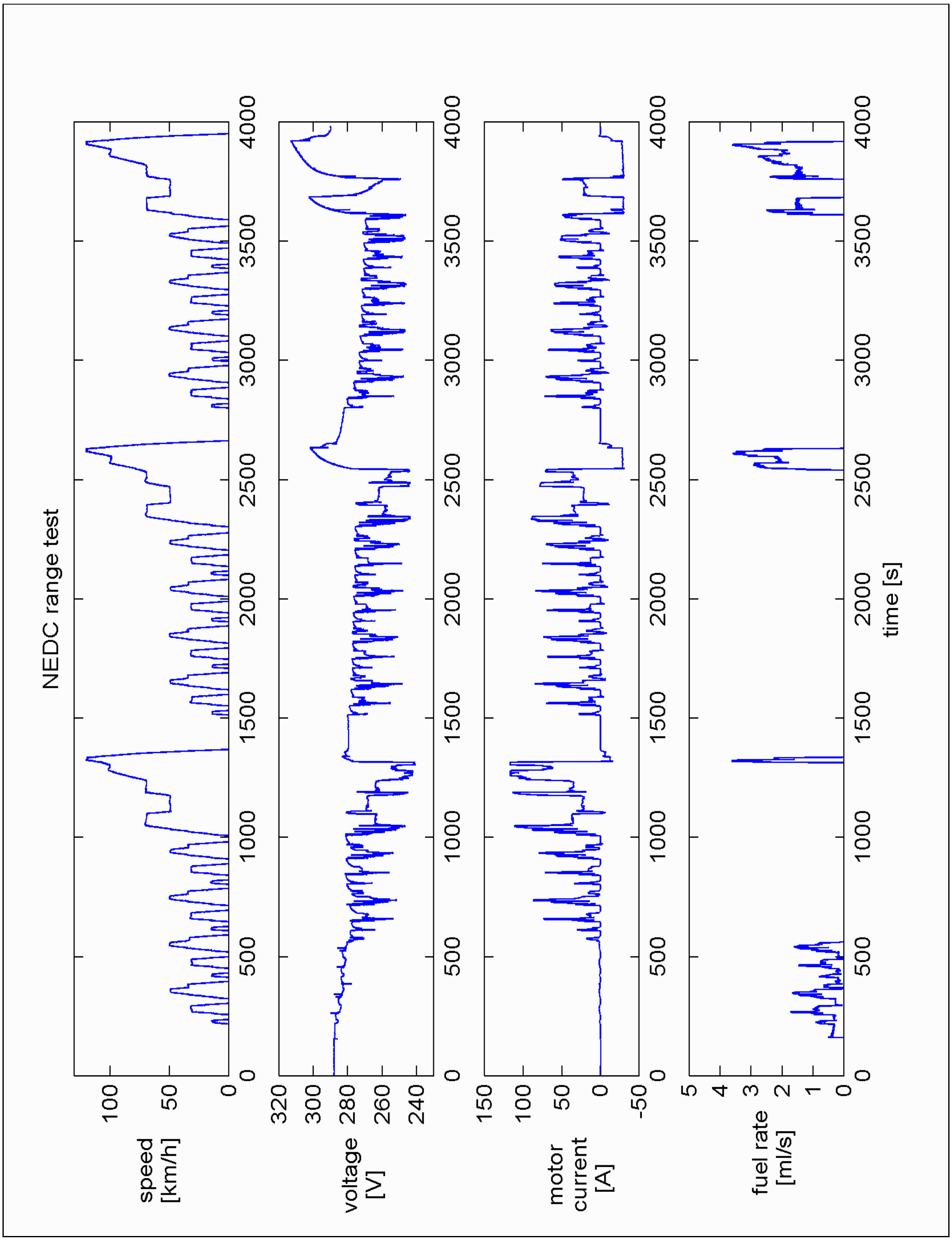

Figure 3.2-7: NEDC energy consumption test in hybrid mode

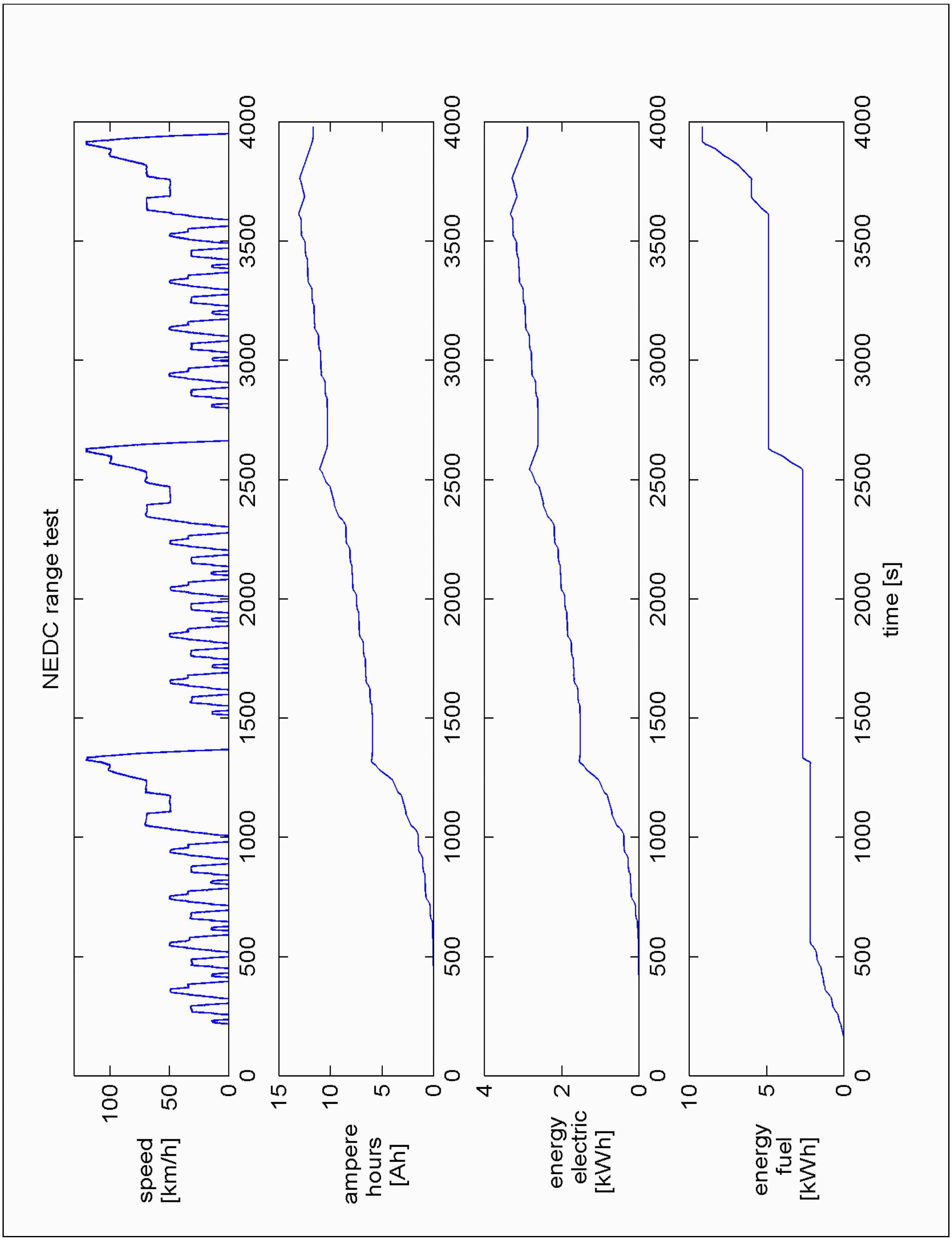

Figure 3.2-8: NEDC energy consumption test in hybrid mode

As the range in pure hybrid mode was about 20 km, the test in hybrid mode was performed over three NEDC cycles. In the first cycle, a warm-up of the ICE occurs. Although the power demands of the cycle are low, the ICE is started immediately after key on and operates until the ICE has reached its operating temperature. The more the SOC decreases with distance, the more the ICE has to propel the vehicle, because the maximum power of the electric motor becomes lower. So at higher speeds or power demands, the ICE is started earlier compared to fully charged batteries.

Additionally, to show that the Audi DUO has no pure ICE mode as described in prEN 1986-2, a test in the user selectable ICE mode has been performed.

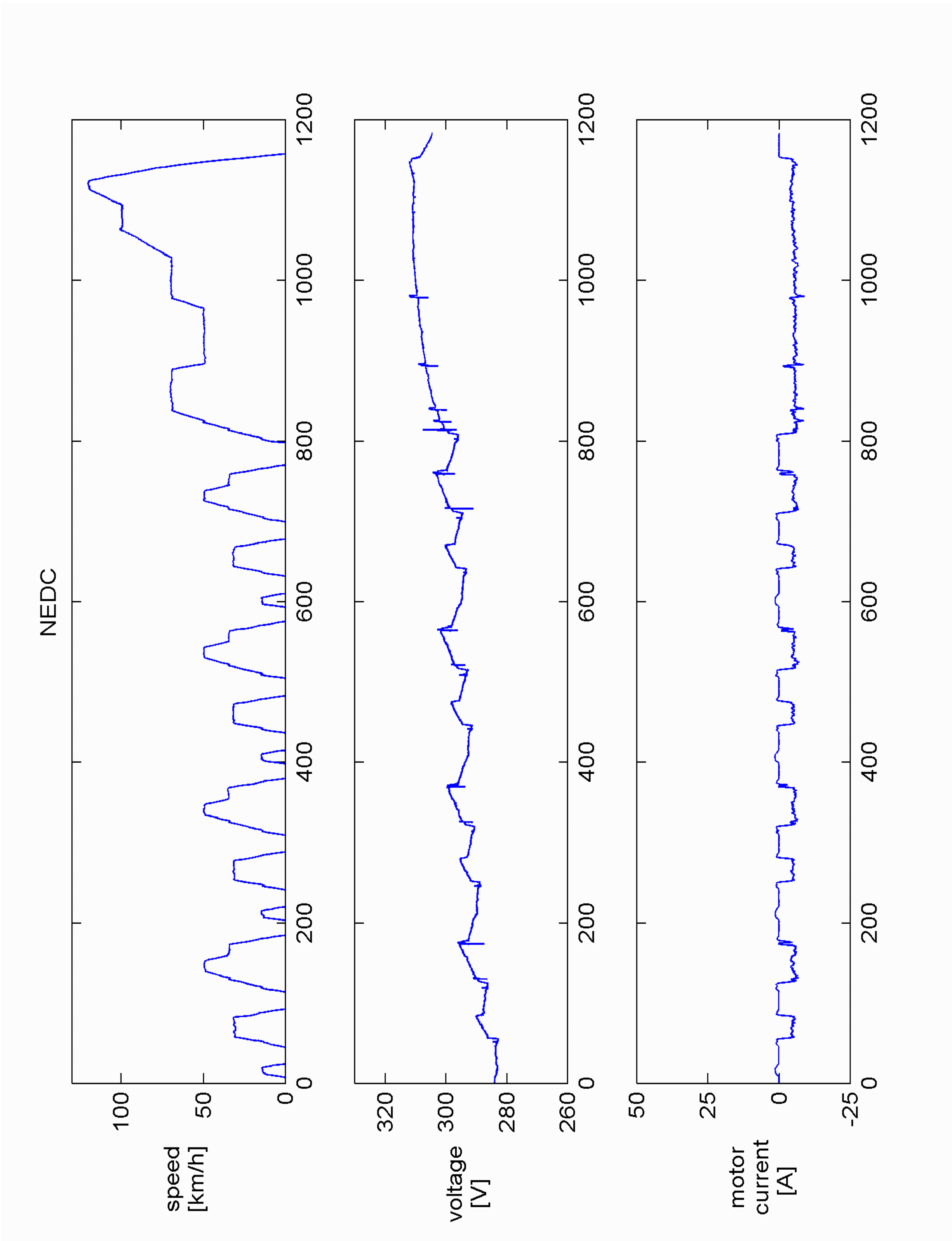

Figure 3.2-9: NEDC ICE mode test

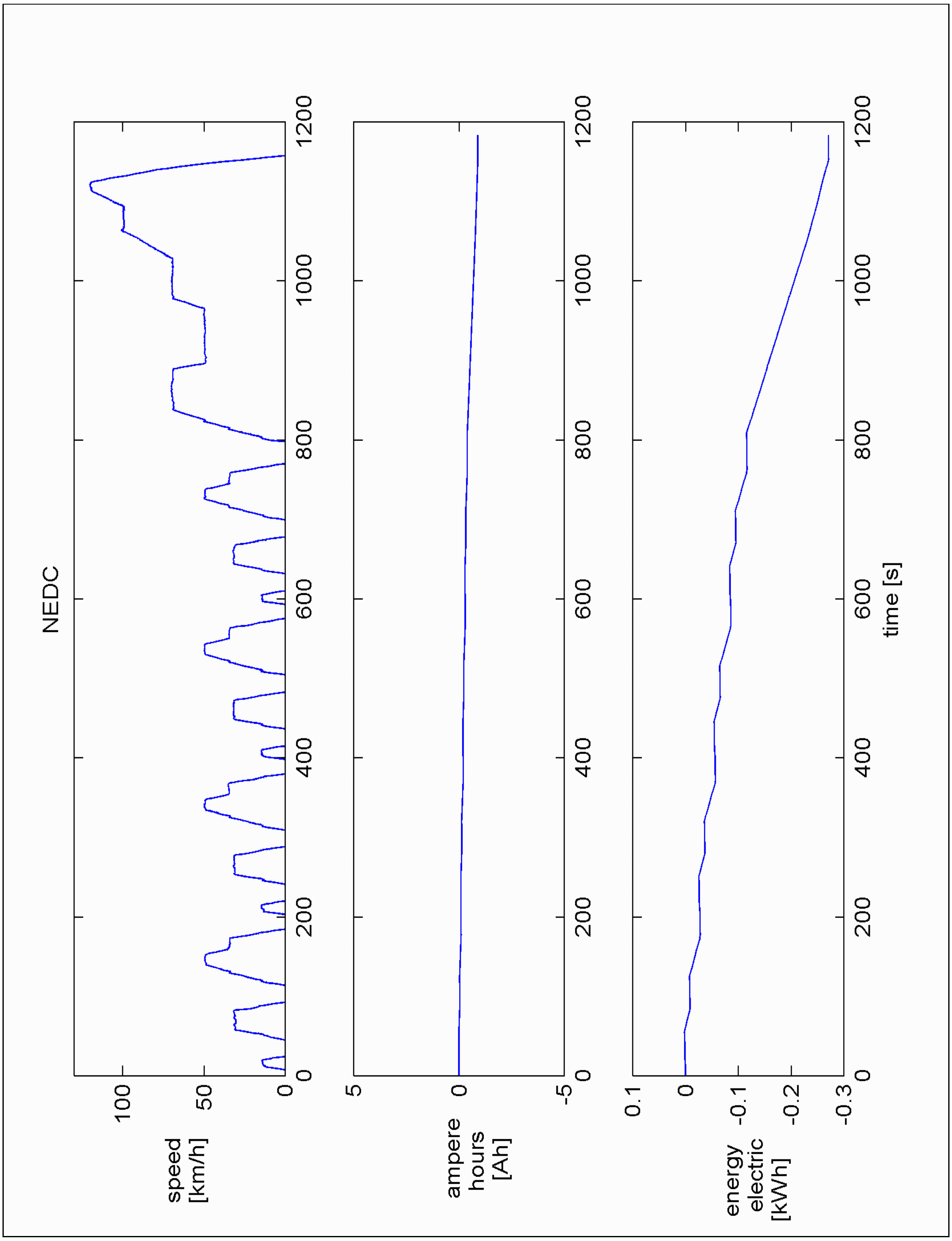

Figure 3.2-10: NEDC ICE mode test

As you see, the electric motor operates at higher speeds as a generator, recharging the batteries. So the electric motor is active, but takes not part in the propulsion of the vehicle. In the meaning of prEN 1986-2 this operation mode is no pure thermal mode, because the electric motor is active. That he does not participate in the propulsion is not the relevant topic.

3.2.3 Measurement according to SAE J1711 (Draft)

As the Audi Duo is charge dependent and off-vehicle charge capable, the following test must be performed:

- DFT (Dependent Full charge Test):
  - UDDS
  - HFWET
  - US06

- EOT (Engine Only Test):
  - UDDS
  - HFWET
  - US06

- EVT (Electric Vehicle Test):
  - UDDS
  - HFWET
  - US06

The DPT (Dependent Partial-Charge Test) must not be performed, because the engine starts in all cycles at the beginning with key on to warm up the ICE.

Due to the fact, that the Audi Duo has no A/C and a Diesel engine, the tests in the SC03 cycle are not necessary.

The following figures show the plots of some relevant data for the different tests.

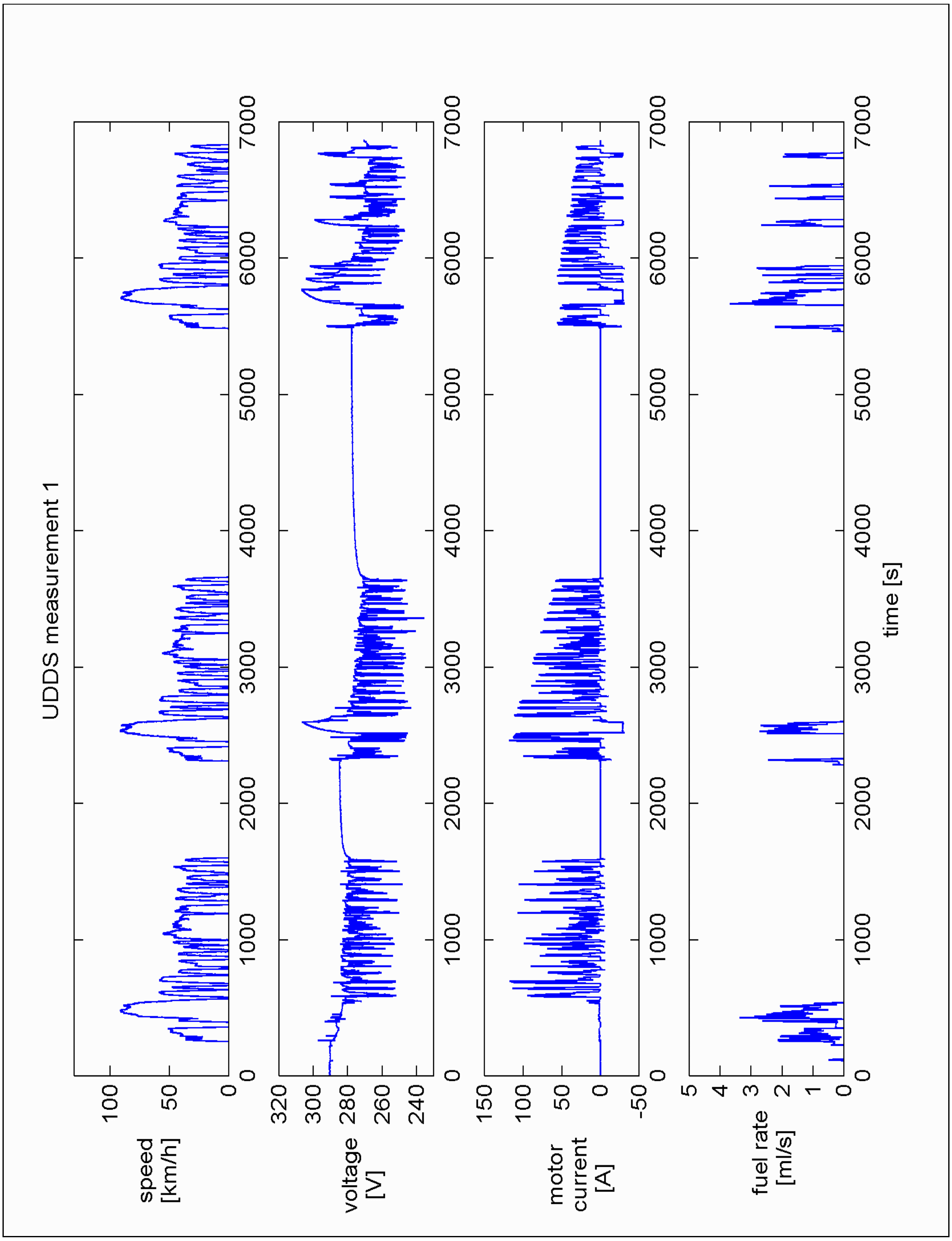

Figure 3.2-11: DFT (UDDS)

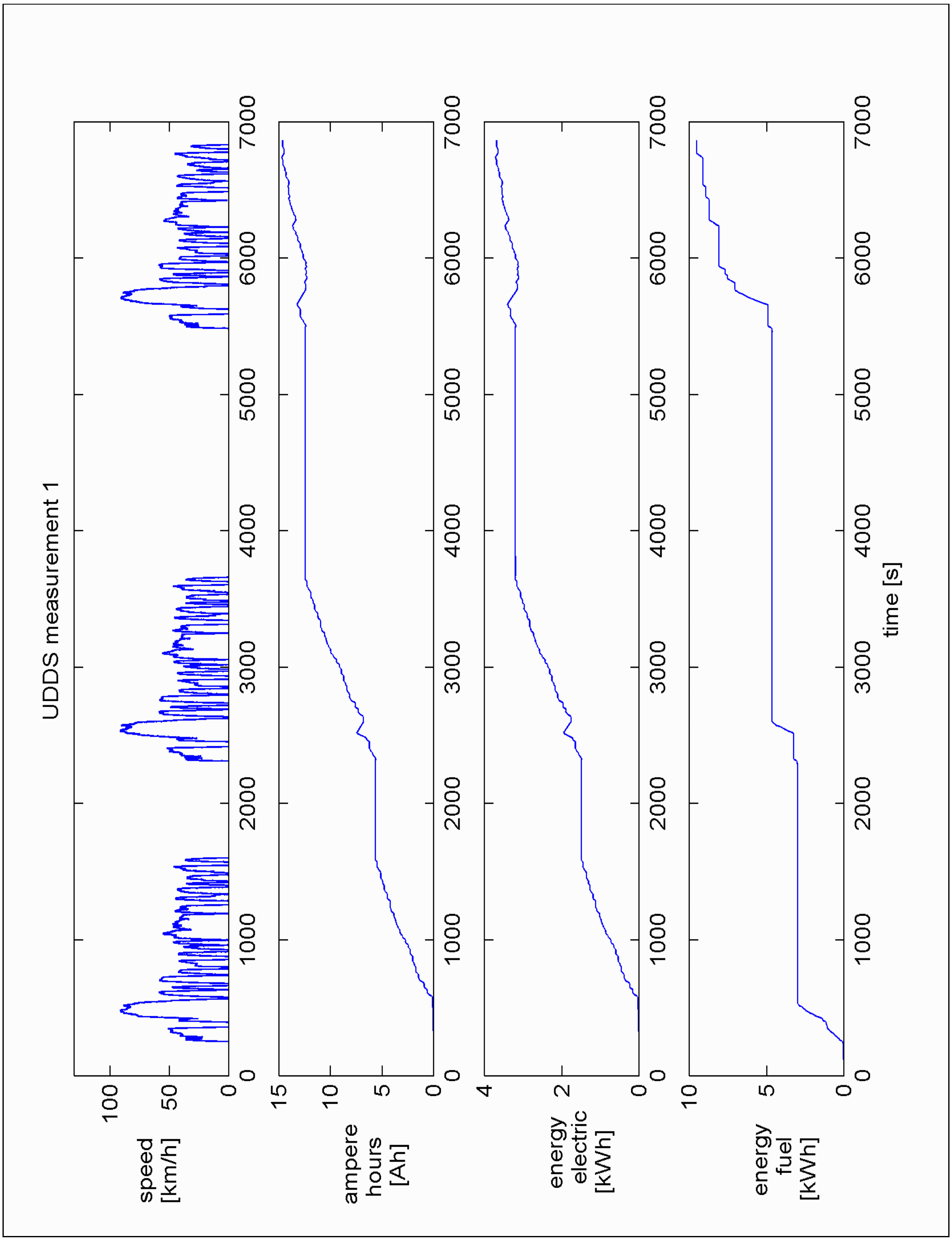

Figure 3.2-12: DFT (UDDS)

In the test shown above, the state of charge of the battery reached 0 % after three test runs of the UDDS instead of the four given intended to drive according to the procedure. Because the vehicle is often operated electrically the relatively low energy content of the batteries is consumed before reaching the foreseen number of cycles.

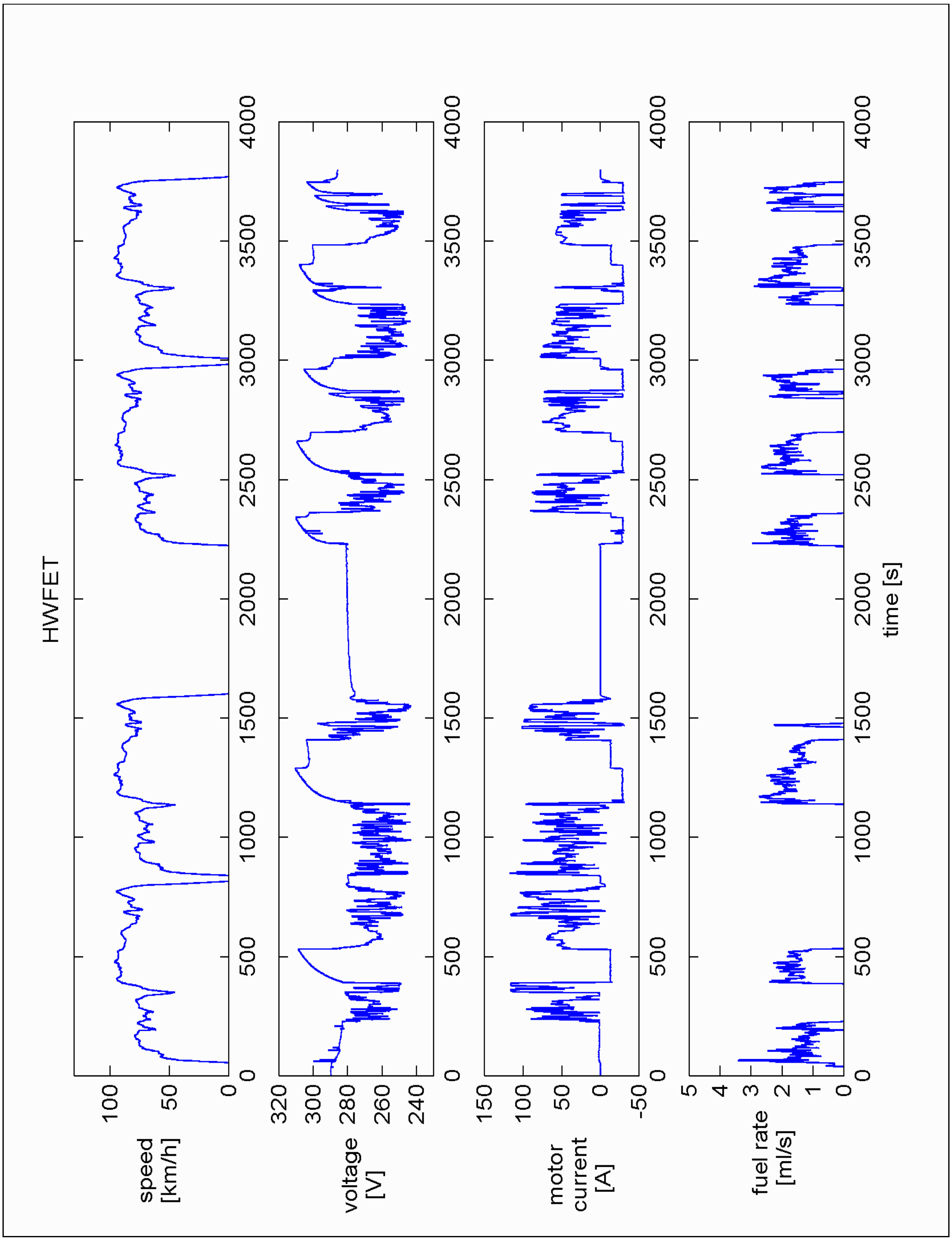

Figure 3.2-13: DFT (HWFET)

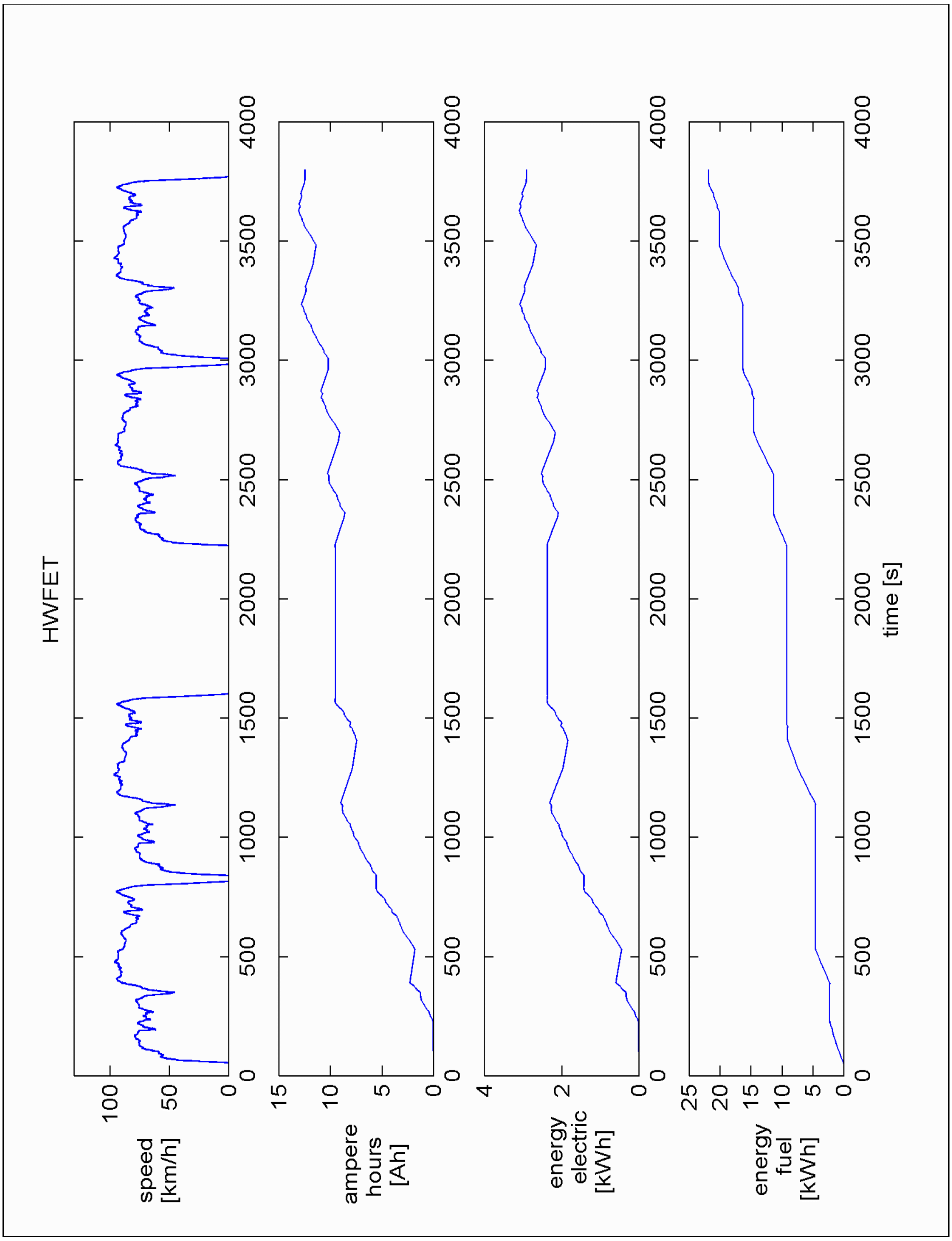

Figure 3.2-14: DFT (HWFET)

In this test, the foreseen number of cycles could be driven. The batteries are charged in this test, when the ICE is running at higher speeds. By this measure, the state of charge of the batteries is maintained high for a longer distance as in the UDDS.

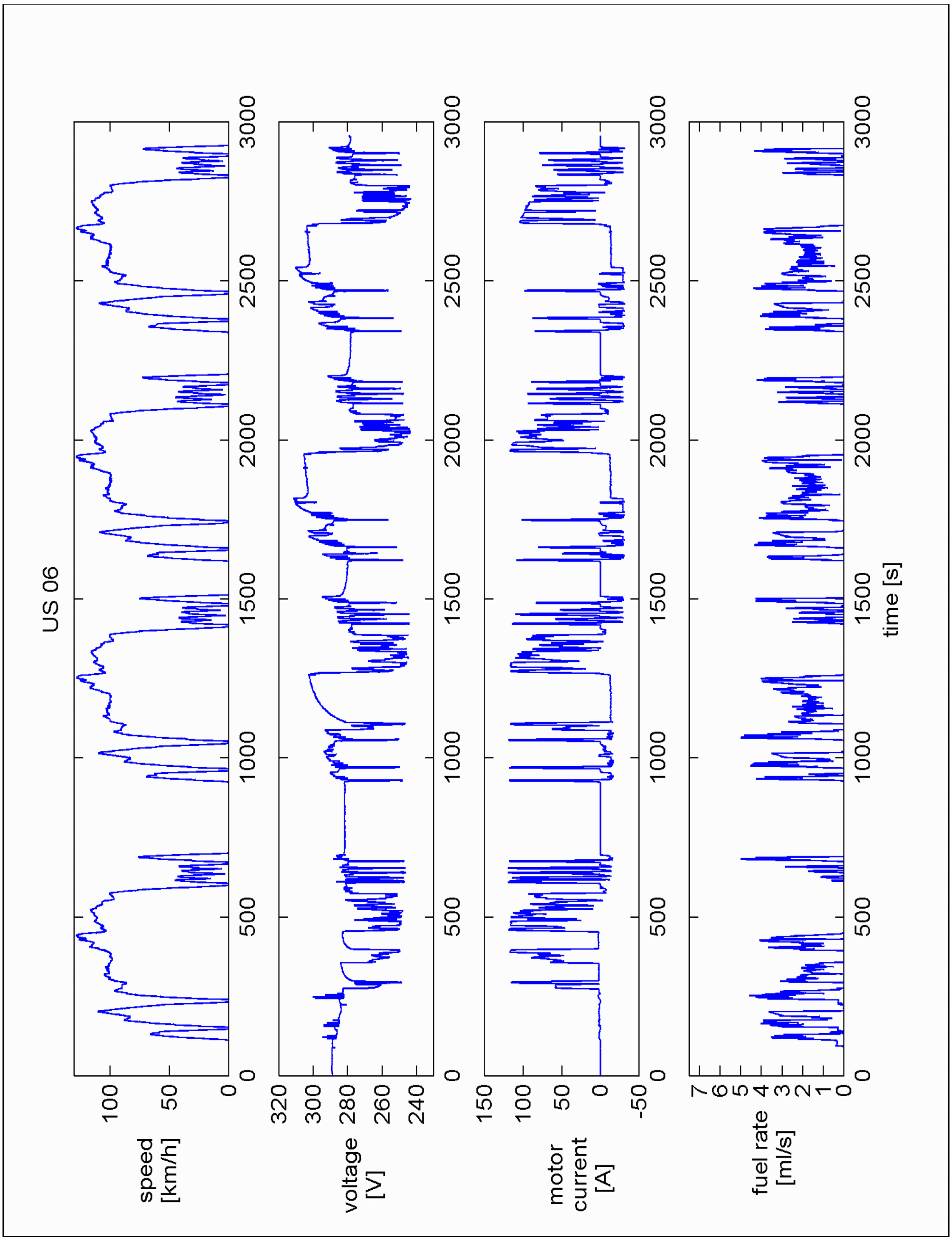

Figure 3.2-15: DFT (US06)

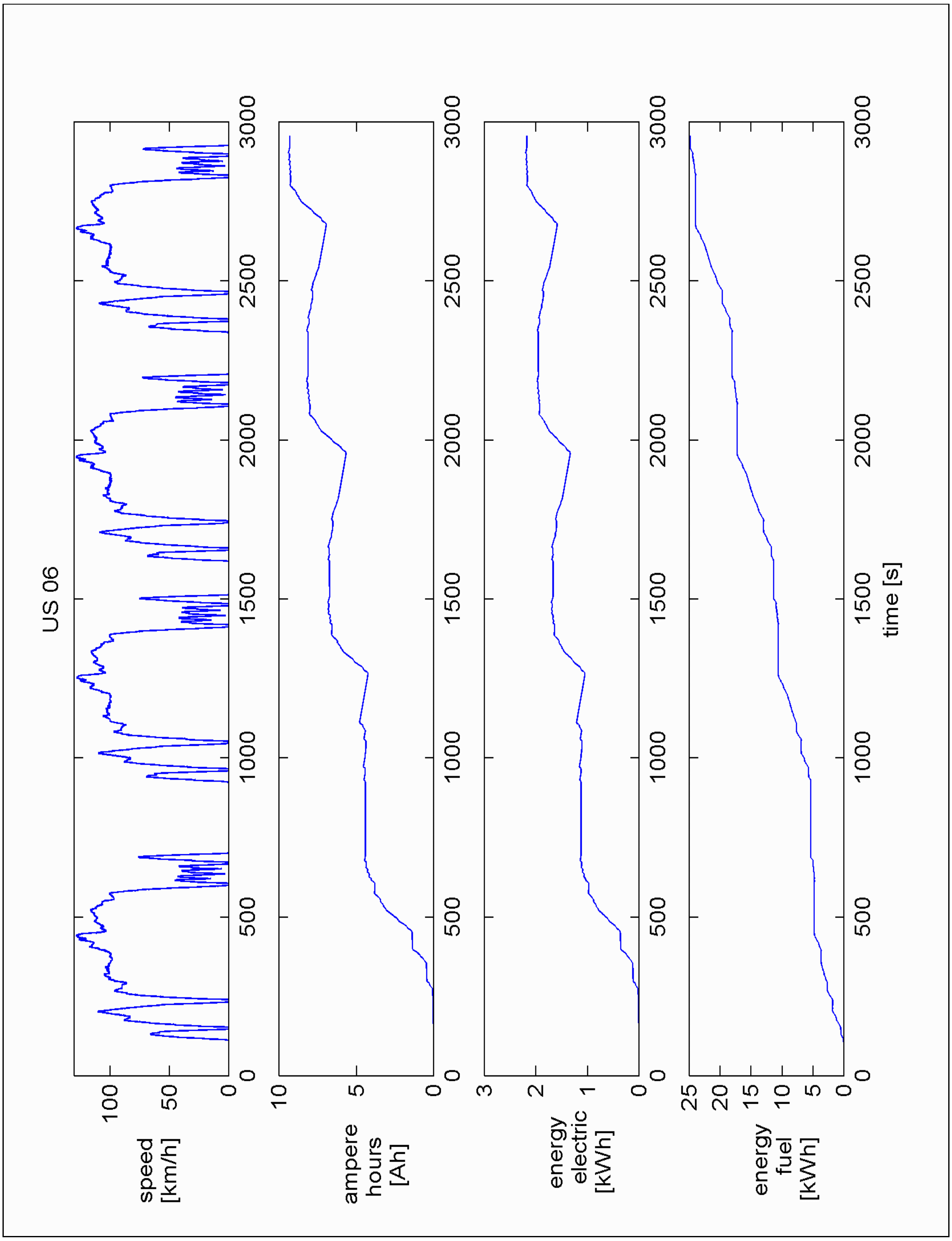

Figure 3.2-16: DFT (US06)

In this test, the ICE is running from the start and because of the high dynamic of this cycle the ICE drives the vehicle for most of the cycle, leading to lower energy demands for the batteries.

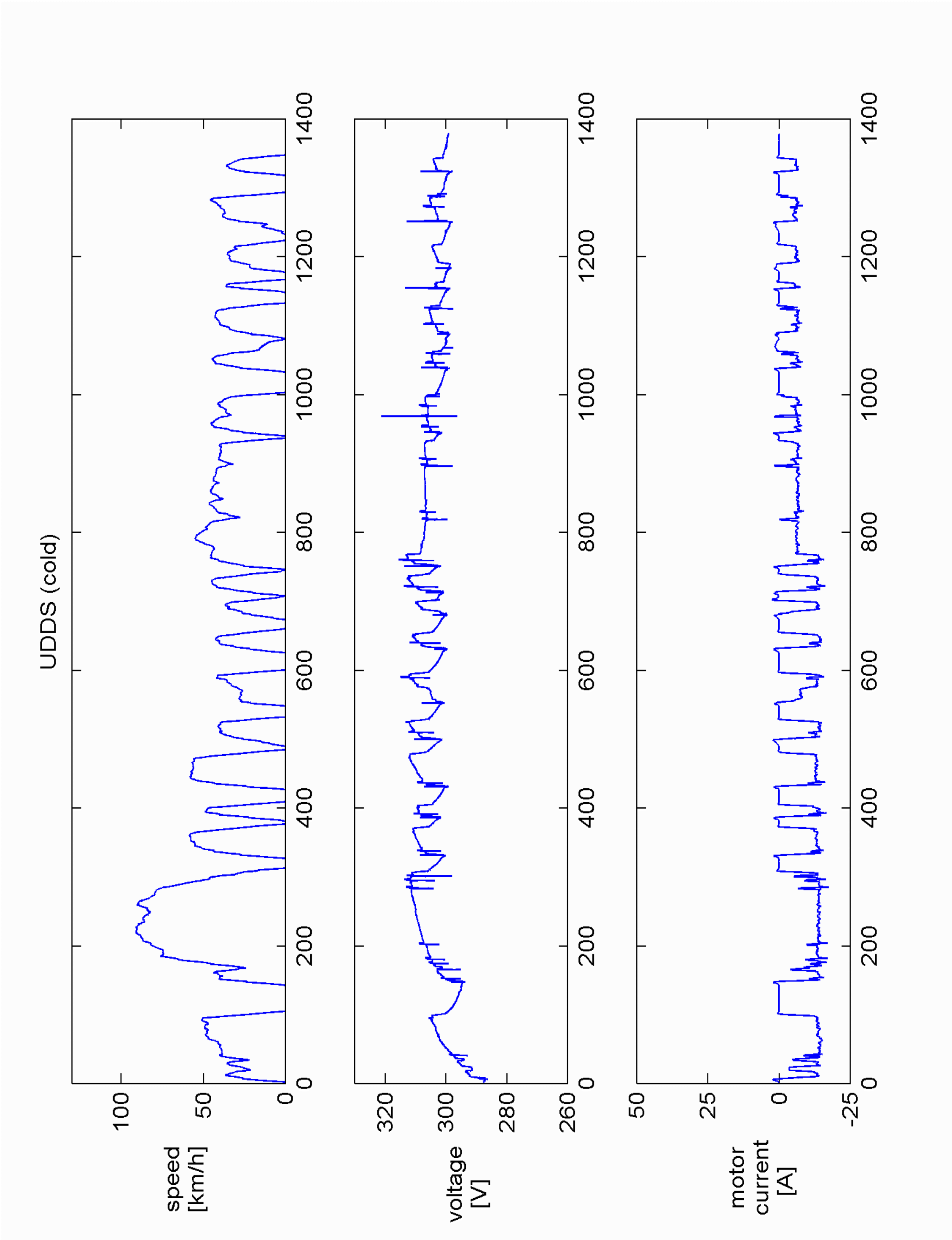

Figure 3.2-17: EOT (UDDS, cold)

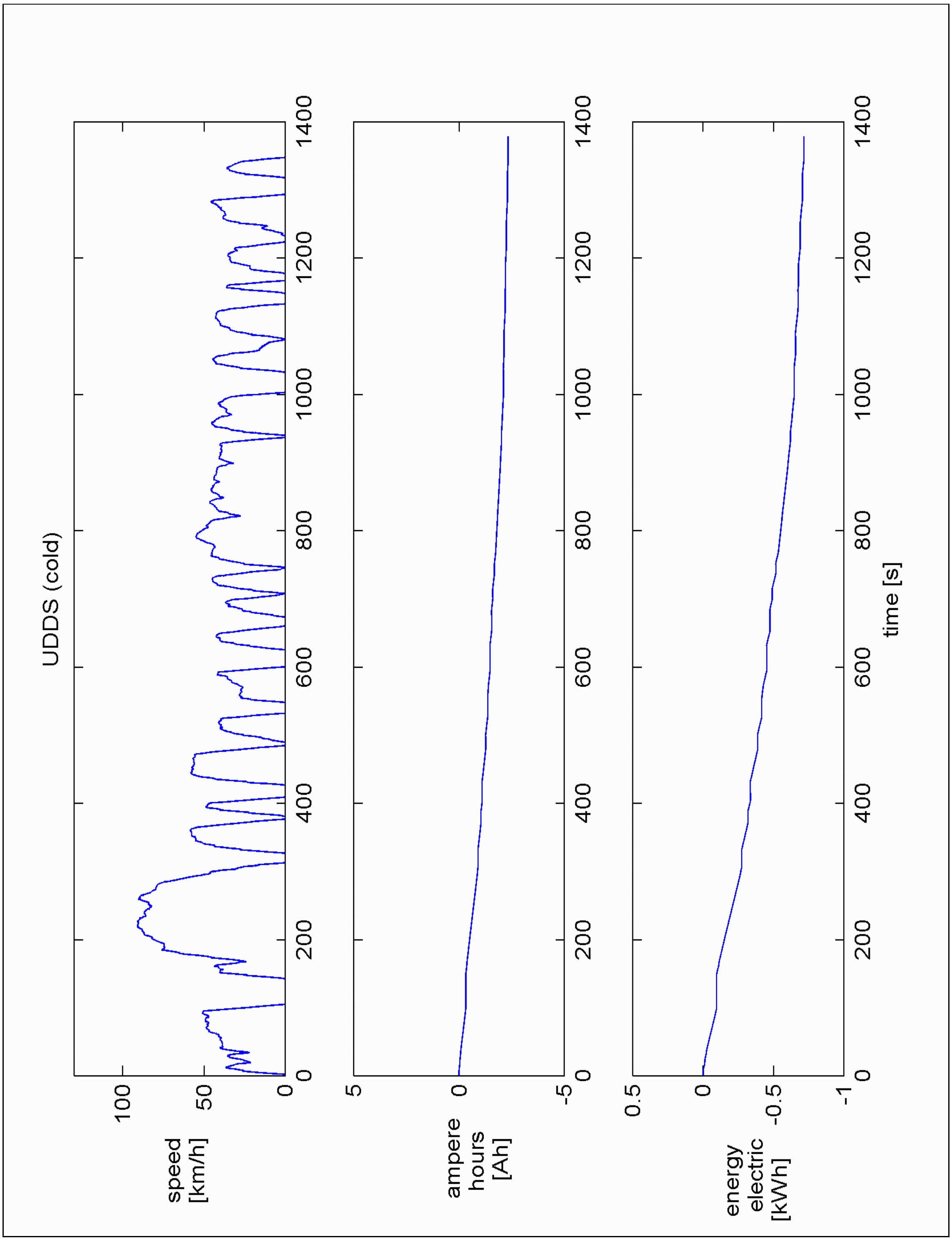

Figure 3.2-18: EOT (UDDS, cold)

Starting with about 77% SOC the batteries are charged through the cycle with about 0.7 kWh. The electric motor acts as a generator at higher speed with up to about 15 A. After about 750 s the current is reduced to maximal about 6 A. At the end, the SOC-meter in the dashboard shows about 97%.

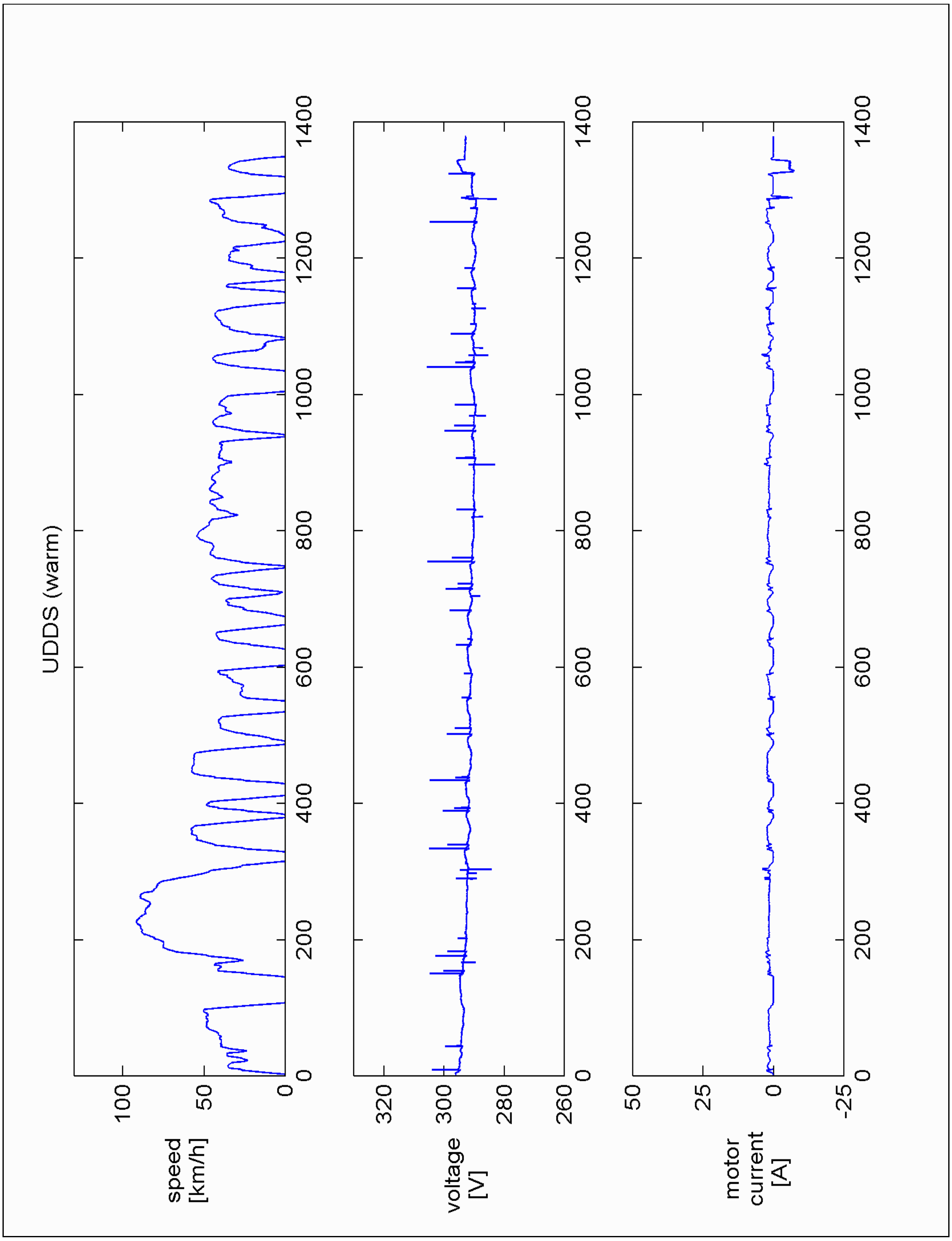

Figure 3.2-19: EOT (UDDS, warm)

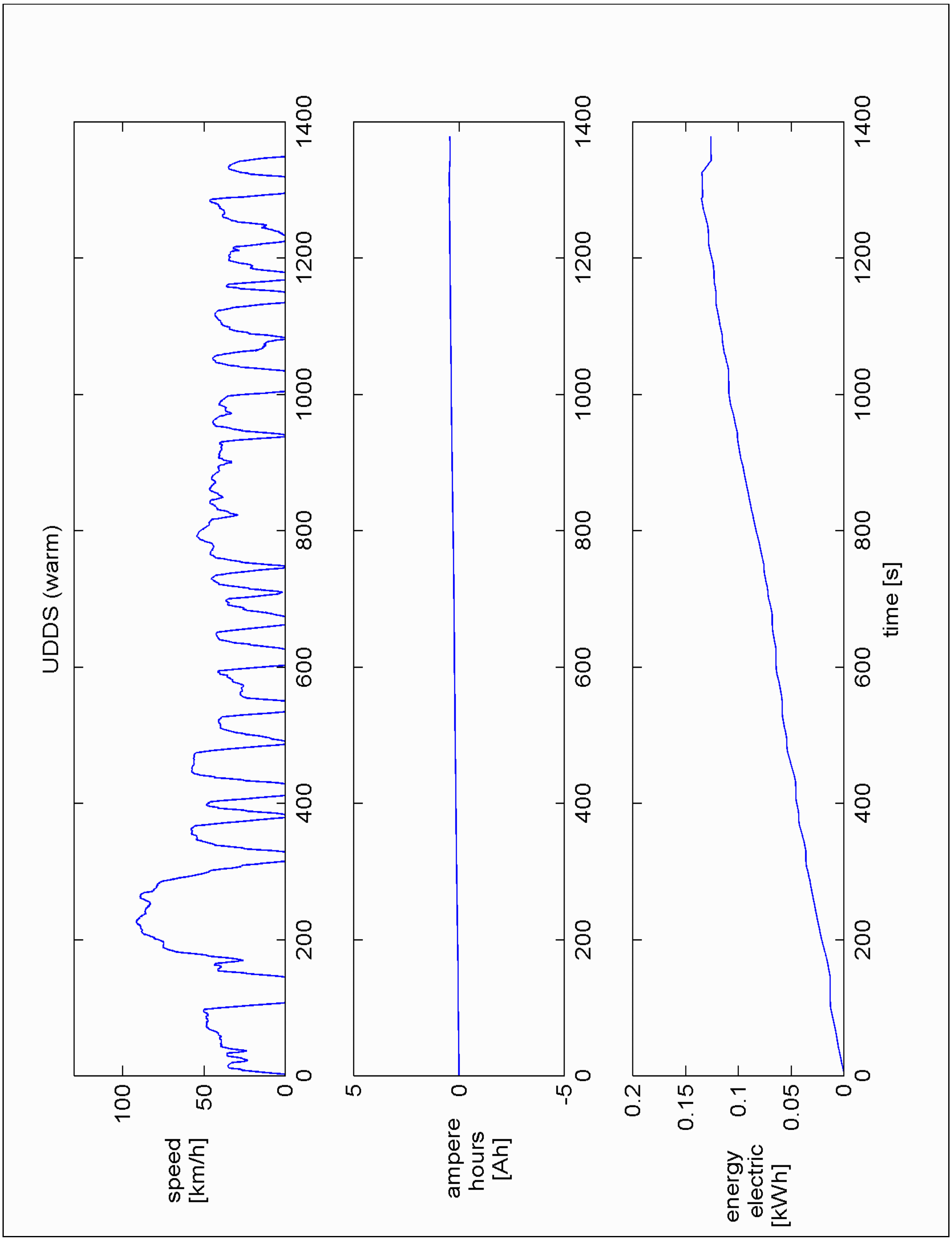

Figure 3.2-20: EOT (UDDS, warm)

In this test, in contrary to the test before with cold engine, the batteries are slightly discharged. About 0.13 kWh is consumed. This little change in the SOC could not be noticed on the analogue SOC-meter. Thus it stays at about 97 %. For the both UDDS together, the final SOC is greater than the initial as demanded in the SAE 1711 procedure.

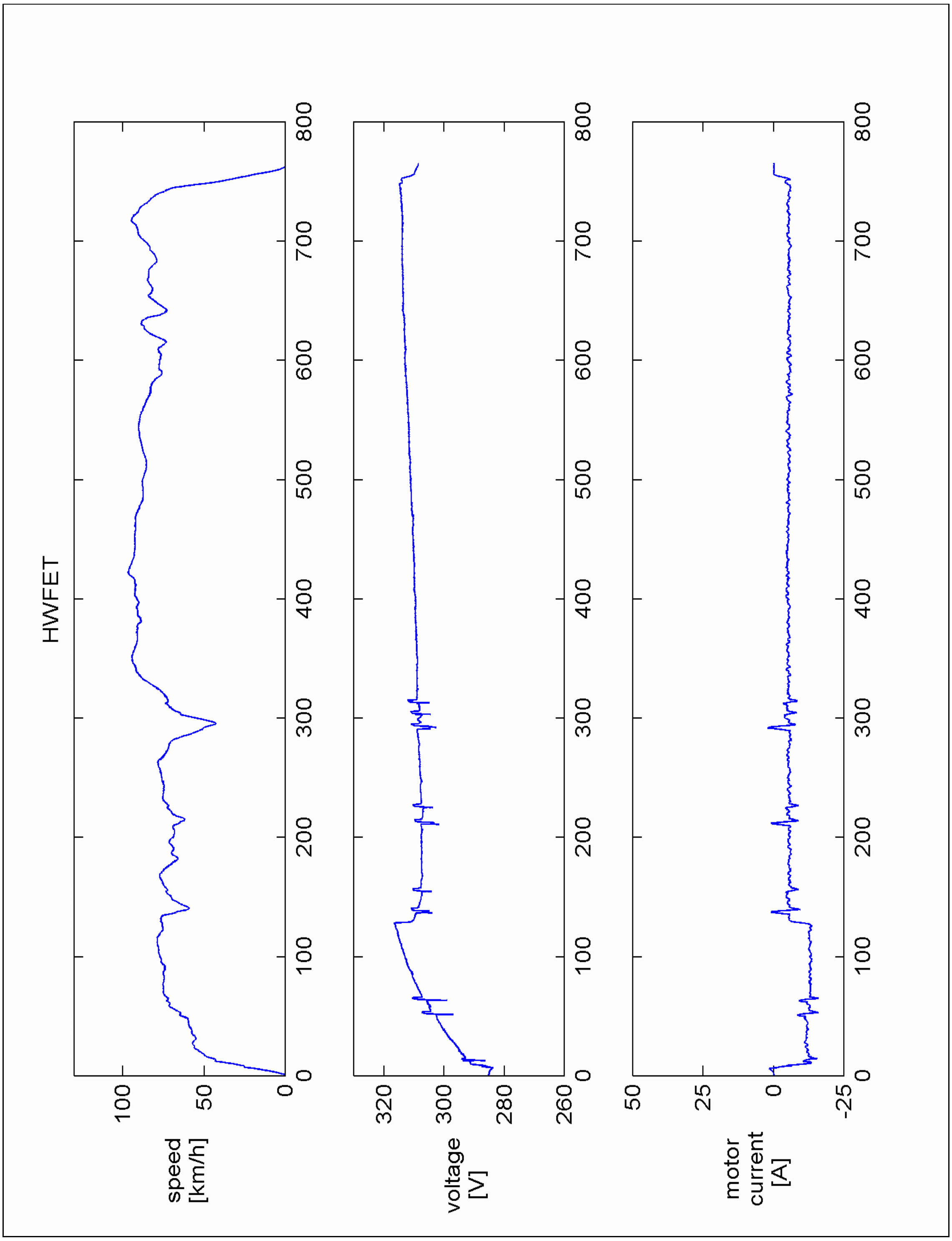

Figure 3.2-21: EOT (HWFET)

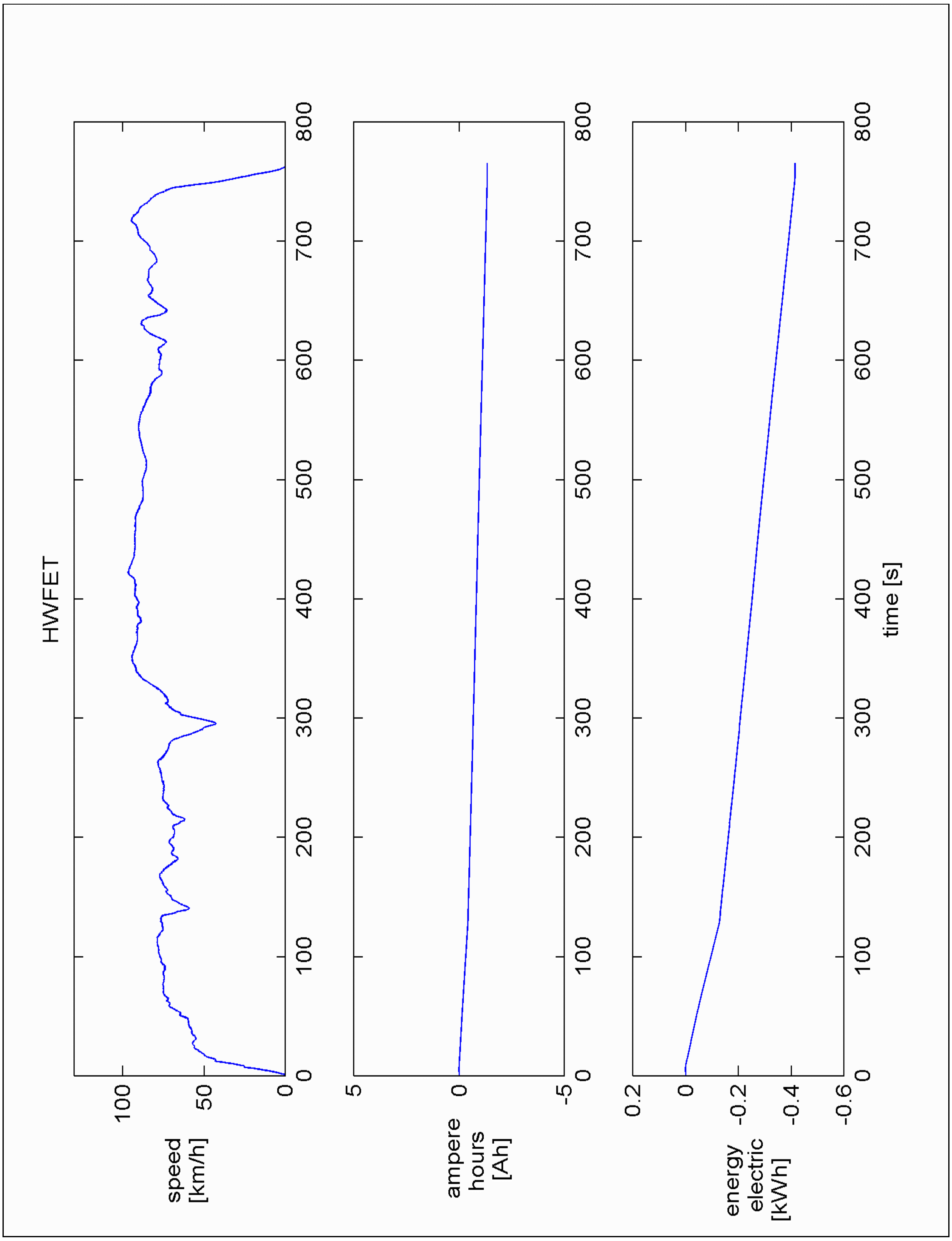

Figure 3.2-22: EOT (HWFET)

This figures (Figure 3.2-21 and Figure 3.2-22) show the data for the HWFET, which was driven with a hot vehicle. Before the vehicle was warmed up by driving one HWFET cycle, in which the initial SOC raised from 77% to 87%. That was the initial SOC for the test shown above. The final SOC was about 97 %, which correspondents to a charge of 0.41 kWh. The both steps in the charging current can be noticed again.

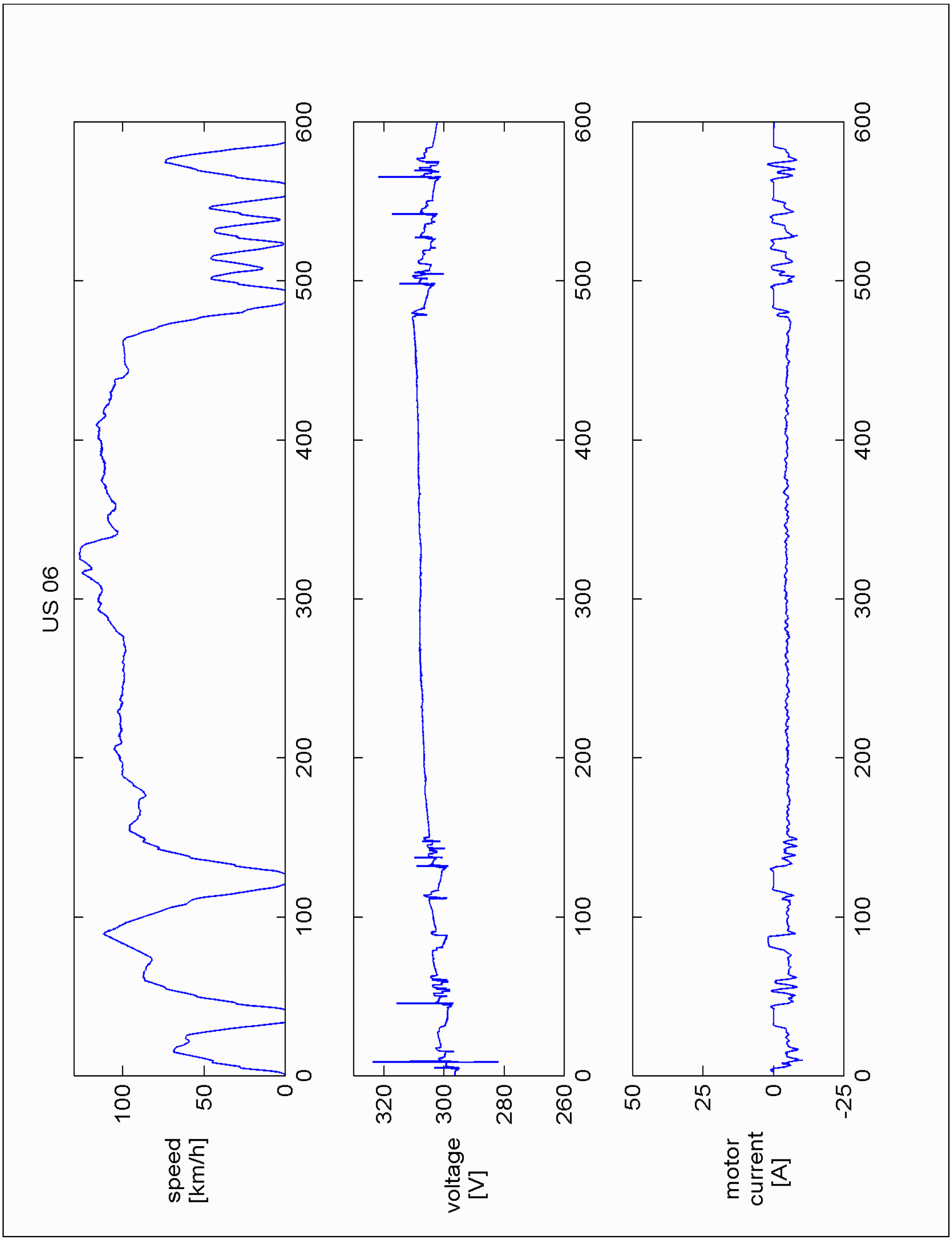

Figure 3.2-23: EOT (US06)

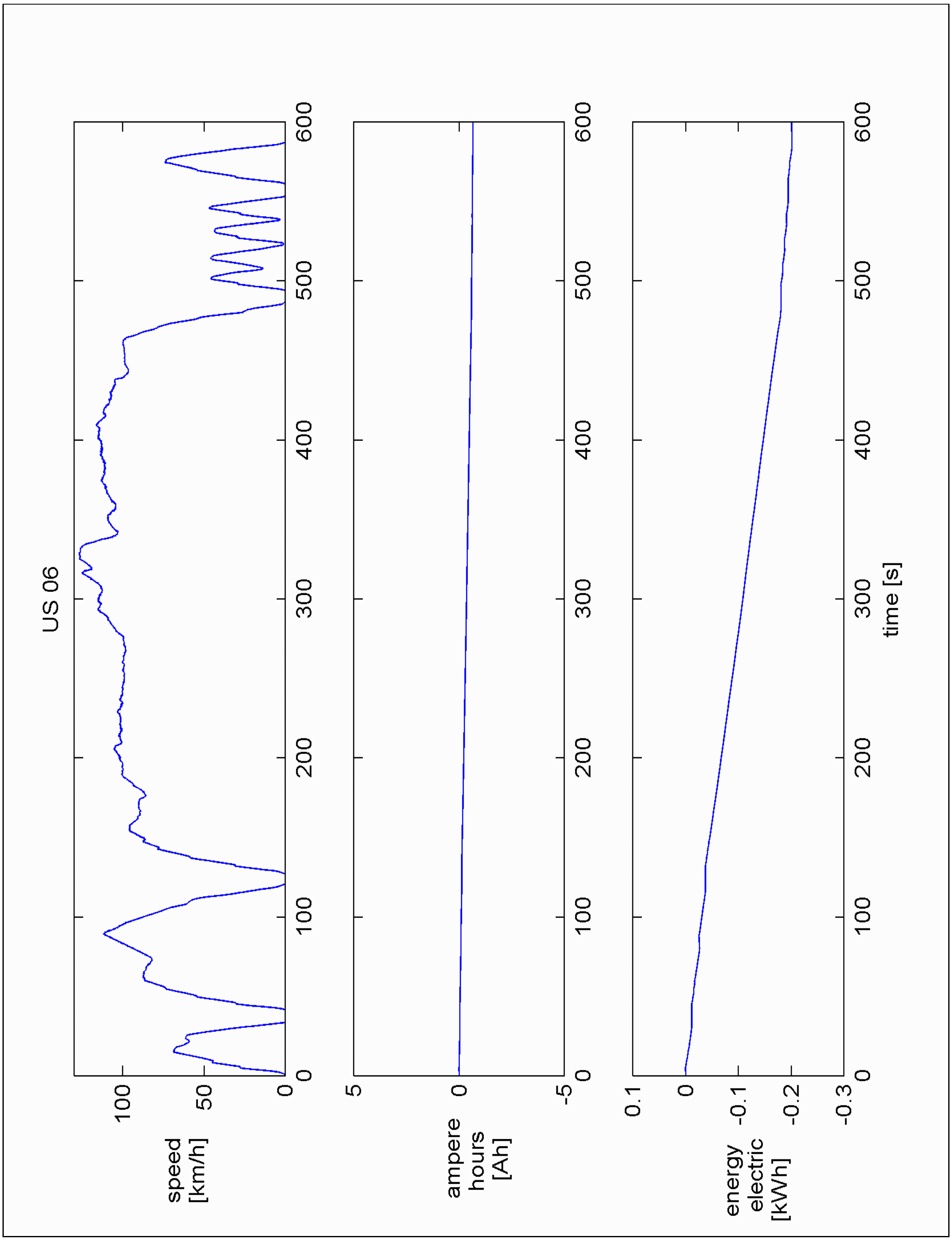

Figure 3.2-24: EOT (US06)

These figures (Figure 3.2-23 and Figure 3.2-24) show the data for the US06, which was also driven with a hot vehicle. Before the vehicle was warmed up by driving one US06 cycle. In this cycle the initial SOC raised from 77% to 88%. That was the initial SOC for the test shown above. The final SOC was about 92 %, which correspondents to a charge of 0.2 kWh.

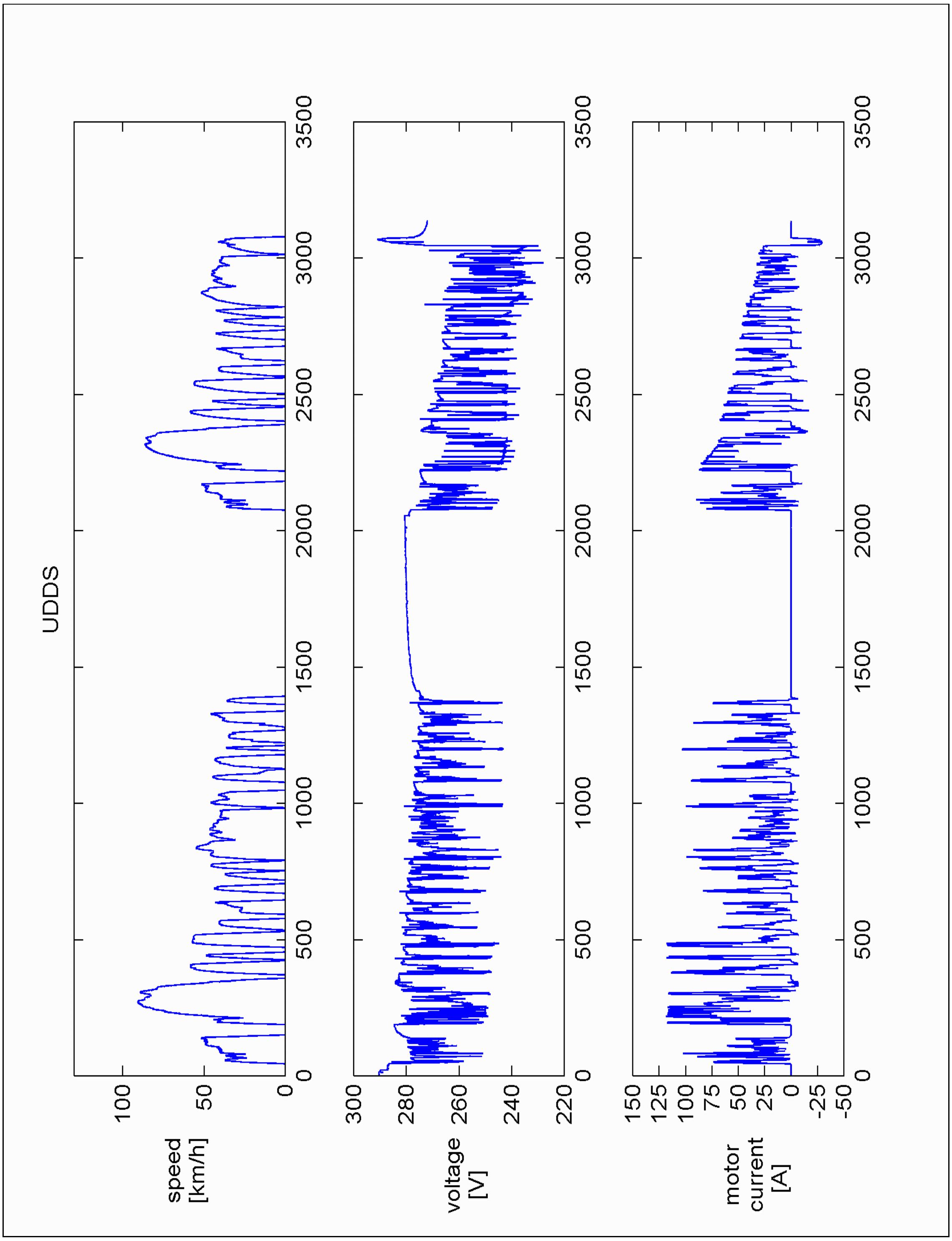

Figure 3.2-25: EVT (UDDS)

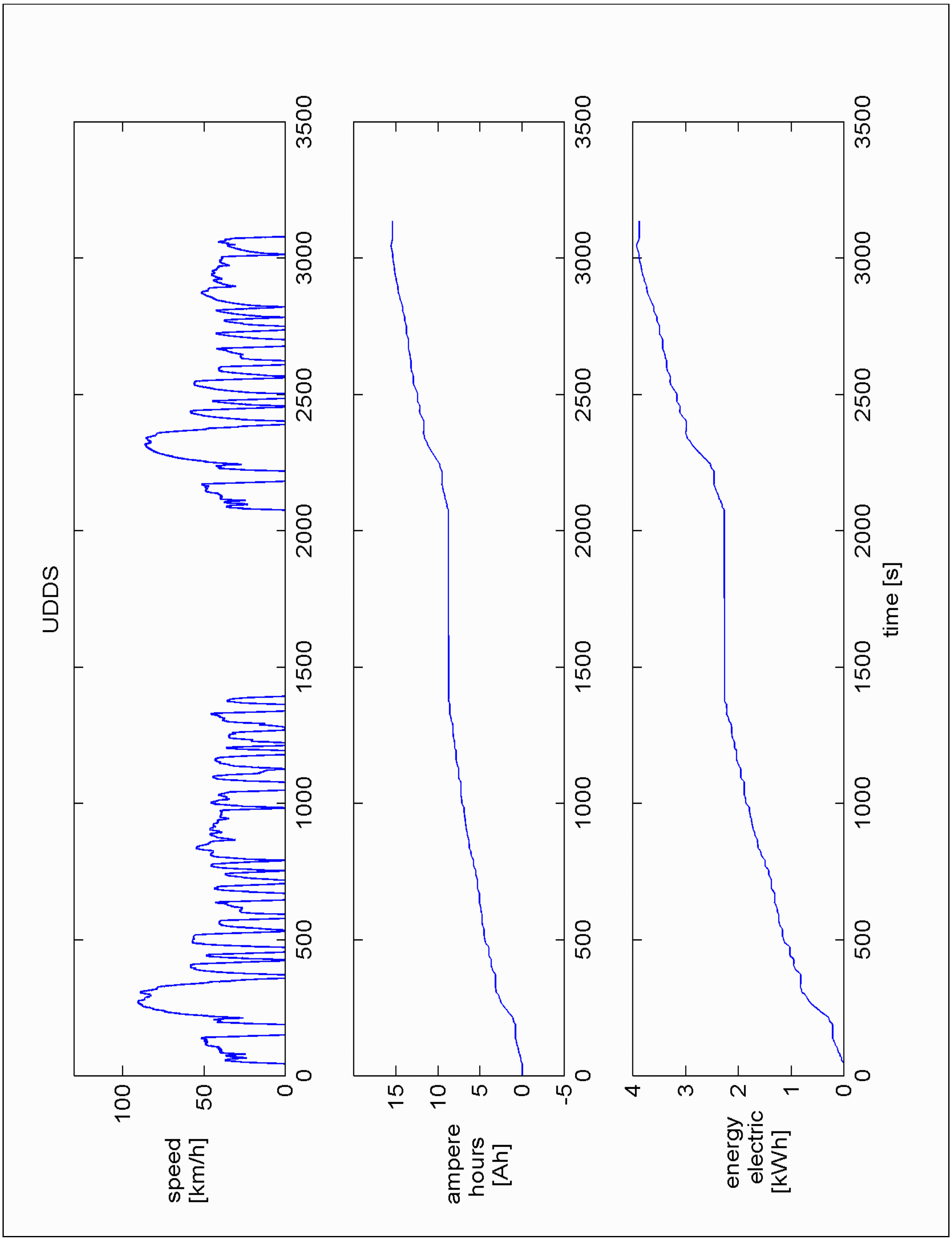

Figure 3.2-26: EVT (UDDS)

In this test the demanded number of 5 UDDS cycles could not be completed. The batteries were fully discharged after about 21 km. About 4 kWh were discharged.

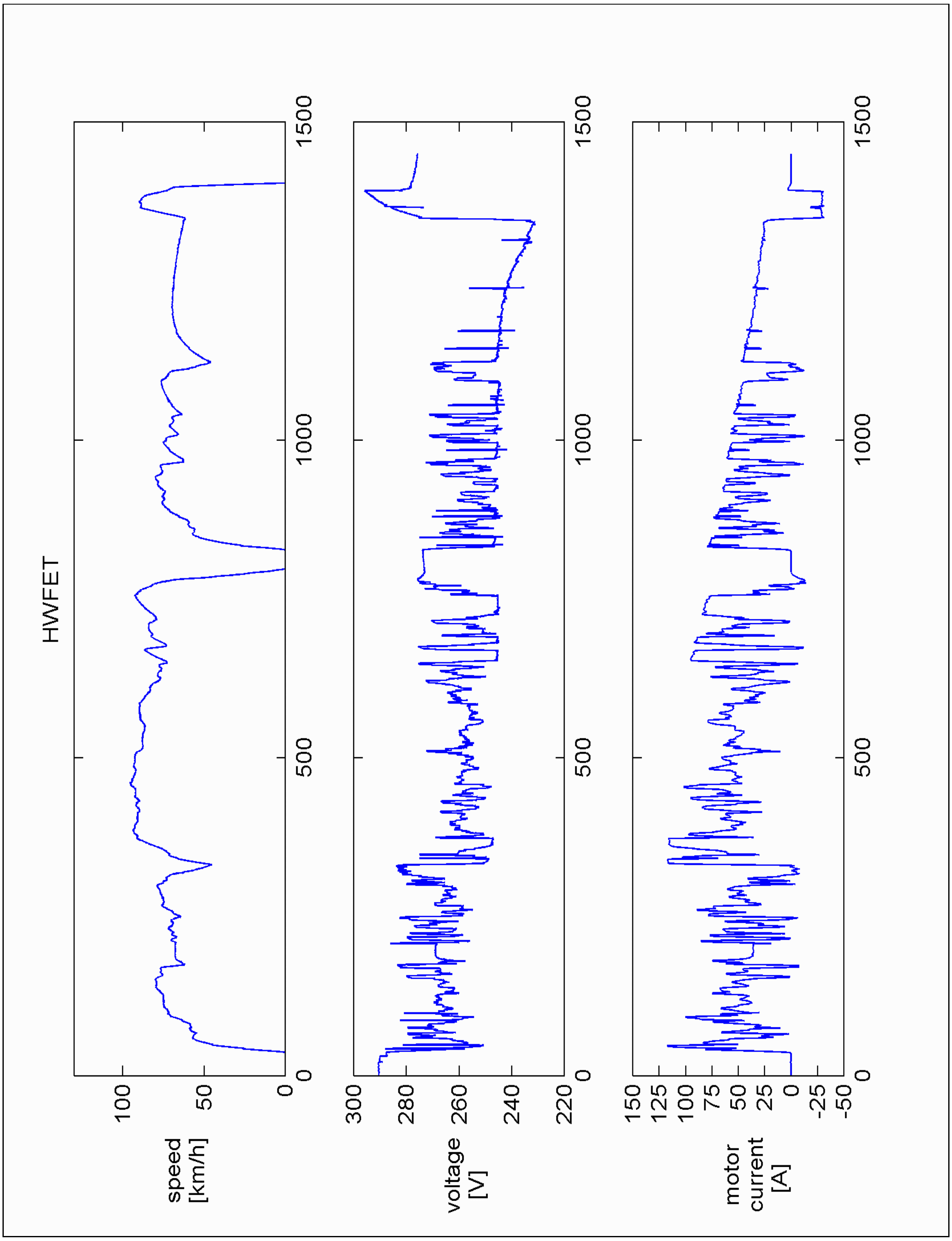

Figure 3.2-27: EVT (HWFET)

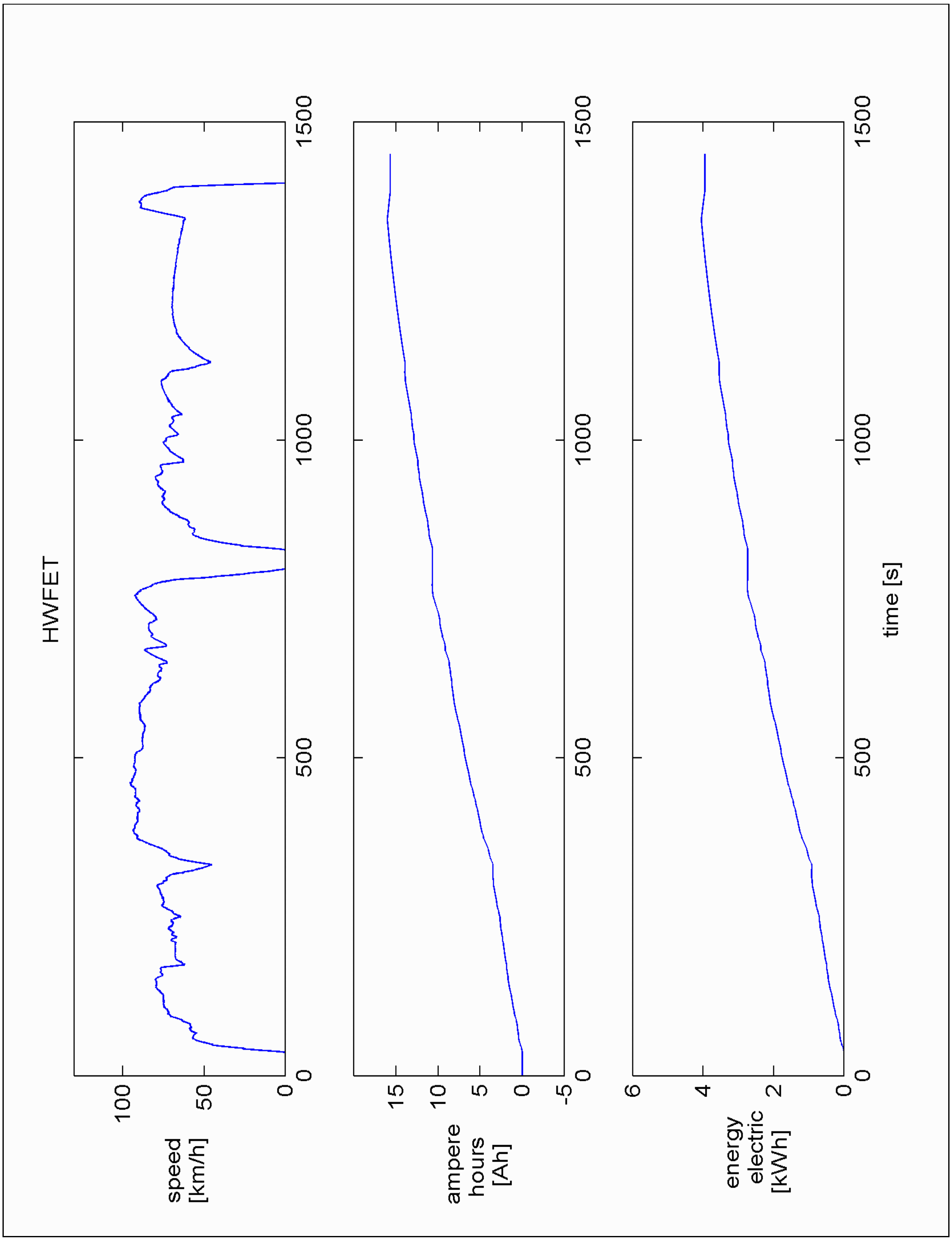

Figure 3.2-28: EVT (HWFET)

Also in the HWFET, the demanded number of cycles could not be completed. The test was stopped after about 26 km as the engine started.

The EVT test in the US06 could not be performed, because the vehicle fails to follow the desired acceleration from the start of the cycle. As mentioned before, the power demands of the US06 exceeds the power of the electric motor, even with fully charged batteries. The test in pure electric mode in the US06 cycle is not applicable to the Audi DUO. This would be the case for most parallel hybrids, where the power of the electric motor is lower than that of the combustion engine. So it seems, that SAE J1711 is addressed more to series hybrid vehicles, which often have full performance available without the use of the ICE.

3.2.4 Results

The results of the different test are shown in the following figures for the different operating modes and cycles.

Table 3.2-1: Results in electric mode

		NEDC range	NEDC consumption	UDDS	HWFET
mech driv	[Wh]	3411.2	1871.3	3789.5	4223.4
mech brak	[Wh]	-931.7	-526.4	-1506.5	-477.6
elek driv	[Wh]	4335.8	2412.8	4849.7	4911.8
elek reg+load	[Wh]	-79.6	-33.7	-193.3	-166.3
charge grid	[Wh]	8404.6	4685.1	8824.5	8666.6
distance	[m]	21135	10963	21619	26276
mech driv	[Wh/km]	161.40	170.69	175.29	160.73
mech brak	[Wh/km]	-44.08	-48.01	-69.69	-18.18
elek driv	[Wh/km]	205.15	220.08	224.33	186.93
elek reg+load	[Wh/km]	-3.76	-3.08	-8.94	-6.33
charge grid	[Wh/km]	397.66	427.35	408.18	329.83

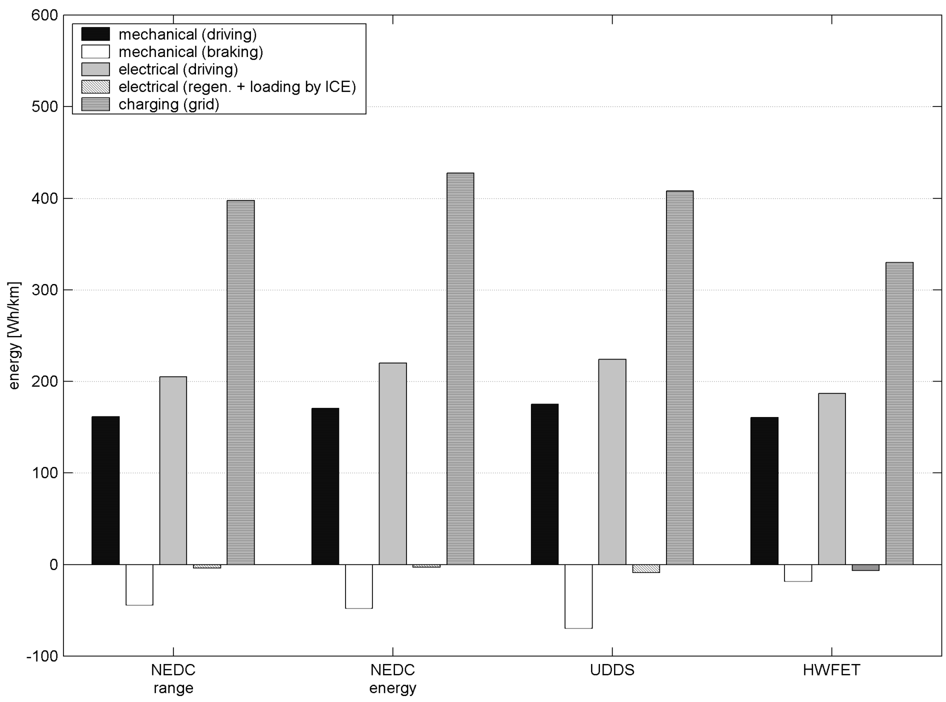

Figure 3.2-29: Energy consumption electric mode

First shown is the mechanical energy (driving) to drive the vehicle through the cycle and cover the losses. These are the rolling and aerodynamic drag for the whole distance and the acceleration power, where the acceleration is positive. The second bar shows the mechanical energy that can be recovered during braking. These values were calculated with the drag characteristic derived from the coast down test.

The electrical energy (driving) is the DC-energy for the electric motor measured at the battery terminals to drive the vehicle. The next bar, electrical (regen + loading by ICE) shows the energy feed back into the batteries due to recuperation or (in hybrid or EOT mode only) due to loading if the ICE is running.

The bar charging (grid) shows the energy from the grid to recharge the battery to 100 % SOC. A signal lamp in the cockpit of the vehicle indicates that the battery is fully charged, and only the energy until reaching this point was taken into account for this investigation. Afterwards the vehicle consumes about only 36 W from the grid for keeping the accessories and controllers needed for charging alive.

Table 3.2-2: Results in hybrid mode

		NEDC range	UDDS (1.st meas.)	UDDS (2.nd meas.)	HWFET	US06
mech driv	[Wh]	4704.6	5202.8	5188.4	8752.2	10117.8
mech brak	[Wh]	-1326.1	-2091.3	-2084.1	-823.9	-2718.7
elek driv	[Wh]	3779.2	4642.0	4478.8	5189.3	3586.1
elek reg+load	[Wh]	-888.4	-955.9	-1073.2	-2274.2	-1409.5
charge grid	[Wh]	5867.9	7109.5	7109.5	5988.6	4570.5
fuel	[Wh]	9165.9	9528.7	10298.2	21883.6	24802.8
distance	[m]	33010	35833	35782	65970	50433
Mech driv	[Wh/km]	142.52	145.19	145.00	132.67	200.62
mech brak	[Wh/km]	-40.17	-58.36	-58.25	-12.49	-53.91
elek driv	[Wh/km]	114.49	129.54	125.17	78.66	71.11
elek reg+load	[Wh/km]	-26.91	-26.68	-29.99	-34.47	-27.95
charge grid	[Wh/km]	177.76	198.41	198.69	90.78	90.63
fuel	[Wh/km]	277.67	265.92	287.81	331.72	491.80
fuel	[l/100 km]	2.79	2.67	2.89	3.34	4.95
combined (grid + fuel)	[Wh/km]	455.43	464.33	486.49	422.50	582.42

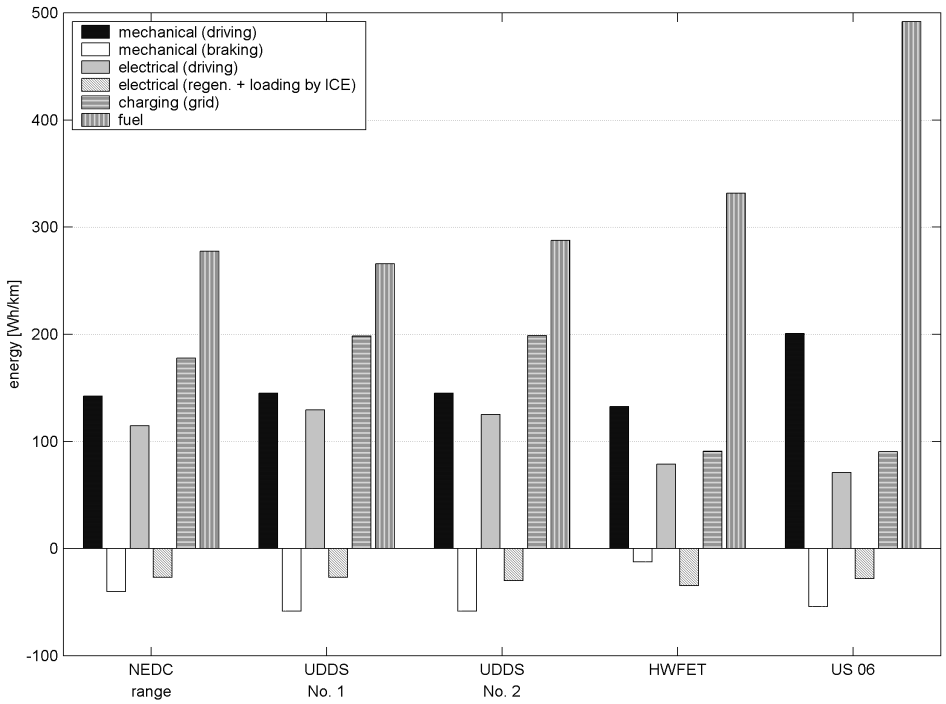

Figure 3.2-30: Energy consumption hybrid mode

For the hybrid tests and the ICE tests, additionally the fuel energy is shown. This is the energy of the fuel consumed over the cycle. It is calculated from the measured volumes of fuel by multiplying with the heat value of Diesel fuel (35800 kJ/l).

Table 3.2-3: Results in ICE mode

		NEDC	UDDS (cold)	UDDS (warm)	UDDS (43/57 weighted)	HWFET	US06
mech driv	[Wh]	1588.5	1772.3	1766.0	1768.7	2209.5	2591.7
mech brak	[Wh]	-454.0	-719.7	-710.6	-714.5	-221.4	-731.3
elek driv	[Wh]	18.5	22.7	141.0	90.1	1.7	6.6
elek reg+load	[Wh]	-289.2	-736.9	-14.9	-325.3	-416.7	-207.9
fuel	[Wh]	9904.7	10441.7	8134.6	9126.6	7726.8	9089.2
distance	[m]	11026	11960	11978	11970.3	16472	12684
mech driv	[Wh/km]	144.07	148.19	147.44	147.8	134.14	204.33
mech brak	[Wh/km]	-41.18	-60.18	-59.32	-59.7	-13.44	-57.66
elek driv	[Wh/km]	1.68	1.90	11.77	7.5	0.11	0.52
elek reg+load	[Wh/km]	-26.23	-61.61	-1.24	-27.2	-25.30	-16.39
fuel	[Wh/km]	898.30	873.05	679.12	762.5	469.09	716.59
fuel	[l/100 km]	9.03	8.78	6.83	7.67	4.72	7.21

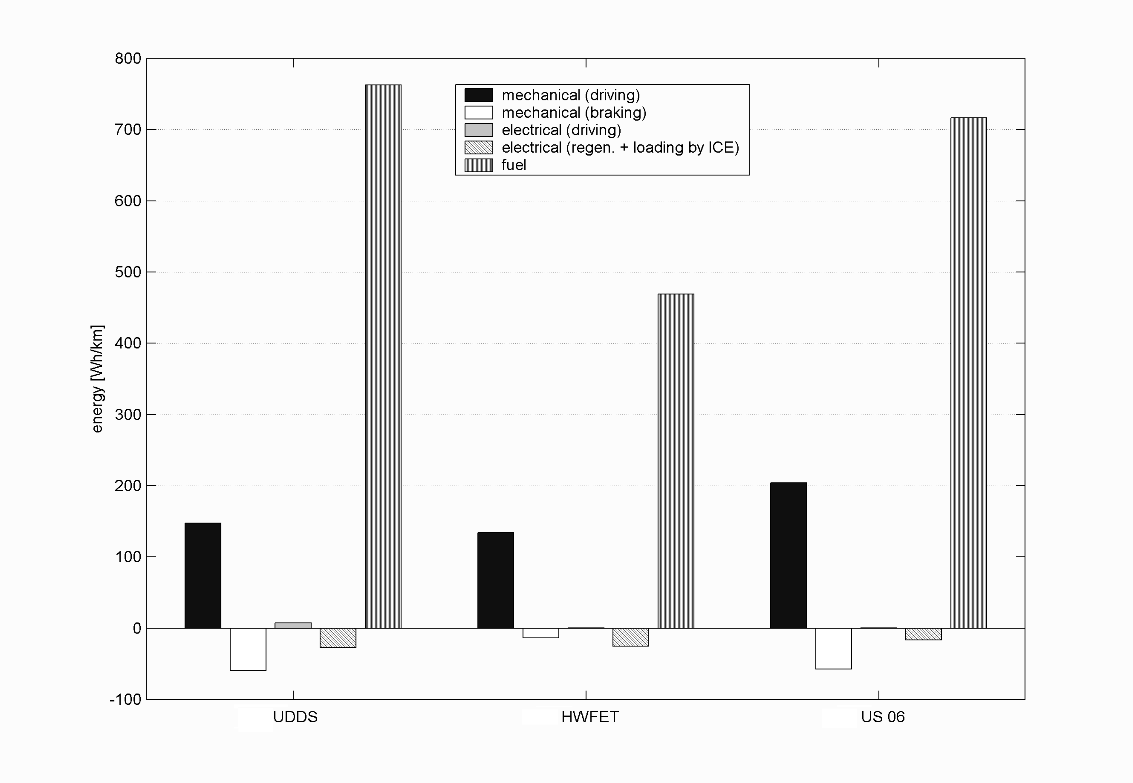

Figure 3.2-31: Energy consumption ICE mode

The bars for the UDDS in ICE mode are the result of the 43/57 weighting of cold and hot test. For the other cycles, only the hot values of the second test are evaluated.

In SAE 1711, the results of the different test should be weighted. For calculating the results in the recharge depleting hybrid mode (RD HEV) the results of the DFT and the average of the IPT (recharge independent partial test) and EOT (engine only test) should be used (see Figure 2.7-1 and Figure 2.7-2). As the Audi DUO has no recharge independent hybrid mode, where the batteries' state of charge is stabilised at a certain level, the IPT could not be performed. Thus the data for weighting is not available. This is an inconsistency of the test procedure. Additionally the range in the DFT and EVT is much lower than intended in the test procedure. So the utility values to calculate the daily travel results should be adapted to the lower range, but the procedure does not clearly state how to do.

3.2.5 Conclusions for testing HEV

The Audi Duo was tested according to prEN 1986-2 and SAE 1711. The tests foreseen in the prEN 1986-2 could be performed without any problems.

Regarding the SAE 1711 draft, some problems occur because of the low range and power in electric mode. Although the SAE1711 tries to cover all possibilities for operating modes, it obviously fails to include the characteristics of the Audi DUO.

Therefore it is recommended to review the procedures of the SAE 1711 that also parallel hybrid with lower electric power capabilities are covered in a correct way. Of course the existing draft reflects, that in the US, especially in California, hybrid vehicles obviously must – in the understanding of the members of the normative group for this standard - have a high electric power and range to receive partial ZEV credits.

Additionally the whole procedure is very complex and the high number of tests to be performed leads to very long and costly tests. Therefore it is recommended, that new standards should demand a much simpler procedure. If the driving schedule and the pattern for the usage of the car (including standstill and recharging times) used for a test is representative, there should be no need to perform tests in for different cycles and all operating modes to perform afterwards a weighting.

4 Investigation on the applicability of the Californian exhaust Emission standards and test procedures

In the course of a research project, which was performed not within the MATADOR-project, another hybrid vehicle was tested at the ika. During this test, beside other aspects, the applicability of the SOC net change tolerances was investigated. The following figure (Figure 3.2-1) shows the change in the energy content of the battery for different cycles, compared to the allowed tolerance calculated with the formula below.

Allowed Tolerance:

$$\Delta Ah_{cycle,allowed} = \pm 0.01 \text{ x } \frac{Fuel\_Mass \times Net\_Heating\_Value}{DC\_Bus\_Voltage \times 3600}$$

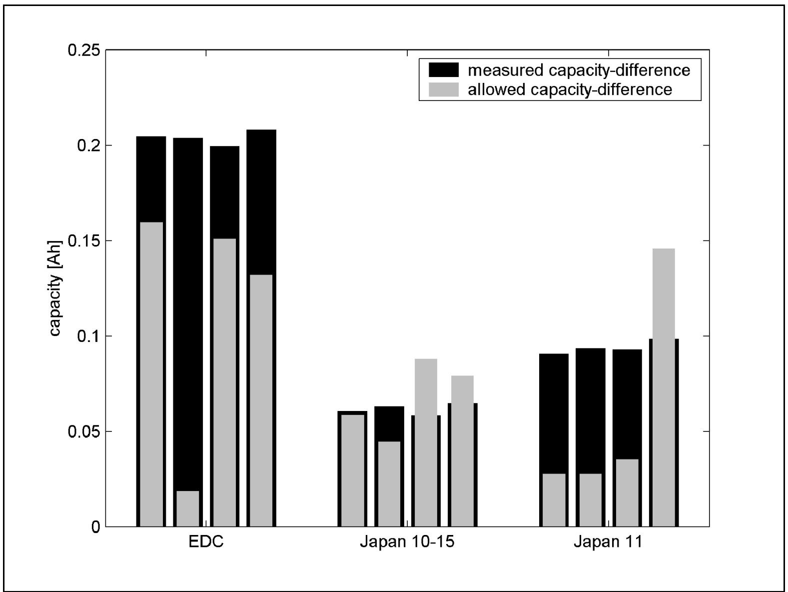

Figure 3.2-1: Comparison of measured and allowed difference in SOC

As can be seen, this tolerance is also applicable to other cycles as the UDDS and HWFET, for which it is originally described. But to achieve this relatively low change in SOC, first some special preparing driving procedures have to be evaluated, with which the initial SOC can established in such a way, that the final SOC falls in the tolerances. To find such procedures could be very complicated and in terms of time and cost not acceptable.

So, also it is possible, to apply this tolerance to other cycles, this big efforts to find the preparing driving procedures must be considered before using this tolerance in the prEN 1986-2 procedure as a tolerance for charge sustaining hybrids. In the understanding of the authors of this report, the interpolation method using the interpolated value of two tests with rising and falling SOC is the easier way to determine the energy consumption of charge sustaining hybrids. For a detailed discussion of delta state-of-charge correction methods, see subtask 2.4.

5 Evaluation of prEN 1986-2 by simulation

The following chapter is based on the longitudinal simulation of a charge depleting hybrid, which are described in detail in the subtask 2.2 report. In order to determine the energy consumption of a hybrid electric vehicle, the European standard prEN 1986-2 defines the following procedure:

1. Determination of the range in electric mode with an initial SOC = 100% (for externally rechargeable hybrid vehicles).

The vehicle shall be driven consecutively over the NEDC until one of the stopping criteria is given. After the stopping criterion is given, the driver shall relief the driving pedals (gas, brake) until 5 km/h, then the vehicle brakes shall be applied.

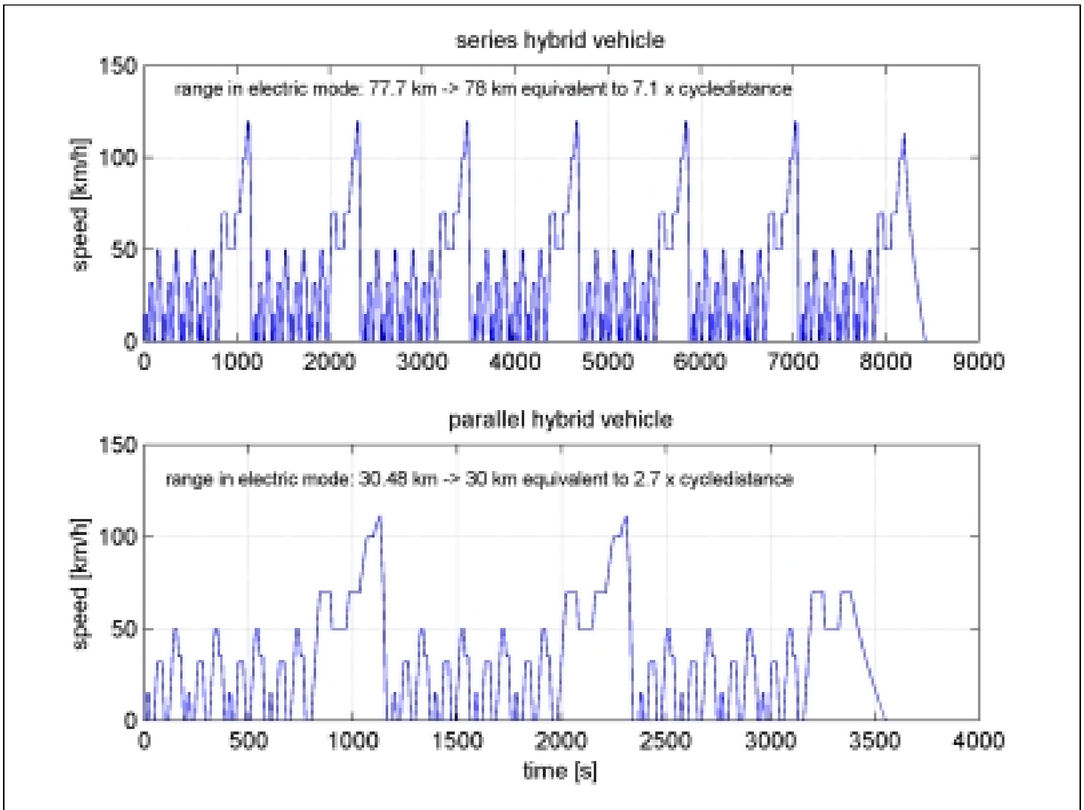

Figure 3.2-1: Time histories of the vehicle speed (determination of the range in EV mode)

In the case of the simulated hybrid vehicles, the stopping criterion is given when the SOC reaches 0 %. When relieving the driving pedals, both the simulated vehicles coast down. The distance travelled is to be rounded to the nearest natural number in kilometres. This is the range in electric mode, which has to be travelled in order to determine the energy consumption in hybrid mode. In Figure 3.2-1 the ranges for the hybrid vehicles in electric mode are shown. As can be seen for the series hybrid vehicle, the stopping criterion is given within the 7th cycle. Due to the following coast down, the rounded travelled distance exceeds the theoretical distance of seven cycles. For the parallel hybrid vehicle, the stopping criterion is given within the 3rd driving cycle.

2. Determination of the <u>energy consumption in hybrid mode</u>

As in the determination of the range in electric mode, the vehicle shall be driven continuously over the NEDC, but now in hybrid mode. The distance that should be travelled has to be equal to the range in electric mode, finishing the current cycle. After that, an additional cycle shall be driven.
In case of the parallel hybrid, the number of cycles to be driven is four, the number of cycles for the series hybrid amounts to nine (EV range is 7.1 times a cycle distance, so the 8th cycle has to be finished and one additional cycle has to be driven).

As can be seen in Figure 3.2-2 and Figure 3.2-3, the differences in energy consumption after one driving cycle and respective nine and four driving cycles are marginal. Due to the fact that the control strategies do not consider the SOC of the battery, the driveline behaviour of the first cycle is the same as of any other cycle. Only the change in battery-efficiency (in the model considered by the internal resistance) over the SOC has an influence on the electric energy consumption. The small differences in electric energy consumption therefore can be led back to the flat efficiency curve of the NiMH battery. The fuel consumptions differ only slightly. This behaviour is also observed if the switch speed of electrical to ICE-operation in control strategy is changed from 50 to 80 km/h.

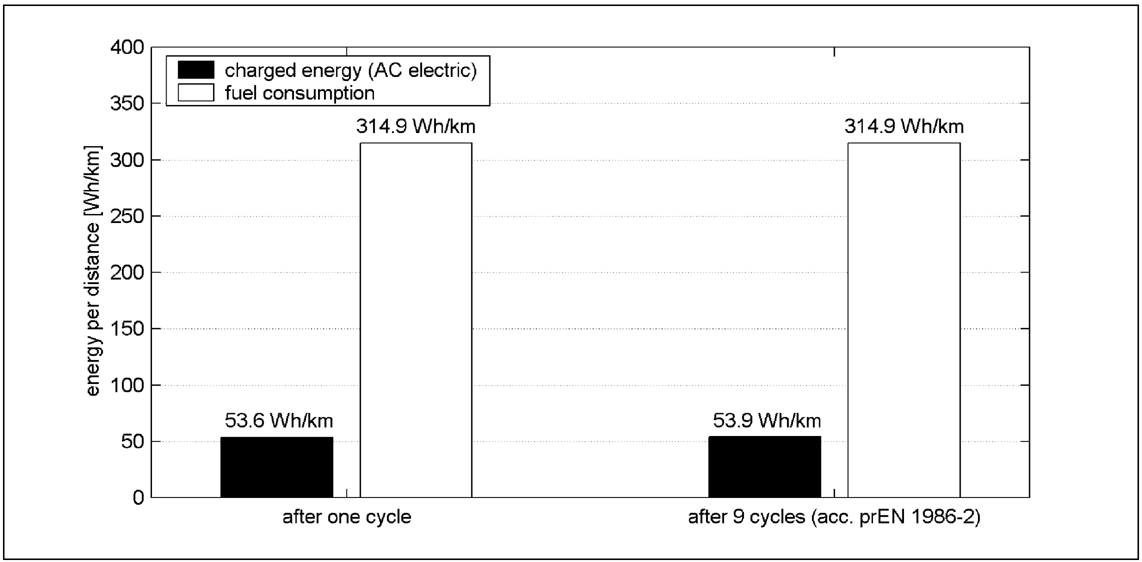

Figure 3.2-2: Energy consumption for the charge-depleting series hybrid vehicle; one cycle compared to prEN 1986-2 standard

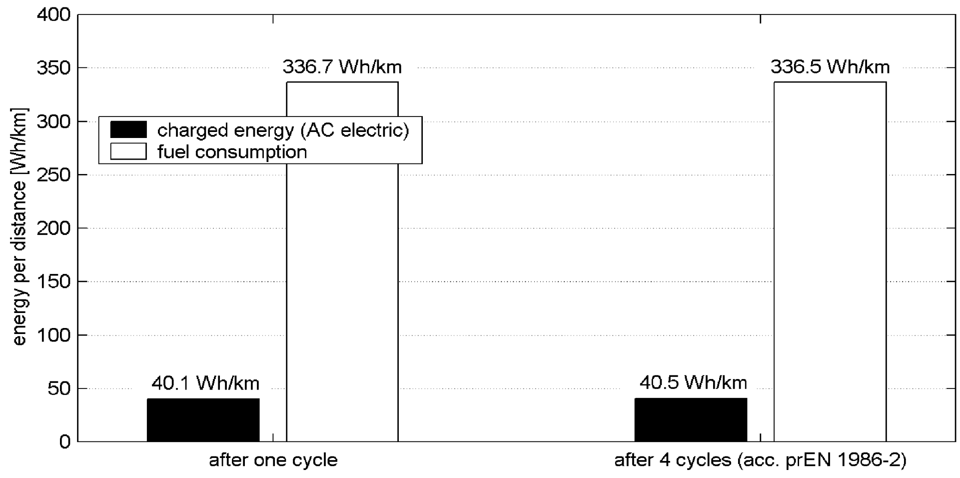

Figure 3.2-3: Energy consumption for the charge-depleting parallel hybrid vehicle; one cycle compared to prEN 1986-2 standard

Consequently, travelling the electric range in order to determine the energy consumption in hybrid mode only makes sense for charge-depleting hybrids without SOC-control, if the efficiency of the traction battery changes considerably over SOC. If this does not apply, it is sufficient to drive only one cycle, saving time and money as a result.
More generally speaking, the procedure can be useful for vehicles with different driveline behaviour (in terms of using the driveline-components differently) over SOC. Then, the measurement of the energy consumption accounts for these differences. In practice, hybrid vehicles often show a warm-up behaviour of the ICE within the first driving cycle, having a different ratio of electric to fuel energy consumption than in the subsequent cycles. The more cycles a hybrid vehicle is driven when determining the energy consumption, the less this behaviour is accounted for in prEN 1986-2.

The repetition of cycles results also in an underestimation of the emissions, because the higher emissions of the cold start are averaged with the lower hot emissions in the following cycles. Conventional vehicles are tested only over one cycle. If a hybrid vehicle, where the cold start occurs during the first cycle, is tested over four or nine cycles, the cold emissions are weighted versus the hot emissions by 1 to 3 or 1 to 8. This leads to an underestimation of the emissions, and secondly it shows, that this implicit weighting is also depending of the vehicle. The longer the pure electric range is, the longer is the test in hybrid mode and the lower is the influence of the cold emissions. This implicit dependency is, in the understanding of the authors of this report, not very useful for a test procedure, which should allow a comparative assessment of vehicles.

For a new testing procedure therefore a fixed number of cycles also for charge depleting hybrids should be used. The problem that the APU must start within this cycle must then be ensured by other measures. But, normally most of the hybrid vehicles have a warm-up strategy for the APU, where the APU is activated at key on and operates until it has been warmed up. For such vehicles no extra measures are necessary to ensure a (cold) start of the APU during the test cycle.
The problem of the weighting of emissions depends on the length of the cycle. If the cycle is representative for the usage of such vehicles and always the same within a comparative assessment, the implicit weighting reflects real life conditions and the measurement of the different is based on the same boundary conditions.

6 Summary and Conclusions

In Task 2 of the MATADOR-project, test methods (Management Tool for the Assessment of Driveline Technologies and Research, EU-contract JOE3-CT97-0081) for battery-electric, hybrid-electric and fuel cell vehicles are analysed in order to support the development of new test procedures for these vehicles with alternative drivelines. In the subtask report presented here the applicability of different standards was investigated both by test and simulation. The goal was to find possible problems of these standards by performing tests according to the standards. The experience and aspects that might turn out into possible problems encountered during the test allow for a deep understanding of the problems of applying and defining test procedures. The standards, which were analysed, are:

- EN 1986-1: Electrically propelled road vehicles – Measurement of energy performances – Part 1: Pure electric vehicles
- SAE J 1634: Electric vehicle energy consumption and range test procedure

Additionally, two testing procedures, which have been established for internal use in the specific institutes, have been discussed too.

- HTA-Biel: Mendrisio BEV Test Procedure
- ENEA: BEV Test Procedure

For hybrid vehicles the following procedures are investigated:

- prEN 1986-2: Electrically propelled road vehicles – Measurement of energy performances – Part 2: Thermal electric hybrid vehicles (Draft)
- SAE J 1711: Recommended practice for measuring the exhaust emissions and fuel economy of hybrid vehicles (Draft)
- California Air Resources Board (CARB): Californian exhaust emission standards and test procedures for 2003 and subsequent model zero-emissions vehicles, and 2001 and subsequent model hybrid electric vehicles, in the passenger car, light-duty truck and medium-duty vehicle class (adopted 5.8.1999)

In the first step, the different standards were analysed. A comparison of the speed profiles shows big differences between the European standards and the US standards. The European ECE-cycle and the NEDC are artificial, consisting of periods with constant velocities and slopes with constant acceleration. These are so called ‘modal’ or ‘stylistic’ cycles. However, the American cycles (UDDS, HWFET, SC03 and US06) are derived from real world driving patterns, giving second by second values for the speed with no constant phases for velocity or acceleration. These are so called ‘transient’ cycles. They generally are more power demanding, especially the US06 test. From the matrices of power over speed it can be seen, that most of the parallel hybrid vehicles, where the power of the electric motor is lower than that of the ICE, might fail to follow the US06 driving schedule in pure EV-mode. As expected, the tested Audi Duo was not able to follow this driving schedule. The key point to solve this problem is the question of the representativity of the driving schedules prescribed in the standards for the given vehicle.

A second difference is the used test weight. The European standards define the test weight at the vehicle curb weight plus 100 kg, whereas the US standards use curb weight plus 136 kg. The resulting influence on energy consumption of 36 kg weight difference may be negligible compared to other uncertainties resulting from the complexity of hybrid drives with different operating modes.

Regarding the vehicle preconditioning, it was evaluated, that especially the condition of the tires has a great influence on the rolling resistance and therewith on energy consumption. This is no special characteristic of BEV or HEV. Conventional vehicles have the same dependency. Therefore , there is no need to warm up the tires before testing, but great care must be taken on the monitoring of pressure and temperature before testing. The temperature should be the same before every test by storing the vehicle at controlled constant ambient temperatures. Existing standards already demand a corresponding time duration between two tests to ensure cold start conditions.

Research on the influence of failure time indicate, that this parameter has an influence on the energy consumption. The energy consumption increases when failure time occurs. Therefore it is reasonable to measure this time during the test. Also all the standards demand to record the time, that a vehicle is not able to follow the cycle. They do not make a difference between allowed deviation times caused by shifting and deviations caused by lack of power. Only these times caused by lack of power should be accounted for as failure time. New procedures should clearly define this difference.

For testing pure electric vehicles, it was recognised that especially heating losses are not consequently regarded by the test procedures. Due to possible differences in charging time, the amount of energy needed for heating can significantly vary, influencing the overall energy consumption. In the European standard EN 1986-1, the recharge duration can vary between minimal 17.98 hours and maximal 23.3 hours. The charge duration according SAE J 1634 is minimal 12 hours, the maximum duration depends on the battery capacity and recharge power and is twice the time of energy capacity (kWh) divided by recharge power (kW). Tests performed with a BEV with a high temperature battery, which has reasonable heating losses, showed a variation in energy consumption due to different recharging times of up to 38 %. If energy consumptions of electric vehicles in a broader sense should be comparable to each other, the charging procedures of SAE J1634 and EN 1986-1 should be combined, using a realistic and representative charging duration. Additionally, an extra measurement of the standstill losses should be introduced into the standards.

The tests of the Audi DUO, a parallel hybrid electric vehicle, show, that the prEN 1986-2 can be applied without any problems. During the test according to SAE J1711, major problems occur, because this procedure obviously does not cover the typical operating characteristics of a typical “European” parallel hybrid vehicle of which the electric performance is only intended for urban conditions. Especially, one inconsistency was found. Following the test procedure, an IPT (recharge independent hybrid mode test) should be performed, but the Audi DUO does not have such a mode. Additionally, the range in the DFT (Dependent Full Charge Test) and EVT (Electric Vehicle Test) is much lower than intended in the test procedure. Thus, the utility values to calculate the daily travel results should be adapted to the lower range, but the procedure does not clearly state how to do that.

Although the SAE J1711 is very complex and demands a high number of different tests in each operation mode, it obviously fails to cover the behaviour of the Audi DUO and its operating strategy. Therefore it is recommended for development of new standards, that new standards should demand a much simpler procedure. If the driving schedule and the pattern for the use of the car (including standstill and recharging times) applied for a test are representative, there should be no need to perform tests in four different cycles and all operating modes to perform a weighting afterwards.

The analysis of the Californian standard shows, that the tolerance given there for the allowed change in the state of charge for a charge sustaining hybrid may be applicable to other cycles than the UDDS, but it needs preparation of the vehicle. The initial state of charge of the batteries must be settled to a value in such a way, that the final state of charge after the test falls within the defined tolerance. To evaluate such procedures could be very complicated, and might not be acceptable, in terms of time and costs. Thus the correction methods analysed in subtask 2.4 are an easier way to determine the energy consumption of charge sustaining hybrids.

An additional analysis of the prEN 1986-2 standard was performed by simulation. For charge depleting hybrids, the energy consumption in hybrid mode is measured over a number of cycles, which is one more than the number, which can be driven in pure electric mode. As a result, the number of cycles to be driven depends on the vehicle. For a comparative assessment, this obviously is not a good solution, if each vehicle is tested over a different number of cycles. A second effect is, that by the repetition of cycles the cold start emissions are underestimated, because the higher emission of the cold start are averaged with the lower hot emissions in the following cycles. For a new test procedure, therefore a fixed number of cycles should be used for charge depleting hybrids also.

Appendix A Volkswagen Bora: Additional graphs

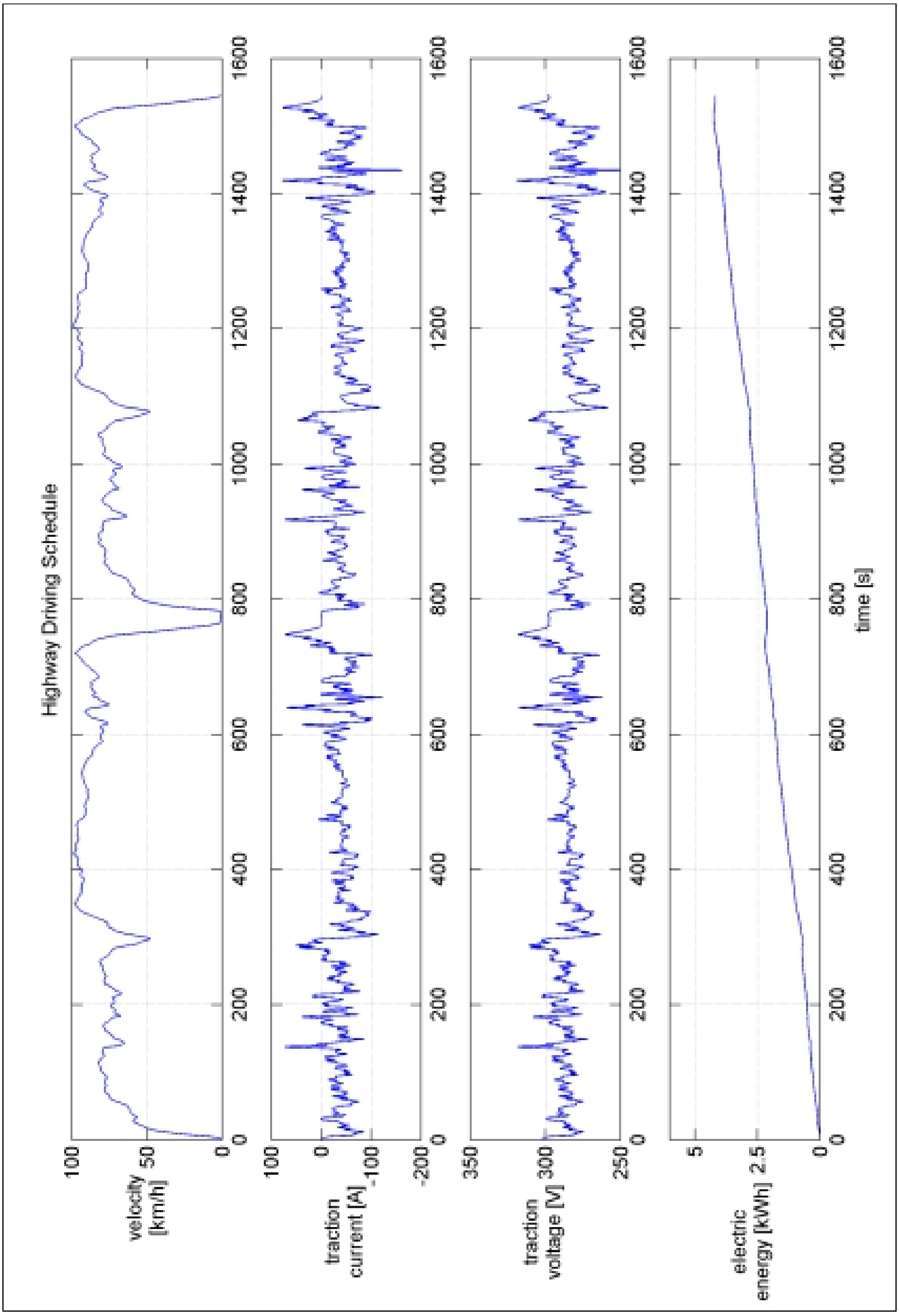

Figure 3.2-1: Highway Driving Cycle (HWFET) as described in SAE J1634

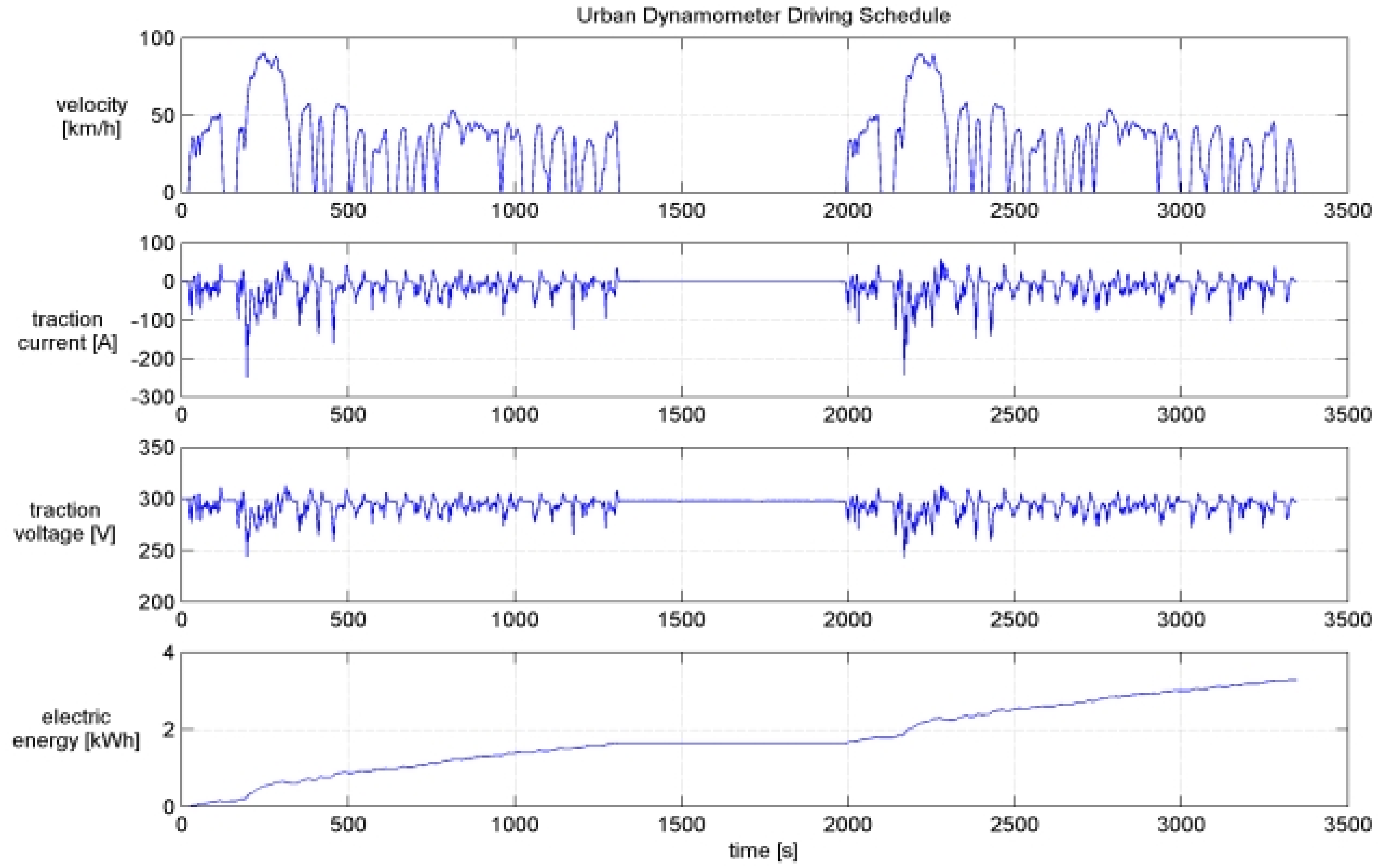

Figure 3.2-2: Urban Dynamometer Driving Schedule (UDDS) as described in SAE J1634

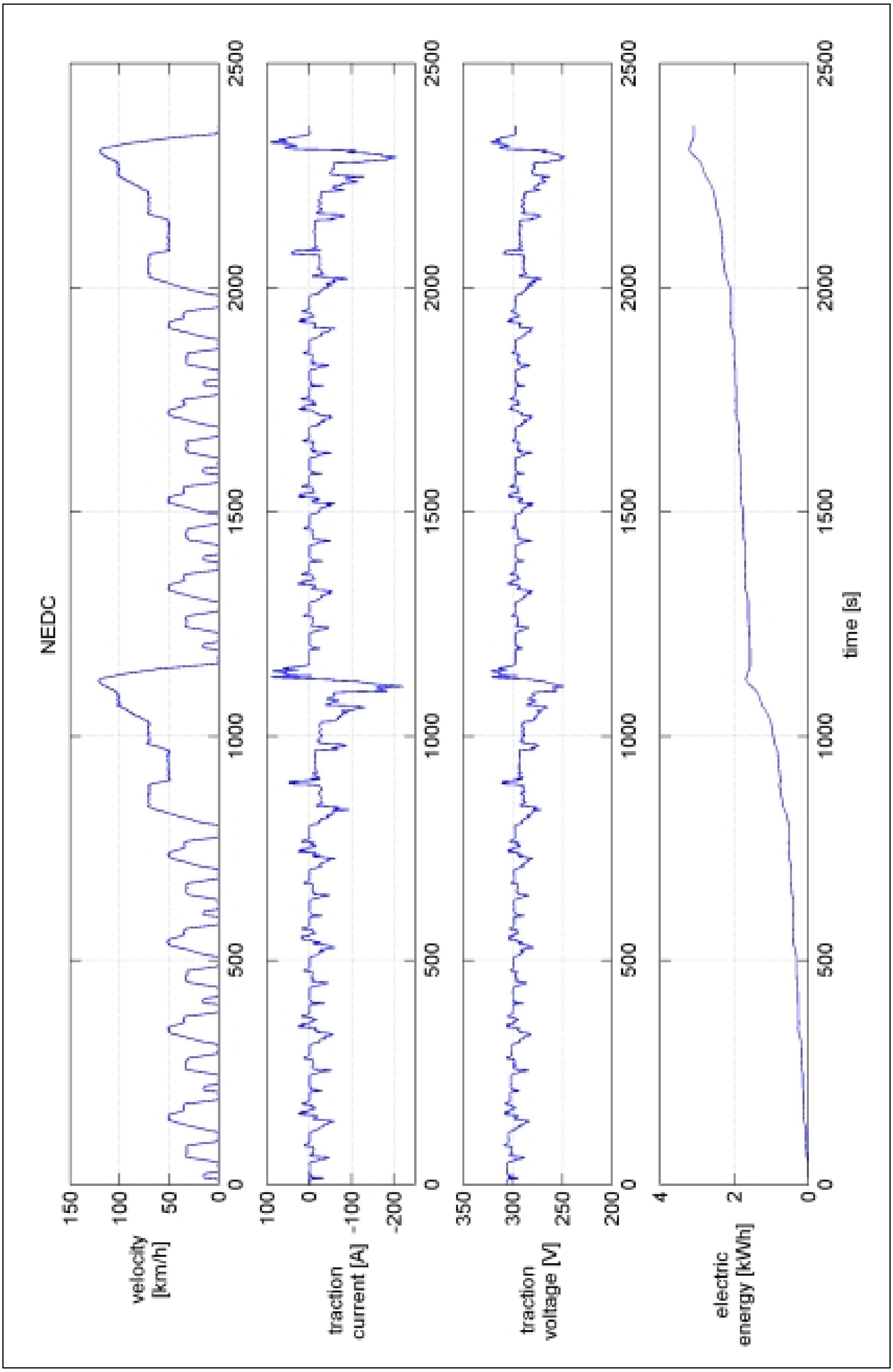

Figure 3.2-3: New European Driving Cycle (NEDC) as described in EN 1986-1

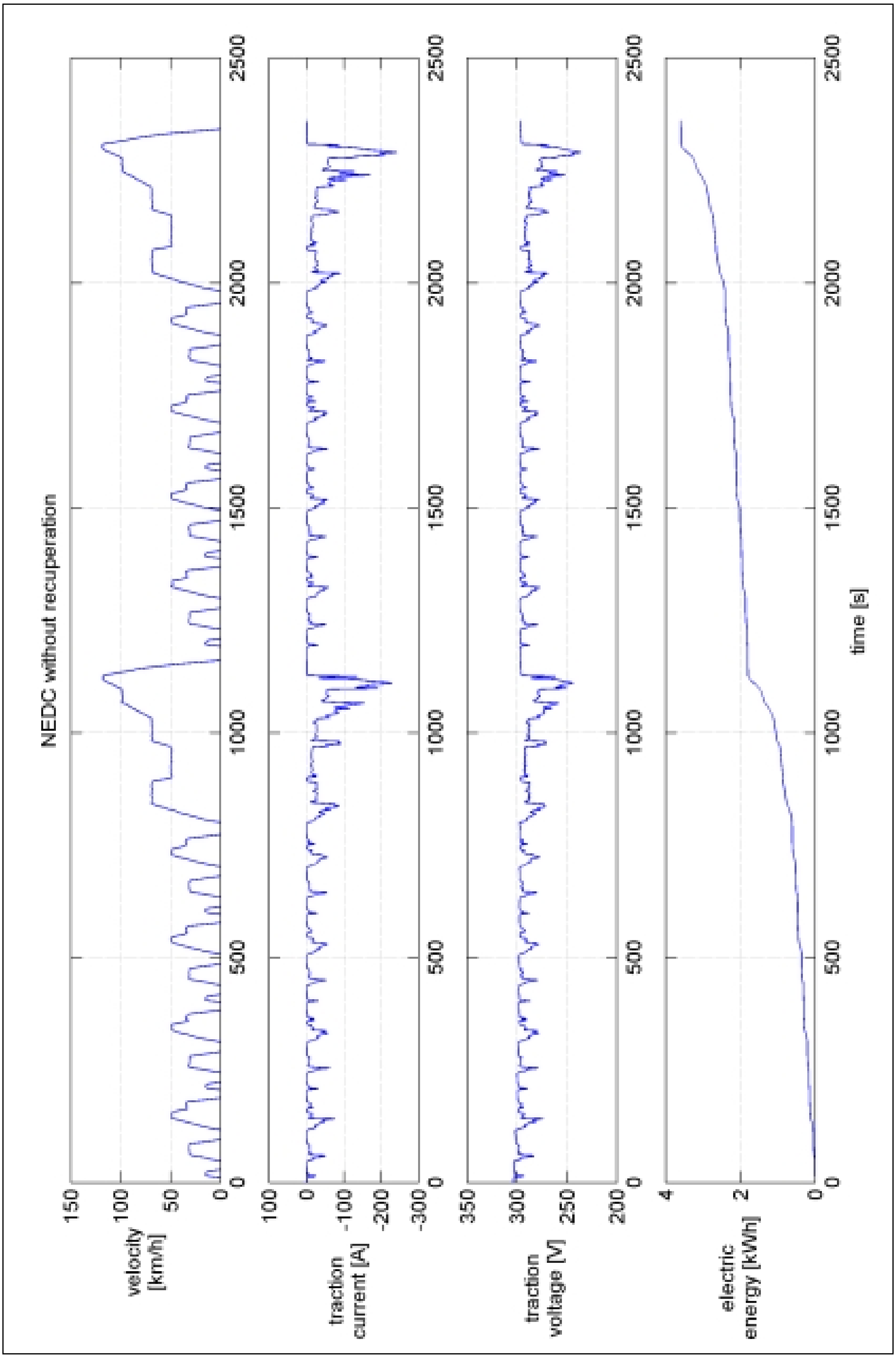

Figure 3.2-4: New European Driving Cycle (NEDC) as described in EN 1986-1 (recuperation-switch off)

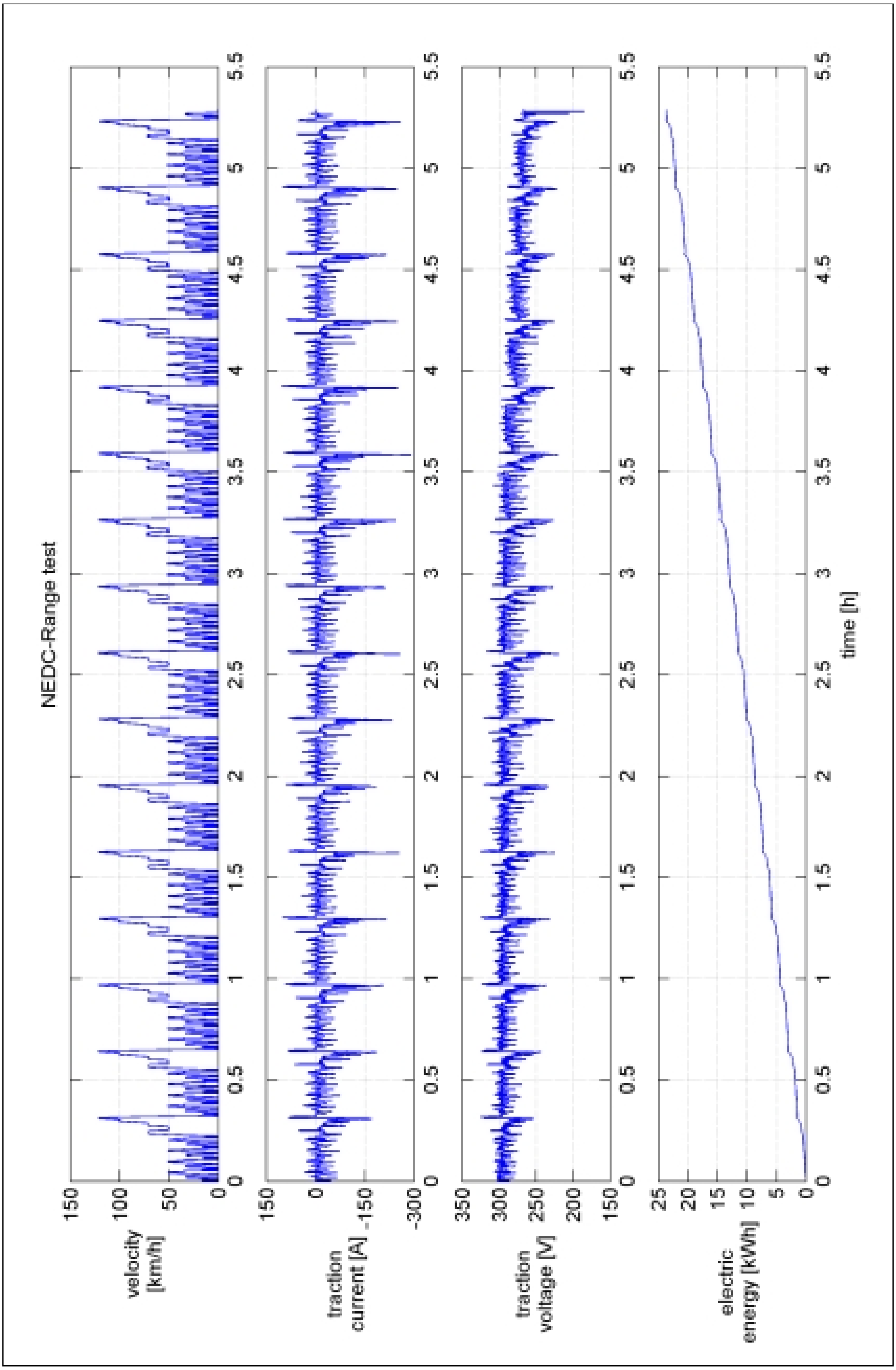

Figure 3.2-5: New European Driving Cycle (NEDC) as described in EN 1986-1 (range test)

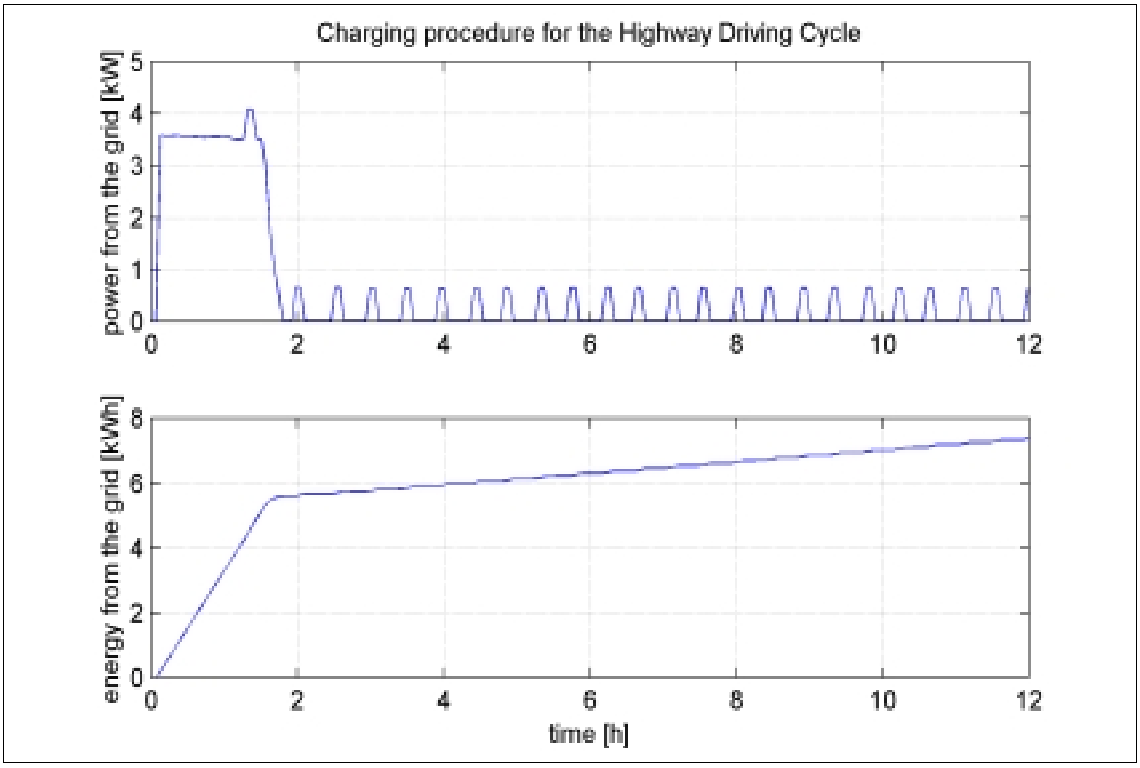

Figure 3.2-6: Charging procedure after HWFET in SAE J1634

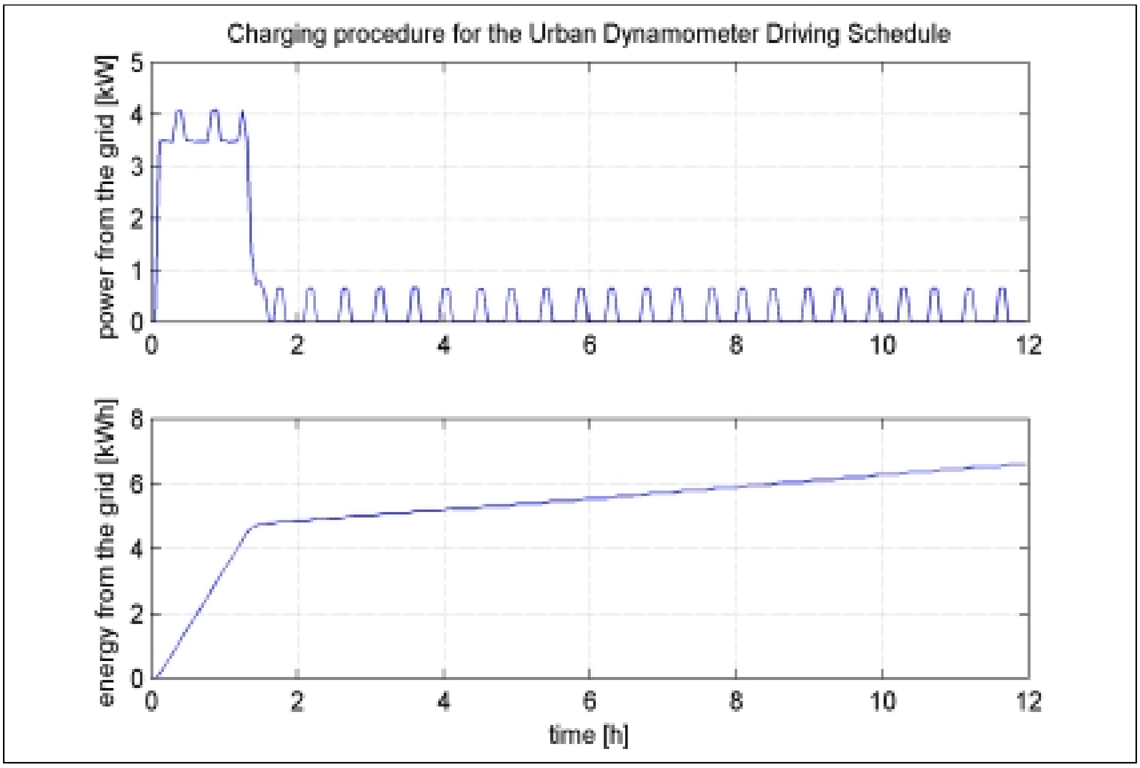

Figure 3.2-7: Charging procedure after UDDS in SAE J1634

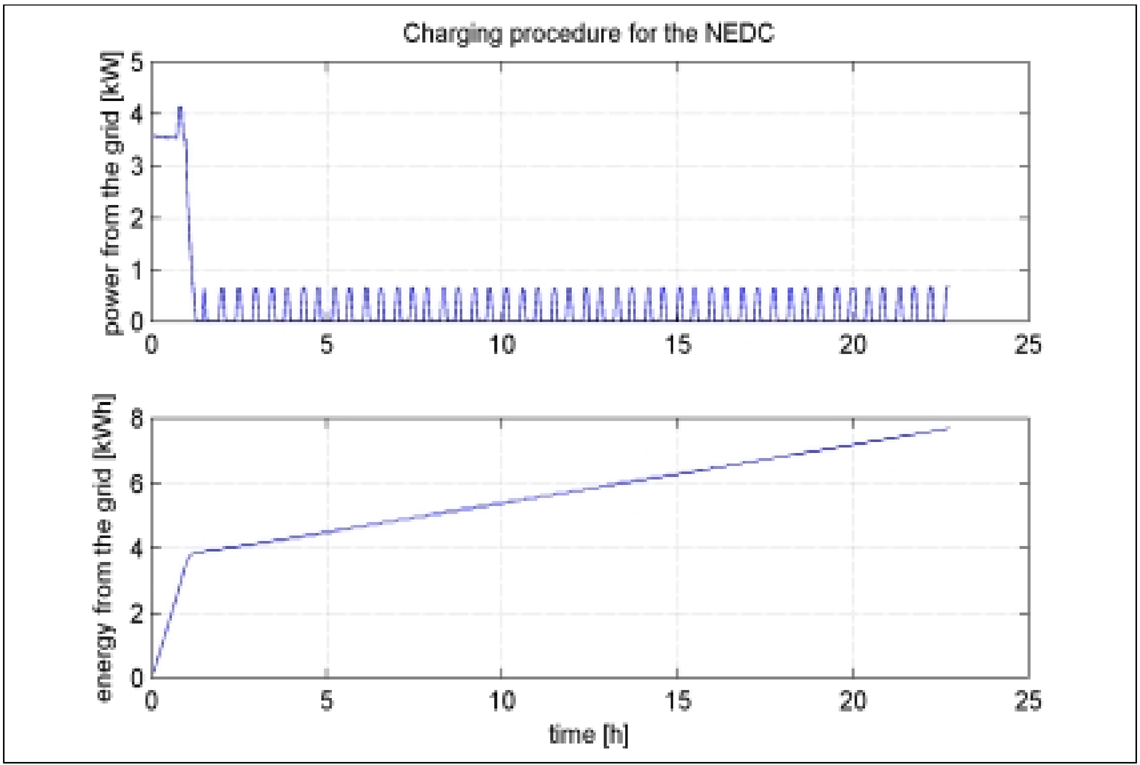

Figure 3.2-8: Charging procedure after the NEDC in EN 1986-1

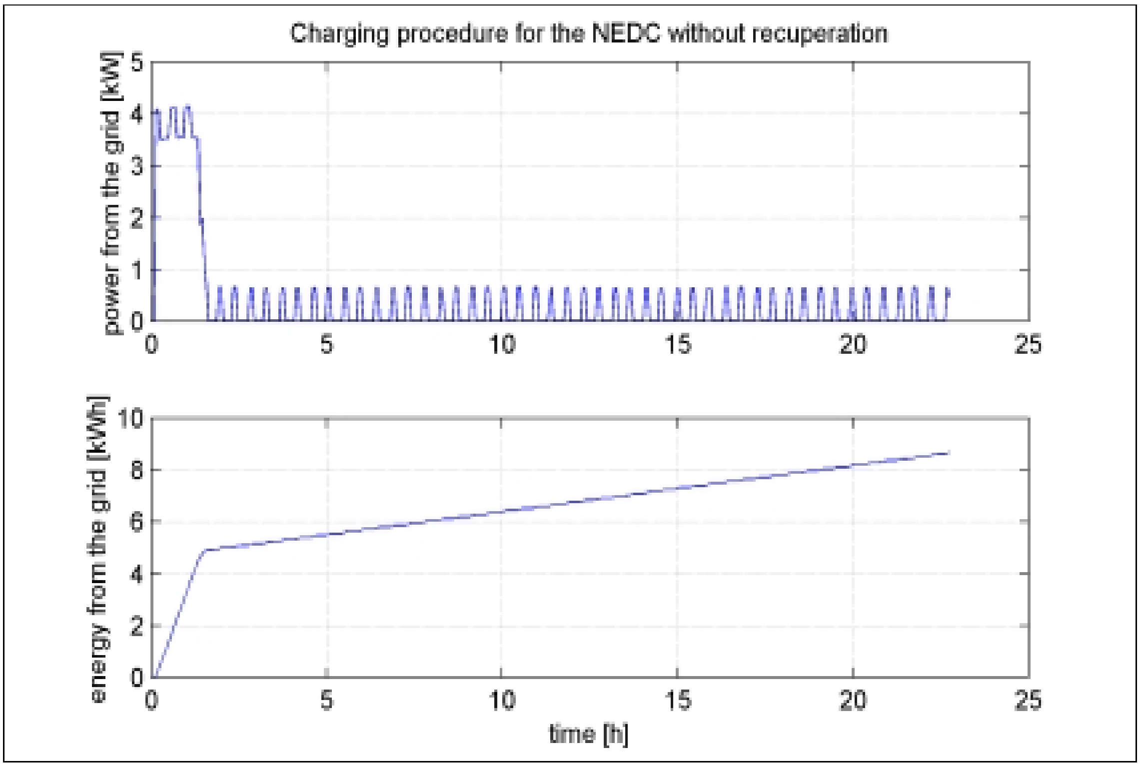

Figure 3.2-9: Charging procedure after the NEDC in EN 1986-1 (recuperation-switch off)

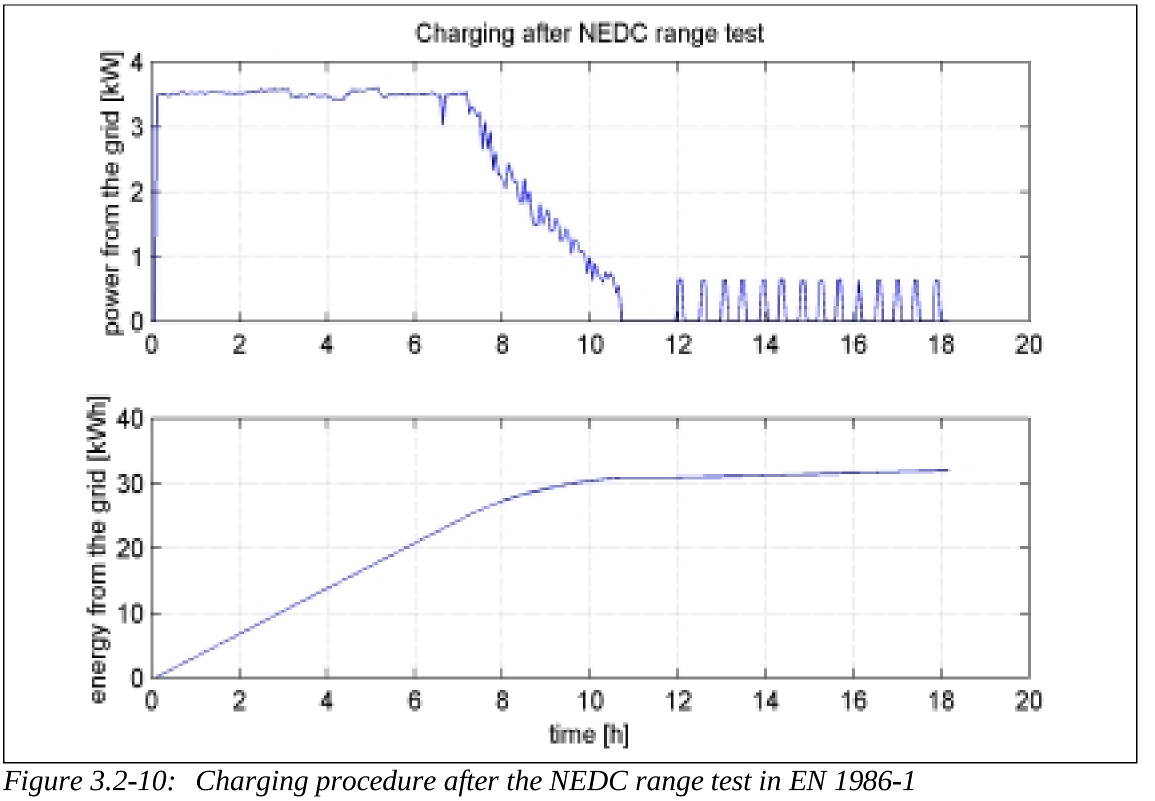

Figure 3.2-10: Charging procedure after the NEDC range test in EN 1986-1

Appendix B prEN 1986-2 (Draft) procedure

CEN/TC301/WG1 N82/revised by Italy
July 15, 1999

new version of prEN 1986-2

Electrically propelled road vehicles — Measurement of energy performances — Part 2 : Thermal electric hybrid vehicles

Elektrisch angetriebene Straßenfahrzeuge — Meßverfahren für Energieausnutzung — Teil 2 : Thermische hybride Elektrofahrzeuge

Véhicules routiers à propulsion électrique — Mesurage des performances énergétiques — Partie 2 : Véhicules hybrides électriques thermiques

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Descriptors:

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Document type: European Standard
Document subtype:
Document stage: CEN Enquiry
Document language: E

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prEN 1986-2:1998

Contents

Foreword

This document has been prepared by CEN /TC 301, "Electrically propelled road vehicles".

CEN TC301 is dealing with "Electrically propelled road vehicles". This title includes, in fact, a wide range of electric road vehicles (see the definitions in prEN YYYY) which can be divided as follows:

- pure electric vehicle : this is an electrically propelled and infrastructure independent exclusively electrically supplied road vehicle ;
- road vehicle fitted with an electric transmission : this vehicle remains in the scope of CEN/TC301 but is considered as a conventional (e.g. an internal combustion engine vehicle) vehicle with a specific transmission (no standards to be developed);
- thermal electric hybrid vehicles where the thermal engine has such a low level of power [1)] compared to that of the power train may be treated as a pure electric vehicle from the measuring point of view;
- other infrastructure independent electric vehicles which are today called electric hybrid vehicles. These electric hybrid vehicles can run with a zero level pollutant emission;
- infrastructure dependent electrically propelled road vehicles are excluded from application of this standard.

A large amount of work has been undertaken on electric hybrid vehicles, and there is still a lot to discover on these vehicles which can, for instance, incorporate several driving modes (more than two);

To remain today within what is most common, the term thermal electric hybrid vehicle will be understood as an electric road vehicle fitted with a thermal machine (which is fed with fuel).

This European Standard prEN 1986 consists of the following parts, under the general title "Electrically propelled road vehicles - Measurement of energy performances" :

- Part 1 : Pure electric vehicles ;
- Part 2 : Thermal electric hybrid vehicles ;
- Part 3 : Other electric hybrid vehicles than those fitted with a thermal machine.

Annex A forms an integral part of prEN 1986-2.

Annex B to Annex E are for information only.

This document is currently submitted to the CEN Enquiry.

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1) In order to be able to use existing measuring facilities.

1 Scope

This standard aims at defining the range in pure electric driving mode and the consumption measurements for a thermal electric hybrid road vehicle from M_1, N_1, or M_2 [2)] category, and for tricycles and quadricycles from the motorcycle types [3)] .

This standard applies to the above mentioned vehicles whose range and consumption can be tested following the provisions already laid down for conventional vehicles (i.e. Internal Combustion Engine vehicle) from the equivalent categories.

2 Normative references

This European Standard incorporates by dated or undated reference, provisions from other publications. These normative references are cited at the appropriate places in the text and the publications are listed hereafter. For dated references, subsequent amendments to or revisions of any of these publications apply to this European Standard only when incorporated in it by amendment or revision. For undated references the latest edition of the publication referred to applies.

EN 1821-1 :	1996,	Electrically propelled road vehicles - Measurement of road operating ability- Part 1: Pure electric vehicles.
EN 1986-1 :	1997,	Electrically propelled road vehicles - Measurement of energy performances - Part 1 : Pure electric vehicles.
EN 1987-1 :	1997,	Electrically propelled road vehicles - Specific prescriptions for safety - Part 1: On board energy storage.
prEN YYYY :		Electrically propelled road vehicles - Terminology (WI n° 11).
ISO 3675 :	1993,	Crude petroleum and liquid petroleum products - Laboratory determination of density or relative density - Hydrometer method.

3 Definitions

For the purpose of this standard, the following definitions apply (see also prEN YYYY).

~~1.1~~3.1 Electrically propelled road vehicle

An electrically propelled road vehicle is a road vehicle in which electric energy is transformed by electrical machine(s) into mechanical energy for traction purposes.

NOTE Traction is the term used with the same meaning as propulsion, but for historical reasons, this is the most widely used term.

2) Categories of vehicle M_1, N_1, and M_2 are defined in Directive 92/53/EEC. In practice, tricycles and quadricycles with a maximum speed over 45 km/h fall within the scope of this standard.

3) Motor tricyles and quadricycles are defined in Directive 92/61/EEC.

~~1.2~~3.2 Electric hybrid (road) vehicle

~~An electric hybrid vehicle is an electrically propelled road vehicle integrating an electric traction system which permits a pure electric driving mode, and having at least one additional other form of on board energy source (for traction purposes).~~

~~NOTE Vehicles integrating electric machine(s) for functional assistance such as load levelling device, starter, electrically driven auxiliary units, etc. shall not be considered as electric hybrid vehicles, in so far they do not allow a pure electric mode.~~

a hybrid vehicle in which one of the reversible energy source delivers electric energy

~~1.3~~3.3 Thermal electric hybrid vehicle

~~A thermal electric hybrid vehicle is an electric hybrid vehicle in which the additional other form of energy source includes a thermal machine (e.g. internal combustion engine, gas turbine).~~

an electric hybrid vehicle in which the traction system contains a thermal machine.

NOTE Vehicle integrating electric machine(s) for functional assistance to the engine such as load levelling devices, starter, electrically driven auxiliary units, etc. shall not be considered as electric hybrid vehicles, in so far they do not participate to the traction.

~~1.4~~3.4 Pure electric mode

The pure electric mode is the driving mode when only the secondary on board electric energy source delivers energy for traction purpose. The pure electric mode can be either selected by the driver or automatically selected by the system.

For definitions of primary or secondary on board electric energy source, refer to prEN YYYY (Terminology).

~~1.5~~3.5 Pure thermal mode

The pure thermal mode for a thermal electric hybrid vehicle is the driving mode which can be selected by the driver when only the additional other kind of on board energy source (including the thermal machine) participates in the propulsion of the vehicle.~~delivers energy for traction purpose.~~ In this case, the on board secondary electric energy source is not active even for energy recovery.

~~1.6~~3.6 Hybrid mode (for an electric hybrid vehicle)

The hybrid mode for an electric hybrid vehicle is another driving mode than the pure electric mode, if selected by the driver, or the pure thermal mode. All the on board energy sources can participate in the propulsion of the vehicle in accordance with~~,~~ the management system logic. The hybrid mode includes the pure electric mode when it is automatically selected by the system.

~~1.7~~3.7 Series electric hybrid vehicle

A series electric hybrid vehicle is a~~n~~ series~~electric~~ hybrid vehicle in which all energy sources deliver electric energy~~for which the wheel propulsion is produced only by an electric power train. The additional other form of on board energy source supplies electric power to the electric power train~~.

~~1.8~~3.8 Parallel electric hybrid vehicle

A parallel electric hybrid vehicle is an electric hybrid vehicle for which the wheel propulsion is produced either by the electric drive train and/or by the additional form of on board energy source delivering mechanical power, both through a transmission which can be common or individual.

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~~1.9~~3.9 On board energy source

~~An on-board energy source is a system which delivers energy (electric or other) for traction purpose. It includes an on board energy storage, an energy delivery system and any ancillary devices. The energy storage can be fed from the outside of the vehicle.~~ is a subsystem of the traction system consisting of a combination of at least storage(s) and possibly converter(s), transmission(s), ancillary device(s). The on-board energy source delivers energy to the power train for traction purpose

EXAMPLE 1 :

For a pure electric vehicle, the on board energy source can be made of :

- for the storage : an electrochemical storage battery,
- for the energy delivery system : cables,
- for the ancillary devices : thermal management of the battery, on board charger, protection devices.

EXAMPLE 2 :

For a series thermal electric hybrid vehicle, the additional other kind of on board energy source can be made of :

- for the storage : a petrol tank,
- for the energy delivery system : a generating set including an IC engine plus an alternator and a rectifier,
- for the ancillary devices : electronic controllers and a cooling system.

~~EXAMPLE 3 :~~

~~For a parallel thermal electric hybrid vehicle, the additional other kind of on board energy source can be made of :~~

- ~~for the storage : a petrol tank,~~
- ~~for the energy delivery system : an IC engine,~~
- ~~for the ancillary devices : electronic controllers and a cooling system.~~

4 Measurement of the range in pure electric mode

The measurement of the range, in pure electric mode, of a thermal electric hybrid vehicle is the same as that described in clause 6 of EN 1986-1 for pure electric vehicles. The end of test criterion - as an alternative to that already provided by EN 1986-1 - is the switching-on of the thermal engine.

The test results can be given as in Annex E.

5 Measurement of the electric energy consumption in pure electric mode

The measurement of the electric energy consumption in pure electric mode of a thermal electric hybrid vehicle is the same as that described in clause 5 of EN 1986-1 for pure electric vehicles.

If the range in pure electric mode of the thermal electric hybrid vehicle is smaller than the required distance in clause 5 of EN 1986-1 (i.e. seven times test sequence 1, about 28 km, or two times test sequence 2, about 22 km), then the test may be done with the highest possible whole number of cycles (sequence 1, about a multiple of 4 km, or sequence 2, about 11 km), compatible with the measured range.

If the range in pure electric mode of a thermal electric hybrid vehicle is smaller than one cycle of sequence 1, then the measurement procedure of the electric energy consumption is not applicable.

The test results can be given as in Annex E.

6 Measurement of the consumption

6.1 Principle

If a pure thermal mode can be selected by the driver, the test of the consumption in hybrid mode shall be performed in pure thermal mode following strictly Directive 80/1268/EEC as amended [4]. Then, the thermal electric hybrid vehicle behaves like a thermal engine vehicle, and no test procedure in hybrid mode is required.

Otherwise, the whole test procedure has to be fulfilled in hybrid mode (see 6.7).

The following test procedure ensures that the additional other form of on board energy source participates to the propulsion of the vehicle (thermal engine). This is the reason why the total distance travelled shall exceed the range of the vehicle in pure electric mode, thus implying at least one cold start of the thermal engine.

Annex A completes the operation mode, defines the measurements to perform and the calculations.

6.2 Cycle

A cycle comprises four urban cycles followed by one extra-urban cycle (test sequence 2) as defined in 4.1 of EN 1986-1.

6.3 Equipment

All the equipment requirements of Directive 70/220/EEC as amended [5] shall apply.

The calibration of the chassis dynamometer is carried out according to Annex A of EN 1986-1.

6.4 Fuel

The fuel used for the test shall be that defined by Directive 70/220/EEC as amended [5].

[4] At the time of the elaboration of this standard, Directive 80/1268/EEC was last amended by directive 93/116/EC. In the case of further amendments, a check of their compatibility with this standard shall be undertaken.

[5] At the time of the elaboration of this standard, Directive 70/220/EEC was last amended by Directive 96/69/EC. In case of further amendments, a check of their compatibility with this standard shall be undertaken.

6.5 Parameters, units and accuracy of measurements

Table 1

Parameter	Units	Accuracy	Precision
Time	s	0,1 s	0,1 s
Length (distance)	m	0,1 %	1 m
Temperature	° C	1 °C	1 °C
Speed	km/h	1 %	0,2 km/h
Mass	kg	0,5 %	1 kg
~~Energy~~ Electric energy	Wh	0,2 %	1 Wh
Hydrocarbon	vol ppm 1)	2 %	1 ppm
Carbon monoxide	vol ppm 1)	2 %	1 ppm
Carbon dioxide	vol % 2)	2 %	0,01 %

1) vol ppm means parts per million in volume.

2) vol % means parts per cent in volume.

6.6 Test conditions

6.6.1 Condition of vehicle

a) The vehicle tyres shall be inflated to the pressure specified by the vehicle manufacturer when the tyres are at the ambient temperature.

b) The viscosity of the oils for the mechanical moving parts shall conform to the specifications of the vehicle manufacturer.

c) The lighting and light signalling and auxiliary devices shall be off, except those required for testing and usual day-time operation of the vehicle.

d) All energy storage systems available for other than traction purposes (electric, hydraulic, pneumatic etc.) shall be charged up to their maximum level specified by the manufacturer.

e) If the electric energy source is operating above the ambient temperature, the operator shall follow the procedure recommended by the vehicle manufacturer in order to keep the temperature of the electric energy source in the normal operating range.

In case of vehicle without charger (on board or not), it is necessary to integrate measurements of the pollutants when performing the consumption measurement as in clause 6.

The vehicle manufacturer shall be in a position to attest that the thermal management system of the electric energy source is neither off, nor reduced.

f) The vehicle shall have undergone at least 300 km in the seven days before the test with those batteries that are installed in the test vehicle.

6.6.2 Climatic conditions

The indoors test steps are carried out at the same conditions as those in Directive 70/220/EEC as amended [6].

6.6.3 Initial condition of charge of the on board secondary electric energy source

The on board secondary electric energy sources for externally chargeble vehicles shall be initially fully charged. It means, depending on its tecnology, after an initial charge of the battery for electrochemical storage battery as described in 5.5.1 in EN 1986-1. If within a test campain, an initial charge of the battery has been already performed (as in clause 5 for instance), it prevents from applying the initial charge procedure only if any other charge of the battery (after the initial charge) has been performed according to the procedure of a normal charge described in EN 1821-1.

The on board secondary electric energy sources for not externally chargeble vehicles shall be initially settled at the state of charge recommended by the car Manufacturer, knowing that it will have to be balanced at the end of the test.

The procedure to settle the initial state of charge has to be defined by the car Manufacturer according to the technology (e.g. speed for a flywheel, voltage for an electric capacitor).

6.7 Operation mode

If several hybrid modes are available, the one to best match the speed curve shall be selected. If several hybrid modes can fulfil the speed curve, then select among them the mode recommended by the vehicle manufacturer. The selected mode shall be maintained during the whole test procedure. Annex D gives for information what could be useful for the test operator.

The on board secondary electric energy source is in its initial condition.

The vehicle shall be driven continuously over the cycle (as described in 6.2) until the distance travelled has equalled to that of the range in pure electric mode (see clause 4), completing the current cycle, and then, drive a further complete cycle. This distance is called the total distance travelled (d).

The tolerances on speed and on time are those from 4.2 in EN 1986-1.

In case of externally chargeble vehicle the electric part of the energy consumption has to be measured at the network by charging the secondary energy source up to the initial conditions.

In case of not externally chargeble vehicle the vehicle shall be operated according to the Manufacturer 's recommendations in order to recharge the ~~the~~ secondary energy source at its initial conditions, measuring the hydrocarbon, carbon monoxide and the carbon dioxide during the charging of the thermal electric hybrid vehicle, taking into account that the travelled associated distance is equal to zero.

6.8 Expressions of the result

The total consumption of the vehicle in hybrid mode is defined by the expression :

$$C = EC\ (Wh/km)\ \text{and}\ FC\ (l/100km)$$

in which EC, Electrical Consumption, is rounded to the nearest whole number, and FC, Fuel Consumption, is rounded to the nearest tenth.

The result may be given as in Annex E.

[6] At the time of the elaboration of this standard, Directive 70/220/EEC was last amended by Directive 96/69/EC. In case of further amendments, a check of their compatibility with this standard shall be undertaken.

Annexe A
(normative)

Measurement of the consumption

A.1 General

A.1.1 The consumption of a thermal electric hybrid vehicle comprises consumption of each kind of energy : electric energy from the mains on one side, volume of fuel on the other side.

The electric energy consumption measurement procedure of a thermal electric hybrid vehicle is derived from that of a pure electric vehicle in EN 1986-1.

The measurement of the fuel consumption of a thermal electric hybrid vehicle is based on the procedures as described in Directive 80/1268/EEC as amended [7]. The exhaust gases containing carbon are measured and the fuel consumption is calculated by carbon atom equivalence.

A.1.2 The densities under reference conditions (see A.3) are the following:

- carbon monoxide (*CO*) : QC_{CO} = 1,25 g/l ;
- carbon dioxide (CO_2) : QCO_2 = 1,964 g/l ;
- hydrocarbon ($CH_{1,85}$) : $QCH_{1,85}$ = 0,619 g/l.

A.2 Recorded values

The recorded values during the test are the following :

- total travelled distance *d*, expressed in kilometres ;
- electric energy *E* taken from the mains, expressed in watthours ;
- sampling time *t*, expressed in seconds ;
- volumetric concentration of carbon monoxide, expressed in vol ppm [8] ;
- volumetric concentration of carbon dioxide, expressed in vol % [9] ;
- volumetric concentration of hydrocarbon, expressed in vol ppm [8] ;
- volume of diluted exhaust gas for the Constant Volume Sampler (CVS) method with gas storage method (expressed in litres per test), or gas flow for the Continuous Analysis Method (CAM) (expressed in litres per second).

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[7] At the time of the elaboration of this standard, Directive 80/1268/EEC was last amended by Directive 93/116/EEC. In case of further amendments, a check of their compatibility with this standard shall be undertaken.

[8] Vol ppm means parts per million in volume.

[9] Vol % means parts per cent in volume.

A.3 Fuel consumption

The reference conditions are the following :

- for temperature : 273,2 K (0 °C) ;
- for atmospheric pressure : 101,33 kPa ;
- for density of test fuel : the values measured according to ISO 3675 at the temperature of 288 K (15 °C), expressed in grams per litre.

There are two methods for the calculation of the fuel consumption.

NOTE CVS with gas storage method is described in Directive 70/220/EEC as amended [10]. The continuous analysis method is widely used with new testing equipments.

A.3.1 CVS with gas storage method

The calculation is made as follows.

A.3.1.1 Emissions of gases

A.3.1.1.1 Calculation of the volume when a variable dilution device with constant flow control by orifice or venturi is used. Record continuously the parameters showing the volumetric flow, and calculate the total volume for the duration of the test.

A.3.1.1.2 Calculation of volume when a positive displacement pump is used. The volume of diluted exhaust gas in systems comprising a positive displacement pump is calculated with the following formula:

$$V = V_o \times N$$

where :

V is the volume of the diluted exhaust gas expressed in litres per test (prior to correction) ;

V_o is the volume of gas delivered by the positive displacement pump on testing conditions in litres per revolution ;

N is the number of revolutions of the pump.

[10] At the time of the elaboration of this standard, Directive 70/220/EEC was last amended by Directive 96/69/EC. In case of further amendments, a check of their compatibility with this standard shall be undertaken.

A.3.1.1.3 Correction of the diluted exhaust-gas volume to reference conditions. The diluted exhaust gas volume is corrected by means of the following formula :

$$V_{mix} = V \times K_1 \times \frac{P_p}{T_p}$$

in which :

$$K_1 = \frac{273,2}{101,33} = 2,6961 \text{ (expressed in K/kPa)}$$

where :

P_p is the absolute pressure at the inlet of the positive displacement pump, in kilopascals ;

T_p is the average temperature of the diluted exhaust gas entering the positive displacement pump during the test, in kelvins.

A.3.1.2 Calculation of corrected concentrations

Calculation of the corrected concentration of gases in the sampling bag is made with the following equation:

$$C_i = C_e - C_d \left(1 - \frac{1}{DF}\right)$$

where :

C_i is the concentration of the gas *i* in the diluted exhaust gas, expressed in vol ppm [11], or vol % [12] according to A.2 and corrected by the amount of *i* contained in the air used for dilution;

C_e is the measured concentration of gas *i* in the diluted exhaust gas, expressed in vol ppm [11], or vol % [12] according to A.2;

C_d is the measured concentration of gas *i* in the air used for dilution, expressed in vol ppm [11], or vol % [12] according to A.2;

DF is the dilution factor, valid only for gasoline and diesel fuel.

---

[11] Vol ppm means parts per million in volume.

[12] Vol % means parts per cent in volume.

The dilution factor is calculated as follows:

$$DF = \frac{13{,}4}{C_{CO_2} + (C_{HC} + C_{CO})10^{-4}}$$

where :

C_{CO_2} is the concentration of CO_2 in the diluted exhaust gas contained in the sampling bag, expressed in vol % [13];

C_{HC} is the concentration of HC in the diluted exhaust gas contained in the sampling bag, expressed in vol ppm [14] carbon equivalent ;

C_{CO} is the concentration of CO in the diluted exhaust gas contained in the sampling bag, expressed in vol ppm [14].

.3.1.3 Special provisions for compression ignition engines in thermal electric hybrid vehicles

The average HC concentration used in determining the HC mass emissions from compression-ignition engines is calculated with the aid of the following formula:

$$C_e = \frac{\int_o^t C_{HC} \times dt}{t}$$

where :

$\int_o^t C_{HC} \times dt$ is the integral of the recording of the heated flame ionisation over the test duration t ;

C_e is the HC concentration of the diluted exhaust sample as calculated from the integrated HC trace, in vol ppm [14] carbon equivalent.

A.3.1.4 Emissions of gases

Emissions of gases are calculated by means of the following equation :

$$M_i = \frac{V_{mix} \times Q_i \times C_i \times a}{d}$$

where :

M_i is the mass emission of the gas *i* in grams per kilometre ;

V_{mix} is the volume of the diluted exhaust gas expressed in litres per test and corrected to reference conditions (273,2 K and 101,33 kPa) ;

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[13] Vol % means parts per cent in volume.

[14] Vol ppm means parts per million in volume.

Q_i is the density of the gas *i* in grams per litre at reference temperature and reference pressure (273,2 K and 101, 33 kPa) ;

C_i is the concentration of the gas *i* in the diluted exhaust gas expressed in vol ppm [15)] or in vol % [16)] as in A.2, and corrected by the amount of gas *i* contained in the air used for dilution;

a is a constant value depending on the gas i : a = 10^{-6} for CO and HC, a = 10^{-2} for CO_2;

d is the total travelled distance expressed in kilometres.

A.3.2 Continuous analysis method

The operating laboratory shall demonstrate that the system used and the calculation method permits to reach the accuracies required in table 1.

Annex B gives for information a possible calculation method.

A.3.3 Calculation of the fuel consumption

FC is the fuel consumption given by one of the following formula as appropriate :

- for petrol engine vehicle

$$FC = \frac{115{,}4}{D}\left[\left(0{,}866 \times M_{HC}\right) + \left(0{,}429 \times M_{CO}\right) + \left(0{,}273 \times M_{CO_2}\right)\right]$$

- for diesel engine vehicle

$$FC = \frac{115{,}5}{D}\left[\left(0{,}866 \times M_{HC}\right) + \left(0{,}429 \times M_{CO}\right) + \left(0{,}273 \times M_{CO_2}\right)\right]$$

where :

FC is the fuel consumption in litres per 100 km ;

M_{HC} is the measured emission of hydrocarbon in grams per kilometre;

M_{CO} is the measured emission of carbon monoxide in grams per kilometre;

M_{CO_2} is the measured emission of carbon dioxide in grams per kilometre;

D is the density of the fuel as indicated in A.3.

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15) Vol ppm means parts per million in volume.

16) Vol % means parts per cent in volume.

A.4 Calculation of the electric consumption

The measurement of the electric energy consumption of a thermal electric hybrid vehicle is the same as that described in clause 5 of EN 1986-1 for pure electric vehicle.

EC is the electric consumption given by the formula :

$$EC = \frac{E}{d} \text{ (in Wh/km) expressed in watthours per kilometre.}$$

where :

E is the electric energy taken from the network, expressed in watthours ;

d is the total travelled distance during the test, expressed in kilometres.

A.5 Expressions of the result

Refer to 6.8.

Annexe B

(informative)

Example of calculation of emission of gases with a continuous analysis method

B.1 General

The system to be used is the constant volume sampler system. This requires that the vehicle exhaust be continuously diluted with ambient air under controlled conditions.

In the constant volume sampler concept of measuring, two conditions shall be satisfied :

- the total gas flow of the mixture of exhaust gases and dilution air shall be continuously measured ;
- a continuously proportional sample of the mixed gas flow shall be analyzed.

The results of mass of gases obtained with the following calculation method may be used in annex A as appropriate.

B.2 Measured values for consumption

The measured values for consumption determination are the following :

- total travelled distance *d*, expressed in kilometre ;
- test duration *t*, expressed in seconds ;
- volumetric concentration of carbon monoxide expressed in vol ppm [17] ;
- volumetric concentration of carbon dioxide, expressed in vol % [18] ;
- volumetric concentration of hydrocarbon, expressed in vol ppm [17] ;
- gas flow expressed in litres per second.

[17] Vol ppm means parts per million in volume.

[18] Vol % means parts per cent in volume.

B.3 Calculation

B.3.1 Calculation of the instantaneous corrected concentration of gases

The calculation of the instantaneous corrected concentration of gases is made with the following equation :

$$C_i = C_e - C_d\left(1 - \frac{1}{DF}\right)$$

where :

C_i is the instantaneous concentration of the gas *i* in the diluted exhaust gas, expressed in vol ppm [19] or vol % [20] as in B.2 and corrected by the amount of *i* contained in the air used for dilution ;

C_e is the instantaneous measured concentration of gas *i* in the diluted exhaust gas, expressed in vol ppm [19];

C_d is the instantaneous measured concentration of gas *i* in the air used for dilution, expressed in vol ppm [19];

DF is the instantaneous dilution factor.

The instantaneous dilution factor for gasoline and diesel fuel is calculated as follows :

$$DF = \frac{13{,}4}{C_{CO_2} + (C_{HC} + C_{CO})\,10^{-4}}$$

where :

C_{CO_2} is the instantaneous concentration of CO_2 in the diluted exhaust gas expressed in vol % [20];

C_{HC} is the instantaneous concentration of HC in the diluted gas expressed in vol ppm [19] carbon equivalent ;

C_{CO} is the instantaneous concentration of CO in the diluted gas expressed in vol ppm [19] .

B.3.2 Calculation of the instantaneous massic flow of gases

$$m_i = V'_{mix} \times Q_i \times C_i \times a$$

where :

V'_{mix} is the instantaneous flow of the diluted exhaust gas expressed in litres per second and corrected to reference conditions ;

Q_i is the density of the gas *i* in grams per litre at reference temperature and reference pressure ;

---

[19] Vol ppm means parts per million in volume.

[20] Vol % means parts per cent in volume.

C_i is the instantaneous concentration of the gas *i* in the diluted exhaust gas expressed in vol ppm [21] or vol % [22] according to B.2, and corrected by the amount of the gas *i* contained in the air used for dilution ;

a is a constant value depending on the gas i : a = 10^{-6} for CO and HC, a = 10^{-2} for CO_2.

B.3.3 Calculation of each gas

Emissions of gases are calculated by means of the following equation :

$$M_i = \frac{\int_0^t m_i \times dt}{d}$$

where :

$\int_0^t m_i \times dt$ is the integral of the recording instantaneous massic flow of the considered gas i in grams per test.

M_i is the mass emission of the gas *i* in grams per kilometre ;

m_i is instantaneous massic flow of gas *i* in grams per second ;

i is the gas considered ;

t is the test duration, in seconds ;

d is the total travelled distance in kilometres.

B.4 Expression of the results

Refer to 6.8.

[21] Vol ppm means parts per million in volume.

[22] Vol % means parts per cent in volume.

Annexe C

(informative)
Energetic values of fuel

The actual value (in kilojoules per litre) of the fuel is that given by the fuel supplier.

For information, table C.1 gives the approximate values for these data, at reference conditions of 288 K (15 °C).

Table C.1

Fuel	Energetic value kJ/l	Energetic value kJ/kg
Unleaded gasoline	32 000	42 600
Diesel	35 600	42 600

Annexe D

(informative)

Technical information of the test thermal electric hybrid vehicle

It is recommended that the following information be provided to the testing laboratory prior testing :

- claimed performances :
  - range in pure electric mode,
  - consumption in pure electric mode,
  - consumption in hybrid mode ;
- type of thermal engine ;
- description of the electrical interface to the mains ;
- description of the charging procedure ;
- description of the driving modes which can be selected by the driver ;
- the possibility to have the information before the engine starts.

Annexe E

(informative)

Test report on energy performances of a thermal electric hybrid vehicle

E.1 Concerning the measurement of the range in pure electric mode (see clause 4), it is recommended to report the following information :

- range in pure electic mode ;
- whole number of cycles travelled with the type of test sequence.

E.2 Concerning the measurement of the electric energy consumption in pure electric mode (see clause 5), it is recommended to report the following information :

- electric energy consumption in watthours per kilometre.

E.3 Concerning the measurement of the consumption in hybrid mode (see clause 6), it is recommended to report the following information :

- electric consumption *EC* (see A.4) in watthours per kilometre ;
- fuel consumption *FC* (see A.3.3) in litres per 100 km.

E.4 Considering that, in the future, the vehicle manufacturers will have to claim for the carbon dioxide emission value of their vehicles, the consumption could be expressed in grams of carbon dioxide per kilometre.

Bibliography

Directive 70/220/EEC of 20 March 1970, on the approximation of the laws of the member states relating to measures to be taken against air pollution by gases from positive-ignition engines of motor vehicles.

Directive 80/1268/EEC of 16 December 1980, on the approximation of the laws of the member states relating to fuel consumption of motor vehicle.

SAE J1634, Electric vehicle energy consumption and range test procedure.

ISO DIS 8714 : 1991, Electric road vehicles - Reference energy consumption.

ISO 10521: 1992,- Motor vehicle road load - Determination under reference atmospheric conditions and reproduction on chassis dynamometer.

Appendix C SAE J1711 (draft) procedure

Recommended Practice for Measuring the Exhaust Emissions and Fuel Economy of Hybrid-Electric Vehicles

SAE J1711
(Draft)

March 27, 1998

SAE HEV Test Procedure Task Force

SAE Light-Duty Vehicle Performance & Economy Measurement Subcommittee

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Address Comments to:

	Phone	Fax
Tommy Chang (Honda)	(313) 994-8441	(313) 665-5998
Susan Field (Toyota)	(734) 995-2086	(734) 995-5971
Mike Fuher (Ford)	(313) 594-2037	(313) 594-2044
Stephen Humay (Nissan)	(248) 488-4024	(248) 488-3914
Anil Paryani (Honda)	(310) 781-5522	(310) 781-5512
Ron Peltier (Ford)	(313) 337-5367	(313) 845-5175
Stephen Poulos (GM)	(248) 857-6427	(248) 857-4715
Yoshiki Sekiya (Nissan)	(248) 488-4018	(248) 488-3914
Dick Swiatek (Chrysler)	(248) 583-5239	(248) 583-5234
Mike Wolterman (Toyota)	(734) 995-7117	(734) 995-7092

Current HEV Task Force Working Group

Ron Peltier
Ford

Mike Fuher
Ford

Anil Paryani
Honda

Tommy Chang
Honda

Dick Swiatek
Chrysler

Stephen Humay
Nissan

Yoshiki Sekiya
Nissan

Stephen Poulos
GM (Chair.)

Susan Field
Toyota

Mike Wolterman
Toyota

Technical Assistance and Consulting

Keith Wipke
NREL

Steve Burch
NREL

Matt Cuddy
NREL

Mike Duoba
ANL

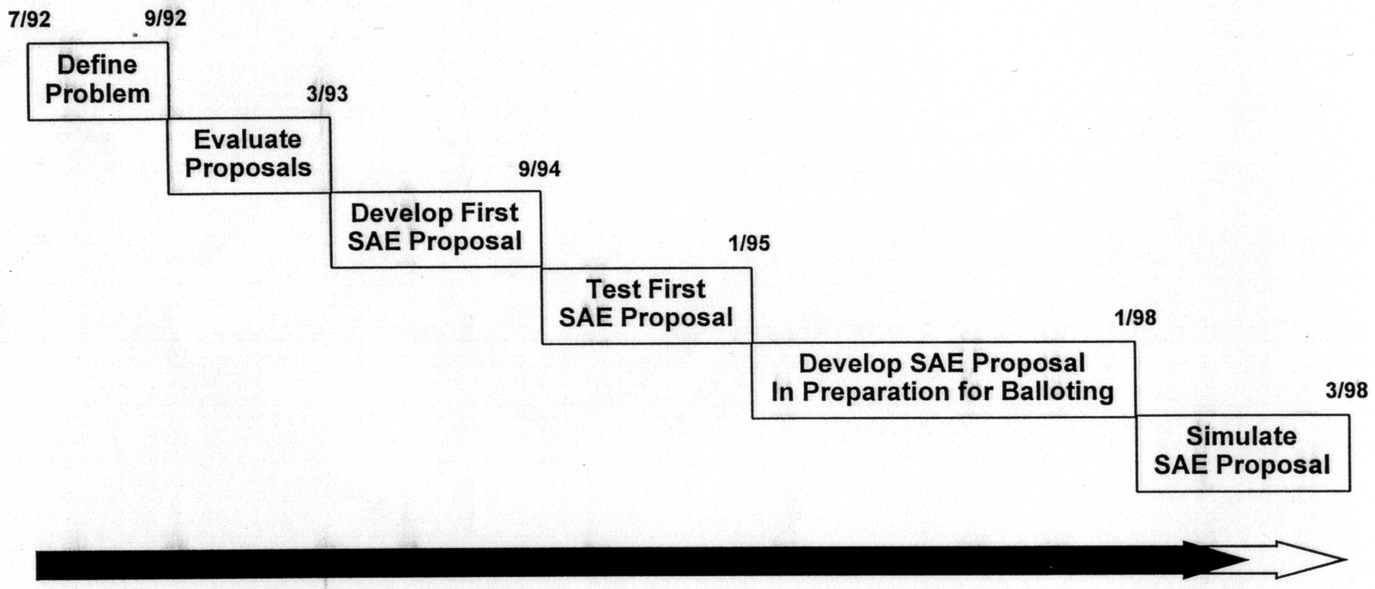
Spencer Quong
AeroVironment

Regulatory Contacts

Mike O'Connor
CARB

Cliff Tyree
EPA

SAE HEV Task Force History



Objectives of the Recommended Practice

1. Measure exhaust emissions and fuel economy of hybrid vehicles, accounting also for any off-vehicle-charged energy used.

2. Provide representative test results for any type of hybrid vehicle:
    - series and parallel configurations
    - using battery, capacitor, or flywheel energy storage
    - with and without a significant all-electric range
    - with and without available/required off-vehicle charging
    - having multiple driver-selected operating modes

3. Use multiples of complete driving schedules already being used for conventional and electric vehicles.

4. Place any hybrid vehicle on a "level playing field" with conventional and purely electric vehicles. This requires that conventional and electric vehicles run on the hybrid test procedure yield the same results as they would if tested on the test procedures currently established for conventional and electric vehicles, respectively.

5. Avoid the need for defeating or otherwise forcing the vehicle's control system to perform differently from how it would perform in customer hands.

6. Be as short and simple as possible.

7. Provide a technical foundation to assist government regulatory agencies in developing fuel economy and emissions certification and compliance tests for hybrid vehicles.

Overview of SAE J1711

1. Classify the Hybrid-Electric Vehicle
- Rechargable Energy Storage System
- Off-Vehicle Charge Capability
- Driver-Selected Operating Modes
- Recharging Dependency

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2. Test the Vehicle in Each Driver-Selected Operating Mode
- Test Conditions
- Test Instrumentation
- Exhaust Emissions and Fuel Economy Tests

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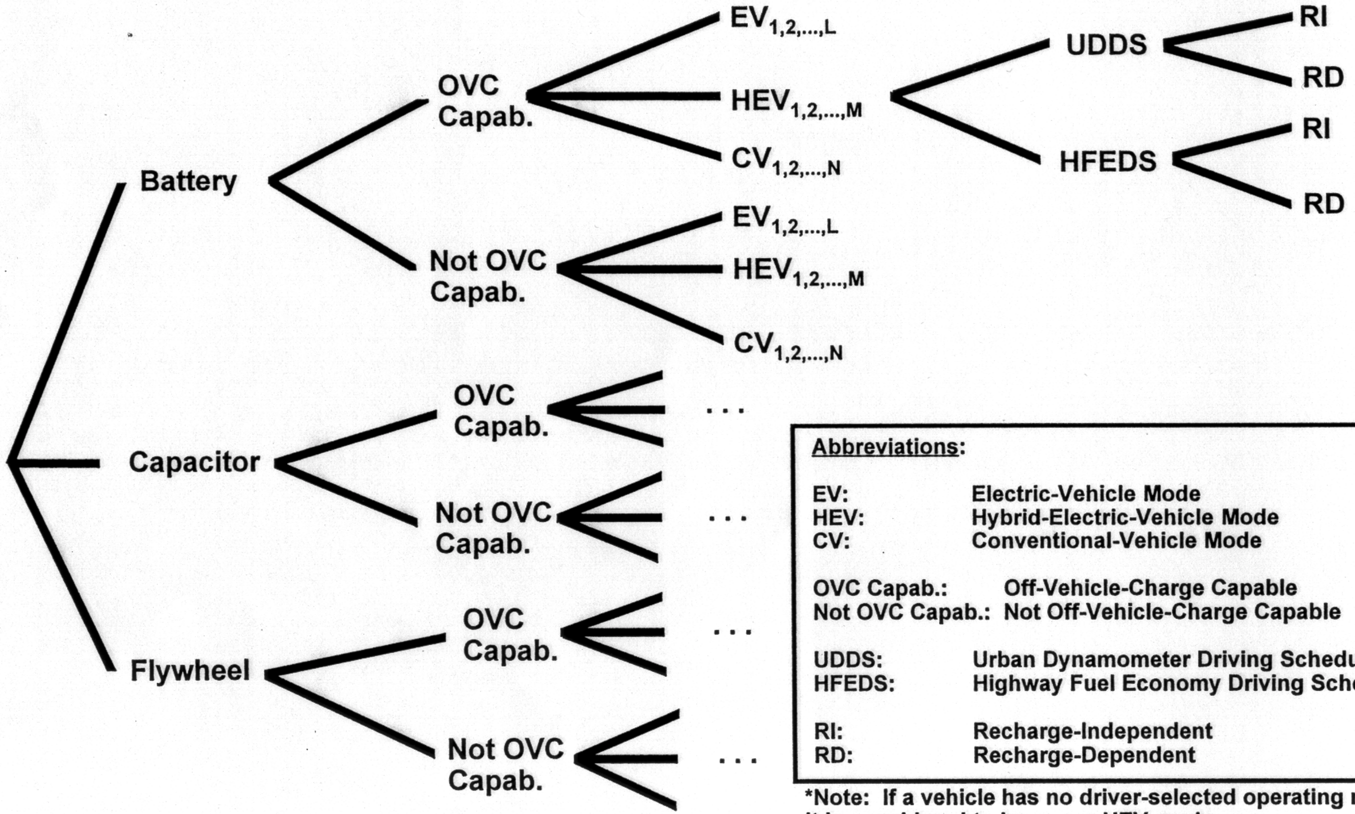
3. Weight the Results
- Cold Start / Hot Start Exhaust Emissions
- Measured Fuel / Off-Vehicle-Charged Equivalent Fuel
- Operating Mode Utility
- Off-Vehicle Charged / Not Off-Vehicle Charged
- HEV / EV / EO Driver-Selected Operating Modes

Classify the Hybrid-Electric Vehicle

Rechargable Energy Storage System (RESS) | Off-Vehicle-Charge Capability | Driver-Selected Operating Modes* | Recharge-Dependency (for OVC-Capable HEV's, in HEV Modes only)



Abbreviations:

EV:	Electric-Vehicle Mode
HEV:	Hybrid-Electric-Vehicle Mode
CV:	Conventional-Vehicle Mode
OVC Capab.:	Off-Vehicle-Charge Capable
Not OVC Capab.:	Not Off-Vehicle-Charge Capable
UDDS:	Urban Dynamometer Driving Schedule
HFEDS:	Highway Fuel Economy Driving Schedule
RI:	Recharge-Independent
RD:	Recharge-Dependent

*Note: If a vehicle has no driver-selected operating modes, it is considered to have one HEV mode

Prepare for Testing

RESS:

- Age with vehicle for 2,000-6,200 mi or equivalent
- Instrument to permit state of charge measurements
- Ensure adequate capability for safe venting, cooling, and containment during testing and off-vehicle charging

Vehicle:

- Stabilize on Durability Driving Schedule for 2,000-6,200 mi
- Turn accessories off (except for SC03 test)
- Add ballast to reach appropriate test weight
- Set tire pressures as for conventional vehicles
- Tires must have at least 62 mi and 50% tread
- Use manufacturer recommended lubricants
- Shift manual transmission at manuf. recommended speeds/loads

Road Coastdown:

- Ensure that regen braking will not occur during coastdown
- Perform road coastdown testing according to SAE J2263

Dynamometer:

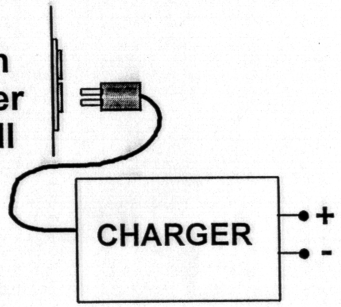
- Ensure that regen braking will not occur during coastdown
- Set dyno road load HP according to SAE J2264
- Ensure regen braking is fully enabled after dyno HP is adjusted
- Connect RESS instrumentation to dyno data acquisition system
- Allow time for driver to practice following driving trace on dynamometer

Special Instrumentation for Hybrid Vehicles

Measurements for IFT, DFT, DPT, EVT

Measure AC kW-h to charger from wall during recharging, after tests (accounts for all RESS recharging losses, whether charger is located on or off vehicle)

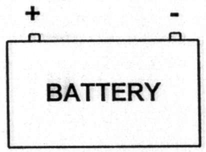
AC kW-h to charger from wall



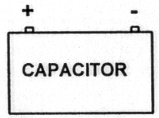
Measured at charger AC input terminals

Measurements for IPT and EOT

Measure net change in DC A-h's in/out of battery, capacitor voltage, or flywheel speed over tests



DC A-h$_{\text{net-out}}$ — Measured at battery +/- terminals



DC Voltage — Measured at capacitor +/- terminals

RPM — Measured at flywheel shaft

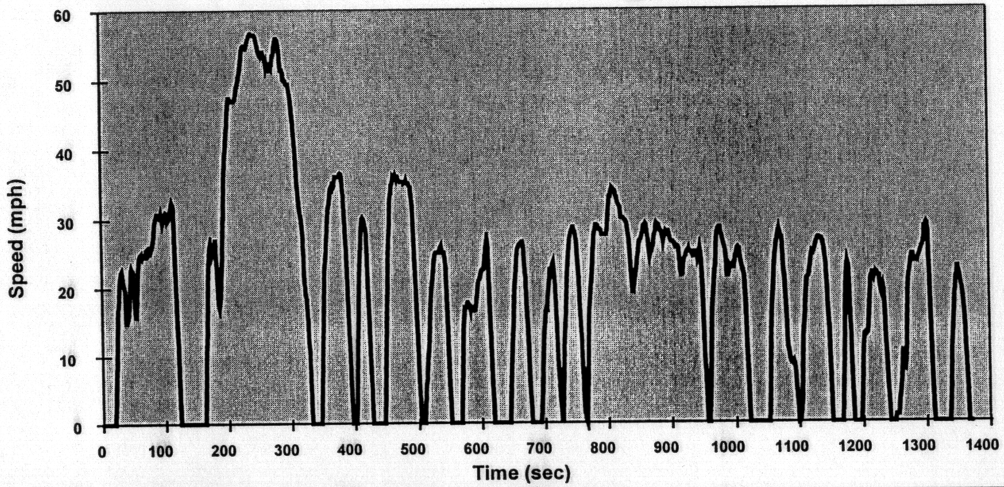
Indication of Engine Starts for DFT, DPT

- Tachometer
- OBD-II port
- Instrument panel light
- Ignition inductive sensor
- Other

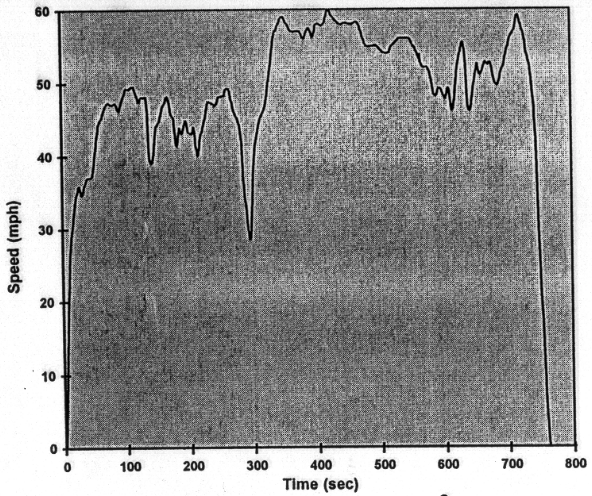
UDDS and HFEDS Driving Schedules

UDDS:

DS = FTP



HFEDS:



	UDDS	HFEDS
Duration (sec.)	1,372	765
Distance (miles)	7.45	10.26
Max. Speed (mph)	56.7	59.9
Average Speed (mph)	19.5	48.3
Max. Acceleration (mph/sec)	3.3	3.2
No. of Exhaust Emission Bags	2	1

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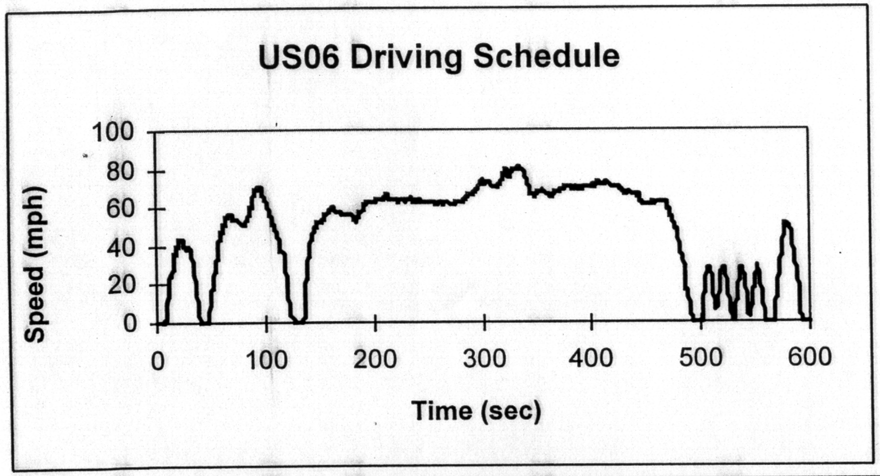
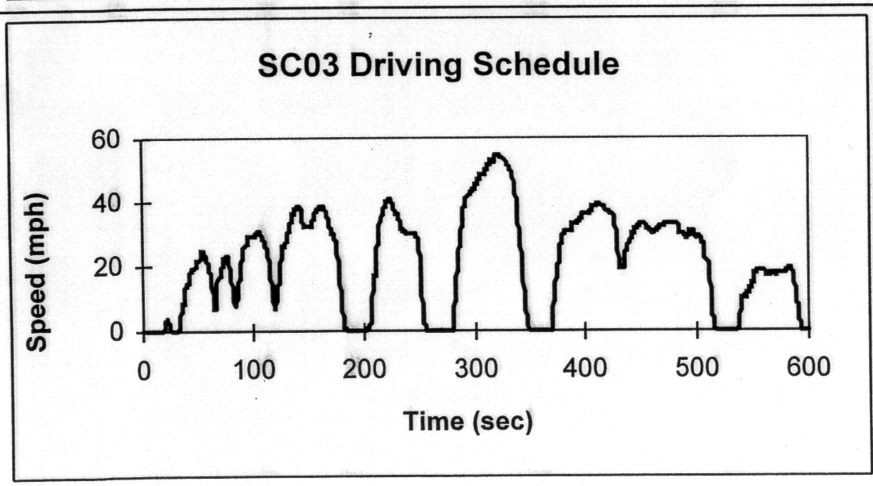
US06 and SC03 Driving Schedules





	US06	SC03
Duration (sec.)	600	600
Distance (miles)	8.01	3.58
Max. Speed (mph)	80.3	54.8
Average Speed (mph)	48.0	21.7
Max. Acceleration (mph/sec)	8.4	5.1
No. of Exhaust Emission Bags	1	1

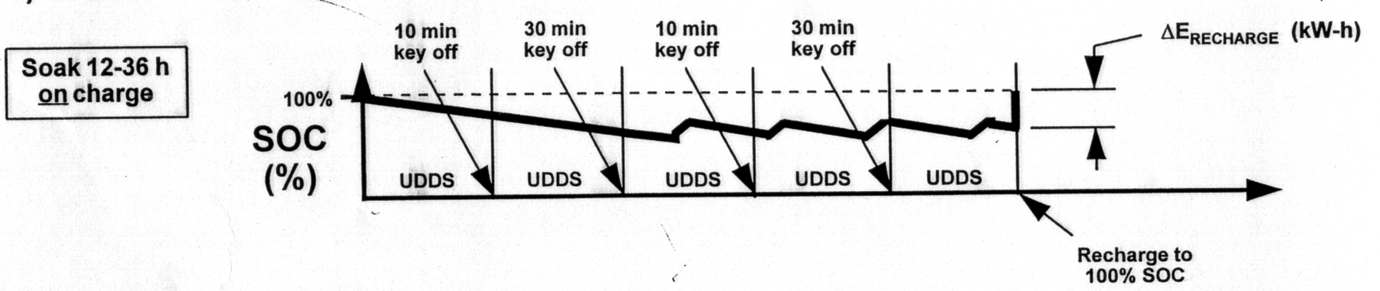
SCO3 is performed in a full environmental chamber (FEC)*:

- **95 F ambient air temp.**
- **100 grains H_2O/lb dry air**
- **Solar load = 850 W/m²**

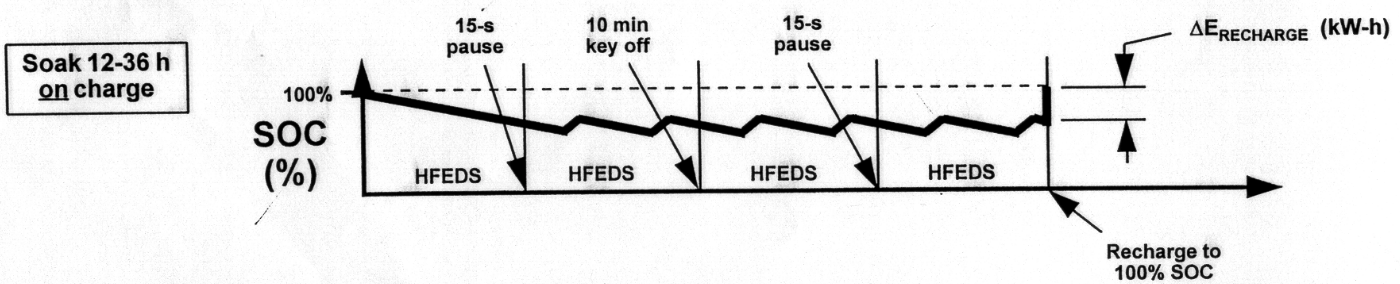
* or alternative corelatable method

Perform Testing in RI HEV-Mode <u>With</u> Daily Off-Vehicle Charging
(Independent Full-Charge Test - IFT)

1) Urban:



2) Highway:

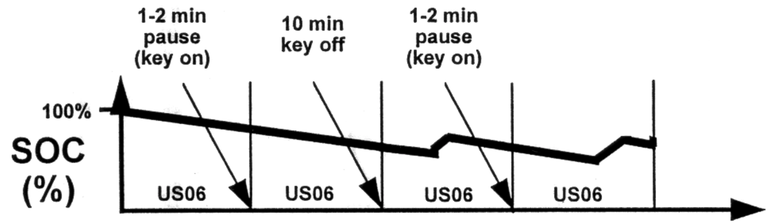


Applicability:	This test applies to OVC-capable HEV's that are recharge independent
Initial State of Charge:	100%
Termination Criteria:	Best-effort test - run to the specific durations shown above and then stop
Emissions Sampling:	Sample emissions for all cycles shown above
Cold/Hot Weighting:	No cold/hot weighting of results, Urban or Highway

Perform Testing in RI HEV-Mode <u>With</u> Daily Off-Vehicle Charging
(Independent Full-Charge Test - IFT)

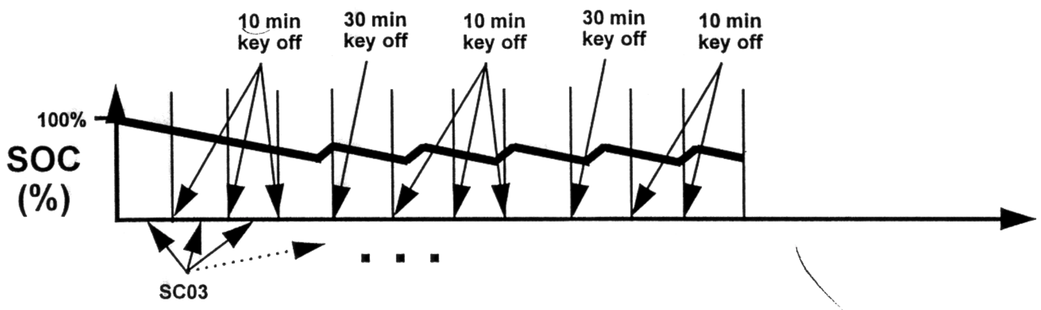
3) US06:

Soak 12-36 h
<u>on</u> charge



4) SC03:

Soak 12-36 h
<u>on</u> charge

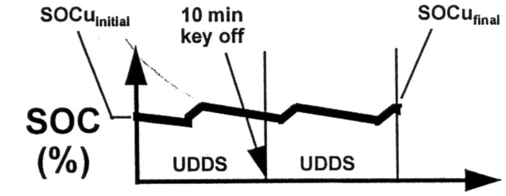


<u>Applicability:</u>	**This test applies to OVC-capable HEV's that are recharge independent**
<u>Initial State of Charge</u>:	**100%**
<u>Termination Criteria</u>:	**Best-effort test - run to the specific durations shown above and then stop**
<u>Emissions Sampling</u>:	**Sample emissions for all cycles shown above**
<u>Cold/Hot Weighting</u>:	**No cold/hot weighting of results**

Perform Testing in RI HEV-Mode <u>Without</u> Daily Off-Vehicle Charging
(Independent Partial-Charge Test - IPT)

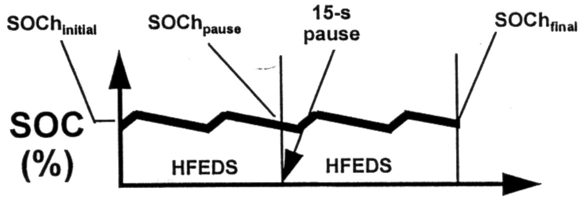
1) Urban:

Soak 12-36 h <u>off</u> charge



2) Highway:

Soak < 3 h



<u>Applicability:</u> This test applies to HEV's that are recharge independent

<u>Initial State of Charge</u>: $SOCu_{initial}$ is specified by the manufacturer to ensure that $SOCu_{final}$ is greater than or equal to $SOCu_{initial}$; $SOCh_{initial}$ is specified by the manufacturer to ensure that $SOCh_{final}$ is greater than or equal to $SOCh_{pause}$

<u>Termination Criteria</u>: Best-effort test - run to the specific durations shown above and then stop

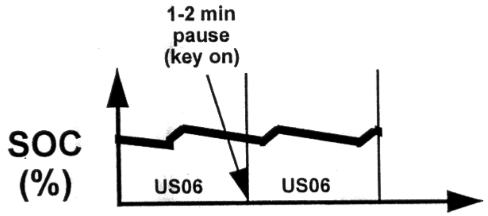
<u>Emissions Sampling</u>: Sample emissions for all UDDS cycles shown above; first HFEDS serves as warmup only; sample emissions from second HFEDS only

<u>Cold/Hot Weighting</u>: Use standard 43/57 weighting for cold/hot start bags in Urban testing; No cold/hot weighting on Highway test

Perform Testing in RI HEV-Mode <u>Without</u> Daily Off-Vehicle Charging
(Independent Partial-Charge Test - IPT)

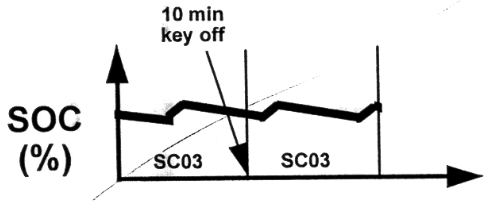
3) US06:

No Soak Required



4) SC03:

No Soak Required



<u>Applicability:</u> This test applies to HEV's that are recharge independent

<u>Initial State of Charge</u>: Initial SOC is lowest of corresponding values used in the same mode for UDDS and HFEDS testing

<u>Termination Criteria</u>: Best-effort test - run to the specific durations shown above and then stop

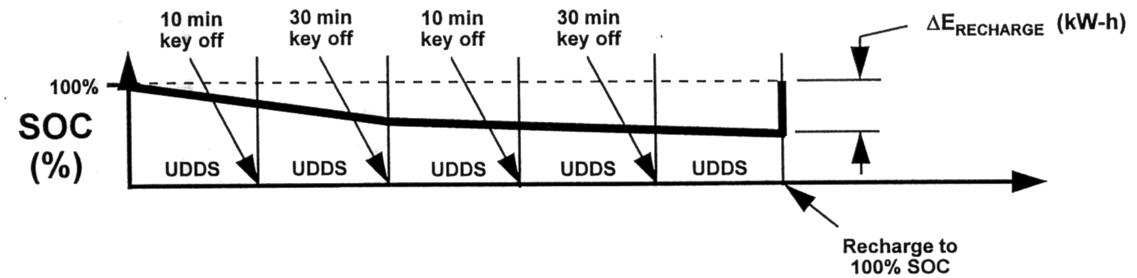
<u>Emissions Sampling</u>: First cycles of US06 and SC03 serve as warmup only; sample emissions from second US06 and SC03 only

<u>Cold/Hot Weighting</u>: No cold/hot weighting

Perform Testing in RD HEV-Mode from 100% SOC
(Dependent Full-Charge Test - DFT)

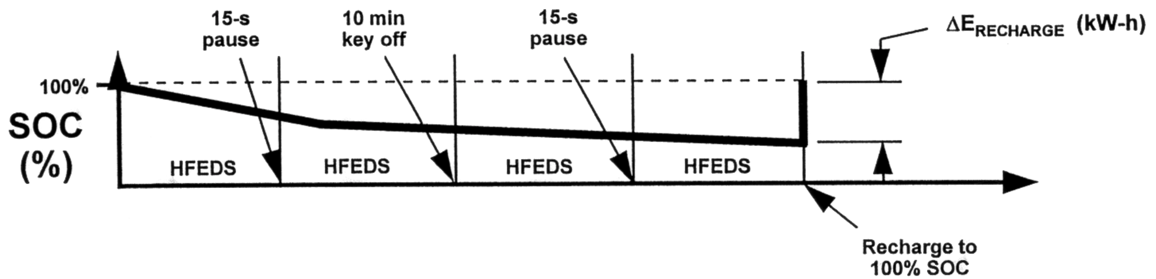
1) Urban:

Soak 12-36 h
on charge



2) Highway:

Soak 12-36 h
on charge



Applicability: This test applies to OVC-capable HEV's that can operate in a recharge-dependent mode

Initial State of Charge: 100%

Termination Criteria: Run to the specific durations shown above or stop earlier if vehicle is unable to follow driving trace within specified tolerances

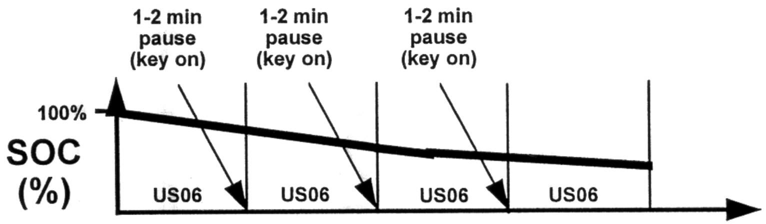
Emissions Sampling: Sample emissions for all cycles shown above, or until can't follow trace

Cold/Hot Weighting: No cold/hot weighting of results, Urban or Highway

Perform Testing in RD HEV-Mode from 100% SOC
(Dependent Full-Charge Test - DFT)

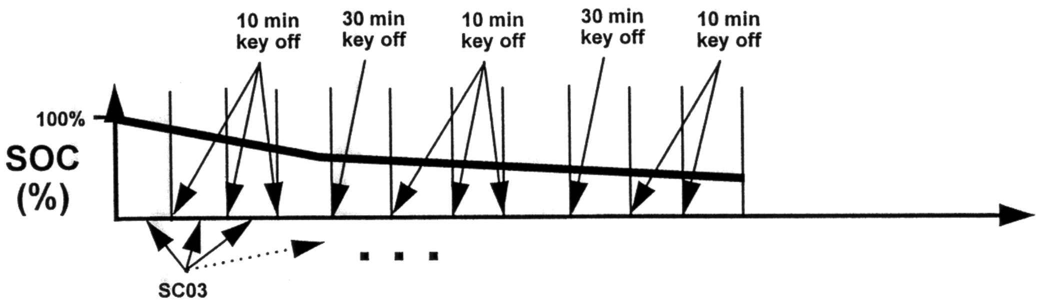
3) US06:

Soak 12-36 h
on charge



4) SC03:

Soak 12-36 h
on charge



Applicability: This test applies to OVC-capable HEV's that can operate in a recharge-dependent mode

Initial State of Charge: 100%

Termination Criteria: Run to the specific durations shown above or stop earlie if vehicle is unable to follow driving trace within specified tolerances

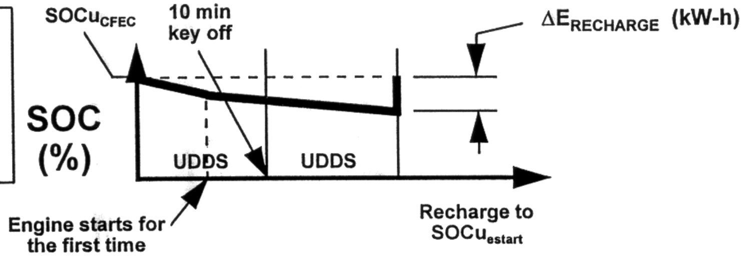
Emissions Sampling: Sample emissions for all cycles shown above, or until can't follow trace

Cold/Hot Weighting: No cold/hot weighting of results

Perform Testing in RD HEV-Mode from SOC Prior to Engine Start
(Dependent Partial-Charge Test - DPT)

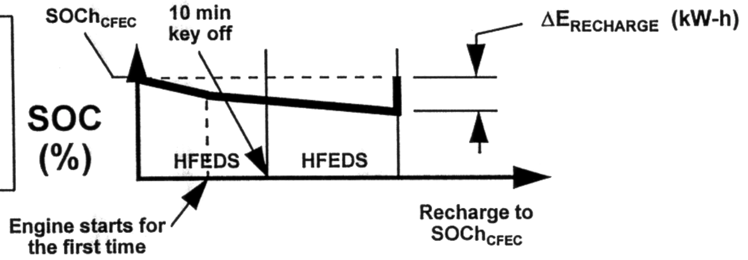
1) Urban:

Soak 12-36 h (CFEC soak only; can count time since last engine start if no engine operation on preceding DFT)



2) Highway:

Soak 12-36 h (CFEC soak only; can count time since last engine start if no engine operation on preceding DFT)



<u>Applicability</u>: This test is needed only if a) engine has not started before the beginning of the last UDDS or HFEDS, respectively, on the Dependent Full-Charge Test (DFT), and b) no other recharge-independent modes are available to the driver

<u>Initial State of Charge</u>: $SOCu_{CFEC}$ is specified by the manufacturer to ensure that engine starts cold in first UDDS; $SOCh_{CFEC}$ is specified by the manufacturer to ensure that engine starts in first HFEDS

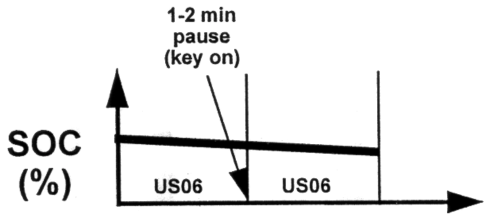
<u>Termination Criteria</u>: Best-effort test - run to the specific durations shown above and then stop

<u>Emissions Sampling</u>: Sample emissions from both UDDS's and both HFEDS's

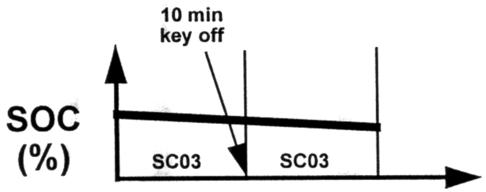
<u>Cold/Hot Weighting</u>: No cold/hot weighting of results, Urban or Highway

Perform Testing in RD HEV-Mode from SOC Prior to Engine Start
(Dependent Partial-Charge Test - DPT)

3) US06:



4) SC03:

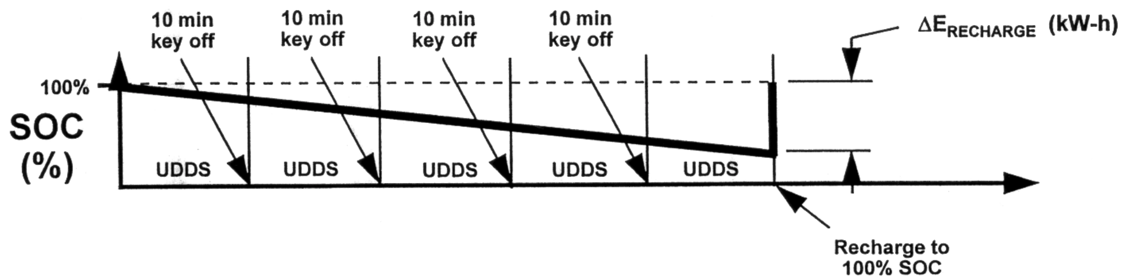


Applicability:	This test is needed only if a) CFEC has not started before the last US06 or SC03, respectively, on the Dependent Full-Charge Test (DFT), and b) no other recharge-independent modes are available to the driver
Initial State of Charge:	Initial SOC is lowest of corresponding values used in the same mode for UDDS and HFEDS testing
Termination Criteria:	Best-effort test - run to the specific durations shown above and then stop
Emissions Sampling:	Sample emissions for all cycles shown above
Cold/Hot Weighting:	No cold/hot weighting of results

Perform Testing in EV-Mode
(Electric Vehicle Test - EVT)

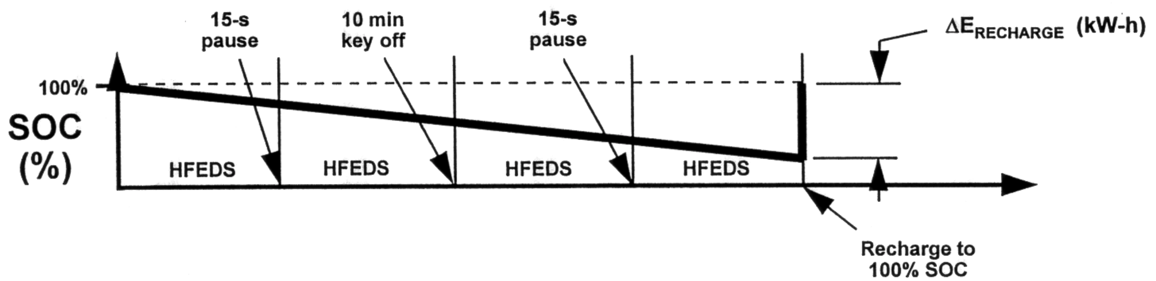
1) Urban:

Soak 12-36 h
<u>on</u> charge



2) Highway:

Soak 12-36 h
<u>on</u> charge



<u>Applicability:</u> This test should be performed only for OVC-capable HEV's with a driver-selected electric-vehicle mode

<u>Initial State of Charge</u>: 100%

<u>Termination Criteria</u>: Run to the specific durations shown above or stop earlier if vehicle is unable to follow driving trace within specified tolerances

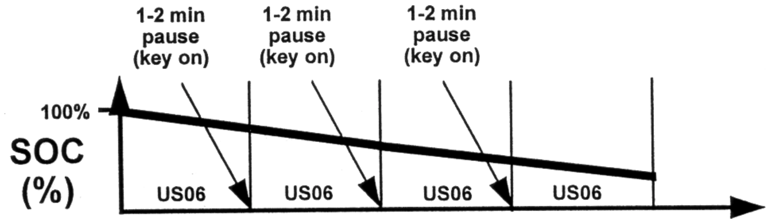
<u>Emissions Sampling</u>: No emissions sampling

<u>Cold/Hot Weighting</u>: No cold/hot weighting of results, Urban or Highway

Perform Testing in EV-Mode
(Electric Vehicle Test - EVT)

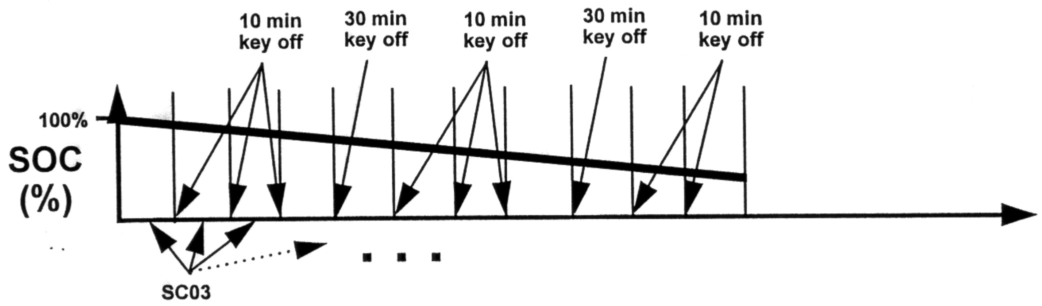
3) US06:

Soak 12-36 h <u>on</u> charge



4) SC03:

Soak 12-36 h <u>on</u> charge



<u>Applicability:</u> This test should be performed only for OVC-capable HEV's with a driver-selected electric-vehicle mode

<u>Initial State of Charge</u>: 100%

<u>Termination Criteria</u>: Run to the specific durations shown above or stop earlier if vehicle is unable to follow driving trace within specified tolerances

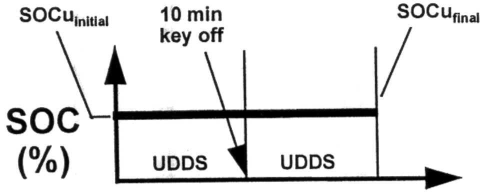
<u>Emissions Sampling</u>: No emissions sampling

<u>Cold/Hot Weighting</u>: Not applicable

Perform Testing in EO-Mode
(Engine Only Test - EOT)

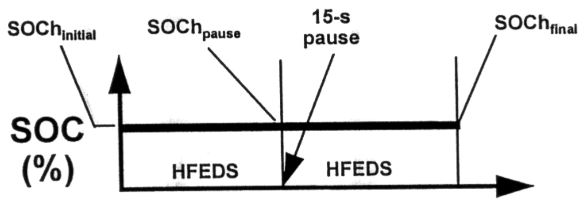
1) Urban:

Soak 12-36 h
<u>off</u> charge



2) Highway:

Soak < 3 h



<u>Applicability:</u> This test should be run only for vehicles with a driver-selected engine-only mode

<u>Initial State of Charge</u>: $SOCu_{initial}$ is specified by the manufacturer to ensure that $SOCu_{final}$ is greater than or equal to $SOCu_{initial}$; $SOCh_{initial}$ is specified by the manufacturer to ensure that $SOCh_{final}$ is greater than or equal to $SOCh_{pause}$

<u>Termination Criteria</u>: Best-effort test - run to the specific durations shown above and then stop

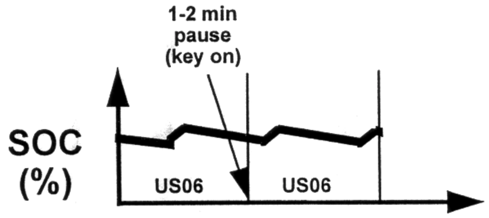
<u>Emissions Sampling</u>: Sample emissions for all UDDS cycles shown above; HFEDS serves as warmup only; sample emissions from second HFEDS only

<u>Cold/Hot Weighting</u>: Use standard 43/57 weighting for cold/hot start bags in Urban testing; No cold/hot weighting on Highway test

Perform Testing in EO-Mode
(Engine Only Test - EOT)

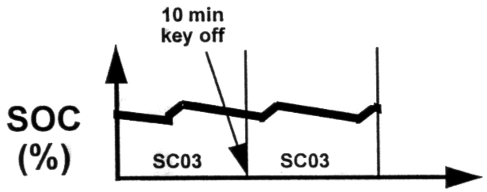
3) US06:

No Soak Required



4) SC03:

No Soak Required

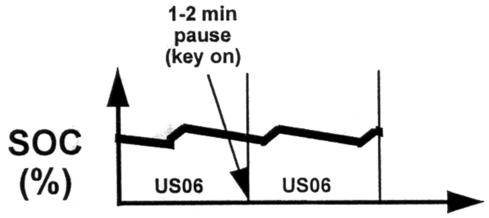


<u>Applicability:</u>	**This test should be run only for vehicles with a driver-selected engine-only mode**
<u>Initial State of Charge</u>:	**Initial SOC is lowest of corresponding values used in the same mode for UDDS and HFEDS testing**
<u>Termination Criteria</u>:	**Best-effort test - run to the specific durations shown above and then stop**
<u>Emissions Sampling</u>:	**First cycles of US06 and SC03 serve as warmup only; sample emissions from second US06 and SC03 only**
<u>Cold/Hot Weighting</u>:	**No cold/hot weighting.**

Perform Testing in EO-Mode
(Engine Only Test - EOT)

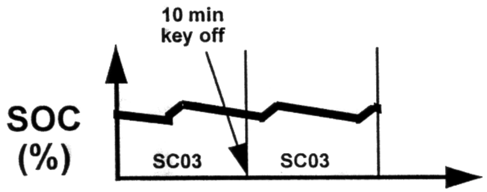
3) US06:

No Soak Required



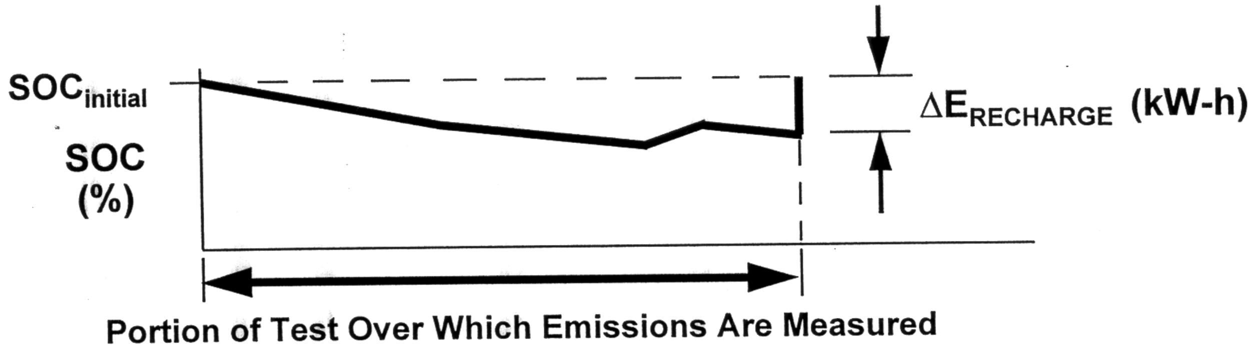
4) SC03:

No Soak Required



Applicability:	**This test should be run only for vehicles with a driver-selected engine-only mode**
Initial State of Charge:	**Initial SOC is lowest of corresponding values used in the same mode for UDDS and HFEDS testing**
Termination Criteria:	**Best-effort test - run to the specific durations shown above and then stop**
Emissions Sampling:	**First cycles of US06 and SC03 serve as warmup only; sample emissions from second US06 and SC03 only**
Cold/Hot Weighting:	**No cold/hot weighting.**

Equivalent Consumable Fuel from OVC Energy



$\Delta E_{RECHARGE}$ = AC electrical energy from wall to recharge to $SOC_{initial}$ (kW-h)

$$FC_{TOTAL} = FC_{CONSUMABLE\ FUEL} + \frac{(\Delta E_{RECHARGE} / K_{E\text{-}CONSUMABLE\ FUEL})}{\text{Total Test Mileage}} \text{ (gallons/mile)}$$

$K_{E\text{-}CONSUMABLE\ FUEL}$ = 38.322 kW-h/gallon (use appropriate value for consumable fuels other than gasoline)

Note: Record AC kW-h's to recharge to $SOC_{initial}$ according to procedure recommended in owner's manual, accounting for charger losses. Convert recharge energy to equivalent consumable fuel using conversion factor specified in Federal Register for EV's (see 10CFR Part 474). Finally, add this fuel consumption to measured consumed fuel ($FC_{CONSUMABLE\ FUEL}$) to obtain total fuel consumption (FC_{TOTAL}).

Assumptions Used in Weighting of Results for Various Driver-Selected Operating Modes

1) In the absence of data to the contrary, all driver-selected RI HEV modes are equally likely to be used by drivers, all driver-selected RD HEV modes are equally likely to be used by drivers, all driver-selected EV modes are equally likely to be used by drivers, and all driver-selected EO modes are equally likely to be used by drivers. Drivers are also equally likely to select an RI HEV mode, as an RD HEV mode, as an EV mode, as an EO mode. However, any emergency or other operating modes designed for infrequent use are ignored for weighting purposes.
2) A hybrid vehicle is considered to be off-vehicle-charge (OVC) capable only if the manufacturer recommends or requires regular OVC in the owner's manual or through other explicit means. Vehicles with OVC capability that is intended only for infrequent battery conditioning and not for routine use of OVC energy are considered not to be intended for regular OVC.
3) In the absence of data to the contrary, a uniform distribution of charging habits across the entire population of drivers is assumed for operating modes with off-vehicle charging capability. This assumption is mathematically equivalent to assuming that such vehicles are equally likely to be fully off-vehicle charged daily as never to be off-vehicle charged at all.
4) The utility of any operating mode that is not recharge independent is equal to the fraction of daily vehicle miles traveled that the vehicle can cover in that operating mode before it must be recharged or the driver is forced to switch to another mode, weighted by travel distance.

Calculation of Daily Travel Results for Each Type of Mode from Individual Test Results (Urban)

Mode	Test	0-38 mi (71% Utility)*	38+ mi (29% Utility)	Weighting for Probability of OVC
RI HEV	IFT	IFT	IPT	x 0.5
	IPT	IPT	IPT	x 0.5
RD HEV	DFT, DPT	DFT	Avg. of (IPT, EOT), or DPT**	x 1.0
EV	EVT	EVT	Avg. of (IPT, EOT), or DPT**	x 1.0
EO	EOT	EOT	EOT	x 1.0

* For RD HEV and EV modes that cannot complete DFT and EVT schedules respectively, use utility value corresponding to actual mileage at which driving trace could not be followed for the first time
** Use DPT results only if driver cannot select a RI HEV or EO mode after RD HEV or EV capability is exceeded

Calculation of Daily Travel Results for Each Type of Mode from Individual Test Results (Highway)

Mode	Test	0-41 mi (74% Utility)*	41+ mi (26% Utility)	Weighting for Probability of OVC
RI HEV	IFT	IFT	IPT	x 0.5
	IPT	IPT	IPT	x 0.5
RD HEV	DFT DPT	DFT	Avg. of (IPT, EOT), or DPT**	x 1.0
EV	EVT	EVT	Avg. of (IPT, EOT), or DPT**	x 1.0
EO	EOT	EOT	EOT	x 1.0

* For RD HEV and EV modes that cannot complete DFT and EVT schedules respectively, use utility value corresponding to actual mileage at which driving trace could not be followed for the first time

** Use DPT results only if driver cannot select a RI HEV or EO mode after RD HEV or EV capability is exceeded

Weighting of Driver-Selected Operating Modes

RI HEV_1 x 1/L
RI HEV_2 x 1/L
...
RI HEV_L x 1/L
→ x A/(A+B+C+D)*

RD HEV_1 x 1/M
RD HEV_2 x 1/M
...
RD HEV_M x 1/M
→ x B/(A+B+C+D)*

EV_1 x 1/N
EV_2 x 1/N
...
EV_N x 1/N
→ x C/(A+B+C+D)

EO_1 x 1/P
EO_2 x 1/P
...
EO_P x 1/P
→ x D/(A+B+C+D)

Σ = Composite Result for All Modes

* If L > 0, then A = 1, otherwise A = 0
If M > 0, then B = 1, otherwise B = 0
If N > 0, then C = 1, otherwise C = 0
If P > 0, then D = 1, otherwise D = 0

Urban vs. Highway Fuel Economy Weighting

$$\text{Composite Fuel Economy} = \frac{1}{\dfrac{0.55}{MPG_{Urban}} + \dfrac{0.45}{MPG_{Highway}}}$$

Urban vs. US06 vs. SC03 Emissions Weighting

Non-A/C Vehicles:

• Urban (FTP):	72%
• US06:	28%

A/C Vehicles:

• Urban (FTP):	35%
• US06:	28%
• SC03:	37%

Open Issues

1. Correct accounting for regenerative braking on 2WD dynos
2. Consistency with SAE EV Test Procedure (J1634) (battery aging, etc.)
3. Effort required to instrument vehicles
   - access to battery terminals
   - dealing with different battery grounding schemes
   - avoiding electrical noise problems
4. Accuracy of SOC estimation
5. Clear protocol for performing off-vehicle charging during testing
6. Compatibility with US06, SC03, and evaporative test procedures
7. Test-to-test repeatability
8. Development of detailed calculation formulas
9. Development of final test data sheets
10. Need to illustrate application of test procedure to various hybrids
11. How to handle ESS charging by engine after key off (subtract A-h's gained during charging after key off from total cycle delta A-h's?)
12. How to handle hybrids with required starting delays
13. Minimum OVC capability to have a utility > 0
14. Applicability of procedure to light-duty vs. other classes of vehicles - clarify
15. Confirm latest test termination criteria for 4 classes of modes

Open Issues

16. What if vehicle overrides manual mode-switch selection?
17. Begin to comprehend non-U.S. testing requirements
18. Consider durability testing:
    - which modes to use?
    - engine and/or ESS may not stabilize by 4,000 mi
    - how to age different types of ESS's in an equivalent way?
    - how to handle scheduled ESS replacement?
    - how to calculate DF's?
19. Possibility that cold-start tests will miss high cooling loads after warmup
20. Understand clearly CARB's issue with diesel hybrids
21. Electrical and emissions measuremenst for RD HEV's are for different periods
22. For RD modes, fuel economy and OVC energy periods may differ
23. How to handle charge depletion during US06
24. RD HEV's will not have cold/hot weighting
25. Driving statistics still need to be clarified
26. What if control logic changes after key off (in same switch position)?
27. What if vehicle is RI on urban cycle but RD on highway cycle?
28. Need to reintegrate US06 and SC03 tests
29. Should prep procedure handle A/C like conventional or electric vehicles?
30. Should 29% utility data for RD HEV come from avg.(IPT/EOT) or from DPT? (if can drive trace > 38 mi)

Open Issues

31. Do we need quick check of dyno settings (55-45 mph) after HFEDS?
32. How to be consistent with US06/SC03/FTP composite weighting?
33. Proposed test procedure will require 4 sets of sampling bags.
34. Will initial 100% SOC for OVC cases still be representative once opportunity-charging becomes widely available?
35. Conversion between electrical energy and gasoline is different for CFR vs. PNGV.
36. May need to expand procedure to hydraulic, pneumatic, and other hybrids.
37. How do we include US06 / SC03 / FTP weighting?
38. A hybrid vehicle with minimal energy storage should approach results for a conventional vehicle. However, RIT provides no cold/hot weighting on UDDS and HFEDS has a cold start, so will not get desired approximation.
39. Some hybrid vehicles that are RI on UDDS/HFEDS may not be able to complete IPT US06 test, because the batteries are completely depleted
40. IPT fuel economy can be very sensitive to initial SOC for vehicles with infrequent engine operation ("thermostat" control logic, in particular)
41. Will J1711 discourage prroducing range extenders with large EV ranges?
42. Due to cold start emissions weightings, IFT and DFT undersestimate emissions on UDDS and overestimate emissions on HFEDS, US06, and SC03

Decisions / Facts / Issue Resolution

1. <u>Decision</u>: US06 and SC03 should be run for RI-HEV and EO short tests
   <u>Reason</u>: Short tests are for operation equivalent to that of a conventional conventional vehicle that must run those US06 and SC03

2. <u>Decision</u>: US06 and SC03 should not be run for RI-HEV, RD-HEV, or EV ext. tests
   <u>Reason</u>: Extended tests benefit from off-vehicle charging and are therefore not worst case

3. <u>Fact</u>: Relevant exhaust emissions for various U.S. regulations are:
   - EPA FTP: THC, NMHC, CO, NOx, PM
   - EPA Hwy: NOx
   - EPA SFTP (US06/SC03): (NMHC+NOx), CO
   - CARB FTP: NMOG, CO, NOx, PM, Formaldehyde
   - CARB Hwy: NOx
   - CARB SFTP: (US06/SC03): (NMHC+NOx), CO
   - CARB 50 F CO: CO, NOx, NMOG (hybrids exempt?)

4. <u>Decision</u>: Soak times between tests > 10 min are unacceptable
   <u>Reason</u>: Input from GM Milford PG VEL staff, leads to poor dyno utilization

5. <u>Decision</u>: Soak times < 8 h are not representative of a true cold start
   <u>Reason</u>: New exhaust heat storage approaches will be designed to maintain catalyst temps high for ~ 8 h

Decisions / Facts / Issue Resolution

6. Fact: US06 must be run on single-roll dyno (Mike Fuher will confirm)

7. Decision: Allow charge-depletion during US06
   Reason: Even modes that are RI on the EPA city and hwy cycles are likely to be RD for the severe US06 schedule. Charge depletion can indicate that the engine is unable to keep the ESS charged even at max power on the US06 schedule.

8. Decision: Do not apply any cold/hot weighting or use an interim soak period on any extended (OVC) tests
   Reason: No practical way of including cold/hot weighting has been found; EV's tested with OVC have no cold/hot weighting; RI-HEV's tested with OVC are also tested without OVC, where cold/hot weighting is used; a conventional vehicle tested on this protocol would never have OVC

9. Decision: Hybrids with engine startup delays will be treated the same as diesels with glow-plug delays: turn sample on at key on, start driving trace as soon as driving is possible.
   Reason: Diesel precedent exists and any required delays in vehicle driving (vs. engine startup) should be handled in the same way for hybrids

10. Fact: Diesel vehicles are required to run US06 cycle, but not SC03; weighting of FTP and US06 results for diesel vehicles is 0.72 x FTP + 0.28 x US06

11. Fact: Required purge times for sampling bags are the same for gasoline and diesel vehicle exhaust

Decisions / Facts / Issue Resolution

12. Fact: Compliance tests are for emissions only, not fuel economy, as follows:

    Cars and Trucks under 6,000 lb GVW must meet stds for 100,000 mi and testing requirements up to 75% of useful life

    Cars and Trucks over 6,000 lb GVW must meet stds for 120,000 mi and testing requirements up to 75% of useful life

    California has a 2% end-of-line audit requirement

    California has a Title 13 and EPA has an SEA (selective enforcement) testing requirement

    All standards, including 50 F testing (only for 50,000 mi) and cold CO, and later all the new test cycles will be a part of the in-use requirement

    These compliance requirements apply to Otto and diesel cycle vehicles

    Europe has in-use requirements for Stage 3 standards (similar to U.S. requirements)

    By MY 2000 there will be revised in-use requirements in the U.S. The manufacturer will be responsible for in-use testing and voluntary recall.

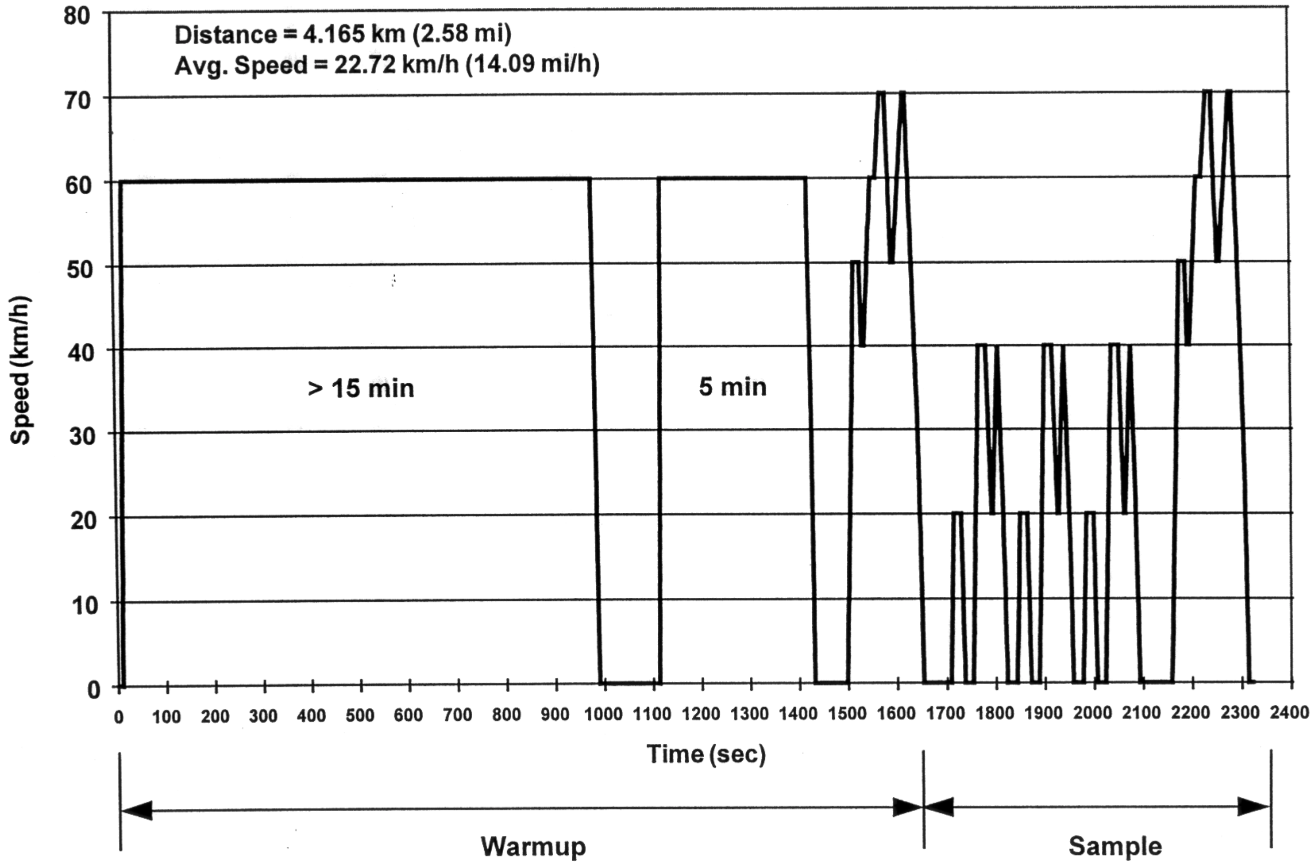
13. Decision: A/C will be handled via SC03, not EV method or +10% dyno load
    Reason: Consistency with A/C testing for conventional vehicles.

Decisions / Facts / Issue Resolution

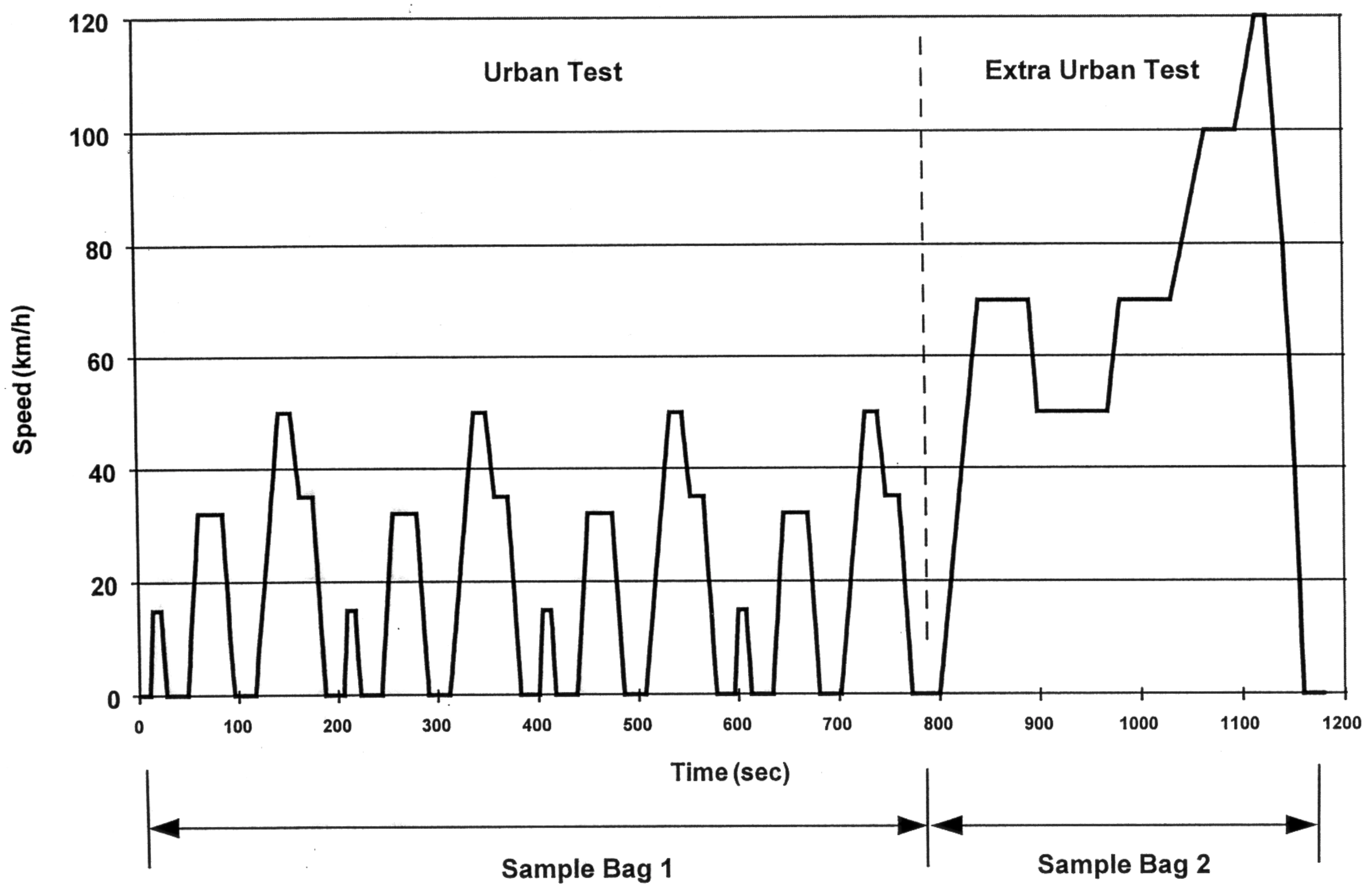
14. <u>Decision</u>: Until there is a final regulatory ruling on the matter, this task force will assume that fuel economy measurements are based solely on UDDS and HFEDS testing, and not on US06 and SC03 test results.

<u>Reason</u>: Expectation is that fuel economy will be obtained by using FTP test test results that are later corrected to compensate for no A/C dyno load

Appendix A: Japan 10.15 Cycle



Appendix B: Europe EUDC Cycle



MANAGEMENT TOOL for the ASSESSMENT of DRIVELINE TECHNOLOGIES and RESEARCH

MATADOR

Contract JOE3-CT97-0081

Task 2:

Testing methods for vehicles with conventional and alternative drivelines

Subtask 2.4

ΔSOC correction methods for HEVs

TNO Automotive

20 July, 2000

by
Erik van den Tillaart (TNO Automotive)

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Nomenclature

Abbreviations

2WD	2 Wheel drive
APU	Auxiliary Power Unit
APU op1, APU op2	APU operating point 1 resp. 2
APU1, APU2, APU3	APU control strategy No.1, 2, or 3
CARB	Californian Air Resources Board
CHEV	Combined HEV
CRT	Continuously Regenerating Trap
DUBC	Dutch Urban Bus Cycle
EUDC	Extra Urban Driving Cycle, part of NEDC
FCHEV	Fuel Cell Hybrid Electric Vehicle
HD	Heavy-Duty
HEV	Hybrid Electric Vehicle
HWFET	Highway Fuel Economy Test
Hyzem H	Hyzem Highway driving cycle
Hyzem R	Hyzem Rural driving cycle
Hyzem U	Hyzem Urban driving cycle
ICE	Internal Combustion Engine
Jap1015	Japanes 10-15 Mode Hot driving cycle
LD	Light-Duty
MATADOR	Management Tool for the Assessment of Driveline TechnOlogies and Research
MODEM	MODEM driving cycle
NEDC	New European Driving Cycle, also known as MVEG-A
NiMH	Nickel Metal Hydride (battery)
PHEV	Parallel HEV
PHEVbat	Parallel HEV with battery
PHEVfw	Parallel HEV with flywheel
PM	Permanent Magnet
SC03	SC03 Air Conditioning driving cycle
SHEV	Series HEV
SHEVbat	SHEV with battery and load-follower strategy
SHEVfw	SHEV with flywheel
THS	Toyota Hybrid System
UDC	Urban Driving Cycle, part of NEDC
UDDS	Urban Dynamometer Driving Schedule, also known as (US)FTP72
ULEV	Ultra Low Emission Vehicle
US06	US06 High speed / High load driving cycle
ZEV	Zero Emission Vehicle

Symbols

A	Frontal area	[m^2]
BSFC	Brake Specific Fuel Consumption	[g/kWh]
CO	Carbon Monoxide emission	[g/km]
CO_2	Carbion Dioxide emission	[g/km]
C_w	Air drag coefficient	[-]
E	Energy	[MJ] [kWh]
EC	Energy Consumption	[MJ/km] [MJ/100km] [kWh/100km]

EC_{M1}	EC on cycle without ΔSOC correction	[MJ/km] [MJ/100km] [kWh/100km]
EC_{M2}	EC determined from numerous cycles	[MJ/km] [MJ/100km] [kWh/100km]
EC_{M3}	EC determined from fuel used and distance travelled on cycle	[MJ/km] [MJ/100km] [kWh/100km]
EC_{M4}	EC determined from fuel used and actually travelled distance until ΔSOC=0 after at least an entire cycle has been driven	[kg]
$E_{WH,drive}$	Propulsion energy at the wheels	[MJ] [kWh]
FC *or* f.c.	Fuel Consumption	[l/km] [l/100km]
$f_{cold/hot}$	Ratio between cold and hot engine emissions	[-]
f_r	Rolling resistance coefficient	[-]
HC	Hydro Carbonate emission	[g/km]
H_{fuel}	Lower heating value fuel	[MJ/kg]
i	Cycle number or gear ratio	[-]
I^2R	Power loss in battery due to internal resistance	[W]
ivSOC	Initial value SOC	[%]
$m_{fuel,cycle\ i}$	Fuel used during cycle	[kg/l]
$m_{fuel,dSOC=0}$	Amount of fuel used between start test until ΔSOC=0 after an entire cycle is driven	[kg]
n	(Integer) Number of cycles	[-]
NO_x	Nitrogen Oxides emission	[g/km]
NoC	Number of Cycles	[-]
P	Power	[W]
R^2	R-squared value	[-]
SOC	State-of-Charge	[%]
st.dev	Standard deviation	[-]
t	Statistical factor according to t-distribution	[-]
T	Torque	[Nm]
U_{nom}	Nominal voltage	[V]
$x_{veh,cycle}$	Travelled distance by vehicle during cycle	[km]
$x_{veh,dSOC=0}$	Travelled distance by vehicle between start of test until ΔSOC=0 after at least one entire cycle has been driven	[km]
Y	Emission factor concentration or Fuel Consumption	[g/km] resp. [l/100km]
$\Delta E_{battery}$	Change of battery energy content	[MJ] [kWh]
ΔQ	Change of battery charge	[Ah] [Ah/km]
$\Delta Q_{allowed}$	Allowed change of battery charge	[Ah] [Ah/km]
ΔSOC	Change of SOC	[%]
ρ	Fuel density	[kg/l]

Contents

1 Introduction

In the context of Task 2 of the MATADOR-project (Management Tool for the Assessment of Driveline Technologies and Research, EU-contract JOE3-CT97-0081), research is carried out in support of the development of test procedures for electrically propelled road vehicles and vehicles with other alternative drivelines. The definition of testing procedures for determining energy consumption and emissions of vehicles with different drivelines requires the evaluation of technical aspects, specific of each vehicle technology. Furthermore, the development of testing procedures that allow for a comparative technical benchmarking of different vehicle power trains is an even more complicated task, because the performance of each technology could be significantly different (alternative fuels, hybridisation, combined energy sources) asking for various measuring needs. Key issues have been addressed and are evaluated in terms of their impact on testing methods.

When testing vehicles whose propulsion energy (partially) comes from reversible energy storage systems, the most critical aspect is the effect of the (change of) State-of-Charge (SOC) on the energy consumption and emissions measurement in a single test. The energy demand at the wheels and the energy consumption and emissions of the vehicles' energy source(s) are not fully correlated in time.

A distinction is made between vehicles that are charge sustaining and those that are charge depleting. The latter means that the SOC decreases on average over time so that the vehicle has to be charged from the grid regularly. For these vehicles the energy consumption therefore always will be expressed in terms of fuel and electricity. In charge sustaining vehicles, on the other hand, the SOC will on average maintain a constant level over time, since charging energy can be withdrawn from fuel alone. Whether a vehicle is charge sustaining or depleting depends on the control strategy and driving pattern applied.

For a correct measurement of energy consumption and emissions of *charge sustaining* HEVs, therefore, the SOC at the end of the test should be the same as at the beginning. If this can not be realised, then the occurring ΔSOC has to be determined and accounted for in a calculation of energy consumption and emissions. Also, the SOC may have to be influenced for conditioning of a HEV prior to testing. Various options for a ΔSOC correction have been identified and will be investigated in this report, which is the result of Subtask 2.4 "*ΔSOC correction methods for HEVs*".

This report starts with an investigation into the SOC behaviour of different drivelines and system conditions, followed by a quantification of the problem. For this purpose, several simulations and vehicle measurements have been carried out. From the results it is derived for which drivelines and/or under which conditions a ΔSOC correction method is required. Next, an overview of possible ΔSOC correction methods is given and subsequently each method is evaluated for its suitability/applicability in practice by the results of simulations and vehicle tests. The report is completed with the overall conclusions and recommendations and ends with a reference list and the appendices.

2 Research on SOC behaviour and quantification of the ΔSOC problem

Before introducing solutions for a possible problem, it is necessary to conduct research into possible causes that are important for a thorough and well thought-out conclusion on how to deal with the problem. For this reason, research is carried out on the SOC behaviour in different drivelines and under several conditions, as well as the influence of certain parameters on this behaviour.

Although the existence of a ΔSOC problem is clear from a theoretical point of view, it is unknown to what extent it really influences the determination of energy consumption and emissions measured on real vehicles under practical test conditions. In order to get insight into the magnitude of occuring ΔSOCs, and to find an answer to the question whether it really poses a problem, simulations of and measurements on vehicles with hybrid power trains over several test cycles have been carried out.

In the simulations, the following power train models, which are described in detail in the Subtask 2.2 report ("*Development of simulation models*"), are used:

- Parallel Hybrid Electric Vehicle with a battery, both in Light Duty (LD, passenger car, '*PHEVbat*') and Heavy Duty (HD, urban bus, '*HD PHEV*') setup
- Parallel Hybrid Electric Vehicle with a flywheel, only for a LD vehicle ('*PHEVfw*')
- Series Hybrid Electric Vehicle with a battery and a load-following operating strategy for the engine-generator set (genset, APU), LD configuration ('*SHEVbat*')
- Series Hybrid Electric Vehicle with a flywheel and a load-following operating strategy for the genset, LD vehicle ('*SHEVfw*')
- Series Hybrid Electric Vehicle with a simple single or multi point APU control (three different algorithms) on the basis of SOC level, both in LD ('*LD SHEV*') and HD ('*HD SHEV*') setup
- Combined Hybrid Electric Vehicle ('*CHEV*') based on the Toyota Prius hybrid vehicle, LD only
- Fuel Cell Hybrid Electric Vehicle ('*FCHEV*'), which actually is equal to the SHEV, yet only the engine-generator set has been replaced by a fuel cell, LD vehicle

A comprehensive set of models is used in order to conduct an extensive investigation on the ΔSOC problem and related aspects. For each model, the main important parameters are listed in Appendix A.

<u>Control strategies</u>
The control strategy has a profound influence on the performances of (hybrid) vehicles, as will become clear in this report. Therefore the main characteristics of several powertrain controls are shortly described here (a full description can be found in the Subtask 2.2 report on "*Development of simulation models*").

An APU control strategy is used in the driveline models where the wheels are not mechanically connected to the main power source (combustion engine or fuel cell), i.e. the series and fuel cell HEVs. Instead, the wheels are driven by an electric motor. The APU (Auxiliary Power Unit = ICE plus generator *or* a fuel cell) can therefore operate independently from the road-load. This requires additional control to determine the operating point(s) of the APU.
The vehicle models are dimensioned to be charge sustaining which means that the battery is only charged by the APU. Many different strategies can be thought of for the APU control. The easiest way probably is to operate the APU in stationary (no transients) and have the

battery provide the peak powers requested by the electric motors. This is called load-levelling operation.

In the APU control strategy it has to be determined what the operating point should be (e.g. on/off, low/high power). The battery State-of-Charge (SOC) tells whether it is full or low on energy. The SOC therefore is a logical parameter to use for the APU control, since it directly relates the charge condition to the charge request (low SOC requires charging, while high SOC requires the APU to be shut off).
Three different APU control strategies based on SOC alone (Figure 1) are introduced for investigating the resulting effects in simulations. The low output operating point represents the optimum BSFC for this engine. The other operating point is selected at a higher speed, together with a torque that ensures the optimum BSFC at that engine speed.
It is important to incorporate hysteresis in this control, to prevent the APU from switching frequently between operating points. Although the LD and HD SHEV models have "physical" differences, the applied control strategy is the same.

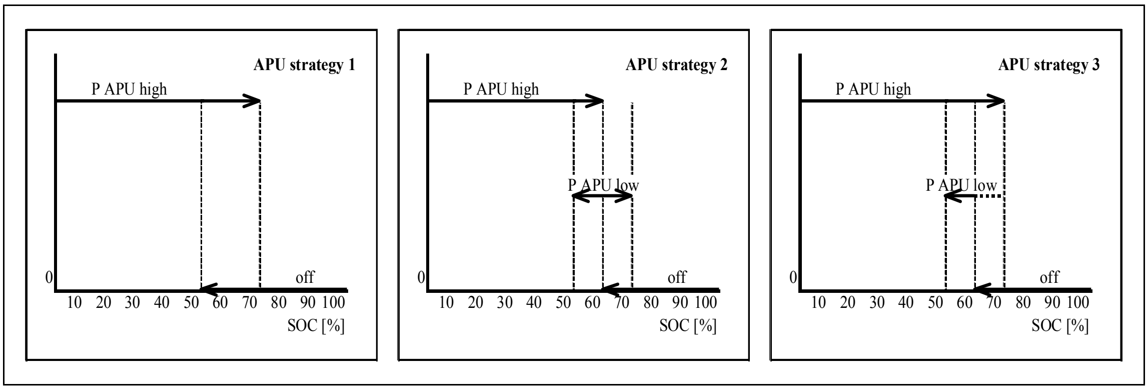


Figure 1: Straightforward SOC based APU Control strategies

Deliberately, an APU control strategy has been chosen which is not very sophisticated. Using load following control strategies with operating lines (and therefore can gradually change operating points with varying power request at the wheels) would almost logically implie that the battery is less adressed. Consequently, a smaller variation of SOC, which is subject of the investigation, might be found. The SOC behaviour might not be as explicit as for the case of large variations.
All powertrain models in which the engine is somehow mechanically coupled to the wheels have a control strategy that uses the electric motor(s) as torque assist (boost) for the engine (primary source) or to charge the battery when it is low on energy. In these models the engine is operated transiently and the operating points lie much closer to the power request at the wheels.

Driving cycles
The driveline models are simulated over a driving cycle (time-speed pattern). For the HD models a highly specific test cycle, the Dutch Urban Bus Driving Cycle, is applied. A real-life driving pattern, that has been recorded on an Australian bus, is used as a second HD cycle. For the passenger car configurations ten LD driving cycles are used. The LD cycles can be divided in currently used cycles (or they will be applied in the near future) for legislative testing and cycles which are derived from real-life driving patterns. The legislative cycles used in this study are:

- New European Driving Cycle (NEDC, also known as MVEG-A)
- Japanese 10-15 Mode Hot driving cycle
- Urban Dynamometer Driving Schedule (UDDS, FTP72)
- Highway Fuel Economy Test (HWFET)

- US06 High Speed / High Load driving cycle (US06)
- SC03 Air Conditioning driving cycle (SC03)

Four non legislative driving cycles, which are (considered) representative for European vehicle use, are used:

- Modem
- Hyzem Urban
- Hyzem Rural
- Hyzem Highway

Figures and detailed information on these cycles can be found in the Subtask 2.8 and 2.9 reports on "*Driving cycles for LD vehicles*" and "*Test methods and driving cycles for HD vehicles*" respectively.

<u>Simulations</u>

In the following sections several simulations will be discussed. Each (set of) simulation(s) is used to discuss the influence of certain parameters on the SOC behaviour over a cycle. For each simulation the following information is specified:

- *Models:* Vehicle and driveline models used for the simulation
- *Simulation aspects:* Input and output variables of the simulation
- *Parameter variation:* The key parameter of which the influence is investigated

The results of simulations are used to investigate the influence of different topics. In those cases the same data may be presented more than once, yet for different purposes.

2.1 Influence of driveline and control strategy on SOC behaviour

HD Simulation

- *Models:* HD PHEV, HD SHEV
- *Simulation aspects:* SOC over consecutive cycles
- *Parameter variation:* Driveline structure and control strategy

Different driveline structures and control algorithms are bound to affect the operating characteristics of a vehicle. Consequently, energy consumption may (or will) be influenced by this. Therefore, different drivelines and different control strategies are introduced to investigate this effect.

The Dutch Urban Bus Driving Cycle is used for simulating the HD PHEV and SHEV. The simulations are all started at the same initial SOC, and the cycles are driven directly one after another (final SOC of cycle 1 is the initial value for cycle 2, etc.) without switching off or 'reseting' the vehicle.

In Figure 2 the initial and final SOCs of the batteries are shown for 10 consecutive cycles. Completely different paths can be seen. With respect to ΔSOC over a cycle, two situations clearly can be distinguished. The parallel HEV and the series HEV with control strategy 2 do not show a change of SOC over the cycle (SOC is periodic with a period time of 1 driving cycle), while the series HEVs with control strategies 1 and 3 show significant ΔSOC (SOC varies periodically with an integer number of driving cycles as period time). These results show that a ΔSOC problem does not necessarily occur. Different control strategies clearly influence the SOC behaviour, while the components have not been changed (i.e. only the control algorithm is altered).

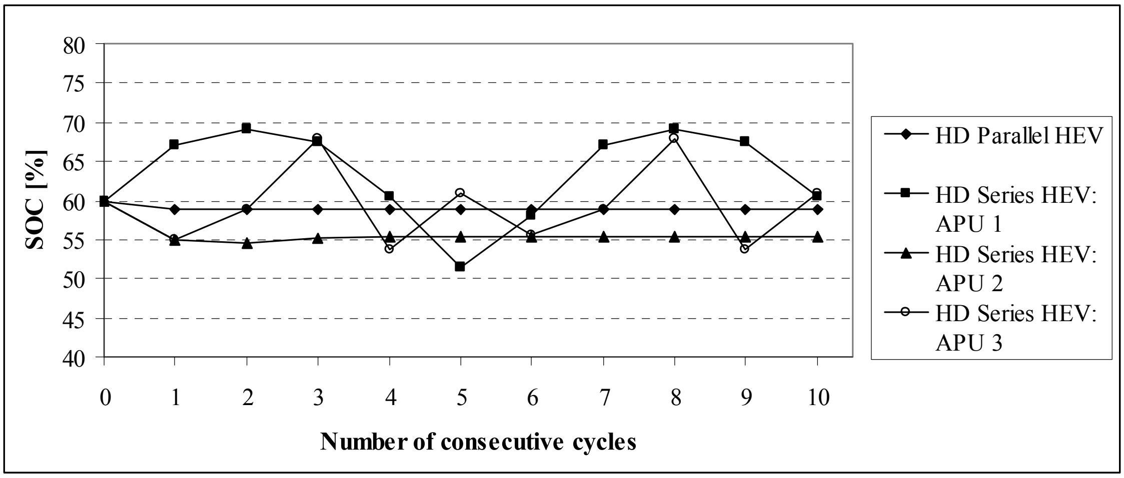


Figure 2: SOC history for four different hybrids: one HD parallel HEV and a HD series HEV with three different APU operating strategies

2.2 Influence of driving cycle on SOC behaviour

HD Simulation

- *Model(s):* HD SHEV with APU1
- *Simulation aspects:* Initial- and final-SOC for consecutive cycles
- *Parameter variation:* Driving cycle

The HD SHEV model with APU control strategy 1 (one operating point) is simulated over 10 consecutive Dutch Urban Bus Cycles (results have previously already been used) and 10 successive Australian Bus cycles. Both cycles have different characteristics (length, time, etc.), which clearly results in a different SOC behaviour (see Figure 3). In both cases a cyclic pattern can be seen and clearly each cycle results in a ΔSOC.

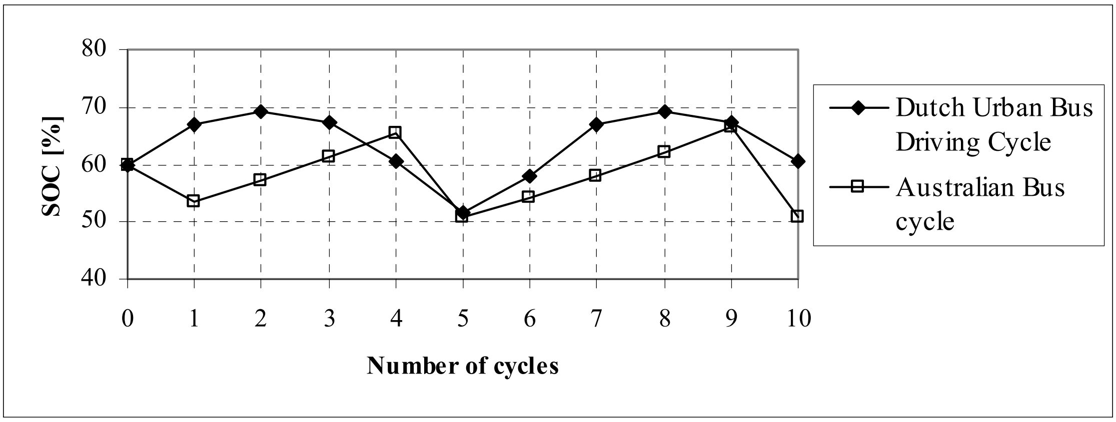


Figure 3: Influence of driving cycle; initial and final SOC for HD SHEV with APU control strategy 1 over 10 consecutive cycles

LD Simulation

- *Model(s):* LD SHEV with APU2
- *Simulation aspects:* Initial- and final-SOC for five consecutive cycles
- *Parameter variation:* Driving cycle

For a number of different LD driving cycles, Figure 4 shows the initial and final SOC of 5 consecutively driven cycles.

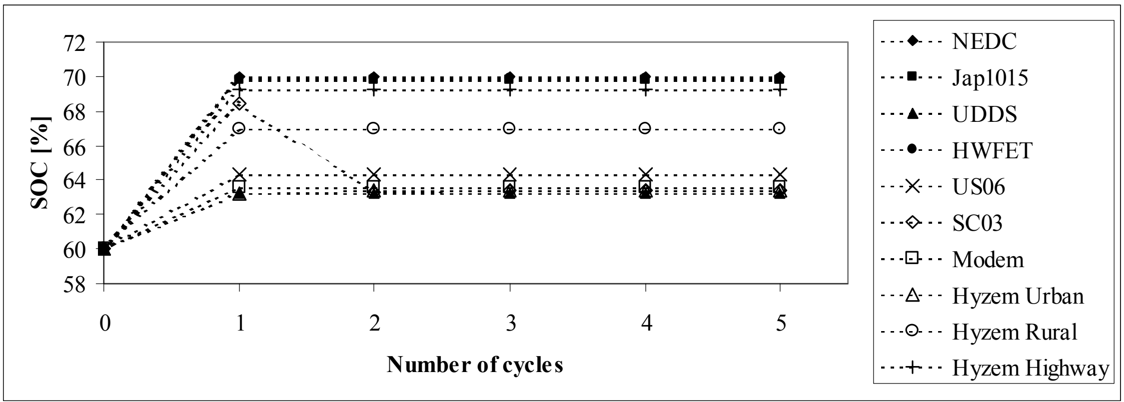


Figure 4: Influence of driving cycle; initial and final SOC for LD SHEV with APU 2 over 5 consecutive cycles

In this simulation, all of the available light duty driving cycles were used, to show their influence.
A first analysis of the results learns that the APU2 control strategy (see Figure 1) is quite stable, as all cycles reach an equilibrium, in most cases after one cycle. Therefore, fuel consumption is easy to determine by taking the measured value over the last cycle.

Despite the fact that all cycles reach an equilibrium, still the influence of the driving cycle cannot be neglected, as the SC03 cycle needs one additional cycle to come into balance. This possibly is the result of an 'unfavourable' initial SOC for this cycle, in combination with the short length of this cycle. This means that the same could happen for the other cycles, if another value had been chosen for the initial SOC. It can be mentioned here that for other drivelines (CHEV and FCHEV, see Appendix B) the results were similar (SOC balanced over two cycles for the SC03 cycle, and one for the others).

2.3 The effect of intial SOC on SOC behaviour

HD Simulation

- *Model(s):* HD SHEV with APU1 and APU2
- *Simulation aspect(s):* SOC over consecutive Dutch Urban Bus driving cycles
- *Parameter variation:* Initial SOC

In the simulations shown so far, the behaviour of SOC over a number of consecutive cycles proved to have a dependency with initial SOC. Figure 5 shows the battery SOC at the beginning and end of each cycle when the series-hybrid urban bus is driven over 10 consecutive Dutch Urban Bus Driving Cycles, with different initial SOC values (50% and 60%) and different APU control strategies. In all cases, the SOC displays cyclic behaviour after one or a few cycles have been driven. In three cases the period of the SOC fluctuations is equal to the length of the driving cycle (n=1). With the exception of the first (few) cycle(s), the ΔSOC is zero over each following cycle. The fuel consumption measured over these cycles gives the correct value, and is equal to the asymptotic value that would be measured by taking the average over a large number of cycles. For APU1 with 60% initial SOC however, the ΔSOC over 6 cycles is also zero, yet the resulting fuel consumption, as a result of different SOC trajectories (and subsequently losses) holds a different energy consumption for that same type of test cycle. Therefore, a zero ΔSOC does not necessarily guarantee an exact representation of actual fuel consumption. Whether it is possible for the SOC to balance at different levels could not be proved.

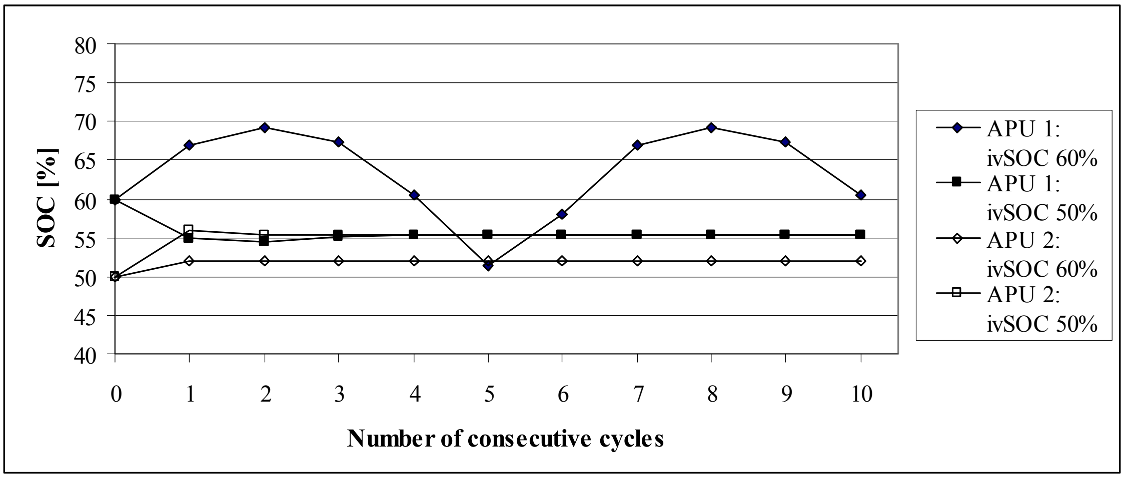


Figure 5: Battery SOC for a series-hybrid urban bus driven over 10 consecutive Dutch Urban Bus Driving cycles, with different initial SOC values and APU control strategies

The fact that periodic behaviour is observed could be expected, as a periodic stimulus (multiple identical cycles) is imposed on a controlled non-linear system. The response to this excitation is either an equilibrium (excitation is dampened by the system) or some kind of cyclic behaviour with a period that is an integer number of driving cycles. In the case of APU 1 with an initial SOC of 60%, the SOC becomes cyclic with a period of 6 cycles.

As can be learned from this example, the period time of this cyclic behaviour is -amongst others- dependent on the initial SOC and the control strategy. Taking a further look into this behaviour, it can be reasoned that the time constant of the system response is dependent on three main aspects:

- the possibilities for the controller to *measure* the energy demand (control inputs),
- the possibilities for the controller to *manipulate* the system (control outputs), and
- the control strategy that converts control inputs into control outputs.

In other words, the response of the system improves when the controller is able to determine changes in energy demand, and can also take counteractive measures on it.
Increased SOC hysteresis in the control strategy for instance affects the response negatively, as it takes more time before a limit is exceeded, and therefore the APU output power is adjusted to the changed energy demand. Introducing more APU operating points provides more control outputs, causing the system to respond better. Note that the difference between APU1 and APU2 in Figure 5 is a combination of more APU operating points, and less hysteresis.
Other factors of influence on the response are:

- accounting for the actual energy demand, by measuring e.g. throttle position (control input)
- total cycle time (more or less time to respond, thus related to the control output)
- battery capacity (more or less time before SOC limits are reached, thus related to control input)

The dependency of initial SOC in Figure 5 is unpredictable; an 'unfavourable' starting condition may accidentally excite the system, where a 'suiting' initial SOC has a dampening effect on the response.

LD Simulation 1

- *Model(s):* LD SHEV with APU2, LD CHEV, LD FCHEV
- *Simulation aspects:* Initial- and final-SOC for five consecutive cycles
- *Parameter variation:* Initial SOC and driving cycle

Since the initial battery SOC is considered to be of influence on the development of the SOC during the cycle, simulations have been carried out with two different models, starting with three different initial SOCs (40, 60, and 80%). Again all available LD driving cycles have been used in order to get a good idea of the possible influence of this factor.

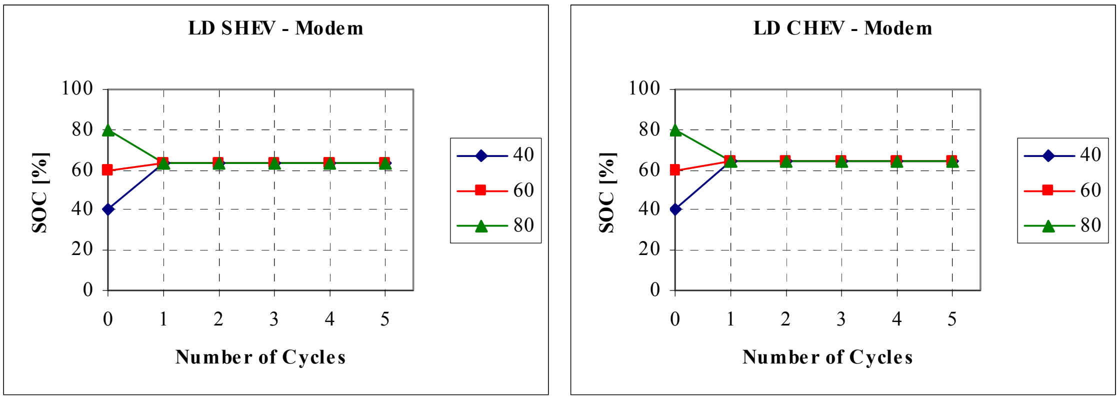


Figure 6: Different initial SOC for SHEV and CHEV over Modem cycle

Figure 6 shows, just as an illustration, two examples of simulations with different initial SOC. It takes one or two cycles for all LD drivelines (SHEV and CHEV) to come into balance, starting from an extreme initial SOC. All other simulations with these models concerning this topic show similar results (Appendix B). Based on these results, it seems that driving one complete cycle is an adequate way to condition the vehicle prior to the actual test, as the ΔSOC over the following cycles is (almost) zero.

LD Simulation 2

- *Model(s):* LD PHEVbat, PHEVfw, SHEVbat, SHEVfw
- *Simulation aspects:* Initial- and final-SOC for consecutive cycles
- *Parameter variation:* Initial SOC and driving cycle

As examples of mixed driving, driving in the city, and heavy loaded driving Figure 41 through Figure 46 (in Appendix B) show the results of several consecutively driven NEDC, Aachen-city, and US06 driving cycles for these four driveline models. For the flywheel as well as for the NiMH battery, the development of fuel consumption and State-of-Charge are presented as functions of time. The beginning c.q. end of an individual cycle is marked with an asterisk symbol (*).

After some time the SOC levels take a periodic course, where the storage device is being charged at least once in a period. In some cases this period is one cycle, but at all times it is an integer number of cycles. The periodic duration of the SOC path does not depend on the initial State-of-Charge. A phase displacement and a slightly different course between curves of different initial SOC values can be seen. Starting at different intial SOC values might lead to different cut-in characteristic for the engine, as is shown in Figure 7 for the parallel hybrid with battery. In case of the lower initial SOC, the engine is switched on one more time per cycle after the SOC has settled in periodic behaviour. For all simulations the results for different initial SOC are included in Appendix B.

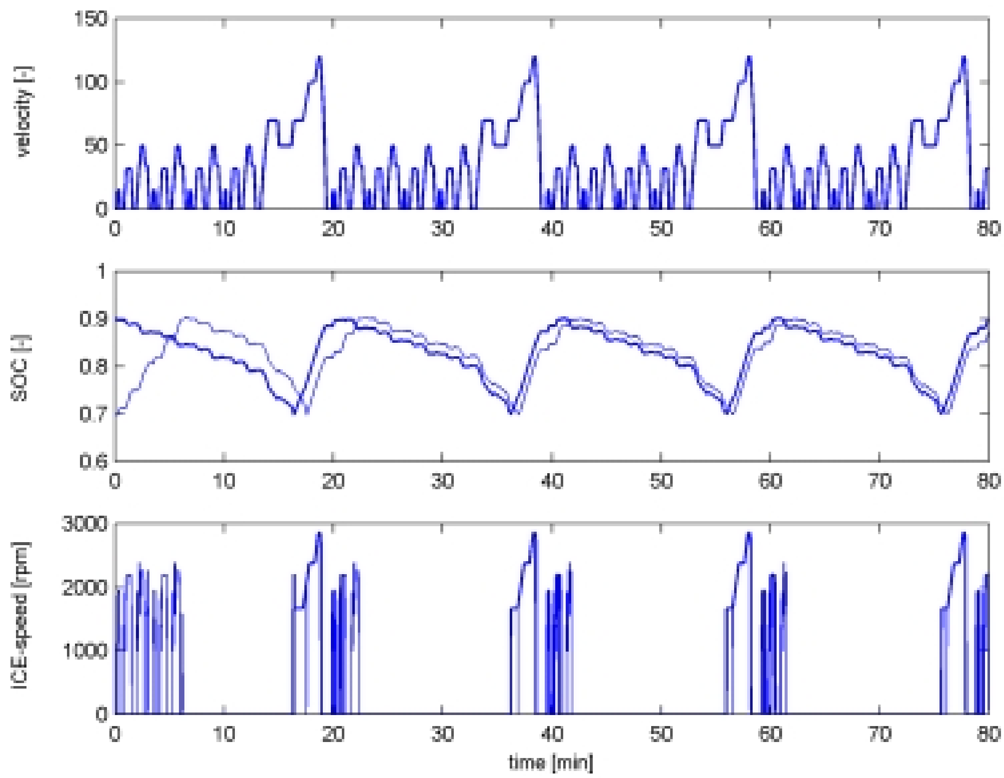


Figure 7: On/off characteristic of the combustion engine in the PHEVbat for different initial SOC on multiple NEDC cycles

In all simulations, the State-of-Charge courses get closer to each other, as a result of the different charging patterns in the first cycle(s), and even cover each other entirely in some cases. Small differences between both curves are caused by differently timed switching on of the charging mode due to reaching the SOC limits with a small time difference. This for example occurs in the Aachen-city cycle with the series hybrid with flywheel storage device. It even leads to a further phase displacement.

The fuel consumption also has a periodic course with the same duration as the SOC. Because of the decreasing influence of the cyclic behaviour, the differences fade away. The actual fuel consumption is found at the convergence limit.

2.4 The effect of energy storage capacity on SOC behaviour

LD simulation 1

- *Model(s)*: LD SHEV with APU2, LD CHEV
- *Simulation aspects*: Initial- and final-SOC for five consecutive cycles
- *Parameter variation*: Battery capacity

Until now, only the effects of some driveline parameters or the control strategy have been investigated. An also interesting issue is the dimensioning of the driveline components, relative to one another. SOC or ΔSOC are directly related to the energy content of the storage system at a certain moment. Therefore, the battery capacity has been changed to investigate the influence on the SOC behaviour.

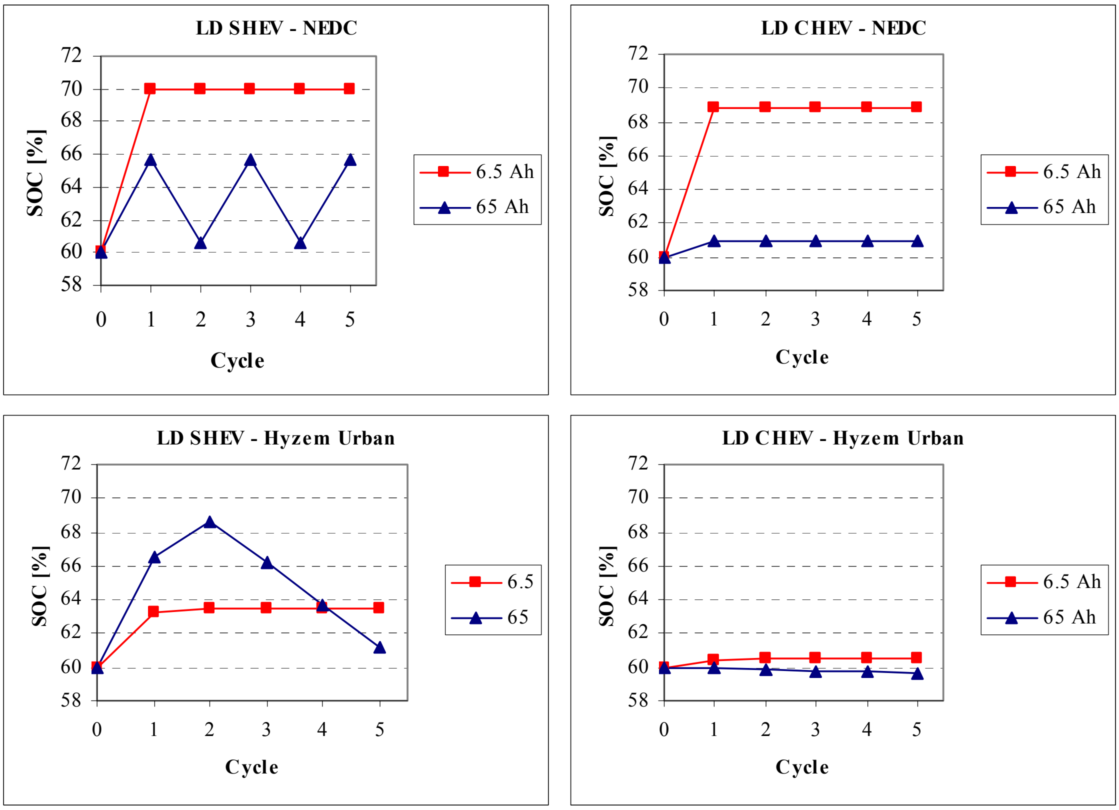


Figure 8: SOC behaviour for LD SHEV and CHEV with different battery capacities over NEDC and Hyzem Urban cycles

Figure 8 shows the SOC behaviour for both the SHEV and CHEV with battery capacities of 6.5 Ah (original model value, ≈2 kWh) and 65 Ah (≈20 kWh) over two different cycles. The increased battery capacity clearly influences the period time of the system. The period time has even changed to such an extent that five cycles clearly are not enough to show the SOC cycle period.
For the case of the CHEV, the effect is much smaller than for the SHEV. As the combined hybrid's control strategy has a fairly direct relationship between SOC, engine operating point, and the required power at the wheels, the driveline is designed to respond quickly to changes in SOC, hence limiting possible ΔSOCs.
For the SHEV however, this is not the case. The SOC hysteresis in the control strategy, together with the higher battery capacity, causes the system to respond slower to the demand in energy at the wheels. This results in a periodic response of two cycles (n=2) on the NEDC,

and an even higher period time on the Hyzem Urban cycle. Therefore, it can be concluded that battery capacity is also an important parameter that influences the period time of the response (as was earlier already discussed).
The results for the other cycles are presented in Appendix B.

Note:
The battery installed in a hybrid vehicle usually has to be able to provide sufficient power to the system. Generally, two different types of batteries can be distinguished: power and traction. A power battery has a high power and low energy density, while these characteristics are the other way around for the traction battery. At this moment, the mutual differences are relatively small, but future performances of these battery types will be more distinct. In other words, when a power and traction battery are to have the same power capability, the traction battery would be heavier due to its lower power density.
Since the differences are small, present batteries in hybrids have an energy capacity that might not be representative for future hybrids. Assuming that the power density will improve for future power batteries, while the energy density does not increase (to the same extent), it is very well possible that the batteries installed in (charge sustaining) HEVs which operate in hybrid mode all the time, will have lower energy content (kWh is directly related to Ah in case of constant system voltage, as is applied), yet higher power capability. The increase of battery capacity in the simulation, then would not be representative. Actually, with respect to the trend of SOC behaviour and battery capacity described above, the results might have to be read the other way around; with lower battery capacity, the SOC window is traversed in less time and, besides a certain ΔSOC to correspond to less energy, less driving cycles might be needed to find a repetitive SOC history. In this case, determination of the energy would actually become less complicated.
As counterargument, however, the following possible trend for future development can be given. Either due to technology improvements (higher power and energy density) or because of more strict legislation (e.g. no emissions in inner cities), the installed energy content of batteries in hybrids might be increased in order to enable a substantial ZEV range. Althoug much depends on the applied control strategy (thermostat or load-follower, small or large SOC window) and operating mode (ZEV or HEV mode, driver selectable?), a (significant) ΔSOC might be found and determination of the energy consumption consequently might be a problem.
Two scenarios for hybrid vehicle development have thus been posed. Each one with its own influence on the testing results; ΔSOC or no ΔSOC. The large variety for possible vehicle configurations and design parameters will probably result in hybrid electric vehicles with all kinds of battery contents. Unpredictable to what extent, but a ΔSOC correction method probably is required.

LD Simulation 2

- *Model(s):* LD PHEVbat, PHEVfw, SHEVbat, SHEVfw
- *Simulation aspects:* Initial- and final-SOC for consecutive cycles
- *Parameter variation:* Energy storage capacity

The energy storage capacities of these vehicle models are all different. Especially the difference between the flywheel and battery systems is large, where the flywheels have a small capacity and the batteries have higher capacity. Figure 41 through Figure 46 (in Appendix B) again are looked at.

The difference between the courses of fuel consumption with high and low initial State-of-Charge decreases for the hybrid vehicles with flywheel after a few cycles, because of the low energy capacity of the flywheel and, together with this, the frequent operation of the

combustion engine. In this respect, the parallel hybrid in Aachen-city-cycle and the series hybrid in the US06-cycle are extremes. In the Aachen-city-cycle the State-of-Charge decreases slowly because of the low power demand, and the combustion engine only runs for a short time for charging during the cycle. So here, for more cycles the amplitude in the path of fuel consumption is quite big. The flywheel of the series hybrid in the US06-cycle is heavily loaded and has to be recharged five times as many as in the Aachen-city-cycle. Therefore the amplitude in the fuel consumption decreases below 0.5 l/100km right after one cycle.
Compared with this, the fuel consumption of the hybrid vehicles with battery storage device reach their final value more slowly, and the differences in fuel consumption between high and low initial SOCs remain on a comparatively high level.

2.5 Quantification

On the basis of the results obtained from the simulations, several cases can be thought of in which a significant ΔSOC is to be expected. Important is that a ΔSOC is actually the result of several factors together. A large battery in combination with a control strategy in which no direct relationship between wheel power and engine (APU) operating points exists, is most likely to show substantial ΔSOC. In the case of a small battery, a large ΔSOC corresponds to a small energy amount, while this same energy amount corresponds to a small ΔSOC for a battery with high energy content.
The change of energy content in absolute figures is important, and not the change of SOC in %.

<u>CARB Criterium</u>
For this reason, it is preferable to look at the change in energy content with respect to the consumed energy over the cycle and not just to a normalised figure (ΔSOC is a percentage of the maximum charge content). The Californian Air Resources Board (CARB) has set limits for the occuring ΔSOC (measured by the Ah) over a cycle. These limits (minimum and maximum $\Delta Q_{allowed}$ in Ah) are calculated with Equation 1. Actually the equation defines that the allowed maximum net energy change of the battery is 1% of the used fuel's energy content. When Equation 1 is valid, the test can be stopped and no additional method is necessary to account for the occuring ΔSOC.

$$\left|\Delta Q_{allowed}\right| \leq 0.01 \cdot \frac{m_{fuel} \cdot H_{fuel}}{U_{DC} \cdot 3600} \qquad \textit{Equation 1}$$

For each vehicle and for each cycle the $\Delta Q_{allowed}$ has a different value, since the fuel used (m_{fuel}) varies for each combination. As a result, longer and more severe cycles, which are likely to give higher fuel consumption, also allow a higher ΔSOC for a vehicle over the test. The relative influence of the ΔSOC over the cycle on the fuel consumption stays the same.

For most simulations Equation 1 is valid after one (preconditioning) cycle has been driven. The periodic time for the SOC in those cases was one cycle. In the other simulations, the period time for the repetitive SOC pattern was more than one driving cycle and substantial ΔSOC was found each time.

Now that it has become clear that a significant ΔSOC does not necessarily mean that the change of energy content (ΔE) is also significant, it is time to combine those results. For all simulations the ΔSOC is looked up and the corresponding change of energy content is determined. The difference in energy content then is related to the propulsion energy needed for the vehicle to complete the driving cycle, in order to quantify the potential of the net difference in energy (Energy_ratio, Equation 2).

$$\text{Energy\_ratio} = \frac{\Delta E_{\text{battery}}}{E_{\text{WH,drive}}} \cdot 100\% \qquad \textit{Equation 2}$$

The results of this calculation are very diverse. ΔSOCs between -20 and +30% were found in the simulations (see Table 1 through Table 3). It has to be remarked that several of the simulations were started with extreme values for the intial SOC. Values which in practise are unlikely to be reached, since the vehicles are meant to be charge sustaining and therefore operate within an intended SOC range. Starting outside this band, already increases the probability for a large ΔSOC. In many cases, a large ΔSOC is only found over the first cycle (especially the LD vehicle models).

The Energy_ratios corresponding to the ΔSOCs, varied between -130 and almost +400%. These figures have to be interpreted as indicative values. Dependent on configuration and dimensions of component, highly different results are obtained. An Energy_ratio of -130% indicates that a cycle has been driven electrically only (with an average efficiency of about 75%). In the same way, it can be concluded that an Energy_ratio of 400% indicates that almost 4 cycles can be driven electrically only with the additionally stored energy.
This last value was obtained with the LD series HEV with a large battery on the first of five consecutive (very moderate) Japanese 10-15 Mode Hot cycles (low $E_{WH,drive}$). The simulation results show that almost four cycles could be driven electrically only after this first cycle, before the APU turned on again. This, of course, is also caused by the large hysteris in the control. Comparison of the ΔSOC of the small and large battery in this vehicle and over this cycle shows that they are almost alike (10 and 8 % for the 6.5 and 65 Ah battery respectively). The $\Delta E_{battery}$, however, are 0.19 and 1.55 kWh respectively, which clearly are distinct (8 times as much for the large battery). Since the propulsion energy at the wheels stays the same, a large difference in Energy_ratio is found.

Leaving out the first cycle (regarding it as the preconditioning cycle), the results of ΔSOC and the energy ratio do change significantly. For the HD vehicle models, the occuring of ΔSOC is mainly dependent on the applied control strategy. In several cases the SOC balances after one cycle, while in other cases a cyclic SOC pattern (with a period time of several cycles) is found.
The results for the LD driveline models are more consistent. Only in case of the LD SHEV with a large battery significant ΔSOCs are found. The other simulations result in a balanced SOC after one cycle, which thus clearly functions as a preconditioning cycle.

Comparison of the Energy_ratios (logically) yields exactly the same results. When the SOC balances after one cycle, the Energy_ratio is zero. When the SOC has a period time of more than one cycle, significant ΔSOCs and Energy_ratios are found and this consequently has influence on the "measured" energy consumption (and emissions).

Table 1: ΔSOC and Energy_ratio for HD vehicle models in several simulations

ΔSOC [%]		Number of cycles									
		1	2	3	4	5	6	7	8	9	10
HD PHEV	DUBC	-1.0	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HD SHEV	Sim 1	7.0	2.2	-1.8	-6.9	-9.0	6.5	9.0	2.2	-1.8	-6.9
	Sim 2	-5.1	-0.3	0.6	0.1	0.0	0.0	0.1	0.0	0.0	0.0
	Sim 3	-5.1	4.0	9.0	-14.2	7.3	-5.4	3.2	9.0	-14.1	7.3
	Sim 4	2.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Sim 5	5.9	-0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Sim 6	-5.1	4.0	9.0	-14.2	7.3	-5.4	3.2	9.0	-14.1	7.3
	Sim 7	-6.4	3.6	4.0	4.4	-14.6	3.3	3.7	4.1	4.5	-15.6

Energy_ratio [%]		Number of cycles									
		1	2	3	4	5	6	7	8	9	10
HD PHEV	DUBC	-8	0	0	0	0	0	0	0	0	0
HD SHEV	Sim 1	26	10	-4	-26	-38	24	30	10	-4	-26
	Sim 2	-20	-5	2	1	1	1	0	0	0	0
	Sim 3	-22	14	32	-52	32	-22	10	32	-52	32
	Sim 4	6	0	0	0	0	0	0	0	0	0
	Sim 5	18	-1	0	0	0	0	0	0	0	0
	Sim 6	-22	14	32	-52	32	-22	10	32	-52	32
	Sim 7	-16	10	9	10	-34	10	10	0	9	-39

Table 2: ΔSOC and Energy_ratio for LD SHEV simulations

ΔSOC [%]		6.5Ah Battery – ivSOC=60%					65Ah Battery – ivSOC=60%				
		Number of cycles									
		1	2	3	4	5	1	2	3	4	5
LD SHEV	NEDC	10.0	0.0	0.0	0.0	0.0	5.7	-5.1	5.1	-5.1	5.1
	Jap1015	9.8	0.0	0.0	0.0	0.0	8.0	-0.1	-2.6	-2.6	-1.8
	UDDS	3.2	0.0	0.0	0.0	0.0	8.6	-7.4	7.9	-7.4	7.4
	HWFET	9.9	0.0	0.0	0.0	0.0	3.1	3.1	3.1	-6.6	-0.7
	US06	4.3	-0.1	0.0	0.0	0.0	-1.9	-1.9	-1.9	-1.9	7.0
	SC03	8.4	-5.1	0.0	0.0	0.0	5.9	3.7	-3.7	-3.7	1.0
	Modem	3.6	0.0	0.0	0.0	0.0	-0.7	0.7	-0.8	0.8	-0.8
	Hyzem U	3.2	0.2	0.0	0.0	0.0	6.5	2.1	-2.5	-2.5	-2.5
	Hyzem R	6.9	0.0	0.0	0.0	0.0	5.7	4.0	-8.1	3.1	5.3
	Hyzem H	9.3	0.0	0.0	0.0	0.0	1.9	-0.5	0.4	-0.5	0.5

Energy_ratio [%]		6.5Ah Battery – ivSOC=60%					65Ah Battery – ivSOC=60%				
		1	2	3	4	5	1	2	3	4	5
LD SHEV	NEDC	18	0	0	0	0	104	-93	93	-93	93
	Jap1015	48	0	0	0	0	390	-6	-126	-126	-88
	UDDS	5	0	0	0	0	138	-119	128	-119	120
	HWFET	13	0	0	0	0	41	41	41	-88	-9
	US06	5	0	0	0	0	-19	-19	-19	-19	72
	SC03	26	-15	0	0	0	180	114	-114	-114	32
	Modem	2	0	0	0	0	-4	4	-5	5	-5
	Hyzem U	14	1	0	0	0	297	99	-115	-115	-114
	Hyzem R	10	0	0	0	0	77	54	-110	42	72
	Hyzem H	3	0	0	0	0	5	-1	1	-1	1

ΔSOC [%]		6.5Ah Battery – ivSOC=40%					6.5Ah Battery – ivSOC=80%				
		Number of cycles									
		1	2	3	4	5	1	2	3	4	5
LD SHEV	NEDC	30.0	0.0	0.0	0.0	0.0	-10.0	0.0	0.0	0.0	0.0
	Jap1015	29.8	-0.1	0.0	0.0	0.0	-10.3	0.0	0.0	0.0	0.0
	UDDS	23.2	0.0	0.0	0.0	0.0	-16.8	0.0	0.0	0.0	0.0
	HWFET	29.9	0.0	0.0	0.0	0.0	-10.1	0.0	0.0	0.0	0.0
	US06	24.3	0.0	0.0	0.0	0.0	-15.6	-0.1	0.0	0.0	0.0
	SC03	23.4	0.0	0.0	0.0	0.0	-16.6	0.0	0.0	0.0	0.0
	Modem	23.6	0.0	0.0	0.0	0.0	-16.4	0.0	0.0	0.0	0.0
	Hyzem U	23.4	0.0	0.0	0.0	0.0	-16.6	0.1	0.0	0.0	0.0
	Hyzem R	26.9	0.0	0.0	0.0	0.0	-13.1	0.0	0.0	0.0	0.0
	Hyzem H	29.3	0.0	0.0	0.0	0.0	-10.7	0.0	0.0	0.0	0.0

Energy_ratio [%]		6.5Ah Battery – ivSOC=40%					6.5Ah Battery – ivSOC=80%				
		1	2	3	4	5	1	2	3	4	5
LD SHEV	NEDC	56	0	0	0	0	-19	0	0	0	0
	Jap1015	150	0	0	0	0	-52	0	0	0	0
	UDDS	39	0	0	0	0	-28	0	0	0	0
	HWFET	41	0	0	0	0	-14	0	0	0	0
	US06	24	0	0	0	0	-15	0	0	0	0
	SC03	74	0	0	0	0	-52	0	0	0	0
	Modem	15	0	0	0	0	-10	0	0	0	0
	Hyzem U	111	0	0	0	0	-78	0	0	0	0
	Hyzem R	38	0	0	0	0	-18	0	0	0	0
	Hyzem H	9	0	0	0	0	-3	0	0	0	0

Table 3: ΔSOC and Energy_ratio for LD CHEV simulations

ΔSOC [%]		**6.5Ah Battery – ivSOC=60%**					**65Ah Battery – ivSOC=60%**				
		Number of cycles									
		1	2	3	4	5	1	2	3	4	5
LD CHEV	NEDC	8.8	0.0	0.0	0.0	0.0	0.9	0.0	0.0	0.0	0.0
	Jap1015	2.1	0.0	0.0	0.0	0.0	-0.2	-0.1	0.1	0.0	0.0
	UDDS	-0.3	0.0	0.0	0.0	0.0	-0.8	-0.1	0.0	0.0	0.0
	HWFET	3.6	0.0	0.0	0.0	0.0	1.0	-0.1	0.0	0.0	0.0
	US06	3.1	0.0	0.0	0.0	0.0	0.4	0.2	0.2	0.0	0.1
	SC03	-0.8	-0.1	0.0	0.0	0.0	-0.3	-0.2	0.0	0.0	-0.1
	Modem	4.5	0.0	0.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0
	Hyzem U	0.5	0.0	0.0	0.0	0.0	-0.1	-0.1	-0.1	0.0	0.0
	Hyzem R	1.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
	Hyzem H	1.6	0.0	0.0	0.0	0.0	0.8	-0.1	0.2	-0.1	-0.1

Energy_ratio [%]		**6.5Ah Battery – ivSOC=60%**					**65Ah Battery – ivSOC=60%**				
		1	2	3	4	5	1	2	3	4	5
LD CHEV	NEDC	16	0	0	0	0	17	1	0	0	0
	Jap1015	10	0	0	0	0	-10	-6	5	-2	-1
	UDDS	-1	0	0	0	0	-12	-1	0	0	0
	HWFET	5	0	0	0	0	13	-1	0	0	0
	US06	3	0	0	0	0	4	2	2	0	1
	SC03	-3	0	0	0	0	-8	-6	1	1	-2
	Modem	3	0	0	0	0	12	0	0	0	0
	Hyzem U	2	0	0	0	0	-4	-4	-3	-2	-2
	Hyzem R	2	0	0	0	0	1	0	0	0	0
	Hyzem H	0	0	0	0	0	2	0	0	0	0

ΔSOC [%]		**6.5Ah Battery – ivSOC=40%**					**6.5Ah Battery – ivSOC=80%**				
		Number of cycles									
		1	2	3	4	5	1	2	3	4	5
LD CHEV	NEDC	28.8	0.0	0.0	0.0	0.0	-11.9	0.7	0.0	0.0	0.0
	Jap1015	22.1	0.0	0.0	0.0	0.0	-17.8	-0.1	0.0	0.0	0.0
	UDDS	19.7	0.0	0.0	0.0	0.0	-20.3	0.0	0.0	0.0	0.0
	HWFET	23.6	0.0	0.0	0.0	0.0	-16.4	0.0	0.0	0.0	0.0
	US06	23.7	-0.6	0.0	0.0	0.0	-16.8	-0.1	0.0	0.0	0.0
	SC03	19.2	-0.1	-0.1	0.0	0.0	-21.0	0.1	0.0	0.0	0.0
	Modem	24.5	0.0	0.0	0.0	0.0	-15.5	0.0	0.0	0.0	0.0
	Hyzem U	20.4	0.1	0.0	0.0	0.0	-17.5	-2.0	-0.1	0.0	0.0
	Hyzem R	21.1	0.0	0.0	0.0	0.0	-18.8	0.0	0.0	0.0	0.0
	Hyzem H	21.6	0.0	0.0	0.0	0.0	-18.4	0.0	0.0	0.0	0.0

Energy_ratio [%]		**6.5Ah Battery – ivSOC=40%**					**6.5Ah Battery – ivSOC=80%**				
		1	2	3	4	5	1	2	3	4	5
LD CHEV	NEDC	52	0	0	0	0	-22	1	0	0	0
	Jap1015	108	0	0	0	0	-87	0	0	0	0
	UDDS	32	0	0	0	0	-33	0	0	0	0
	HWFET	32	0	0	0	0	-22	0	0	0	0
	US06	24	-1	0	0	0	-16	0	0	0	0
	SC03	60	0	0	0	0	-64	0	0	0	0
	Modem	15	0	0	0	0	-9	0	0	0	0
	Hyzem U	95	0	0	0	0	-81	-9	0	0	0
	Hyzem R	30	0	0	0	0	-26	0	0	0	0
	Hyzem H	7	0	0	0	0	-6	0	0	0	0

2.6 Measurements on a Toyota Prius

The Toyota Prius (Figure 9) is the first series produced hybrid electric vehicle. Its THS (Toyota Hybrid System) has a combined hybrid structure. The available Prius is a Japanese vehicle. A modified vehicle will become available on the European and American market in 2000.

Figure 9: Toyota Prius on the rollerbench at TNO

Similar to the previous simulations, this vehicle has been tested over several different driving cycles. More information on the vehicle and the measurements can be found in Appendix C. The test cycle was driven in sequences of five with a ten minute rest in between (ignition turned off), see Figure 10. A preconditioning cycle followed by 16 hours of conditioned soak was performed the day before the sequential test.

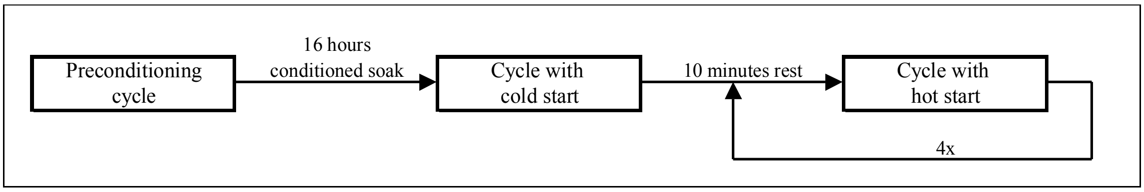


Figure 10: Test sequence used for measurements on a Toyota Prius

Before each cycle the Prius had to be brought into 'Service Mode' in order to be able to test the vehicle on a 2WD rollerbench. On the road the vehicle is driven in 'Normal Mode'. It is assumed that the 'Service Mode' does not affect the drivetrain management, and thus that the results are representative for the vehicle performances on the road.
The measurements have been performed under standard test conditions. For all consecutive cycles the bag emissions (HC, CO, CO_2, and NO_x) were sampled per cycle, and sometimes separate bags were used to divide characteristic phases (e.g. the NEDC was split into the UDC and EUDC). The emission factors are calculated for each phase and for the complete cycle using the actually driven distance on the chassis dynamometer. The fuel consumption (FC [l/100km]), in turn, is calculated from the bag emissions using the carbon balance method

for petrol fuelled vehicles (Equation 3). The concentrations of HC, CO, and CO_2 are in g/km and the fuel's density (ρ) is in kg/l.

$$FC = \frac{0.1154}{\rho_{fuel}} \cdot (0.866 \times HC + 0.429 \times CO + 0.273 \times CO_2) \qquad \textit{Equation 3}$$

During the tests the current into and out of the NiMH power battery is measured. From this signal the change of capacity in Ampèrehours (Ah) is calculated by integrating the current. The ΔSOC value is obtained by relating the ΔQ (in Ah) to the maximum battery capacity (6.5 Ah).

Six different driving cycles have been used to test the Toyota Prius on the rollerbench:
- European Driving Cycle (UDC+EUDC)
- Japanese 10-15 Mode Hot driving cycle (Jap1015)
- Urban Dynamometer Driving Schedule (UDDS, FTP72)
- Hyzem Urban, Rural, and Highway (three separate cycles)

The SOC behaviour of the vehicle over different (consecutive) cycles is investigated. Since the computer model for the Combined Hybrid Electric Vehicle is entirely built on the basis of information on the Prius (at the time of modelling only little information was available from several papers), it is very interesting to see whether the behaviour of the model and the vehicle are alike or if remarkable differences exist.

As an example Figure 11 contains the history of ΔSOC (thus change of SOC with respect to initial SOC value) over the NEDC for the real Prius and the CHEV computer model. Unfortunately the measurement data on the first cycle (cold) was lost due to a bad connector. The other cycles were driven with a hot engine. The first cycle (0-1180 s) for the simulation can be seen as preconditioning (the vehicle was preconditioned the day before the test). Of course, the intial cycle in the simulation was also started at a zero ΔSOC, but the data has been shifted in order that the other cycles start with a zero ΔSOC. All following cycles result in a (practically) zero ΔSOC. The same kind of results have been obtained on the other tested cycles.

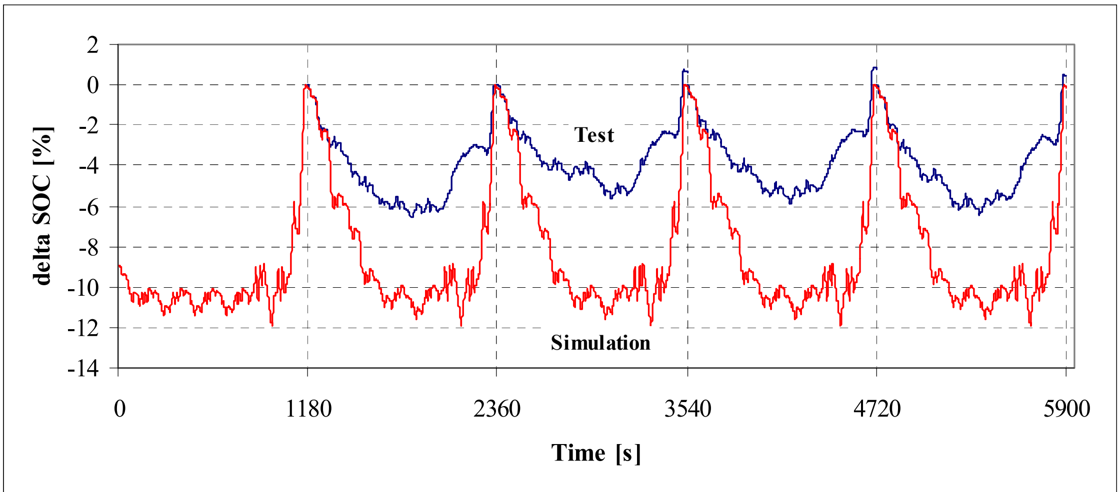


Figure 11: ΔSOC history of a Toyota Prius test and the CHEV simulation on five consecutive New European Driving Cycles

The general conclusion is that the overall behaviour is quite similar. Characteristic changes in SOC can be distinguished in both the test and the simulation. During the cycle the SOC first decreases, halfway it more or less stabilises (only minor changes), and towards the end SOC increases again.
Since the available engine and battery data in the simulation are different from the actual components in the Prius, this is bound to have an influence on the absolute values of variables. The change of capacity in the simulation is almost twice as high as that in the actual test. From the SOC behaviour it might be concluded that the simulation model gives a good insight into the actual control strategy of the Prius vehicle. Dissimilarities have occurred as a result of assumptions that had to be made for the modelling.

Even more, this model (and therefore all models) shows behaviour that is representative for a real hybrid vehicle. The results of the simulations therefore are representative and realistic. Conclusions that are drawn on the basis of the simulation results therefore are valid.

The tests with the Toyota Prius also indicate that it is very well possible that pure hybrid vehicles with a smart control will not show a distinct and significant ΔSOC over the cycle. The THS system in the Prius has showed to be charge sustaining. The change of charge (ΔAh were measured) over a complete cycle always remained within a small band. The maximum observed ΔQ was -0.19 Ah/cycle, recorded on the first hot Hyzem Urban cycle. This amount of Ah corresponds to approximately 3% of the battery's capacity of 6.5 Ah at full charge. More information and a further analysis of the measurement results is presented in Chapter 4.

2.7 Measurements on the TNO P2010 series hybrid testrig

TNO, in cooperation with a number of other companies, is currently working on a demonstrator vehicle with an advanced series hybrid electric powertrain. This project is called '*P2010*', the development of a mid-sized passenger car for the year 2010. More information on the project can be found in Appendix D.

In one of the pre-study phases of this project a testrig (Figure 12) has been built to validate and optimise the control strategy, as well as to investigate the driveline behaviour. Within the MATADOR-project, the need for measurements on hybrid electric vehicles was high, therefore the testrig has been used to perform several tests.

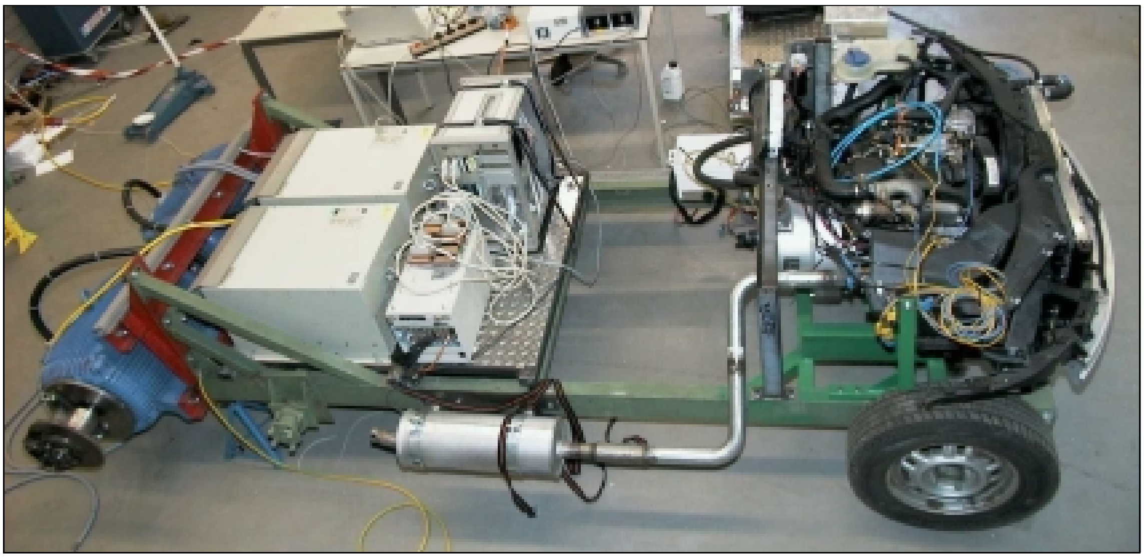


Figure 12: The P2010 testrig (without rear wheel tyres)

The testrig was driven over several driving cycles on a rollerbench. Although only a limited number of measurements was conducted, it has resulted in additional support for previously posed conclusions. Data on the following cycles is available:

- *NEDC*
  3 times a single cycle
  1 cycle driven in ZEV mode
- *MODEM*
  3 times a single cycle in HEV mode
  1 cycle driven in ZEV mode
  3 cycles in a row in HEV mode (regarded as one cycle, since only initial and final values are listed)
- *USFTP75*
  1 cycle in HEV mode
  1 cycle in ZEV mode

The 3 single NEDC and MODEM cycles are regarded as consecutive cycles, since the breaks in between were quite short. The differences between final and initial SOC of two successive cycles are neglected.

As examples, Figure 13 and Figure 14 (all tests are shown in Appendix D) present the SOC history and APU operation on the first and third New European Driving Cycle. The incoming SOC signal was filtered and recorded with low resolution (causing the displayed SOC to change with steps of ±8%). Especially at the start of the measurements, yet also throughout the test, this has influence on the logged (plotted) value, which thus is not the actual value at each moment.
Despite the ‘deformed’ signal, comparison of both tests shows that the courses of SOC are quite ‘similar’. Both tests were started in the same system’s condition (SOC in the same area of the control window). As a result, the APU is started at roughly the same times and for almost equal periods.

About three quarters of the SOC window is crossed several times during the tests. The occurance of (significant) ΔSOC consequently is very well possible. Table 4 lists the ΔSOC for all measurements. These values show that a ΔSOC almost as large as the SOC window is found.

Table 4: ΔSOC for P2010 testrig on three driving cycles

	ΔSOC [%]		
	NEDC	MODEM	USFTP75
HEV1	19.6	9.6	3.8
HEV2	-4.8	2.8	
HEV3	11.4	-0.2	
ZEV[1]	-60.4	-184.4	-119.4
3x HEV		4.4	

1. Testrig operated as Battery Electric Vehicle, possible since a battery with higher energy content is used. Listed ΔSOC value is 20 times higher than testrig battery pack value.

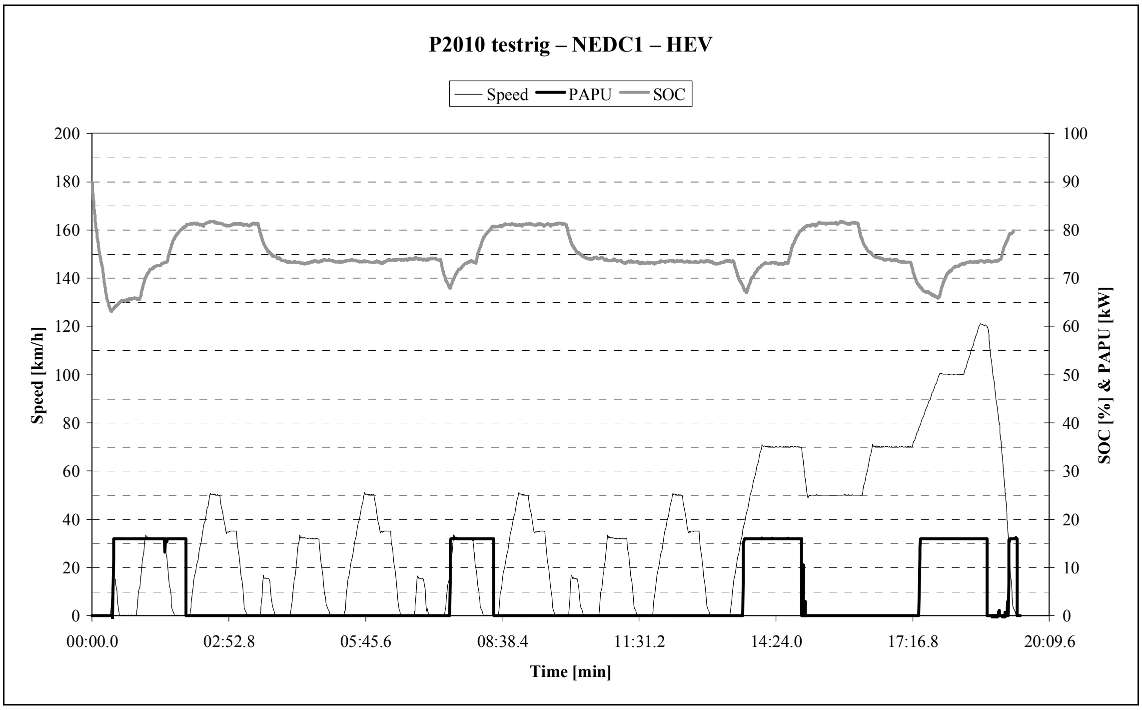


Figure 13: SOC history and APU operation for the P2010 SHEV testrig on the first NEDC

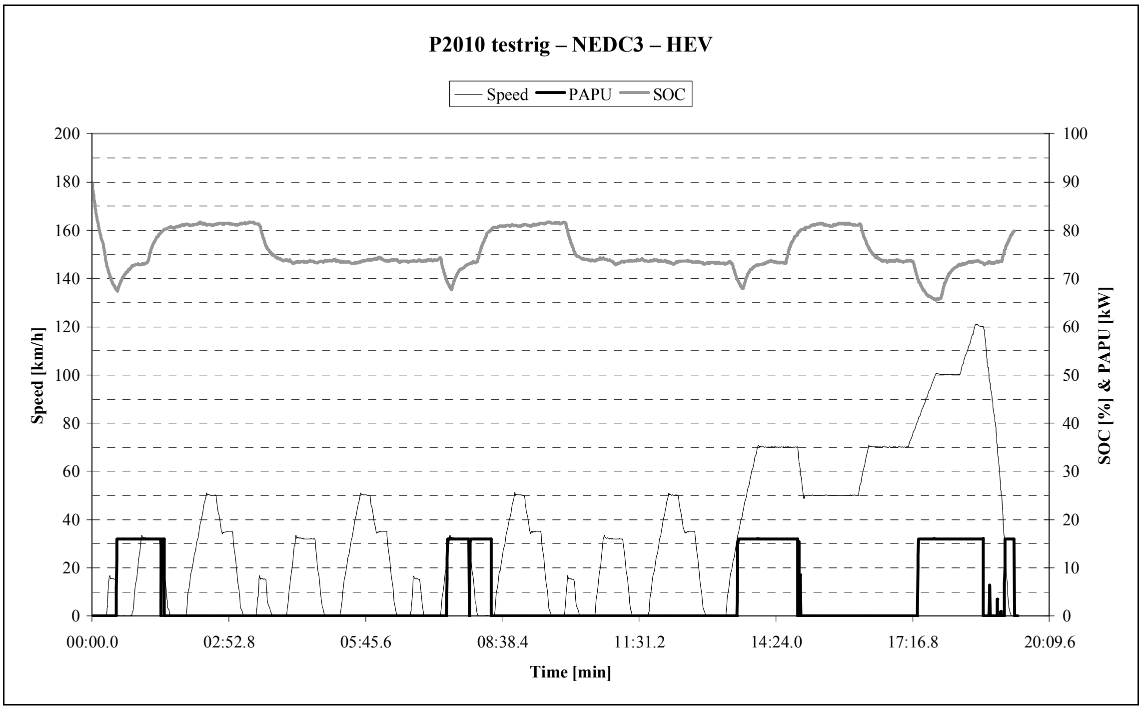


Figure 14: SOC history and APU operation for the P2010 SHEV testrig on the third NEDC

Figure 15 displays the course of SOC for three 'consecutive' cycles. The number of cycles clearly is not enough to determine the period for the SOC to be repetitive. The ΔSOC over one MODEM cycle seems to converge to zero after three cycles. This might indicate that the cycles driven so far are used to 'precondition' the battery before the system is able to respond with a one cycle SOC period. It nevertheless is also possible that a larger ΔSOC is found with several more consecutive cycles and that a SOC period of several driving cycles is found. Due to the limited data, a realistic prediction of ΔSOC for the following cycle cannot be given.

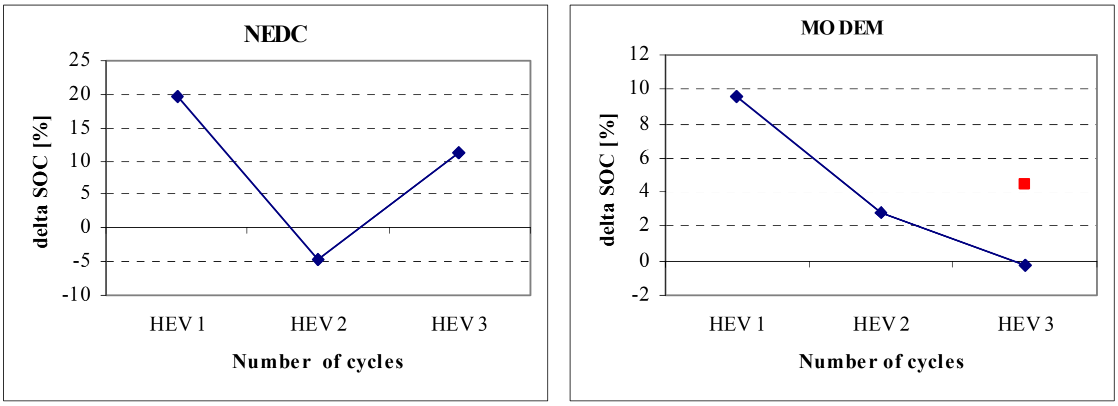


Figure 15: Initial and final SOC for three 'consecutively' driven NEDC and MODEM cycles with the TNO P2010 testrig.

2.8 Measurements on the ALTROBUS

A series hybrid electric bus was available for several test in the framework of the MATADOR project. The measurements were conducted at the ENEA facilities. The ALTROBUS (Figure 16) is 6 metres long, and can carry about 21 passengers. Additional information can be found in Appendix E.

Figure 16: The ALTROBUS on the dynamic rollerbench at ENEA, Italy

The vehicle was driven over sequences of six different driving cycles. Due the speed limitation (maximum 55 km/h), only urban parts of the official driving cycles were used.

First point of interest, is the SOC behaviour over a series of cycles and the ΔSOC over a single cycle. The State-of-Charge is meant to be kept between the lower and upper limits (75% and 85% respectively). Figure 17 shows the SOC history on 11 consecutively driven MODEM cycles. Although 11 cycles have been driven, a repetitive SOC pattern, as obvious as in the simulations, cannot be distinguished. One of the reasons is that actual measurements are always less repetitive than simulations. In real measurements, the driving cycle is not always followed exactly the same. In computer simulations each cycle gives exactly the same load for the system, and consequently the dynamic response is also the same for each cycle. Furthermore, it is likely that in practise even more limitations to the system's response are present due to even more complex component behaviour. The results for the other driving cycles can be found in Appendix E.

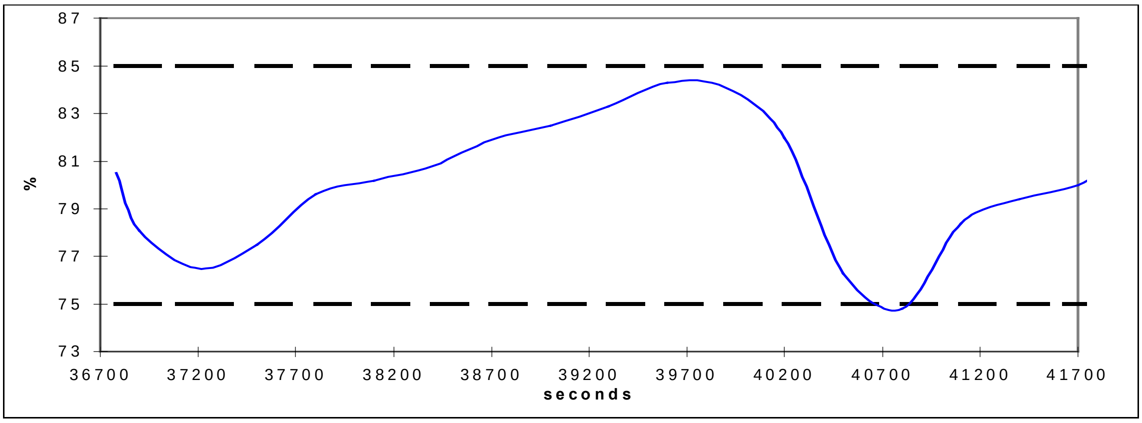


Figure 17: SOC history on the MODEM (slow urban) driving cycle

The ΔSOC for all tested driving cycles is presented in Table 5. In general the largest ΔSOC is found over the first cycle, which is started with the engine off. A decrease of SOC therefore results. During the first or second cycle, the engine is started and for most driving cycles, it stays on untill the end of the measurements. In the MODEM and Casaccia sequences, the engine is shut down once (MODEM: 8^{th} cycle; Casaccia: 7^{th} cycle), and a larger ΔSOC is immediately established. Considering all driving cycles, ΔSOCs between 0 and ±8% are found, thus almost covering the entire SOC control window (10%). Since the battery also has a considerable energy content (approximately 15kWh), a significant amount of energy is involded in the recorded ΔSOCs. Determination of the actual energy consumption of the vehicle therefore requires a method to correct for change of State-of-Charge.

Table 5: ΔSOC (%) for the ALTROBUS over 6 different driving cycles

NoC	Driving cycle					
	UDC	Jap1015	UDDS	MODEM	Hyzem Urban	Casaccia
1	-4.0	-5.4	-5.8	-4.0	-7.8	-3.9
2	2.4	2.0	0.3	2.5	-0.5	2.5
3	1.2	0.9	-0.3	1.4	-2.1	2.5
4	0.4	1.3	-0.5	1.3		1.3
5	0.1	0.6	0.2	1.1		1.7
6	1.3	0.8		1.5		-1.3
7	0.1	0.3		-0.8		-6.0
8		0.5		-7.1		3.5
9		0.2		0.0		
10		0.0		3.0		
11				1.6		

2.9 Conclusions

- The simulation and measurement results indicate that ΔSOC (when it occurs) will complicate the determination of energy consumption of (charge sustaining) HEVs. The occurance of ΔSOC is highly dependent on control strategy, battery capacity, and, to a somewhat smaller extent, driving cycle, and initial SOC.
- From the quantification it follows that ΔSOC not necessarily is the problem. More important is the amount of energy related to that ΔSOC, since that can directly be compared to other energy flows (fuel or propulsion; for instance through Equation 1 or Equation 2). In the simulations the first "preconditioning" cycle regularly was the only cycle resulting in significant ΔSOC.
- The response of a driveline system to an excitation of consecutive cycles is a periodic one, with a period time equal to one (equilibrium) or an integer number of cycle-lengths (at least in the simulations). This time constant of the response depends on the ability of the controller to determine the energy demand (inputs), and the possibility to take counteractive measures (outputs), together with the way in which these outputs are processed from the inputs. Different periods can appear because of an 'unfavourable' initial SOC. Although periodicity is expected in actual vehicle measurements, this might not occur in practise due to irregularities with respect to the simulations (e.g. driver repeatability).
- If no change of SOC occurs over *one* measured cycle, the resulting fuel consumption may be regarded as the actual fuel consumption over that cycle, although levelling of SOC at different values might as well result in a different value for the energy consumption. Consequently, for cycles that do show a ΔSOC, the measured fuel consumption is a misrepresentation of the actual fuel consumption, as there has been a net electrical energy exchange. A ΔSOC correction method therefore has to be applied. In case that the SOC can level at different values, this might also influence the exact value of the energy consumption. It could not be proven that this effect does actually appear and accordingly no estimation of a possible error can be made.
- The first cycle(s) normally do not fit into the regular pattern of the SOC over the following cycles. In case an equilibrium is reached, the only cycle(s) showing a non-zero ΔSOC are the first one(s).
- The influence of the driving cycle on the repetitiveness of SOC is minimal, but not negligible. In the LD simulations it showed that for all drivelines the SOC balanced after one cycle; only the SC03 cycle needed one extra.
- The SOC behaviour that was found in the simulations gives a good representation of the real SOC behaviour in a hybrid electric vehicle. Simulations therefore are a very good as well as a necessary support to the measurements. This has been derived from measurements on a Toyota Prius and simulations with a combined hybrid electric vehicle model.
- In simulations a periodic behaviour of the SOC can always be found by simulating enough cycles. The ideal number of measurements is reached when the SOC has its initial value again after a whole number of cycles. It is not certain that this periodic behaviour also will occur in practise.

It is not unlikely that the energy density as well as the power density of batteries will become (much) higher in the future. As a result HEVs might be equipped with batteries which can provide a significant ZEV range, other than just peak powers. Occurrence of significantly higher ΔSOC for this condition is shown in the simulations.
Hybrid (electric) vehicles with smart control and low energy capacity batteries might possibly not give significant ΔSOC. The more the control strategy is able to adapt energy flows instantaniously to the requested energy at the wheels, the smaller ΔSOC will be.

ΔSOC is most likely to occur when a combination of the following is present in a vehicle:

- battery with high energy capacity
- control strategy in which engine (APU) power has no direct relation with wheel power, i.e. a control strategy with several discrete ICE operating points combined with large hysteresis.

3 ΔSOC correction methods

From the previous sections, it has become apparent that ΔSOC certainly will influence the determination of the actual energy consumption for hybrid vehicles. A need for a method which enables a consistent determination of the energy consumption by correcting for a change of State-of-Charge therewith has arised.

In [1], however, the proposed method for measuring energy consumption of (thermal) hybrid electric vehicles is to express the energy consumption in terms of electrical consumption as well as in terms of fuel consumption. For *charge depleting* hybrids this seems quite logically, since their depleting status indicates that they regularly have to be charged from the grid.

For *charge sustaining* hybrid electric vehicles, that do not have to be charged from the grid, however, it is desirable to express the energy consumption only in terms of fuel consumption, since that is the only energy source that is actually consumed. When a ΔSOC is found, it therefore is requested that a method is available that consistently accounts for this change of energy content. In the measurement proposal [1], however, the manufacturer has to define a charge procedure in case the vehicle is not externally chargeable. The additionally used fuel is accounted in the energy consumption, additional distance is not. When the vehicle can be connected to the grid, two energy consumption terms are used and the results of different vehicles are mutually (almost) not comparable. The proposed procedure does not really offer a method that allows for a consistent comparison of the energy consumption and emissions.

Various options for ΔSOC correction have been identified and are implemented in the energy consumption determination. Below, an enumeration of possibilities is given, along with an explanation. The following chapter will discuss these methods by applying them to the simulation and measurement results.

3.1 Consumption without ΔSOC correction

Until now, determination of the energy consumption has been done without any ΔSOC correction, as it does not occur in conventional vehicles, nor is it a problem in battery electric vehicles. For these vehicles, the fuel or electric consumption are determined. In Europe, the fuel consumption (in l/100km) for a conventional vehicle is determined according to the Carbon Balance Method (Equation 4) from the CO_2, CO, and HC emissions measured in g/km during the NEDC cycle. The US procedures also apply a carbon balance method.

$$FC = \frac{0.1154^{1}}{\rho_{fuel}} \cdot \left(0.866 \times HC + 0.429 \times CO + 0.273 \times CO_2\right) \qquad \textit{Equation 4}$$

1. for gasoline, for diesel: 0.1155

For Battery Electric Vehicles the electric energy consumption (in Wh/km) is determined from the charging energy from the mains after the test cycle has been driven.

For means of comparison, it is easier to use the same units. For this reason, the term energy consumption is used in the rest of this report. The energy consumption for conventional vehicles can be derived by converting the fuel consumption values into MJ/100km by multiplying Equation 4 with the fuel's density (ρ_{fuel}) and heating value (H_{fuel}).

The output of the simulations is the amount of fuel used, in (kilo)grams. The energy consumption then is calculated by multiplying the amount of fuel with the heating value and a factor 100, and then dividing by the driven distance (Equation 5).

$$EC = \frac{m_{fuel,cycle} \cdot H_{fuel}}{x_{veh,cycle}} \cdot 100 \quad [MJ/100km]$$ *Equation 5*

Application of this method for hybrids does not account for a change of energy content of the storage system (battery, flywheel, or any other accumulator than the fuel tank). In case of significant ΔSOC, this uncorrected value deviates unacceptably much from the real energy consumption over that cycle, which calls for a correction method. In the following paragraphs, several methods are introduced.

3.2 Averaging multiple cycles

For *charge sustaining* hybrids, the State-of-Charge will vary continuously over a sequence of cycles resulting in different ΔSOC values. Since the vehicle is charge sustaining, both positive and negative ΔSOC will be found and the fuel use and emissions will vary correspondingly. By driving a large number of cycles, the effect of SOC-variations dampens out. The energy consumption calculated is then the average over the number of cycles (Equation 6). For the emissions an average value is determined too.

$$EC = \frac{\sum_{i=1:n} EC_i}{n} = \frac{\sum_{i=1:n} m_{fuel,cycle\,i} \cdot H_{fuel}}{\sum_{i=1:n} x_{veh,cycle\,i}} \cdot 100 \quad [MJ/100km]$$ *Equation 6*

This method is fundamentally correct, yet, although averaging the energy consumption and emissions of several cycles will give the desired result, many cycles might be necessary before the calculated average value is found, especially if the first cycle starts with from an extreme SOC condition (initial value much higher or lower than the average over the cycle). This method therefore might be very time consuming, and consequently might also be expensive.

3.3 Extension of the test

The previous methods did not actually take into account the change of State-of-Charge over the driving cycle. Other methods require the SOC (or at least ΔSOC) to be monitored during the measurement. When a ΔSOC is found at the end of the driving cycle, the test is continued until a zero ΔSOC is reached again. Two procedures can be thought of to conclude the measurement.

3.3.1 Driving cycle continuation

This method to correct for ΔSOC, either positive or negative, implies that the test is prolonged by driving the same cycle again until the initial SOC value is achieved. During the test, the SOC obviously has to be monitored, as well as the actually driven distance and the consumed fuel and emissions. In Figure 18, an example of a driving cycle extended measurement and the necessary available data is given. The official cycle ends after 1180 seconds, yet the test is continued because a ΔSOC is found. After another 200 seconds, zero ΔSOC is reached and the measurement is complete.

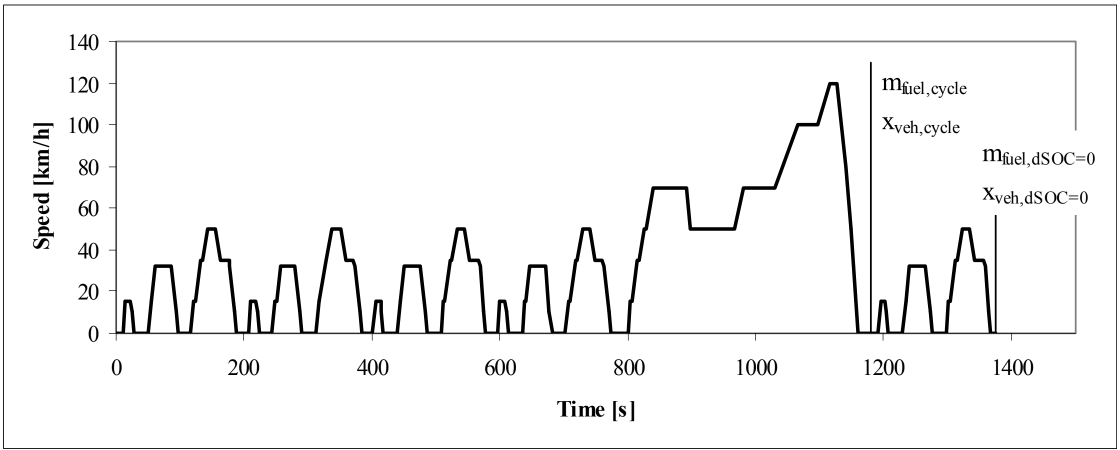


Figure 18: Example of a NEDC extended measurement

The effect of the additionally driven part (the ΔSOC correction) can be accounted for in two ways in the energy consumption calculation. For the emissions a similar calculation has to be carried out. The difference is found in what is to be regarded as representative for the driving cycle.

1. The total amount of fuel used ($m_{fuel,\ \Delta SOC=0}$) in combination with the cycle distance ($x_{veh,cycle}$) is used to calculate the consumption according to Equation 7. The total amount of fuel used thus is regarded to be consumed over the driving cycle. The additionally driven kilometres are excluded.

$$EC = \frac{E_{fuel}}{x_{veh,cycle}} \cdot 100 = \frac{m_{fuel,\Delta SOC=0} \cdot H_{fuel}}{x_{veh,cycle}} \cdot 100 \quad [MJ/100km] \qquad \textit{Equation 7}$$

2. Both the total amount of fuel ($m_{fuel,\ \Delta SOC=0}$) and the entire distance ($x_{veh,\ \Delta SOC=0}$) are used to calculate the energy consumption (Equation 8). In this case, the characteristics of the extra driven part (average speed, RPA, etcetera) are regarded to be representative for the driving cycle. Consequently, the fuel used over the total test is representative for the cycle.

$$EC = \frac{E_{fuel,\Delta SOC=0}}{x_{veh,\Delta SOC=0}} \cdot 100 = \frac{m_{fuel,\Delta SOC=0} \cdot H_{fuel}}{x_{veh,\Delta SOC=0}} \cdot 100 \quad [MJ/100km] \qquad \textit{Equation 8}$$

For both calculations, the representativity gives reason to doubt the applicability of these methods to determine the actual values of energy consumption and emissions. From the example above (Figure 18) it can easily be understood that the cycle characteristics are influenced by driving an additional part of the driving cycle.

3.3.2 Manufacturer defined extension

Instead of continuing the test with the same driving cycle, it is also possible to continue with a ΔSOC correction predefined by the vehicle manufacturer. In case a ΔSOC is found, the test then is continued by charging or depleting the battery in a condition that is recommended by the manufacturer. From a point of simplicity and uniformity, this method is not to be supported, since many procedures then can be thought of. Some of the possibilities:

- Continuation with the same driving cycle (same options as in 3.3.1).
- Continuation with a different speed profile (e.g. other driving cycle, constant speed, etcetera).
- In case of negative ΔSOC, charging the storage system on-board of the vehicle at standstill (when possible) according to a predefined charge pattern.

The energy consumption can be determined with Equation 8.

This method, however, has some clear disadvantages. First of all, the manufacturer defined part of the test will probably not be representative for the driving cycle. Secondly, as a results of the first, the results of measurements will be less accurate and a consistent comparison of different vehicles is impossible.

3.4 Linear correction methods

3.4.1 Linear regression

This method uses linear regression to determine the energy consumption and emissions at zero ΔSOC over a driving cycle. In order to be able to apply this method, several cycles have to be driven. The SOC (or at least ΔSOC) has to be recorded and the energy consumption and emissions for a single cycle can be determined according to section 3.1. Data points (ΔSOC and uncorrected energy consumption/emissions over one cycle) are then available which enable application of regression techniques.

For a set of data, a linear trendline is calculated with the least squares method, resulting in a line represented by an equation with the form:

$$Y = a \cdot X + b \qquad \textit{Equation 9}$$

where *a* is the slope and *b* is the intersect value for X equals 0.

The intercept value represents the ΔSOC corrected energy consumption over the cycle. The slope is a measure for the average charging efficiency over the driving cycle.

Preferably data points with both positive and negative ΔSOC are found. These allow for interpolation between the data points. In case only positive or negative ΔSOC is present, the intercept value can only be found through extrapolation (forecasting) through the linear equation, which yields in lower accuracy. Interpolation and extrapolation are shown in Figure 19 for two different data sets. The X-values always are the ΔSOC-values, and the Y-values can be the energy consumption or the emissions.

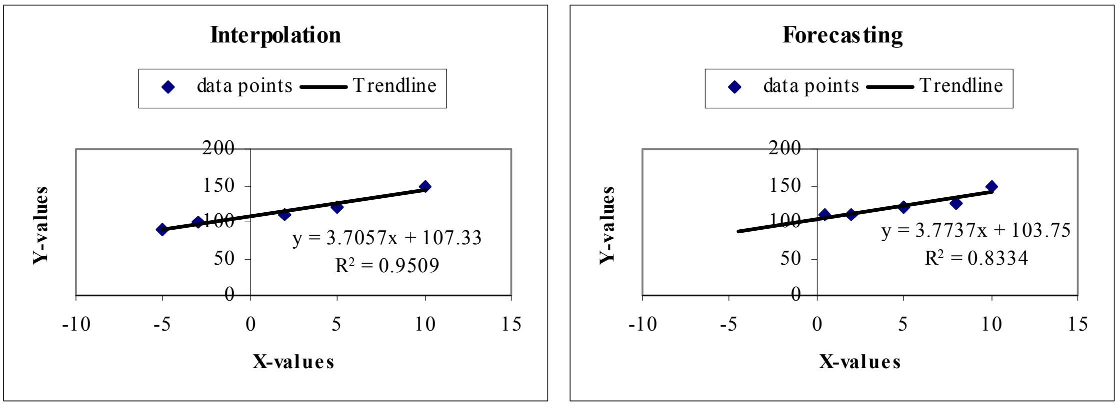


Figure 19: Linear regression method (interpolation: left; extrapolation: right)

Along with the determination of the trendline equation, a so-called R-squared (R^2) value is calculated (Equation 10, as used in Microsoft Excel). This value is a correlation factor and gives an indication for the match of the linear fit ($R^2 = 1$ indicates linearity).

$$R^2 = 1 - \frac{(Y_i - \overline{Y_i})^2}{Y_i^2 - \frac{(\ \ Y_i)^2}{n}} \qquad \textit{Equation 10}$$

Although the R^2-value gives an idea about the relation between data points, it does not give the actual accuracy of the calculated coefficients *a* and *b* of Equation 9. A confidence interval can be calculated in order to determine the actual accuracy of the intercept value, based on the available data set.

3.4.2 Linear interpolation

Two possible methods are presented here. Application of linear interpolation assumes that the relation between energy consumption and emission on the one hand, and the change of energy content of the storage system on the other hand, is always linear.

Method 1

The first method uses the same data points as those that were used in the regression method, i.e. the tests performed are the same, yet the energy consumption and emissions are derived in a different way.

To find the actual energy consumption and emission, the data points on each side of the vertical axis are averaged and then linear interpolation between the two resulting points is used to determine the intercept value at X=0. In Figure 20 (left) this is presented. The data points (black markers) have been derived by driving the cycle five times. Next step is to average the positive (on the right), as well as the negative (on the left), which give the open square and circular markers. Next, interpolation is performed on these two points and the intersect value at X=0 represents the requested actual value for energy consumption or emissions.

In case of an unequal distribution of data points with positive and negative ΔSOC-values (for instance only 1 positive, and 4 negative), an imbalanced weighting of the data points will be applied and it can be doubted whether the intercept value represents the actual energy consumption or emissions.

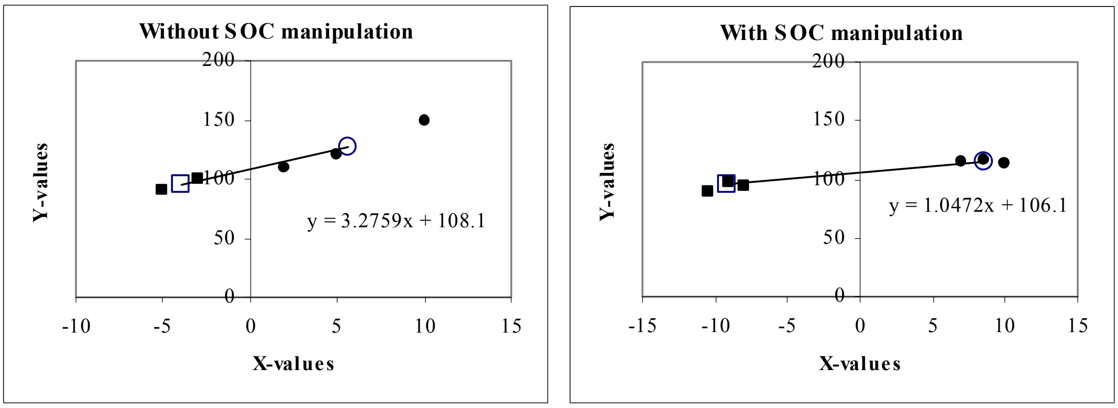


Figure 20: Interpolation methods; with (right) and without SOC manipulation

Method 2
The second method requires a cycle to be driven at least two times, but it is better to drives it a multiple of two for reasons of accuracy. The battery of the vehicle is manipulated, so that one test is performed with an initial SOC that is much higher than the average SOC over the cycle and one with an initial SOC that is much lower than the average SOC over the cycle (Figure 21). This manipulation can generally be done by driving the vehicle for some time under an extreme condition that either charges or depletes the battery. These initial SOC-values are generally outside the bandwidth in which the SOC is controlled when the cycle is driven continuously (regression method). These two measurements automatically yield one point with a large positive ΔSOC and one with a large negative ΔSOC. The energy consumption and emissions at ΔSOC=0 then are found through linear interpolation between the two data points. When the test is perfomed several times, the positive and negative values are averaged (Figure 20 right; three complete tests), before the interpolation is performed.

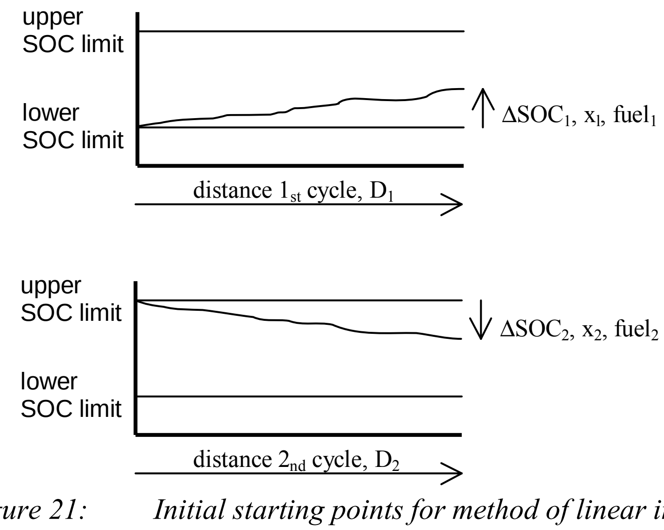


Figure 21: Initial starting points for method of linear interpolation

3.5 Other ΔSOC correction methods

Besides the above mentioned ΔSOC correction methods, more possibilities exist. These involve the experimental determination of ΔSOC and estimation of the fuel consumption that corresponds to the net increase or decrease of the SOC. This can be represented by Equation 11 where the uncorrected energy consumption (EC_{uncor}) is calculated with Equation 5 and ΔEC is a function of ΔSOC.

$$EC_{cor} = EC_{uncor} + \Delta EC(\Delta SOC) \qquad \textit{Equation 11}$$

The way in which ΔEC is to be defined gives the biggest problem. One of the options is to define a charging effiency. This can be either over the cycle or during standstill. Either way, it will be an average value, since the battery effiency is not constant, and probably neither is that of the fuel convertor.
In order for the charging efficiency to be determined, it is required that data becomes available during the measurement that allows for determination of components' efficiencies. This brings the need for continuous monitoring of SOC, fuel, battery power, engine power, etcetera. Extensive data logging therefore would be required, which in turn necessitates expensive equipment. Another point that has to be mentioned, is the vast variety of different vehicles, which probably will not give the same possibilities for determining the required output.
All these consideration give reason to doubt the practical applicability of a ΔSOC correction method that is based on the separate components' efficiencies. Possible methods therefore will not be discussed in depth.

4 Evaluation of ΔSOC correction methods

Several methods for accounting the ΔSOC over a cycle have been presented in the previous chapter. This chapter discusses the suitability of these methods. Previously mentioned simulations and measurements are used to determine the suitablility/applicability of those methods in practice.
Dependent on which simulations are referred to, some of the methods are applied and discussed.

4.1 Cumulative consumption, regression analysis, and linear interpolation

This section discusses the graphical methods which can be used to determine a HEV's energy consumption. The simulations in Section 2 that show ΔSOC are used here to evaluate the methods of Chapter 3.

HD Simulation No.1

- *Models:* HD PHEV, HD SHEV
- *Simulation aspects:* SOC over consecutive cycles
- *Parameter variation:* Driveline structure and control strategy

Regression analysis
In Figure 22 the fuel consumption of each cycle is plotted versus the change in charge content (ΔQ in Ah, another way of representing ΔSOC) over that same cycle for two different control strategies. This relation appears to be (almost) linear. A trend line is added through the data, and judging by the R-squared value, only a very small error is made by assuming this linear relationship.
The interception point of the trend line with the vertical axis represents the fuel consumption for a cycle without a change in charge content. This way of determining the fuel consumption is referred to as the 'regression method'.

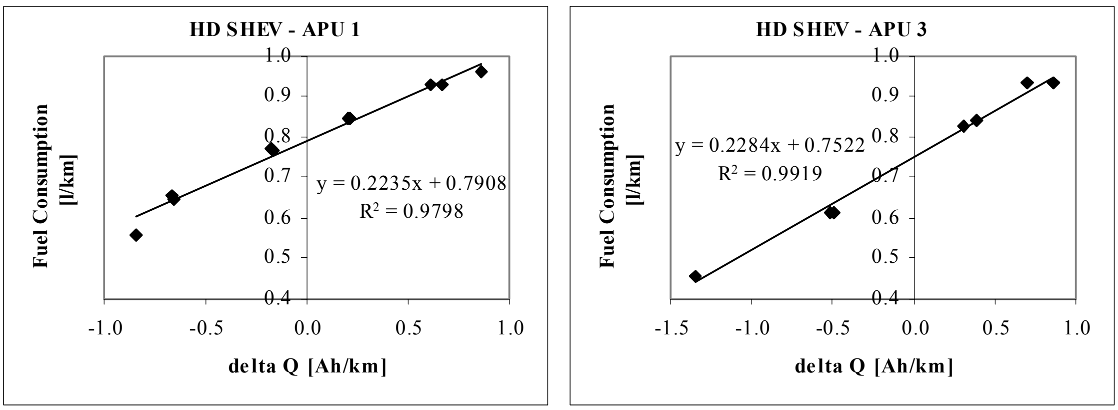


Figure 22: Fuel consumption versus change in battery charge content (ΔQ) for a HD SHEV

The resulting fuel consumption is not the same for both control strategies. This mainly is the result of three effects. First, there is a difference in timeshares for the three defined APU operating points. As each operating point has its own BSFC, the overall fuel consumption

changes accordingly. Another effect is caused by differences in energy routing. If the APU power (dictated by the control strategy) follows the desired power at the wheels quite well, little power is diverted via the battery. The overall efficiency will benefit from this, resulting in a lower fuel consumption. Finally, the control strategy of APU 3 makes use of an extra operating point, which represents the optimum BSFC for this engine. Therefore, the efficiency of APU 1 is (slightly) lower.
Note that the gradient of the trend line is a measure for the fuel consumption of the APU for charging the battery over the cycle (0.22 and 0.23 l/Ah respectively). Apparently, in this case this efficiency is hardly dependent on the control strategy. During the cycle, (short) periods exist where the vehicle is at standstill and the APU is running; the battery then thus is charged. For both simulations (APU1 and APU3) the charging efficiency during standstill (as the gradient in l/Ah is a measure for that) is determined. The results are listed in Table 6. The cycle average clearly is lower than the gradient for charging at standstill. This actually is no surprise when the battery losses due to the internal resistance (the I^2R-losses) are considered. During driving, when most of the charging is done, (a large) part of the APU power is directly consumed by the electric motors. Consequently, the power to the battery is lower than during standstill. With higher power, the battery current also is higher and, as a result, the I^2R-losses are too and the charging efficiency is lower.

Table 6: Charging efficiency (l/Ah)

Control Strategy	Cycle average	Operating point - standstill	
		low	high
APU1	0.22	-	0.27
APU3	0.23	0.25	0.27

Averaging multiple cycles
Another way of determining the fuel consumption, is by calculating the average over multiple cycles. Figure 23 shows the influence of the number of cycles on the cumulative fuel consumption. Although a real asymptotic value cannot be seen yet, a rough approximation of the fuel consumption can be made. The fuel consumption for APU 3 varies around 0.75 l/km. During the first number of cycles the deviation is still substantial. With an increased number of cycles the variance becomes smaller and will eventually end in an asymptotic value. The intercept value of 0.75 l/km, which was found through the linear regression method, is the same.
For APU 1 the cumulative fuel consumption concluded over the last cycles is roughly 0.80 l/km. It is hard to say whether this is also the asymptotic value. Figure 22 has learned that 0.79 l/km is indeed the correct fuel consumption, but even after 10 cycles this cannot clearly be read from Figure 23.

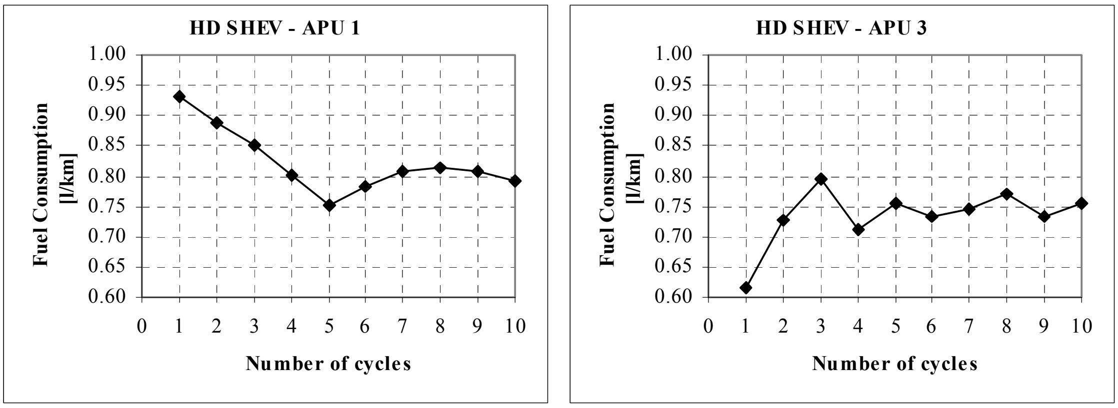


Figure 23: Cumulative fuel consumption for HD SHEV as a function of the number of cycles

One might expect that for APU 1 the high fuel consumption of the first cycle has disturbed the cumulative result to such an extent, that it takes 5 cycles to compensate for this deviating value. However, this is not the case. Figure 24 shows the cumulative fuel consumption for APU 1, also leaving out the 1st (FC2), 2nd (FC3), and 3rd (FC4) cycle (regarding them as 'conditioning' cycles). The intended effect of a less fluctuating result does not appear.

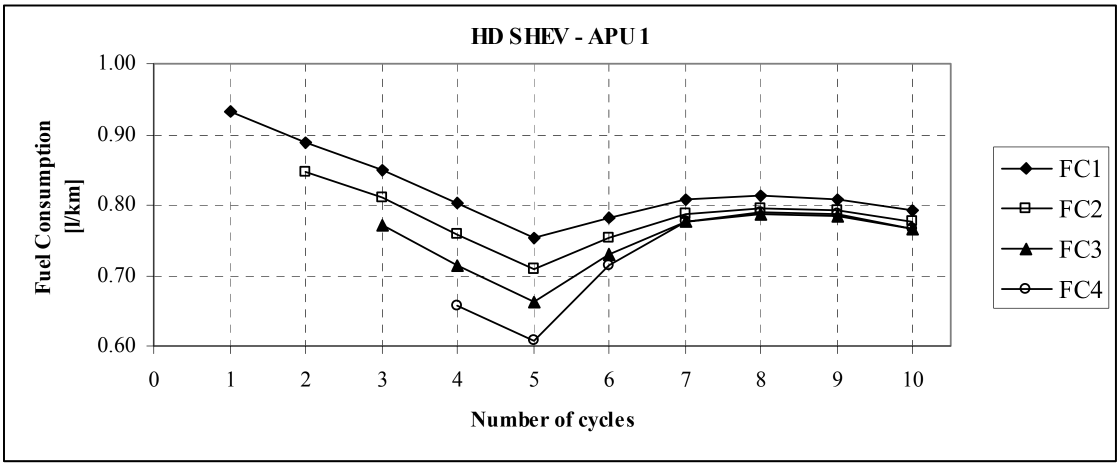


Figure 24: Cumulative fuel consumption based on different numbers of cycles

At this point, it can be concluded that the regression method shown by Figure 22 provides a better accuracy than taking the cumulative fuel consumption over multiple cycles. Even with only two cycles, provided one has a positive and the other a negative ΔSOC, quite an accurate result is obtained. The cumulative method however needs at least 10 cycles, but even then it is difficult to say whether the cumulative fuel consumption is a good representation of the actual value.

Errors

The next thing to examine is the magnitude of the errors which are made when just a few measured points are used for the ΔSOC correction. This in order to determine the minimum number of cycles that has to be driven in a test, to achieve the required accuracy. How this is examined will be shown using the previous example of the HD SHEV with APU control strategy 1.

First the 'real' fuel consumption is determined. The regression method above has showed to be quite a good ΔSOC correction method. The number of cycles, however, was large enough to find a sequence of cycles after which the initial SOC is reached again and the entire SOC path can be predicted. In Table 7, this data is listed. Cycles 2 through 7 show a zero ΔSOC. As zero ΔSOC is requested for the real energy consumption, it can be determined from these cycles. Figure 25 shows the resulting interpolation line. The regression value at ΔSOC = 0 is a little lower than that in Figure 22, for which all cycles were used (the R^2-values are the same since several points overlap).

Table 7: Simulation results of HD SHEV with APU 1

Cycle nr.	SOC [%]	ΔSOC [%]	Fuel Consumption per cycle [l/km]
0	60.0	-	-
1	67.0	7.0	0.93
2	69.2	2.2	0.85
3	67.4	-1.8	0.77
4	60.5	-6.9	0.66
5	51.5	-9.0	0.56
6	58.0	6.5	0.93
7	67.0	9.0	0.96
8	69.2	2.2	0.85
9	67.4	-1.8	0.77
10	60.5	-6.9	0.65

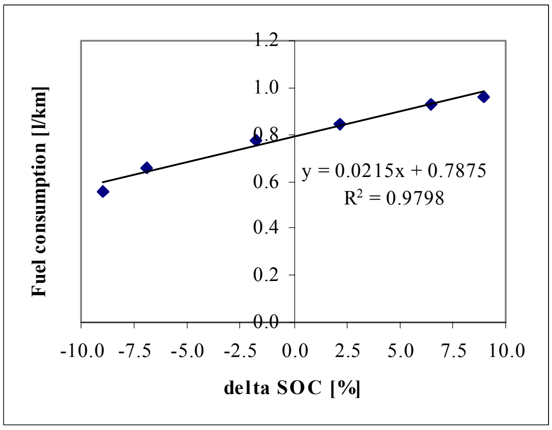


Figure 25: Interpolation of the simulated points of cycles 2 - 7

From Figure 25 it follows that the 'real' fuel consumption is 0.79 l/km.

Now every arbitrary set of two, three, four and five measured points out of the ten is taken. From these points the fuel consumption is determined using interpolation or extrapolation. This calculated value is compared with the value we declared to be the 'real' one. The results are shown in Figure 27. For reasons of comparison, Figure 26 shows the error for the ten measured points if no ΔSOC-correction is applied. Note that the vertical scale is different in each figure.

It is obvious, that if all pairs of measured points are considered, a lot of them need extrapolation to find the fuel consumption at ΔSOC = 0. These are the sets of two measured points for which both ΔSOCs have the same sign. Especially the points that are near to each other can cause a large error in the fuel consumption if extrapolation is applied.

If one measured point belongs to a cycle with positive ΔSOC and the other to a cycle with negative ΔSOC, then interpolation can be applied, and the resulting error will on average be smaller.

Therefore, all sets of two measured points are separated into sets that allow for interpolation and sets that need extrapolation. The results are shown in Figure 28 (note the different vertical scales).

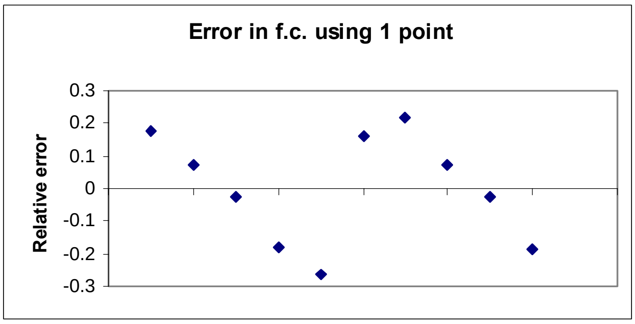


Figure 26: Error in fuel consumption when no ΔSOC correction is applied

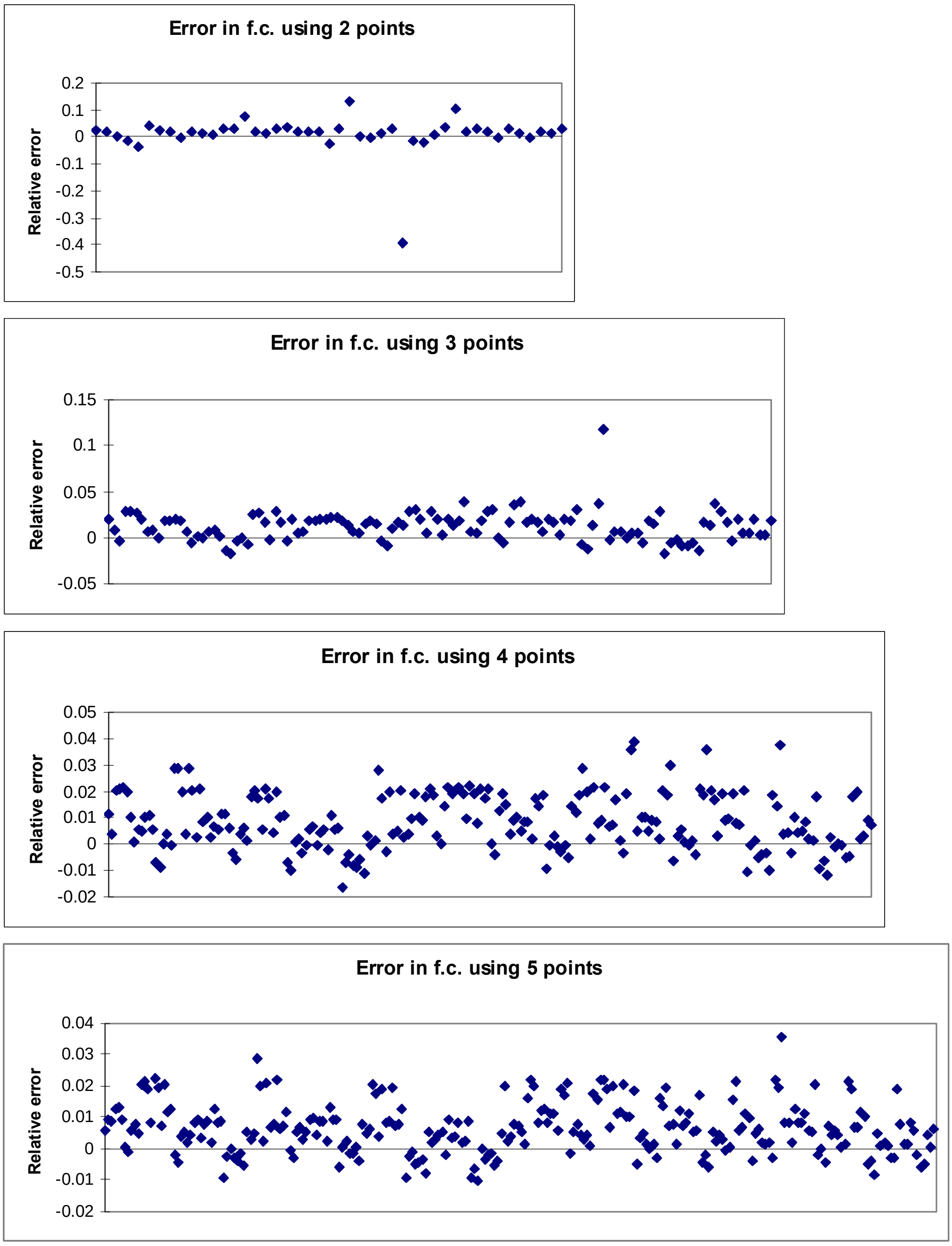


Figure 27: Error in fuel consumption when each set of 2, 3, 4, or 5 simulated points is used for ΔSOC correction

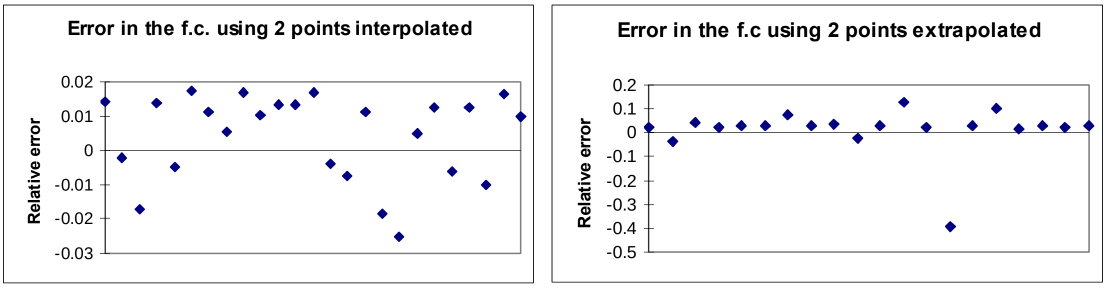


Figure 28: Error in the fuel consumption when sets of 2 points are used which allow interpolation (left) and extrapolation (right) respectively.

From this figure it can be read that in the considered example the relative error is always smaller than 3% when points are used that can be interpolated, even when the first cycle is left out from the calculations. This suggests that the number of cycles to be driven does not have to be high. The test can therefore be stopped as soon as interpolation of the measured points is possible.

The results of the interpolation also have to be considered using statistics, because it is possible to determine a confidence interval for the average value of the fuel consumption if a lot of measurements with zero ΔSOC are performed. If an infinite number of measurements with ΔSOC =0 is available, the average value for the fuel consumption from those measurements is the true value. If statistical analysis for regression lines is performed on all values in Figure 25, the 98% confidence interval for the fuel consumption at zero ΔSOC is from 0.76 to 0.81 l/km. This means that from the interpolation between points 2 through 7, it may be concluded that with a certainty of 98%, the average value of the fuel consumption for ΔSOC = 0 is within that interval. The borders of this interval represent an error of 3.4%. Figure 28 (left) shows that if interpolation between only two points is performed, the average fuel consumption according to that interpolation lies less than 3% from the average over the points 2 through 7. As expected, this is within the 98% confidence interval. It is save to assume that the accuracy of the fuel consumption at ΔSOC = 0 wil be 96.6% (=100% - 3.4%) in this example.

The figures and values above all refer to just one simulation. They are used here to illustrate the method. All HD simulations show similar results though.

An additional remark has to be made with respect to these results. In simulations there are no errors due to the measuring instruments. In real measurements the confidence interval will be larger and consequently the accuracy will be lower.
The error that is made in testing the fuel consumption and emissions of conventional vehicles is less than 3% in an Eurotest. The errors that are shown above are due to the ΔSOC correction and come on top of the errors due to conventional tests.

Sensitivity analysis

- *Model(s)*: HD SHEV with APU 3
- *Simulation aspects*: Fuel consumption and SOC over consecutive Dutch Urban Bus Cycles
- *Parameter variation*: BSFC of APU operating points

Until now, the BSFCs of the different APU operating points are quite similar. In order to determine the sensitivity of the regression method, this influence is investigated.

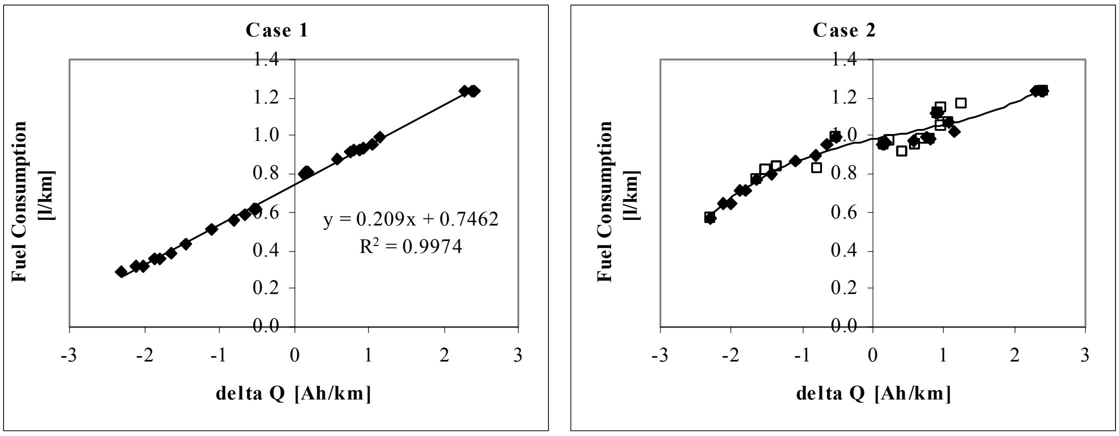


Figure 29: Fuel consumption over a single drive cycle versus ΔSOC for a series-hybrid urban bus with an APU operated at two operating points. Case 1: both APU operating points have about the same BSFC. Case 2: APU operating points have strongly different BSFC's (closed checkers are for separate cycles, open squares represent consecutively driven cycles)

Case 1 in Figure 29 is a simulation with the series-hybrid urban bus with APU control strategy 3, driven over single cycles with varying initial SOC. The BSFC of the two APU operating points, as derived from the engine map of a representative existing Otto engine, is almost the same. As can be seen, the fuel consumption at ΔSOC = 0 can be derived by linear regression with an R^2-value close to 1. As stated earlier, interpolation between the results of only two cycles would lead to an approximation of the actual fuel consumption within 3% accuracy, due to the linear behaviour of the model.

Case 2, however, corresponds to the same simulation, but now with the assumption that the intermediate APU operating point has a BSFC that is a factor 2 higher than its original value. As the BSFC of the APU operating points does not influence the behaviour of the driveline, the ΔSOC over each cycle is the same as in case 1. The fuel consumption, though, is significantly altered. The spread of the 'measurement' points in case 2 is not random, as the SOC behaviour for Case 1 and 2 are not influenced by the BSFC of the engine operating points. Consequently, it has to be concluded that the functional relationship between fuel consumption per cycle and corresponding ΔSOC is not fundamentally linear (as indicated by the higher order polynomial trendline). A linear regression therefore does not necessarily give a correct value for the fuel consumption at ΔSOC = 0. This non-linear behaviour is the result of the difference in BSFC, combined with different timeshares for the APU operating points. This effect can be explained by realising that the net energy produced by the intermediate point during a certain period can be equalled by a combination of the high output operating point and a switched off APU in the same period, resulting in a lower fuel consumption. Figure 30 shows the timeshares of the simulation; they are identical for both cases. Cycles with large negative ΔSOC values (created by a high initial SOC) show large timeshares for the intermediate operating point, and 0% for the high operating point. For cycles with a high ΔSOC (as a result of very low initial SOC) only the high operating point is used. Taking the large differences in BSFC for the operating points in consideration, the non-linear behaviour of the trendline in case 2 can be explained.

It could be expected that cycles driven one after another may cause more deviation from the trendline than separate cycles. After all, if a cycle is ended, the control strategy may still be in another operating point than would follow from the actual SOC after the system is 'reset' (note in Figure 1 that between 50 and 70% SOC the APU can be operated in multiple operating points). To show the difference between separately- and consecutively driven cycles, the latter are represented in Figure 29 with open squares. At this point, however, it is difficult to conclude that indeed a larger spread can be observed.

This simulation shows that the relationship between ΔSOC and fuel consumption is not necessarily linear. Therefore it can be inaccurate to use the regression method for a limited number of measurement points, especially at considerable distance from the ΔSOC = 0 axis. In practice, however, the non-linearity will not be so excessive like in this example, as this is a rather extreme simulation in terms of initial SOC and differing BSFC. Moreover, control strategies will normally be more sophisticated and have more possibilities to react to the actual energy demand, thereby pushing the result towards a smaller ΔSOC over a cycle.

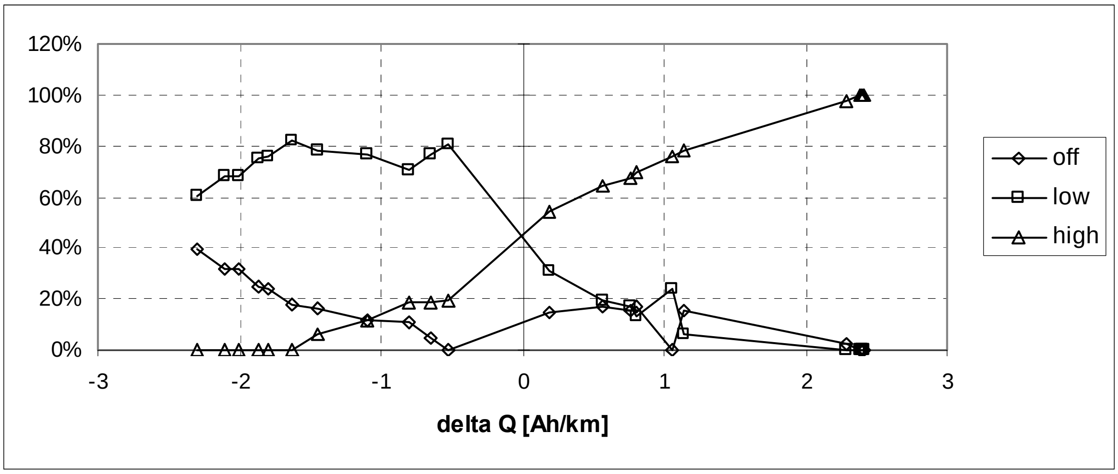


Figure 30: Timeshares of operating points as a function of ΔSOC (represented by delta Q)

HD Simulation No.2

- *Models:* HD SHEV with APU control strategy 1
- *Simulation aspects:* SOC behaviour on different cycles
- *Parameter variation:* Driving cycle

Besides the Dutch Urban Bus Driving Cycle, a second cycle has also been used. In Figure 3 it is shown that the Australian cycle also shows ΔSOC. Although the cycle is different, this is not expected to pose a difficulty to the determination of the energy consumption of the vehicle. The actual energy consumption of course is likely to be different due to the cycle characteristics.

Regression analysis

In Figure 31 the data points for fuel consumption versus change of energy content (delta Q) over each cycle are plotted. Note that the left figure is the same as the one in Figure 22. Besides the difference in energy consumption (which was expected), the distribution of data points for these cases is different. The observed ΔSOC over the Dutch Urban Bus Cycle shows more evenly distributed data points, while over the Australian Bus cycle a cluster of points with almost similar changes of energy content and, fortunately, similar fuel consumption too. Only the presence of a couple additional data points allows the use of linear regression for this case. When the data points are too close together, a trend cannot be distinguished clearly. This is shown by adding a trendline through the data points with positive ΔSOC. The R-squared value only is 0.5644, indicating that the data points are quite far from the trendline. The fuel consumption that is found through extrapolation of the trendline to ΔSOC=0, is almost 6% higher than found with all data points. Use of extrapolation of course always should be done very cautiously, since one tries to forecast outside the data range.

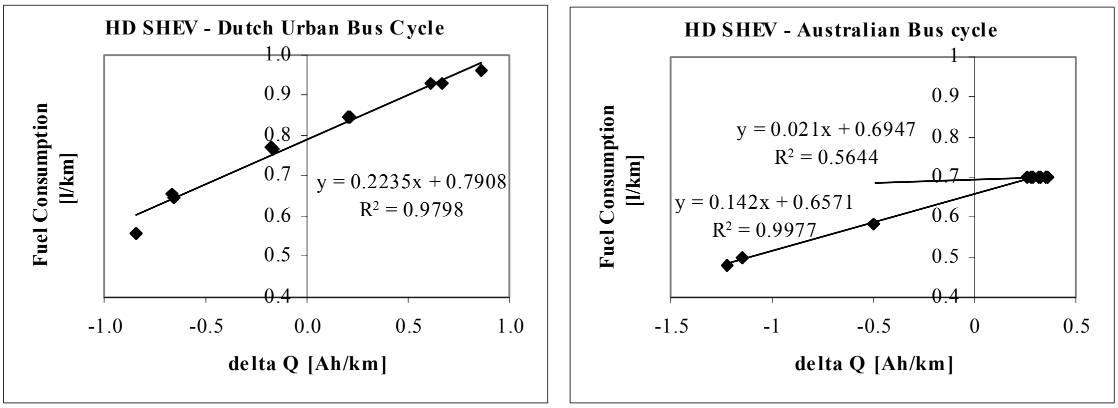


Figure 31: Regression lines for HD SHEV (APU1) on two different cycles

Averaging multiple cycles
For this cycle too, the fuel consumption is determined on the basis of cumulative values. In Figure 32 the results of this calculation are plotted. Again (see Figure 24), no asymptotic value can be derived from this figure. Even more, the tenth cycle shows a distinct change instead of dampening.
Clearly, the determination of energy consumption on the basis of averaging multiple cycles does not provide an easy and quick way of obtaining the desired figure.

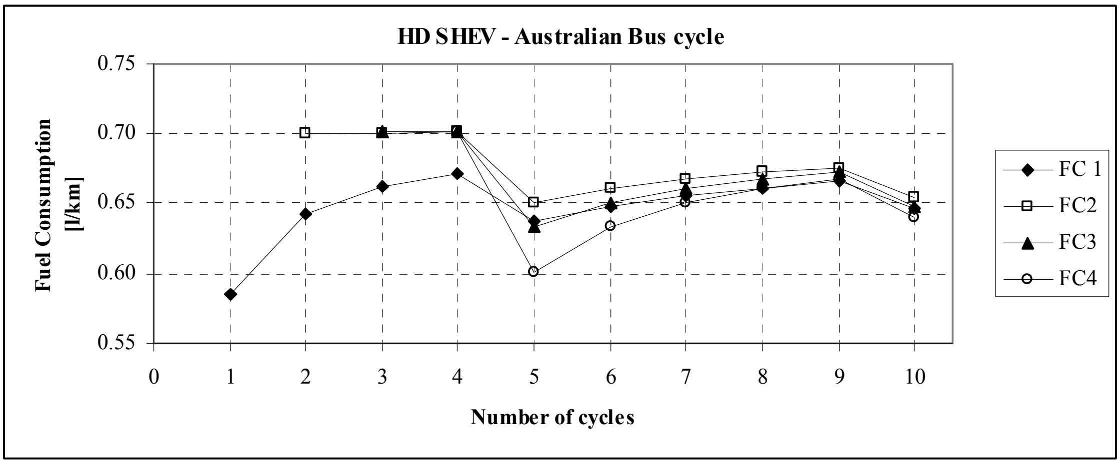


Figure 32: Cumulative fuel consumption HD SHEV (APU 1) over Australian Bus cycle based on different numbers of cycles

LD Simulation

- *Model(s):* LD PHEVbat, PHEVfw, SHEVbat, SHEVfw
- *Simulation aspects:* Initial- and final-SOC for consecutive cycles
- *Parameter variation:* Initial SOC and driving cycle

In Section 2.3 these simulations showed that the energy consumption could not be determined from one single cycle. Here, graphical methods are discussed using these simulations.

Linear regression
For examining the correlation characteristics between two parameters, it is necessary to have an adequate number of values. When a recognisable trend exists, it should be described mathematically. It is important to use as many different values as is necessary to visualise the trend. The closer the points are next to one another, the harder it is to recognise it. In case of the dependency between fuel consumption and a change of State-of-Charge (ΔSOC), it is most likely to use the fuel consumption over the cycle and the SOC points with positive and negative values (preferably both).

The results of the repetatively driven cycles can be used, since each single cycle results in a value for fuel consumption and a difference between initial and final SOC. Different couples are found due to the number of driven cycles (influence of history on system). Additionally, various operating modes (charging or electric mode) are incorporated at the beginning of the cycles. Figure 33 shows the simulation results of the parallel hybrid with flywheel (PHEVfw) on the Aachen-city-cycle. Uncorrected fuel consumption is displayed versus the ΔSOC.

Because the initial State-of-Charge of the first cycle has a large influence on the further course of SOC, the results of simulations with high, middle, and low initial SOC are separately marked. This way, the differences in fuel consumption due to the diverse SOC histories can be shown.

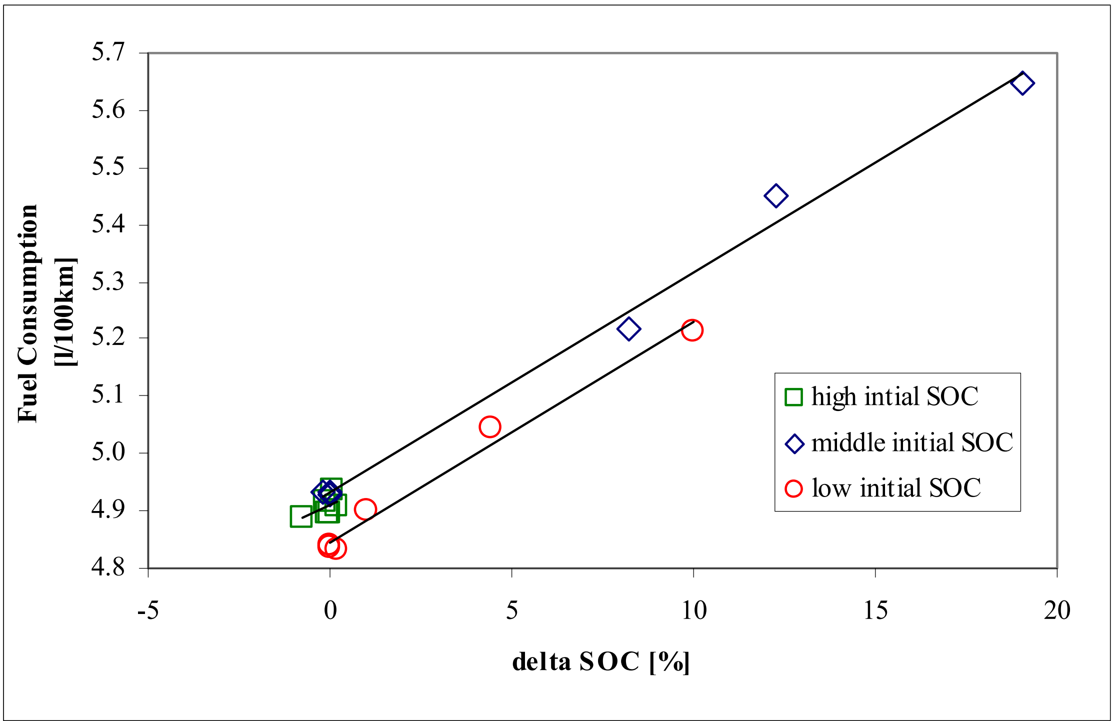


Figure 33: Regression lines for the parallel hybrid with flywheel over consecutive Aachen city cycles with different initial SOC

A linear relation between both parameters follows when using the method of least squares (the sum of all squared deviations from the regression line is minimal).

Besides a linear relation, it can be seen that different intial SOC, and accordingly different SOC courses, lead to a slight change in fuel consumption (also compare Figure 43). The gradients of the regression lines, however, are the same. The fuel correlation to a specific

ΔSOC therefore can be determined independently from the course of SOC. This together with the small divergence between the lines allows to combine the results of the different initial State-of-Charge into one total set of data per type of driving cycle. In the same way, the correlation for other driving cycles can be investigated.

As an example, Figure 34 shows the results for all four hybrid vehicle models used here over the UDDS cycle. The number of cycles for the hybrids with flywheels has been set to six for the parallel and ten for the series one respectively, since these numbers allowed the system to settle in the repetitive SOC pattern. For the hybrids with battery storage, the number of cycles was raised until periodic SOC behaviour was found.

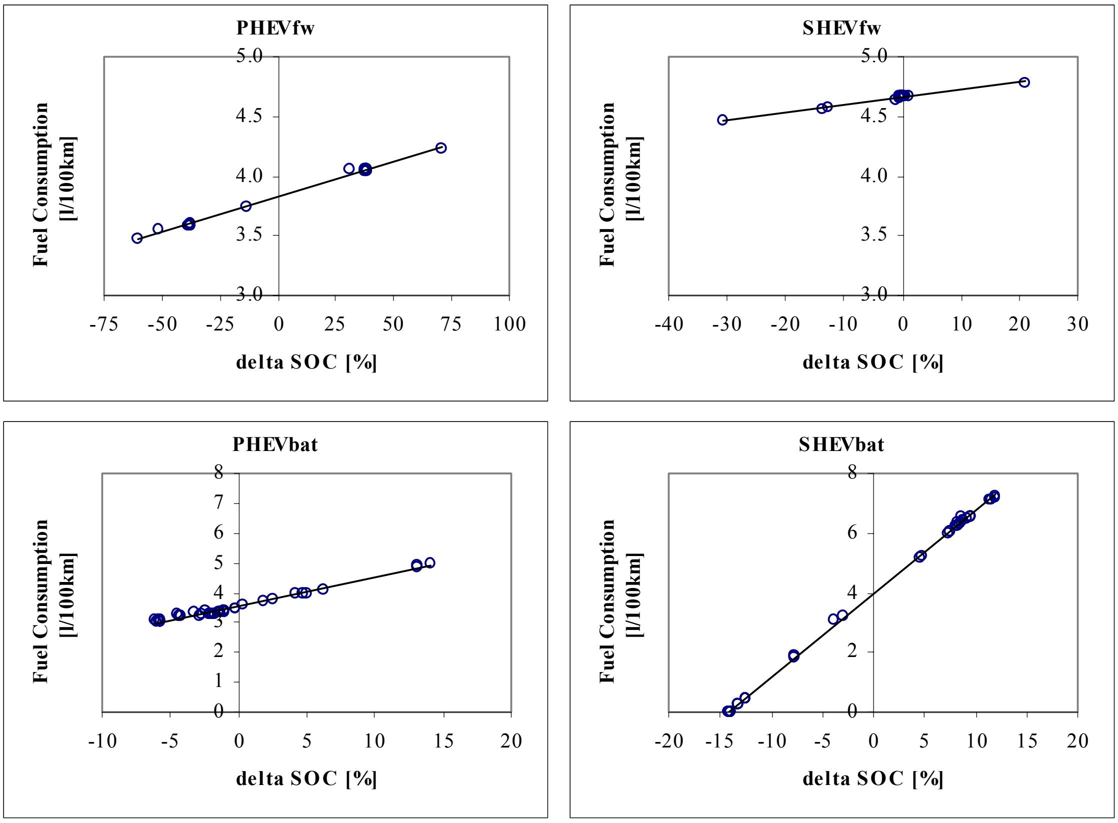


Figure 34: Correlation between fuel consumption and ΔSOC for consecutively driven UDDS cycles with different initial SOC

Figure 34 shows that for all hybrid vehicles a linear relation is obtained. The faster convergence (into the repetitive SOC pattern) of the SOC in the hybrids with flywheel storage systems is recognisable by the concentrations of points at a few places in the diagram. Without the data points outside these concentrations, superposition of the linear connection would not be allowed. The wide scattering of the data points in the parallel hybrid with battery is caused by different SOC histories, resulting in a 0.05 l/100km difference in fuel consumption between the high and low initial SOC sequences.

It also is remarkable that, even with the large differences in fuel consumption, a strong linear correlation is found for the series hybrid with battery. The fuel consumption varies between 0 and more than 7 l/100km for the first cycles of the simulation with high and low initial SOC respectively. In case of the Aachen-city-cycle (relatively short), the values for this hybrid are between 0 and 53 l/100km, yet the intermediate points all are very close to the regression line.

For all simulated driving cycles, Table 8 and Table 9 list the intersect values for fuel consumption at zero ΔSOC for the individual initial SOC values. Additionally, the intersect values for the entire number of data points on each type of driving cycle for each vehicle is also determined.
The deviation of the intersect values for each initial SOC with respect to the overall regression value at ΔSOC=0 is within 0.1 l/100km for all simulations. The biggest difference is found at the parallel hybrid with flywheel storage on the Aachen-city-cycle. The other parallel hybrid as well as the series hybrid with flywheel also show the largest differences on this cycle. The main reason for this is that the covered distance in the Aachen-city-cycle is much shorter than in the other cycles. Since the energy capacity of the storage devices stays the same, more time is needed for the SOC to cross the control window and settle into a cyclic pattern. The parallel hybrids, furthermore, show larger differences in fuel consumption than the series hybrids.

Table 8: Fuel consumption (l/100km) for the parallel hybrids; obtained with linear regression

Driving cycle	Intersect value regression line at ΔSOC=0							
	Parallel hybrid with flywheel				**Parallel hybrid with battery**			
	high	middle	low	overall	high	middle	low	overall
ECE	3.57	3.57	3.57	3.57	3.10	3.11	3.10	3.10
NEDC	3.64	3.64	3.64	3.64	3.25	3.25	3.27	3.25
Aachen city	4.91	4.93	4.84	4.89	4.23	4.29	4.23	4.28
UDDS	3.82	3.83	3.82	3.82	3.53	3.55	3.57	3.55
HWFET	3.70	3.68	3.68	3.69	3.67	3.68	3.68	3.68
US06	5.41	5.40	5.40	5.40	5.36	5.41	5.37	5.40
SC03	3.94	3.92	3.99	3.96	3.76	3.83	3.76	3.81

Table 9: Fuel consumption (l/100km) for the series hybrids; obtained with linear regression

Driving cycle	Intersect value regression line at ΔSOC=0							
	Series hybrid with flywheel				**Series hybrid with battery**			
	high	middle	low	overall	high	middle	low	overall
ECE	5.25	5.26	5.26	5.26	3.84	3.86	3.84	3.86
NEDC	4.74	4.74	4.74	4.74	3.87	3.88	3.87	3.88
Aachen city	7.40	7.35	7.35	7.37	5.69	5.69	5.70	5.69
UDDS	4.66	4.67	4.67	4.66	3.94	3.94	3.94	3.94
HWFET	3.99	3.99	3.99	3.99	3.68	3.69	3.68	3.69
US06	5.52	5.52	5.52	5.52	5.60	5.64	5.61	5.63
SC03	4.74	4.73	4.74	4.74	4.09	4.08	4.09	4.08

Linear interpolation
With the results of the previous paragraph, it is possible to formulate a method that allows for an easy and quick way to determinate the fuel consumption of a hybrid vehicle. The linear relation between fuel consumption and ΔSOC enables the calculation of fuel consumption for a balanced energy capacity of the storage system with only two different couples of data points (at least according to the simulation results). Most important is that the differences in ΔSOC for the two points are far enough apart. Instead of linear regression for which a considerable number of cycles is required to find the fuel consumption at zero ΔSOC, only two cycles are necessary for linear interpolation as long as these two cycles yield clearly distinct values.

These two clearly distinct data points can be found by setting the initial State-of-Charge slightly below the upper SOC limit for the first run and just above the lower limit for the second test. These conditions are obtained by driving the vehicle on the rollerbench until the desired operating mode is set.
First, the vehicle is driven until the combustion engine is started by the control strategy (SOC is at lower limit) in order to charge the storage device. At this moment, the actual test is started and at the end of the driving cycle the first couple of values, existing of fuel consumption and the measured Ampere-hours change over the cycle, is found.
Then, the vehicle is driven until the charging is completed (high SOC limit) and the operating mode switches to electric operation. The second cycle can now be driven and the fuel consumption and Ampere-hours give another data point. From the two measurements, the fuel consumption at zero ΔSOC can now be calculated through linear interpolation between the data points.

The fuel consumptions, obtained by applying this method, for the hybrids on the simulated driving cycles are listed in Table 10. The regression values and the differences between the two methods have been included as well.
The differences are in the same order as those between the simulations with different initial States-of-Charge (and SOC histories). The SC03 driving cycle shows the largest deviation, approximately 0.1 l/100km. The fuel consumption on the Aachen-city-cycle that is calculated through interpolation is lower than the regression value. This is probably due to the short cycle duration, which causes the battery to be operated at fairly high SOC (where the efficiency is higher as well) throughout the entire cycle, since the energy demand is low. This too is valid for the cycle with low initial SOC, since the battery can quickly be charged and then operate at high SOC level.

Table 10: Interpolated fuel consumption and difference with respect to regression value

Vehicle	[l/100km]	ECE	NEDC	Aachen	UDDS	HWFET	US06	SC03
PHEVfw	interpolation	3.56	3.69	4.91	3.82	3.78	5.42	4.05
	regression	3.57	3.64	4.89	3.82	3.69	5.40	3.96
	difference	-0.01	0.05	0.02	0.00	0.08	0.02	0.09
PHEVbat	interpolation	3.08	3.22	4.18	3.55	3.70	5.38	3.73
	regression	3.10	3.25	4.28	3.55	3.68	5.40	3.81
	difference	-0.03	-0.03	-0.10	-0.01	0.03	-0.02	-0.08
SHEVfw	interpolation	5.22	4.76	7.39	4.65	3.96	5.53	4.85
	regression	5.26	4.74	7.37	4.66	3.99	5.52	4.74
	difference	-0.04	0.02	0.02	-0.01	-0.02	0.00	0.11
SHEVbat	interpolation	3.82	3.91	5.62	3.94	3.66	5.59	4.04
	regression	3.86	3.88	5.69	3.94	3.69	5.63	4.08
	difference	-0.04	0.03	-0.07	0.00	-0.03	-0.04	-0.05

Increasing the number of cycles improves the accuracy with which fuel consumption is determined. As an example, Figure 35 shows the results for the cycle with the largest initial difference (SC03). As more cycles are driven consecutively, the divergence ratio decreases. Due to the fact that the State-of-Charge quite slowly settles into the periodic behaviour in this cycle, distinct improvements are better recognisable at higher cycle numbers. The improvements, then again, pale into insignificance with respect to the additionally required time.

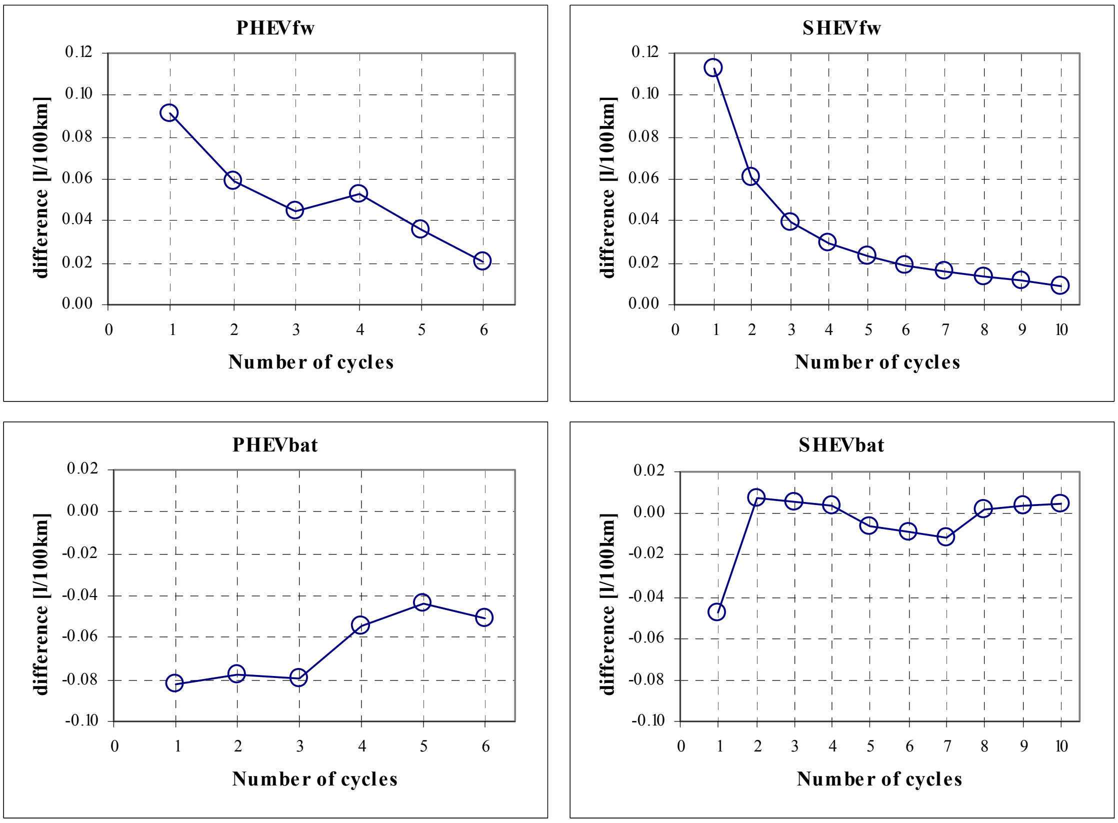


Figure 35: Differences between interpolated and regression values with increasing number of cycles for all vehicle on the SC03 driving cycle

Measurement on a Toyota Prius Hybrid Electric Vehicle
In section 2.6 the measurement method and performed tests have already been described. Especially the SOC behaviour was investigated there. The conclusion was that hardly any ΔSOC could be determined over the cycle. Although a correction method does not seem to be necessary, the method of linear interpolation is applied to all parameters which are of interest for the real performance of a vehicle, i.e. the real fuel consumption and emissions. A linear equation is obtained by using the least-squares method.

The results of the tests are presented in Table 11. The applied sign convention for ΔQ (change of charge) is that negative values are a net discharge (lower final SOC) and that positive values mean a net charge (increased SOC) of the battery.

First, the change of battery capacity (Ah/100km) is compared to the allowed value according to the CARB criterium (Equation 1, page 19). For all cycles (hot and cold), the net change of Ah is much smaller than defined by CARB. A ΔSOC correction thus would not be needed and the calculated energy consumption is the actual consumption over the cycle.

The results nevertheless are further looked into in order to investigate repeatability and hot versus cold start.

Table 11: Emission and fuel consumption of a Toyota Prius over several driving cycles

	ΔQ [Ah/100km]	**HC** [g/km]	**CO** [g/km]	**CO_2** [g/km]	**NO_x** [g/km]	**FC** [l/100km]
NEDC (UDC+EUDC) (cold)	-	0.02	0.13	132. 6	0.05	5.54
NEDC (UDC+EUDC) (hot)	-0.098	0.01	0.03	112.8	0.04	4.71
	0.372	0.01	0.03	112.9	0.05	4.71
	0.462	0.01	0.06	113.4	0.05	4.74
	0.243	0.01	0.05	112.6	0.05	4.71
Japanese 10-15 (cold)	-0.289	0.18	0.70	169.3	0.08	7.13
Japanese 10-15 (hot)	-1.070	0.01	0.09	108.0	0.02	4.51
	-0.175	0.01	0.05	108.7	0.02	4.54
	0.570	0.01	0.03	110.9	0.04	4.63
	-0.061	0.01	0.03	109.9	0.03	4.59
USFTP75[1] (cold)	0.323	0.04	0.29	126.8	0.04	5.32
USFTP72[2] (hot)	-1.879	0.01	0.05	104.8	0.05	4.38
	0.275	0.01	0.07	110.1	0.04	4.60
	-0.146	0.01	0.05	109.2	0.05	4.56
	0.269	0.01	0.05	110.9	0.06	4.63
Hyzem Urban (cold)	1.358	0.15	0.98	175.7	0.05	7.42
Hyzem Urban (hot)	-5.445	0.01	0.12	119.2	0.12	4.98
	0.036	0.01	0.12	130.3	0.12	5.45
	0.540	0.01	0.05	129.4	0.11	5.40
	0.306	0.01	0.04	127.4	0.14	5.32
Hyzem Rural (cold)	0.864	0.10	0.72	140.9	0.11	5.94
Hyzem Rural (hot)	-0.371	0.01	0.15	123.6	0.14	5.17
	0.394	0.01	0.08	123.4	0.16	5.15
	0.409	0.01	0.11	123.5	0.12	5.16
	0.409	0.01	0.14	122.6	0.11	5.13
Hyzem Highway (cold)	0.527	0.03	0.22	156.1	0.22	6.53
Hyzem Highway (hot)	0.159	0.01	0.12	147.4	0.19	6.15
	0.096	0.01	0.12	148.0	0.18	6.18
	0.063	0.01	0.20	148.7	0.20	6.22
	0.308	0.01	0.15	149.4	0.17	6.24

1. US-FTP75 is equal to US-FTP72 (cold start) with, additionally, the transient part of the US-FTP72 with hot engine.
2. Also known as Urban Dynamometer Driving Schedule (UDDS).

In Figure 36 the data with their regression lines from Table 11 are plotted for each cycle. The trend that can be read from Figure 36 is that charging the battery (corresponds to increasing ΔQ) results in a higher fuel consumption, as can be expected since additional energy from fuel is stored into the battery.

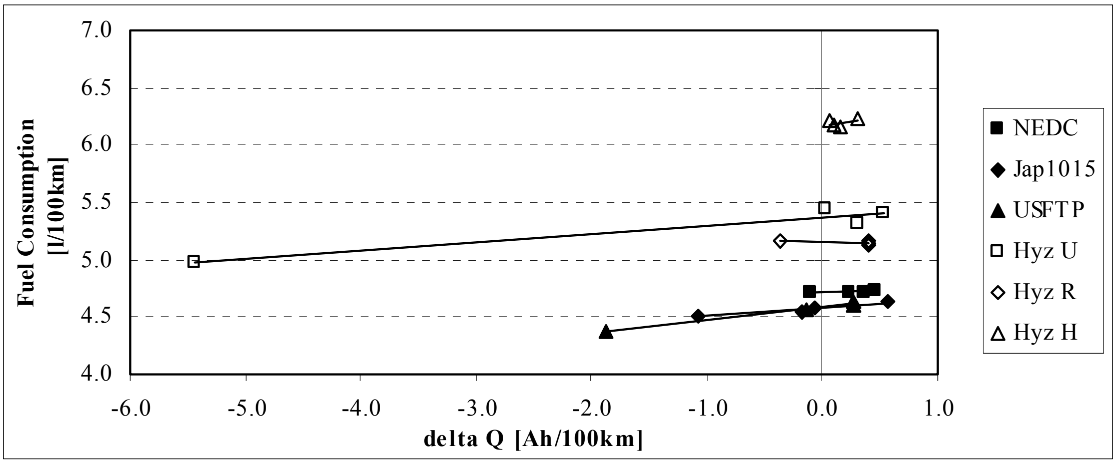


Figure 36: Fuel Consumption vs. change in charge (ΔQ) for a Toyota Prius over six different driving cycles

Another interesting point that can be seen in Figure 36, is that longer cycles seem to give lower ΔSOC. The Hyzem Urban, Rural, and Highway cycles illustrate this. An explanation for this behaviour is that the (dynamic) drivetrain system needs time to 'adjust' to the load pattern. Provided that the driving cycle characteristics are evenly spread over the cycle, longer cycles give more time to do this and for that reason a smaller ΔSOC is found.

For the emission components linear regression has also been used to determine the emissions at zero ΔSOC. Both the ΔSOC corrected fuel consumption and emissions are listed in Table 12. The correlation factor (R^2) is also given.
On the basis of the data points in Figure 36, an estimation of the actual fuel consumption can be read through interpolation, since the relation between fuel consumption and change of battery capacity seems to be explicit. The R^2-value, however, does not indicate an unambiguous relation. In case the data points are sufficiently widely spread, a R^2-value of approximately 1 is found and a linear relationship may be assumed.
For the case that the data points are closely together (on the Hyzem Highway for instance), the R^2-value does not assume a good linear relationship. Yet, for the case that the cloud of points is concentrated around the vertical axis, the estimation for the intersect value is highly accurate, since each data point itself is already quite representative. This also follows when looking at the 95% confidence interval for the CO_2-emissions and the fuel consumption. With 95% confidence, these values are predicted with a maximum deviation of approximately 1 or 2%. For the other emission components (CO and NO_x give ± 100% and 50% deviations respectively) the confidence interval is much wider. The resolution of the measurement equipment in combination with the low emissions introduce difficulties, as will be discussed furtheron. The statistical results, in this case, seem to indicate problems for using the linear regression method. From a practical point of view, however, that is a much to strong conclusion. It therefore is important that the position of points is always checked, even though this might seem trivial.

Table 12: Regression values for emission factors and fuel consumption for a Toyota Prius

	HC g/km	**CO** g/km	**CO_2** g/km	**NO_x** g/km	**FC** l/100km
NEDC (hot) intersect	0.01	0.034	112.7	0.043	4.71
± 95% confidence interval	± 0.00	± 0.049	± 1.1	± 0.007	± 0.049
R^2 hot	1.00	0.34	0.32	0.87	0.35
Japanese 10-15 (hot)	0.01	0.043	109.7	0.030	4.58
± 95% confidence interval	± 0.00	± 0.030	± 1.3	± 0.014	± 0.052
R^2 hot	1.00	0.85	0.86	0.71	0.87
USFTP (hot)	0.01	0.057	109.7	0.050	4.58
± 95% confidence interval	± 0.00	± 0.026	± 0.9	± 0.023	± 0.038
R^2 hot	1.00	0.18	0.99	0.00	0.99
Hyzem Urban (hot)	0.01	0.072	128.5	0.123	5.37
± 95% confidence interval	± 0.00	± 0.099	± 3.9	± 0.04	± 0.176
R^2 hot	1.00	0.39	0.92	0.01	0.93
Hyzem Rural (hot)	0.01	0.131	123.4	0.135	5.16
± 95% confidence interval	± 0.00	± 0.077	± 1.2	± 0.067	± 0.039
R^2 hot	1.00	0.38	0.20	0.06	0.47
Hyzem Highway (hot)	0.01	0.161	147.7	0.200	6.17
± 95% confidence interval	± 0.00	± 0.188	± 3.8	± 0.04	± 0.189
R^2 hot	1.00	0.06	0.26	0.64	0.18

As an example Figure 37 shows the emissions with respect to the change of battery charge over the Hyzem Urban driving cycle for the cycles that were driven with a hot engine (data listed in Table 11).

Looking at the regression analysis of the emissions, several remarks have to be made. For the HC component in the cycles, which were driven with warm engine, an R^2-value is found that is always 1.0. This is caused by the resolution of the measurement equipment (1ppm for the bag as well as the background concentration); because of the very low HC exhaust the value cannot be presented with a higher accuracy (as a result always 0.1 g/km, see Table 11 and Figure 37).

A second interesting point is the correlation between fuel consumption and CO_2 emissions. Over each cycle they show similar R^2-values. This actually is no revelation given that the fuel consumption is equivalent to the CO_2 emission when the CO and HC emissions are low (see the carbon balance method, Equation 3)

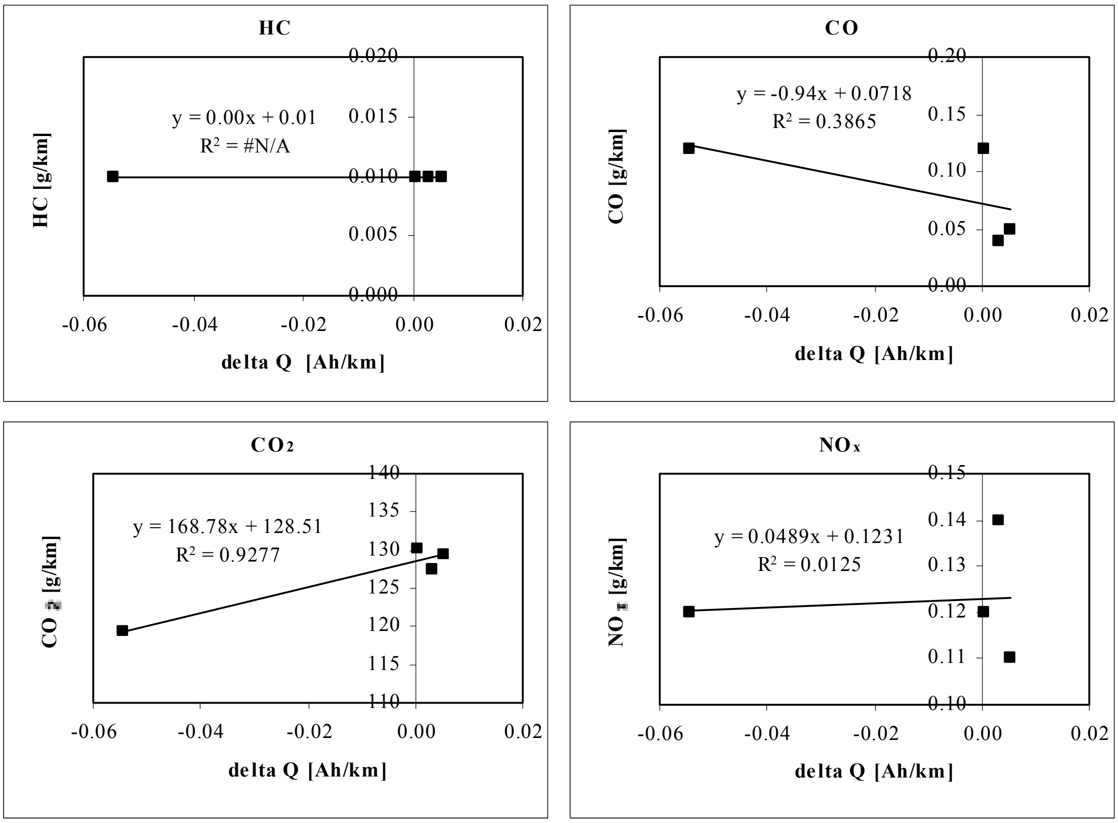


Figure 37: Emissions vs. ΔQ for a Toyota Prius with hot engine over consecutive Hyzem Urban driving cycles (note that all verticale axes have different scales)

The measurement data for the CO and NO_x emissions do not repeat very well. At nearly equal ΔQ different values are found. The R^2-values are small, indicating that the data points lie at quite some distance from the regression line. Although this might imply that the intersect value does not necessarily give a good representation of the real performance, and consequently linear regression should not be applied to find the "real" emissions, this conclusion is not fully correct. Part of the problem is caused by small ΔSOC values and low emissions, resulting in a small spread of the data points. The method, for that reason, is not to be doubted. As long as data points with both positive and negative ΔSOC are available, linear regression is expected to give the best prediction for the emissions values, as it is a combination of calculating averages and correcting for ΔSOC.

The analysis of the measurements is extended in depth. For the emissions and fuel consumption the average values and the repeatability of the four hot cycles have been calculated with Equation 12 and Equation 13 respectively. For *Y* either the concentration of the emission factors or the fuel consumption has to be filled in. The parameter *n* stands for the number of cycles, *st.dev* is the standard deviation , and *t* is a factor according to the t-distribution, which is dependent on the number of measurements, the number of degrees of freedom, and the defined confidence interval (99%).

$$\overline{Y}_{hot} = \frac{\sum_{i=1}^{l=n} Y_i}{n}$$ *Equation 12*

$$\text{Abs. repeatability} = \frac{t \cdot \text{st.dev}}{\sqrt{n}}$$ *Equation 13*

The results of these calculations are presented in Table 13. Above it has already been shown that, with exception of CO_2 (and consequently fuel consumption), no direct relation between emissions and ΔSOC is found. The problem not only comes from the repeatability of the measured object (a hybrid vehicle which shows very small variations of ΔSOC over the complete cycle), but also from the resolution of the measurement equipment, and the repeatability of the driver. When the measured bag-concentrations of HC, CO, and NO_x are very low, the resolution is not good enough to get reproducable values that allow the use of ΔSOC correction methods which are based upon linear correlation of emissions with the battery's ΔQ.

Table 13: Average and repeatability for measurements on a Toyota Prius

	ΔQ [Ah/100km]	**HC** [g/km]	**CO** [g/km]	**CO_2** [g/km]	**NO_x** [g/km]	**FC** [l/100km]
NEDC (average hot)	0.245	0.01	0.04	112.92	0.05	4.72
Abs Repeatability (99% confid.)	0.557	0.00	0.03	0.77	0.01	0.03
Japanese 10-15 (average hot)	-0.184	0.01	0.05	109.38	0.03	4.57
Abs Repeatability (99% confid.)	1.534	0.00	0.06	2.96	0.02	0.12
USFTP72 (average hot)	-0.370	0.01	0.06	108.73	0.05	4.54
Abs Repeatability (99% confid.)	2.327	0.00	0.02	6.19	0.02	0.25
Hyzem Urban (average hot)	-1.141	0.01	0.08	126.59	0.12	5.29
Abs Repeatability (99% confid.)	6.531	0.00	0.10	11.44	0.03	0.48
Hyzem Rural (average hot)	0.210	0.01	0.12	123.26	0.13	5.15
Abs Repeatability (99% confid.)	0.880	0.00	0.07	1.00	0.05	0.04
Hyzem Highway (average hot)	0.156	0.01	0.15	148.35	0.19	6.20
Abs Repeatability (99% confid.)	0.246	0.00	0.09	1.96	0.03	0.09

So far, only the hot cycles have been investigated. The fuel consumption and the emissions of the cold cycles are now compared to the average values for the hot cycles. In Table 14 the relation between hot average and cold is presented. The relation is determined with Equation 14.

$$f_{cold/hot} = \frac{Y_{cold}}{\overline{Y}_{hot}} \qquad \textit{Equation 14}$$

Table 14: Cold fuel consumption and emissions relative to hot cycle for a Toyota Prius

	Distance [km]	**$f_{cold/hot}$** HC	CO	CO_2	NO_x	FC
NEDC (UDC+EUDC)	11.029	2.0	3.1	1.2	1.1	1.2
Japanese 10-15	4.171	18.0	14.0	1.5	2.9	1.6
Hyzem Urban	3.460	15.0	11.9	1.4	0.4	1.4
Hyzem Rural	11.220	10.0	6.0	1.1	0.8	1.2
Hyzem Highway	46.184	3.0	1.5	1.1	1.2	1.1

The general conclusion is that the emissions and fuel consumption in the cycles with cold start are higher than over a cycle that is entirely driven with a hot engine and catalyst. Especially the HC and CO emissions are influenced by the engine and catalyst temperatures; as long as the engine and catalyst are cold, the emissions are much higher. This can clearly be seen on the relatively short cycles (Japanese 10-15, Hyzem Urban, and Hyzem Rural). Since the cycle is short (both in distance and time), there is only little time for the engine to warm up. Of course, the load pattern also is of importance for the heating, but the mentioned (short) cycles are not that demanding either. Therefore, the cold period of the engine is even longer.

Measurement on the TNO P2010 series hybrid testrig
Only little information is really available for ΔSOC correction (see Section 2.7). An attempt nevertheless is made to apply correction through regression and on the basis of cumulative values. In Figure 38 both methods are displayed. As explained in Appendix C, the energy over the cycle is determined from the electric power delivered by a DIGATRON (substitute for the generator set). The absolute figure therefore is not equal to the energy consumption of the vehicle with a combustion engine, since an ICE's efficiency is not 1. This however is not expected to have significant influence on the ΔSOC correction methods, which are investigated in this report.

Table 15: Results P2010 testrig on NEDC and MODEM driving cycle

	NEDC			
	Distance [km]	ΔSOC [%]	EC per cycle [kWh/100km]	EC cumulative [kWh/100km]
HEV 1	11.096	19.6	11.71	11.71
HEV 2	11.097	-4.8	8.10	9.91
HEV 3	11.090	11.4	10.61	10.14
ZEV	11.093	-60.4[1]	8.55[2]	8.55[2]
	MODEM			
	Distance [km]	ΔSOC [%]	EC per cycle [kWh/100km]	EC cumulative [kWh/100km]
HEV 1	25.294	9.6	11.75	11.75
HEV 2	25.225	2.8	11.21	11.48
HEV 3	25.225	-0.2	11.01	11.33
ZEV	25.211	-184.4[1]	11.19[2]	11.19[2]
3x HEV[3]	75.016	4.4	11.16	11.16

1. Testrig operated as Battery Electric Vehicle, possible since a battery with higher energy content is used. Listed ΔSOC value is 20 times higher than testrig battery pack value
2. Energy from battery instead of from DIGATRON
3. Three cycles driven in a row. Only initial and final SOC value available

For the NEDC and MODEM cycles, both positive and negative ΔSOC were found. Using the regression method therefore does not introduce errors due to extrapolation to a zero ΔSOC. The R^2-value is close to 1, indicating that energy consumption is almost linearly dependent on ΔSOC. The value at ΔSOC=0 seems to be the 'real' energy consumption for this vehicle. Only three points were available though.

For the MODEM cycle a fourth data point can be added, since another sequence of three cycles was driven. This measurement also resulted in a ΔSOC and energy consumption. Although an additional data point can be expected to give more information, the resulting value actually leads to a less clear picture. The data point is added in the right column in

Figure 38. Quite surprisingly, this data point does not seem to 'match' the other data points; the same type of driving cycle, the same 'vehicle', yet three cycles instead of one. The explanation might possibly be found in different operating times for the APU due to different initial SOC of the cycles, pauses between the separate cycles, or the temperature of tyres, bearings, or the rollerbench.
Another possible cause, is found in the control strategy. The first three cycles were not driven directly one after the other (pauses in between), and before the start of each measurement the vehicle was reset.
The fourth data point, though, was derived from a three cycle sequence whithout any pause nor reset. Since the control strategy does incorporate the systems history (Appendix B), this probably (also) influences the on/off shifting for the APU and the response to the same initial SOC is different.

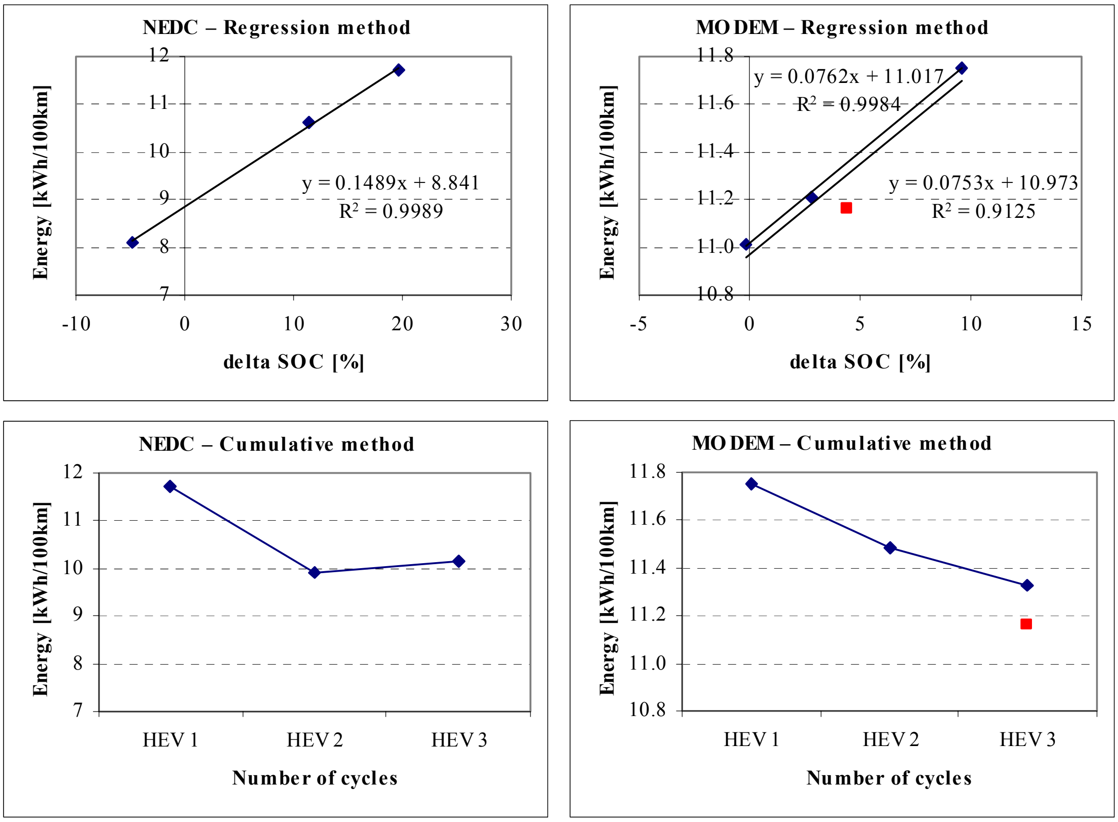


Figure 38: Regression and cumulative consumption for the P2010 testrig on NEDC and MODEM

As a result however, a less good fit between the data points is found. Since one of the three earlier points has almost zero ΔSOC, the corresponding energy consumption on that cycle has to be very close to the actual value. The first regression line seems to be more logically. Question arise for the fourth data point, although the previously described aspects and differences between the measurements might have caused this inconvenience.

The energy consumption calculated with the cumulative values does not give a converged value. Although it seems to converge, the number of cycles is not sufficient to give accurate results. Assuming that the regression method gives the 'actual' energy consumption, comparison of regression and cumulative values after three cycles leads to the conclusion that the cumulative method has not given a good approximation.

Measurement on the series hybrid ALTROBUS
In Section 2.8, the SOC behaviour of the ALTROBUS over six different cycles was presented. Significant ΔSOC was found over all types of driving cycles. For each cycle several methods to determine the real energy consumption have been applied and are presented here.

During the measurements, the SOC and fuel were monitored. Linear regression is applied on the basis of ΔSOC and fuel consumption per cycle. The intersect value represents the actual fuel consumption over one driving cycle. Preferable, both positive and negative ΔSOC should be available, yet this was not always possible.

Table 16 presents the results of the regression method for all six used driving cycles. For the MODEM slow urban, the regression plot is shown in Figure 39. For the other cycles, Appendix E is to be cheched. The data points on the MODEM cycle clearly show a spread. Generally, the trend is that higher ΔSOC also causes a higher fuel consumption. The differences between cycles, nevertheless, can also be significant. As examples, two cycles are regarded here. One has zero ΔSOC (14 l/100km) and the other has low negative ΔSOC (24 l/100km). Although the ΔSOC are very close to eachother, the calculated fuel consumptions show significant differences.

Table 16: Test data and regression analysis for the ALTROBUS

Driving cycle	Number of Cycles	Test Time [h]	Total Distance [km]	Fuel consumption [l/100km]			
				Intercept value	R^2	95% confidence	relative [%]
UDC	7	1.58	29.05	16.3	0.89	±0.7	±4.4
Jap1015	10	1.25	19.67	18.5	0.92	±1.0	±5.5
UDDS stabilised	5	1.18	27.06	14.8	0.99	±0.4	±2.4
MODEM slow urban	11	1.41	17.55	21.0	0.84	±2.3	±11.1
Hyzem Urban	3	0.48	9.71	18.5	0.89	±9.2	±49.6
Casaccia	8	1.50	25.86	14.6	0.87	±2.2	±15.0

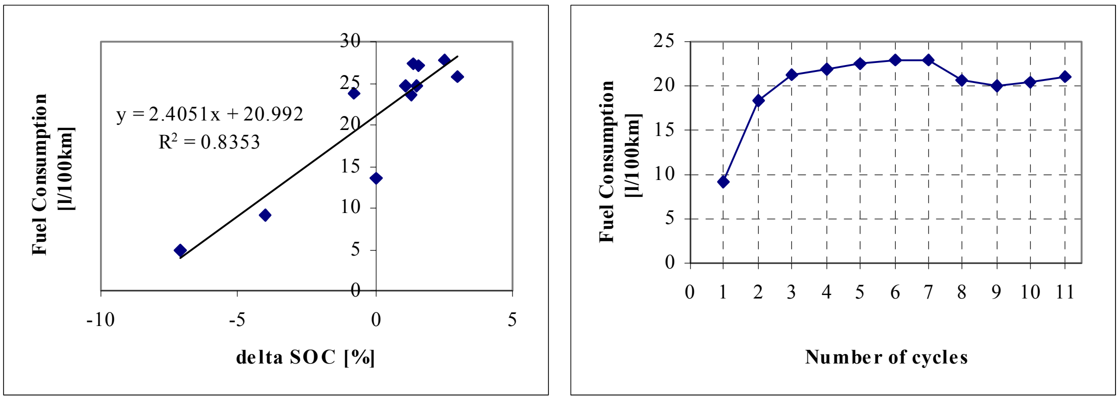


Figure 39: Regression for MODEM slow urban cycle

In Figure 39, the result of calculating the fuel consumption on the basis of cumulative values is shown too. After three or four cycles the actual value almost seems to be in reach. After 8 cycles, however, a significant change is found again. It therefore is not possible to read the actual fuel consumption from these results. Even more cycles would be necessary.

Looking at all driving cycles, it can be seen that the R^2-values vary between 0.84 and 0.99. These values are clearly not as high (good) as those found for the simulations, yet they do indicate that, in general, a linear trend is present.
In order to give an indication for the accuracy of the regression values, the 95% confidence interval has been calculated. The results show that the accuracy varies between several percent and almost 50%. The latter value, however, is obtained on the Hyzem Urban cycle, which was driven only 3 times, each resulting in a negative ΔSOC. When it had been possible to drive more cycles (the vehicle showed to be charge depleting), more data points would have been available, a trend might have been more clearly visible, and the confidence interval would have been smaller for sure (a small data set is always more penalised).

The number of cycles that have been driven, influences the accuracy with which the energy consumption is determined. In general, more cycles will give a more apparent view of a possible trend. On the other hand, more cycles also (might) result in a larger spread, and consequently the R^2-value might become lower. When the cycles are very consistently driven, however, it can be expected that more cycles only contribute to more accurate results.

4.2 Extension of the measurement

Two methods were described in Chapter 3 that can be used to eliminate ΔSOC by extending the measurement. These methods are applied to the simulations with ΔSOC.

4.2.1 Driving cycle continuation

The first method is to continue the test by driving additional kilometers of the same cycle type and then calculate the energy consumption of the vehicle by either excluding or including the additional kilometers. This is explained in Section 3.3.1.

Since consecutive cycles have been simulated only several cycles can actually be used here (the last one never, since there is no continuation). Several simulations showed results that did not make it possible to apply these methods, since the initial SOC value was not reached again. Models with a large battery sometimes suffered from increasing (or decreasing) SOC over several cycles in a row without reaching the initial SOC value of the considered cycle. This already gives reason to doubt the applicability of this method to eliminate ΔSOC. In case more cycles have to be driven, then application of the regression method is also possible.

The results of all simulations have been combined to find the figures of Table 17. These figures thus are average values for the simulations with different powertrains, driving cycles, control strategies, and parameters. In Table 17, the methods are indicated with a code consisting of 'M' for Method, and a number to indicate which method. In Chapter 3, these methods are already explained. Below, the codes and methods are summarised.

M1 No ΔSOC correction; single cycle fuel and distance (3.1, Equation 5)
M2 Averaging multiple cycles (3.2, Equation 6)
M3 Extension of the test; total amount of fuel, cycle distance (3.3.1, Equation 7)
M4 Extension of the test; total amount of fuel, total distance (3.3.1, Equation 8)

All values are calculated with respect to the intercept value of the regression method (relative values therefore 0% is found for the regression).

Table 17: Comparison of energy consumption calculations with respect to regression method (positive values indicate higher energy consumption, negative is lower energy consumption)

	Regression	M1	M2	M3	M4
Average difference	0%	16%	18%	57%	2%
Standard deviation difference	0%	9%	4%	15%	2%
Average maximum deviation	0%	80%	78%	161%	21%
Maximum deviation	0%	309%	309%	404%	75%
Average minimum deviation	0%	-30%	-12%	-37%	-2%
Minimum deviation	0%	-106%	-39%	-106%	-6%

In the previous section the regression method showed good results. Therefore the other methods now are compared to the regression values, which are regarded as the actual energy consumption of the vehicle. The average difference in Table 17 represents the average deviation from the regression values. The standard deviation on the difference is the standard deviation that is found on the average difference. Further, the maximum and minimum deviation as well as their averages are listed in order to give an indication of the range of values.

The third method (M3) on average shows a significant higher (57%) consumption with a large standard deviation. The maximum deviation (of all simulations) as well as the average of these maximum values indicate that a large variance can be expected when the energy consumption is calculated from additional fuel and the cycle distance. This implies that this method is not suitable.
When the additional distance that was travelled to reach a zero ΔSOC is also incorporated in the energy consumption calculation (M4), this yields results that on average are quite well related to the regression values. The difference is only 2% and the corresponding standard deviation also is low. The results with this method seem to be almost as good as with the regression method. Keep in mind that for Method 3 and 4 a cycle is driven, which is extended when a ΔSOC is found. The regression method needs several cycles anyway, thus on a the basis of test time there is no disadvantage for these methods. The characteristics of the used cycle are very important for this method to give representative results. The distribution of the requested power over the cycle is of great consequence. The additionally driven distance has to be representative for the actual cycle too. In the NEDC, for instance, no even distribution of power is present. The first 780 seconds of the cycle consist of urban driving, while the final 400 seconds are an extra urban part, which requires higher (average) power.
The difference between method 1 and 3 comes from the amount of fuel. Both methods use the same distance for calculating the energy consumption. Apparently the use of additional fuel over the same distance results in a larger error (difference and standard deviation) for the actual energy consumption than not applying any methods to account for ΔSOC at all.
Using cumulative values of several cycles (in a row) generally gives better results than single cycle data, yet also requires that more cycles are driven, while the result only get marginally closer to the regression values for the same number of cycles.

4.2.2 Extension of the test

In case a negative ΔSOC is found over a testcycle, this ΔSOC can be eliminated by charging the battery on board of the vehicle in a condition defined by the manufacturer (for instance low power operating point for the APU). No additional distance is travelled, but more fuel is used.
This method is only executed in case a negative ΔSOC is found. It does not provide a general method to account for the ΔSOC problem, since fuel consumption is not corrected for positive ΔSOC. When a vehicle cannot be charged when the vehicle is at standstill (for instance

parallel hybrids when the electric motor is always coupled to the wheels), this method cannot be applied either.

The simulation results for the HD series hybrid electric vehicle have been scanned for application of this method. Charging periods where the vehicle is at rest, were used to determine the charging efficiency in l/Ah (compare to Section 4.1, page 42). With this, the amount of fuel that corresponds to the ΔSOC (or ΔQ in Ah) under this charging condition is calculated. Next, the ΔSOC corrected fuel consumption is calculated from the fuel over the cycle together with the fuel used during the additional charging period.

As an example, the results of the HD SHEV with APU control strategy 3 are used to illustrate the findings. This simulation has both small and large, as well as positive and negative ΔSOC values.
Table 18 lists the change in charge content (ΔQ in Ah), the fuel consumption, and the devitation from the regression method (regarded to be most accurate; for this simulation: 0.75 l/km). The additional charging was done with the lower APU power. The charging efficiency during standstill is 0.25 l/Ah.

Table 18: ΔSOC correction by additional charging at standstill for HD SHEV with APU3

Cycle	ΔQ [Ah]	Fuel on cycle [l]	Fuel correction [l]	corrected fuel [l]	FC [l/km]	difference [%]
1	-2.57	3.23	0.65	3.87	0.74	-2
2	2.00	4.40				
3	4.50	4.89				
4	-7.09	2.39	1.78	4.17	0.80	6
5	3.66	4.89				
6	-2.68	3.21	0.67	3.89	0.74	-1
7	1.60	4.33				
8	4.50	4.89				
9	-7.08	2.39	1.78	4.16	0.79	6
10	3.66	4.91				

Dependent on the magnitude of the ΔSOC, the difference between the regression value and the value derived with additional charging also varies. Small negative ΔSOC has resulted in a lower fuel consumption, while large negative ΔSOC gives a higher fuel consumption. The charging correction thus can give quite different results for the fuel consumption at ΔSOC=0. This is mainy caused by the different charging efficiencies. Charging during driving or standstill is different. Charge sustaining hybrids are charged during vehicle operation (which includes driving and standstill). During this operation the actual (average) charging efficiency occurs. The additional charging, is not part of the normal system's operation (over the cycle) and therefore gives deviating values.

4.3 Conclusion

This chapter has discussed several methods to account for the influence of ΔSOC on the determination of energy consumption and emissions. The result of the performed analysis on computer simulations and vehicle measurements is that two methods seem most promising to correct for a change in energy content of the storage system:

- Linear Regression
- Linear Interpolation

Both linear regression and interpolation give comparable accuracy. This, in itself, is not that striking, since both assume a more or less linear relationship between the ΔSOC and energy consumption/emissions of a (charge sustaining) hybrid electric vehicle.
Practical validation of these methods could only be done on the basis of a limited number of vehicles and measurements. Especially, the accuracy of the determination of emissions is unclear. It therefore is highly recommended that additional measurements are conducted when more hybrid vehicles become available.

5 Conclusions and Recommendations

The research in this subtask report concentrates on methods to determine the actual energy consumption and emissions of charge sustaining vehicles on a driving cycle. For a correct measurement of the energy consumption and emissions of such a vehicle, the State-of-Charge (SOC) of the energy storage system at the end of a test should be the same as at the beginning. If this cannot be realised, then the occuring ΔSOC has to be determined and accounted for in a calculation of energy consumption and emissions.

It is investigated whether the problem of ΔSOC will occur and what the effect then will be. By means of computer simulation and vehicle measurements, answers to these questions are given.

State-of-Charge and the problem (Chapter 2)

- The State-of-Charge (SOC) shows periodic behaviour over multiple consecutively driven cycles (Figure 40). This could be expected as a periodic stimulus (multiple driving cycles) is imposed on a controlled non-linear dynamic system (the driveline and control).

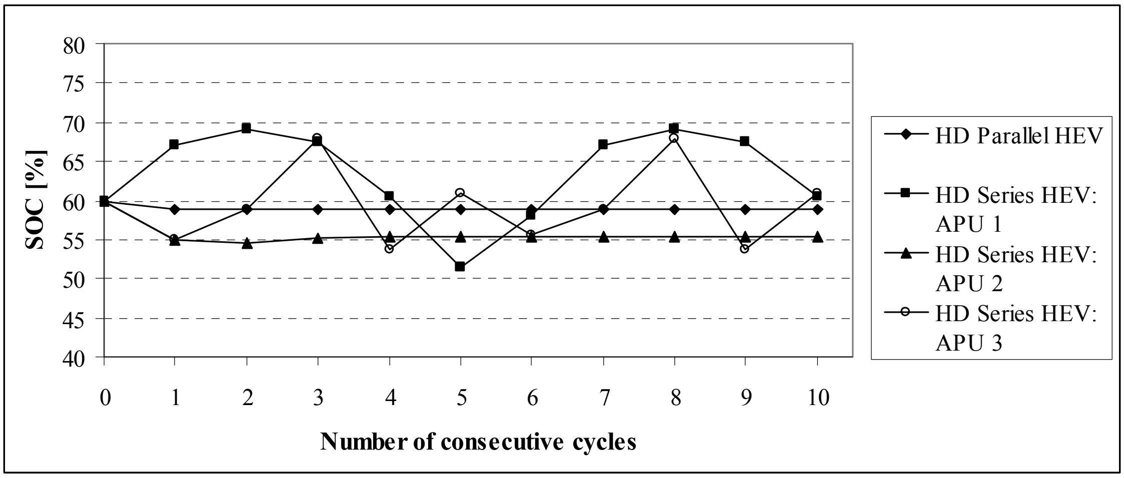


Figure 40: SOC history for four different hybrids: one HD parallel HEV and a HD series HEV with three different APU operating strategies

- The cyclic response has a period time that equals an integer number of driving cycles. In the simulations this behaviour can easily be found. In actual measurements, the response of the driver will not be identical for each consecutive driving cycle of the same type, and, as a result of that, the system might not settle into a clearly recognisable repetitive pattern. The Toyota Prius measurements showed that the SOC history was fairly similar over the successively driven cycles.
- Before settling into a repetitive SOC pattern, several cycles are needed for the system to adapt to the load pattern (the initial conditions first have to dampen out). It may therefore take a lot of time before the SOC pattern can be recognised and the period time can be determined.
- Different initial conditions for the SOC influence the on/off operation of the internal combustion engine. This does not influence the occurrence of periodic response. Simulations show that it might result in a phase shift though.
- The size of the energy storage system can affect the period time of the SOC. This was found in the simulations of a series and combined hybrid electric vehicle with a small and

a large battery (Figure 8). In case of a control strategy solely based on the State-of-Charge, a large influence was found, while the influence was much smaller in case of a control strategy that uses the momentaneous power request at the wheels. The series hybrid with a simple on/off control for the APU, showed a period time of one driving cycle for the low energy battery, and a longer period time for the higher energy battery. The response of the combined hybrid vehicle model was hardly influenced by the change of battery energy content.

Apart from the SOC behaviour, which has given insight into HEV operation, the simulations and measurements were needed to confirm the existence of the ΔSOC problem. Both in simulations and measurements, the SOC showed that significant variations are possible. A large ΔSOC, however, does not necessarily have a large influence on the determined energy consumption of the vehicle. The energy content corresponding to the ΔSOC in this respect is more important. The Californian Air Resources Board (CARB) for this reason has defined a criterion for acceptable change of battery energy content over the cycle. When the change is within 1% of the used fuel's energy, then no correction or other tests are necessary. The ΔSOC, which is a relative measure, has to be put into perspective of the real amount of energy associated with it.

The analyses in Chapter 2 clearly indicates that the ΔSOC problem exists, and thus calls for a method that can accurately account for it. Various options for ΔSOC correction have been identified and discussed.

ΔSOC correction and energy consumption determination

In Chapter 3 the ΔSOC correction methods are fully explained and in 4 they are further analysed and evaluated. The methods are shortly described and discussed here.

1. *Energy consumption without ΔSOC correction (Section 3.1, page 33)*
   The energy consumption and emissions of a vehicle are determined from one measurement on one driving cycle. For conventional and battery electric vehicles this yields the correct value for the environmental performances, since these vehicles are only powered from one energy source (either the fuel tank or the battery). For hybrid vehicles, this measurement results in a misrepresentation of the actual energy consumption and emissions over the cycle. Especially in case of significant ΔSOC (change of energy content), this would lead to large errors.

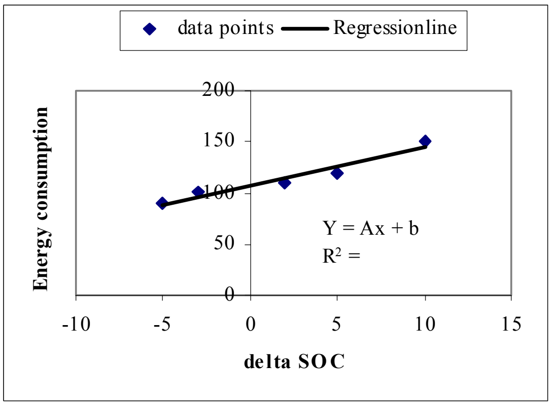
2. *Averaging multiple cycles (Section 3.2, page 34)*
   For charge sustaining vehicles, the SOC will increase and decrease for consecutively driven cycles. The fuel consumption will vary correspondingly. By driving a large number of cycles, the effect of SOC-variations (ΔSOC) will dampen out. Eventually, the (average) fuel consumption and emissions calculated are the representative values for a cycle. This method is fundamentally correct, yet, when used in actual tests, an (unpredictable) large number of cycles is required. An advantage is that the SOC does not have to be measured (although it has to be known that the vehicle is charge sustaining), since it is not included in the energy consumption calculation. In simulations, this method has been used to determine the true asymptotic fuel consumption of vehicles, with which the outcome of other methods can be compared.

3. *Extension of the test (Section 3.3, page 34)*
   In case of ΔSOC, the measurement is continued until ΔSOC = 0 is reached. At that point the test is finished. The options are:
   1. Same driving cycle is driven until the stop criterium is met. The energy consumption and emissions then can be determined by either attributing the additional fuel use and emissions to the distance driven on the cycle or to the total distance (cycle + extension). From the simulations these methods turned out to be inaccurate and unreliable.
   2. A manufacturer defined test is applied in case that a negative ΔSOC occurs (no correction is applied when a positive change results from the test). The vehicle manufacturer defines a charging procedure. This procedure can be at standstill, driving at a constant speed or any other speed profile to be maintained until zero ΔSOC is reached. This method is currently used in the draft CEN-procedure for thermal hybrids (prEN 1986-2). With respect to simplicity for the body performing the test(s), it is not desired that each manufacturer defines a (different) procedure.

   Another shortcoming of these correction methods is that the additional part of the test is not representative for the test cycle, since it most likely will have other characteristics than the test cycle. These methods, therefore, do not give a solid basis for a consistent comparison of energy consumption and emissions.

4. *Linear regression (Section 3.4.1, page 36)*
   This method requires a driving cycle to be driven several times. During each test, the ΔSOC and fuel consumption/emissions are measured. Each measurement thus results in a data set, and by plotting the consumption/emissions against the ΔSOC (Figure 41, left), the actual energy consumption and emissions at ΔSOC=0 can be estimated.
   The use of this method requires the measurement of the (change of) SOC of the reversible energy carrier. The measurement to be carried out furthermore follows the same procedures as are currently already used for conventional vehicles.
   On the basis of the simulation results, this method provides quite good accuracy. Due to the low number of vehicle tests, actual validation of the method is only limited. Yet as far as results have been obtained, this method seems promising.

5. *Linear interpolation (Section 3.4.2, page 37)*
   Even more than the linear regression method, from which it is derived, this method assumes a linear relationship between the ΔSOC and the energy consumption/emissions. This linear interpolation method requires the cycle to be driven twice. The energy storage system of the vehicle is manipulated so that one test is performed with an initial SOC much higher than the average value over the cycle, and the second test with an initial SOC that is much lower than the average over the cycle. These initial SOC values can generally be reached by driving the vehicle under an extreme condition that either charges or depletes the battery. Due to the high and low initial SOC, this method automatically yields a large positive and negative ΔSOC. The energy consumption and emissions then can be found through linear interpolation (Figure 41, right).
   With respect to the current (conventional) procedure, this method, just like the regression method, requires the additional measurement of ΔSOC. Besides that, it also requires the battery to be specially conditioned (manipulated) prior to driving the cycle.



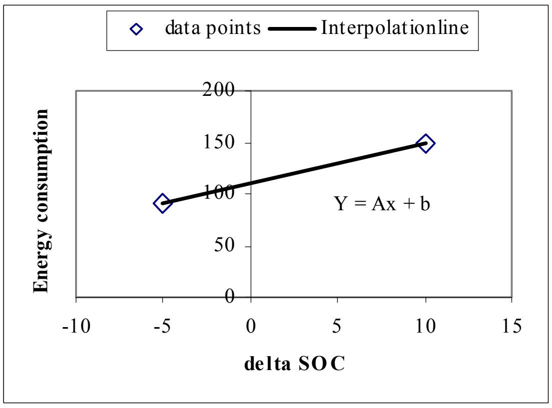


Figure 41: Regression (left) and interpolation (right) method for energy consumption

Proposed ΔSOC correction method

The research of this subtask learns that, on the basis of a presumed linear relation between ΔSOC and energy consumption and emissions, two methods seem possible to account for the change of charge content over the driving cycle. Both linear regression and linear interpolation give quite accurate and similar results. This is not surprising since both methods have the same assumptions. Main differences are found in the battery conditioning prior to conducting the test and the number of cycles to be driven. Furtermore, the ΔSOC that will be found in the test is also different (one starts from extreme initial values and thus is bound to give large ΔSOC, while the other will probably vary around the average SOC) and, along with this, the area over which linearity is assumed is much wider when starting from extreme initial SOC values. The implementation of these methods in a test procedure depends on several practical considerations like feasibility for battery manipulation, cold engine starts, or the total amount of test time needed. In the test procedure framework for (charge sustaining) hybrid electric vehicles these conditions are taken into account and a workable measurement procedure is given there.

Recommendation

Unfortunately, only a limited number of measurements could be carried out, since only a few (charge sustaining) hybrid vehicles were available for tests. This limited number of tests does not provide a very solid basis for conclusions. It therefore is highly recommended that, when more hybrid vehicles come available, more tests are performed to validate the applicability of the proposed ΔSOC correction methods.

References

[1] prEN 1986-2, Electrically propelled road vehicles – Measurement of energy performances – Part 2: Thermal electric hybrid vehicles. (CEN/TC301/WG1 N82/revised by Italy; July 15, 1999).

Appendix A Main parameters simulation models

	Heravy Duty		Light Duty								
	PHEV	**SHEV**	**BEV**	**PHEVfw**	**PHEVbat**	**SHEVfw**	**SHEVbatfol**	**SHEVbatsoc**	**CHEV**	**FCEV**	**FCHEV**
IC engine	Otto	Otto	–	diesel	diesel	diesel	diesel	Otto	Otto	–	–
P [kW]	130	130		60	60	55	55	65	49	–	–
APU op 1		27						13.5			
APU op 2		69						38			
Fuel Cell	–	–	–	–	–	–	–	–	–	H_2	H_2
P [kW]										90	36.5
APU op 1											10.95
APU op 2											36.5
Generator	–	PM	–	–	–	PM	PM	PM	PM		
P [kW]		75				31	31	75	22.5		
base speed [rpm]		3500				2400	2400	4000	4000		
Electric Motor	PM	PM	PM	PM	PM	PM	PM	PM	PM	PM	PM
P [kW]	120	247.5	(2x)	20	20	65	65	(2x) 37.5	30	(2x)	(2x) 37.5
base speed [rpm]	500	2500	3000	480	480	480	480	3000	940	3000	3000
Battery	NiCd	NiCd	NiCs		NiMH		NiMH	NiCd	NiCd	–	NiCd
Capacity [Ah]	50	50	65					6.5	6.5		6.5
Cell Voltage [V]	1.2	1.2	1.2					1.2	1.2		1.2
Rinternal [mΩ]	0.72	0. 72	0.72					0.72	0.72		0.72
Number of cells	500	500	240					240	240		240
P [kW]					22		72				
E [kWh]					3.6		11.5				
Flywheel											
P [kW]				22		72					
E [kWh]				0.733		0.27					
Vehicle											
Mass [kg]	15000	15000	1350	1328	1387	1477	1669	1350	1350	1350	1350
C_w	0.6	0.6	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
A [m^2]	7	7	2	2	2	2	2	2	2	2	2

PHEV – HD Parallel HEV; SHEV – HD Series HEV with simple APU control (3 algorithms); BEV – LD Battery Electric Vehicle; PHEVfw – LD Parallel HEV with electromechanical flywheel storage; PHEVbat – LD Parallel HEV with battery storage; SHEVfw – LD Series HEV with flyheel storage; SHEVbatfol – LD Series HEV with load follower CS and battery; SHEVbatsoc – LD Series HEV with battery and simple APU control 2; CHEV – LD Combined HEV; FCEV – LD Fuel Cell Electric Vehicle; FCHEV – LD Fuel Cell HEV with battery and simple APU control 2

Appendix B Simulation results

In the main text, examples are given for several simulations. In this appendix the other results that are mentioned in the main text, are showed and listed. This concerns the results of more drivelines, other conditions, etcetera. Whenever a reference to this appendix is given in the main text, the figure, table and/or page numbers are used for reference here.

Figure 4, Page 13

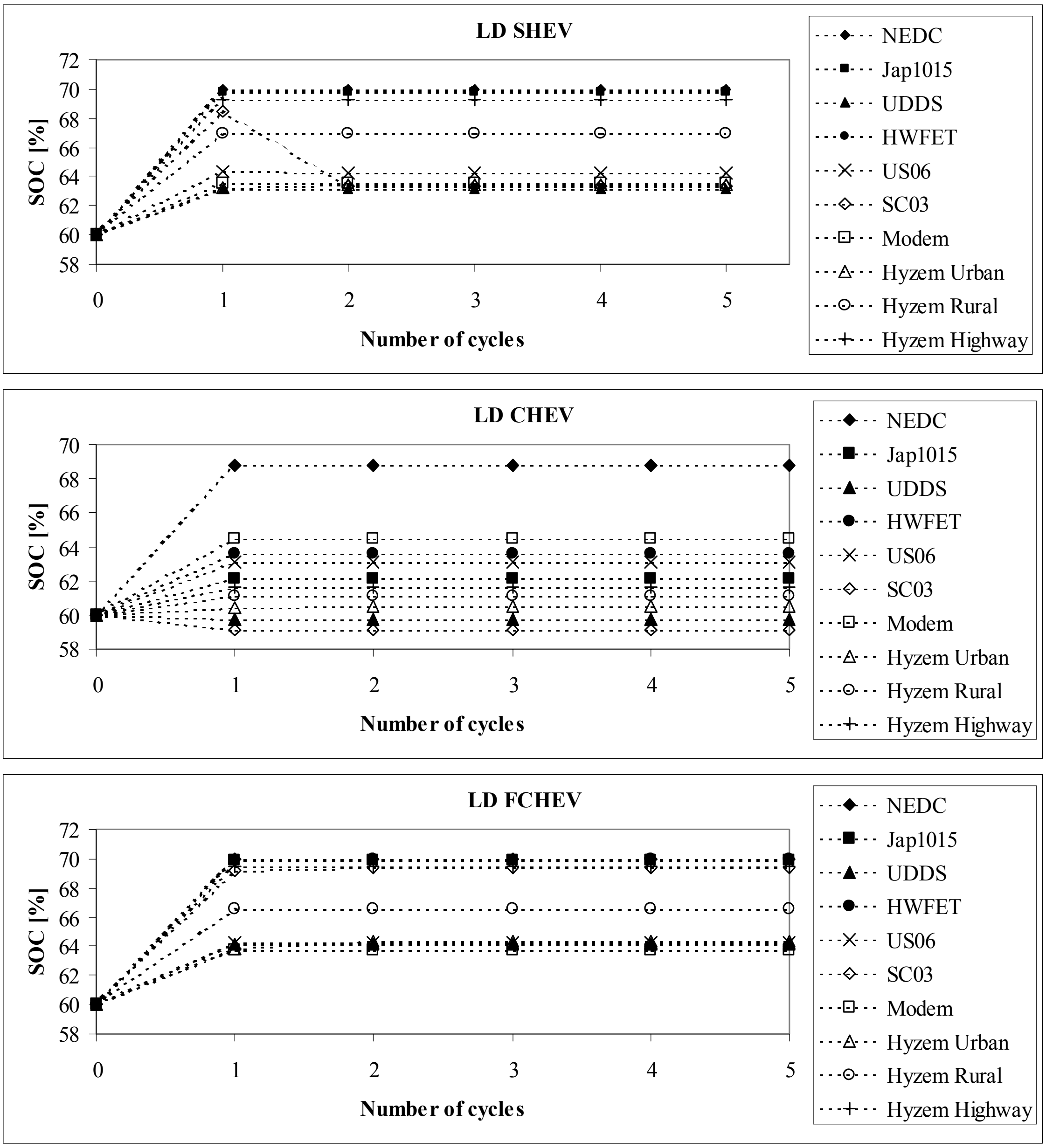


Figure 40: Influence of driving cycle; initial and final SOC for LD vehicles over 5 consecutive cycles

Page 10

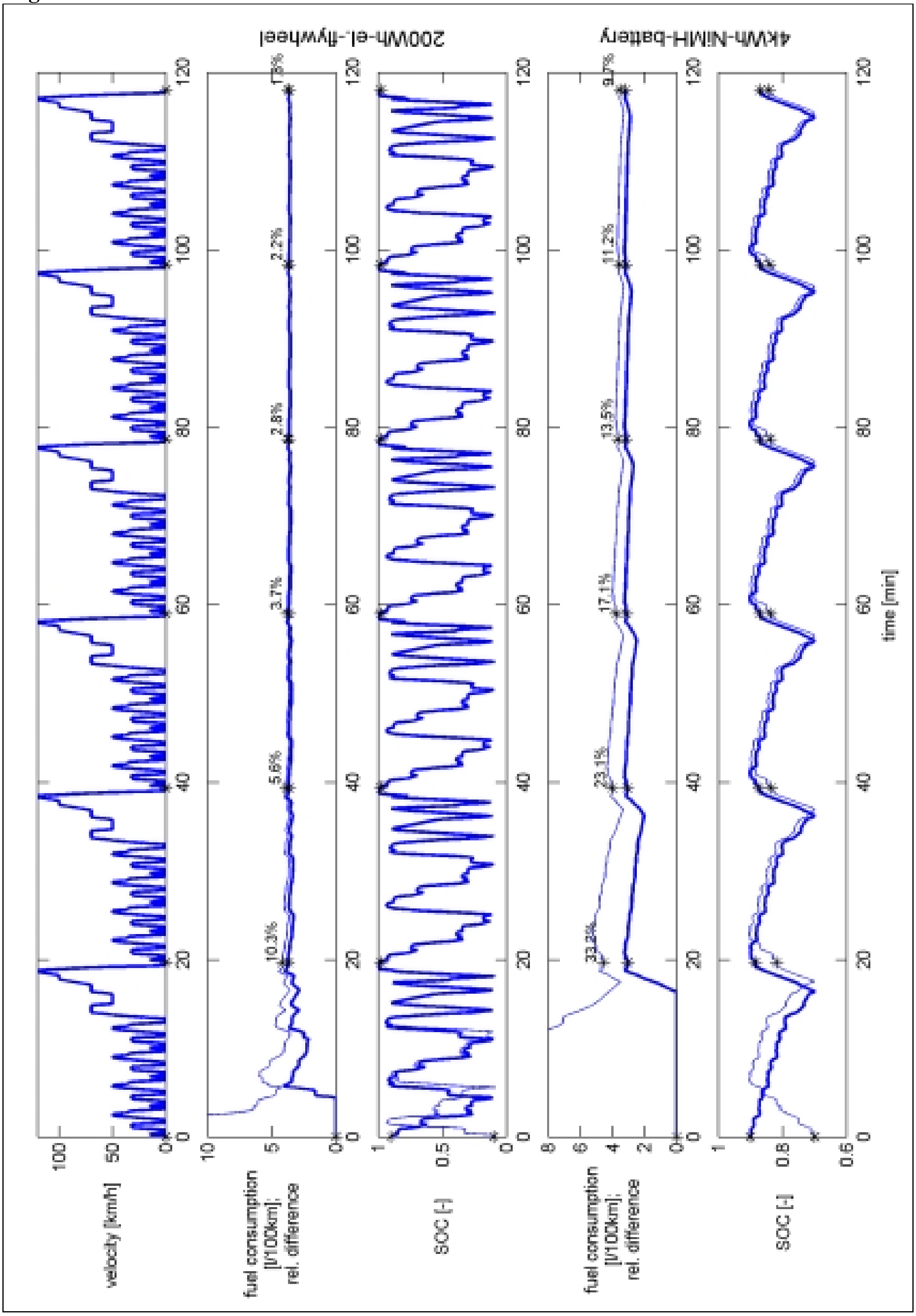


Figure 41: Simulation results for the PHEV with battery or flywheel in the NEDC driving cycle

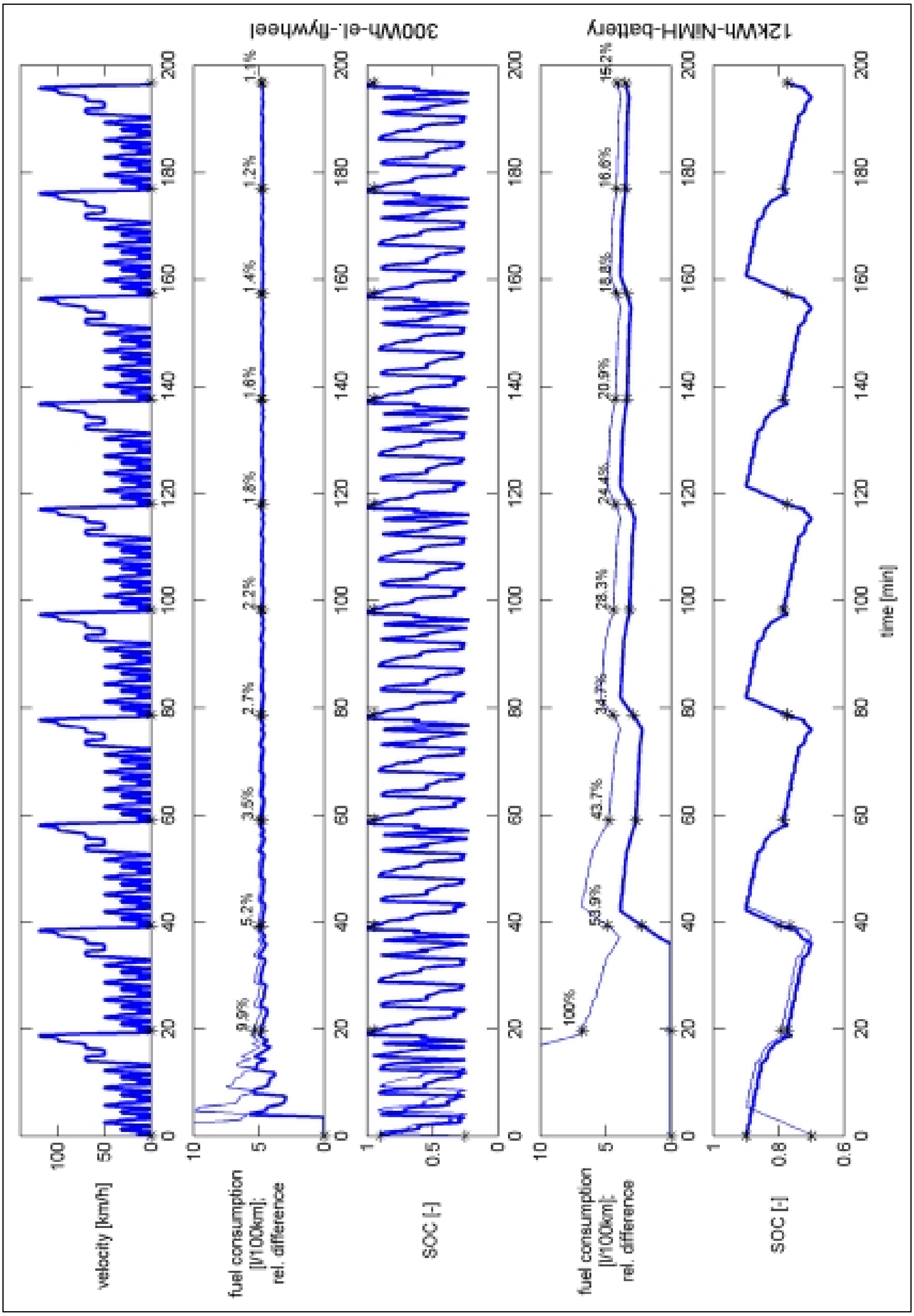


Figure 42: Simulation results for the SHEV with battery or flywheel in the NEDC driving cycle

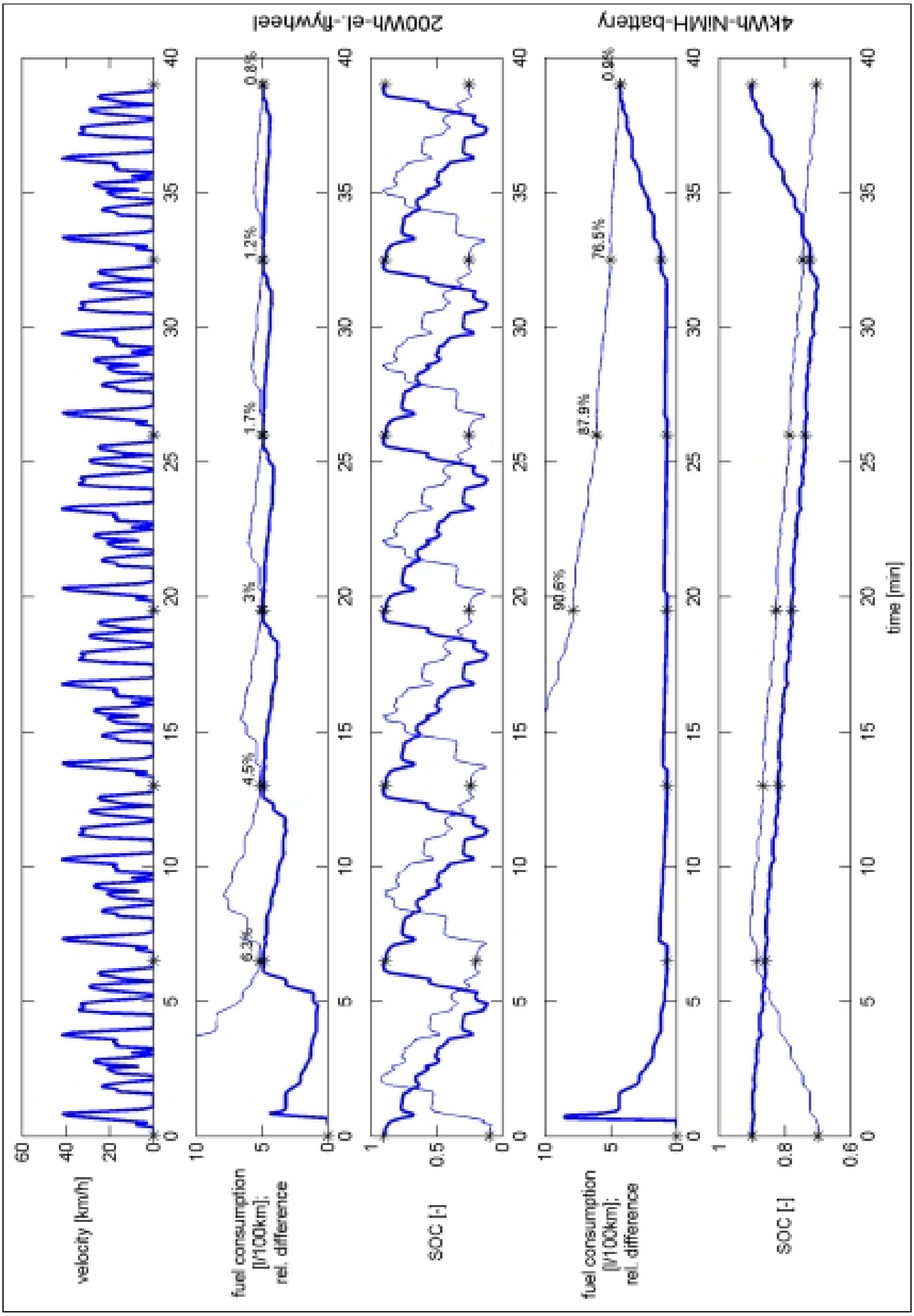


Figure 43: Simulation results for the PHEV with battery or flywheel in Aachen-city cycle

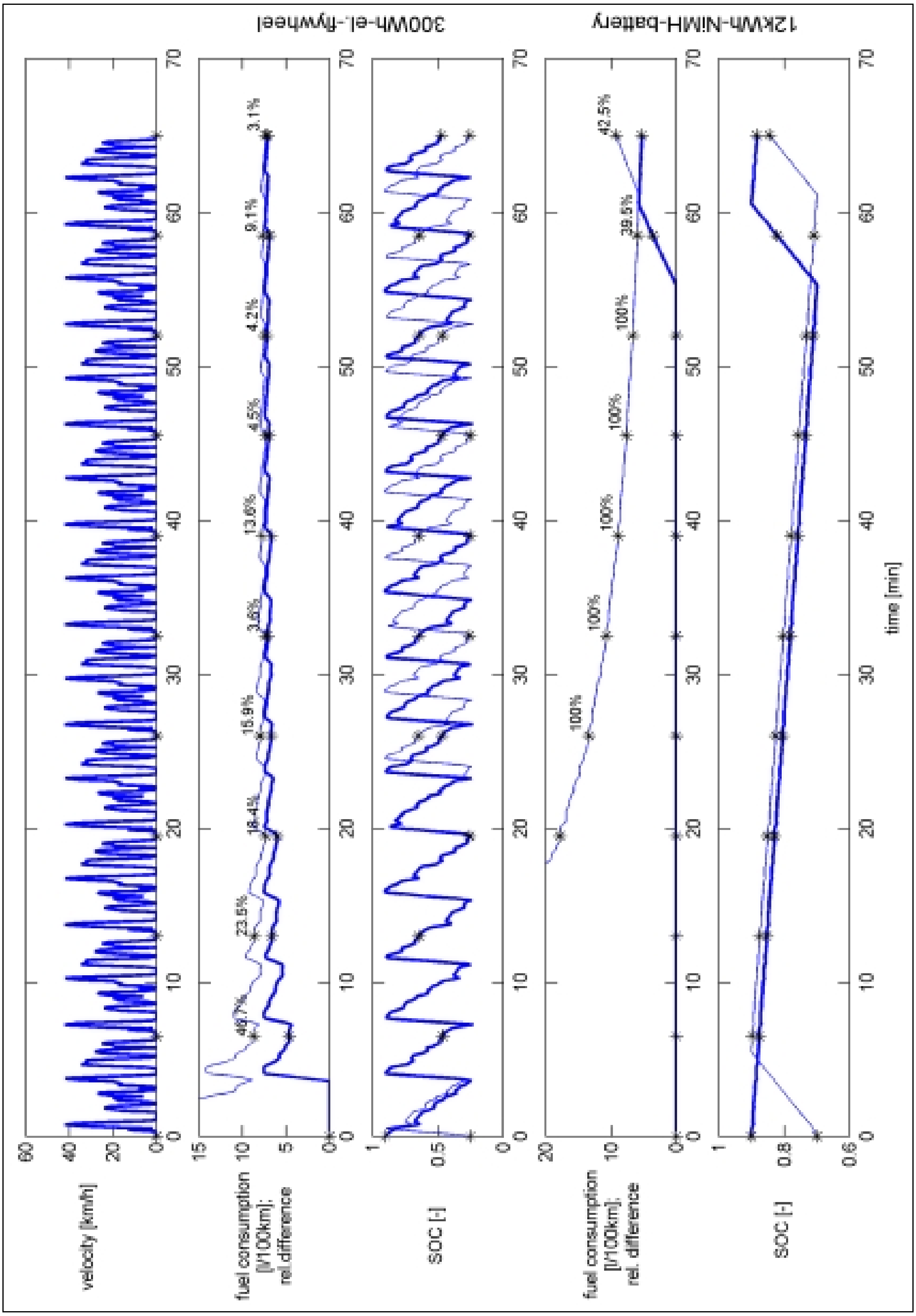


Figure 44: Simulation results for the SHEV with battery or flywheel in the Aachen-city cycle

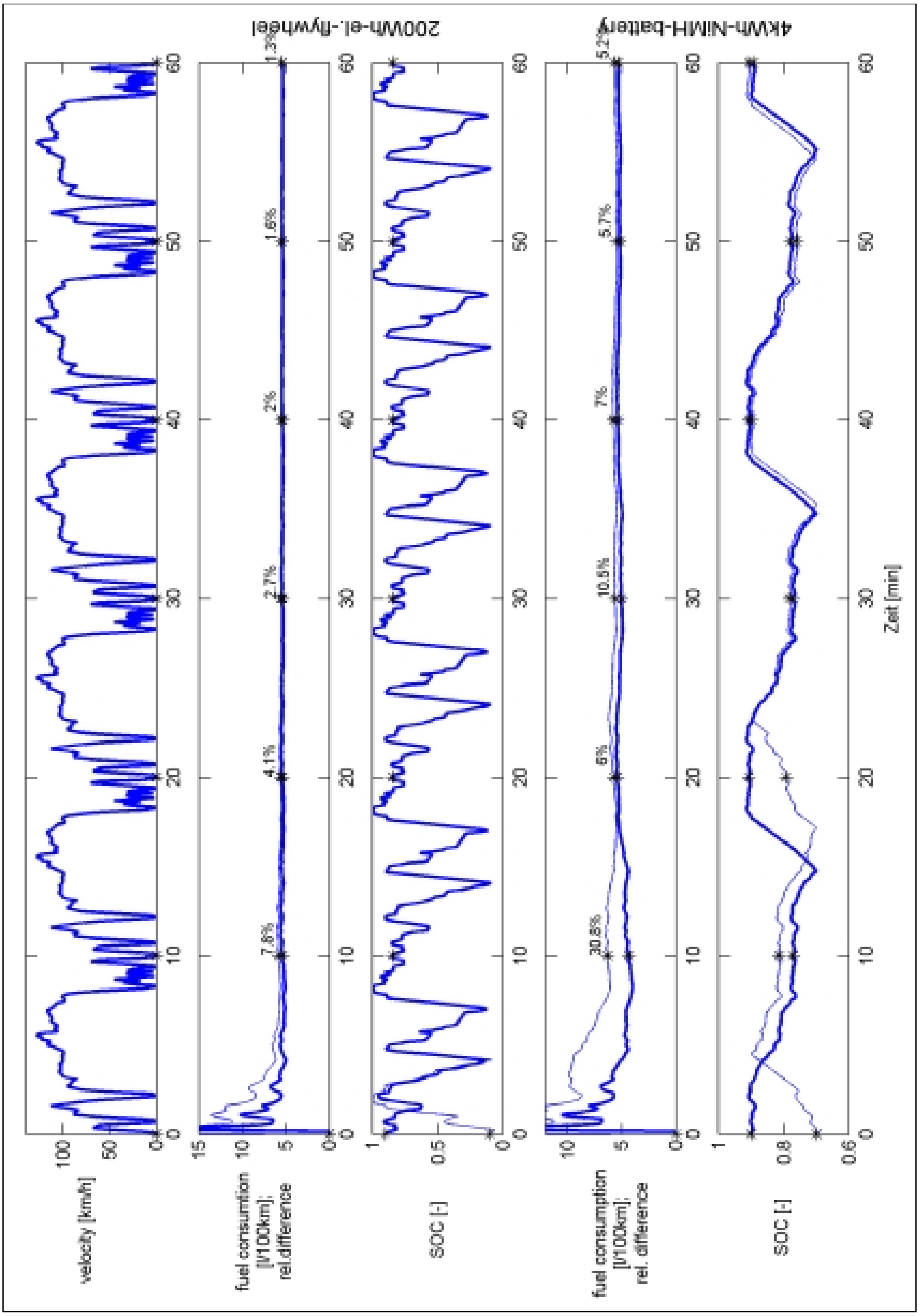


Figure 45: Simulation results for the PHEV with battery or flywheel in US06 driving cycle

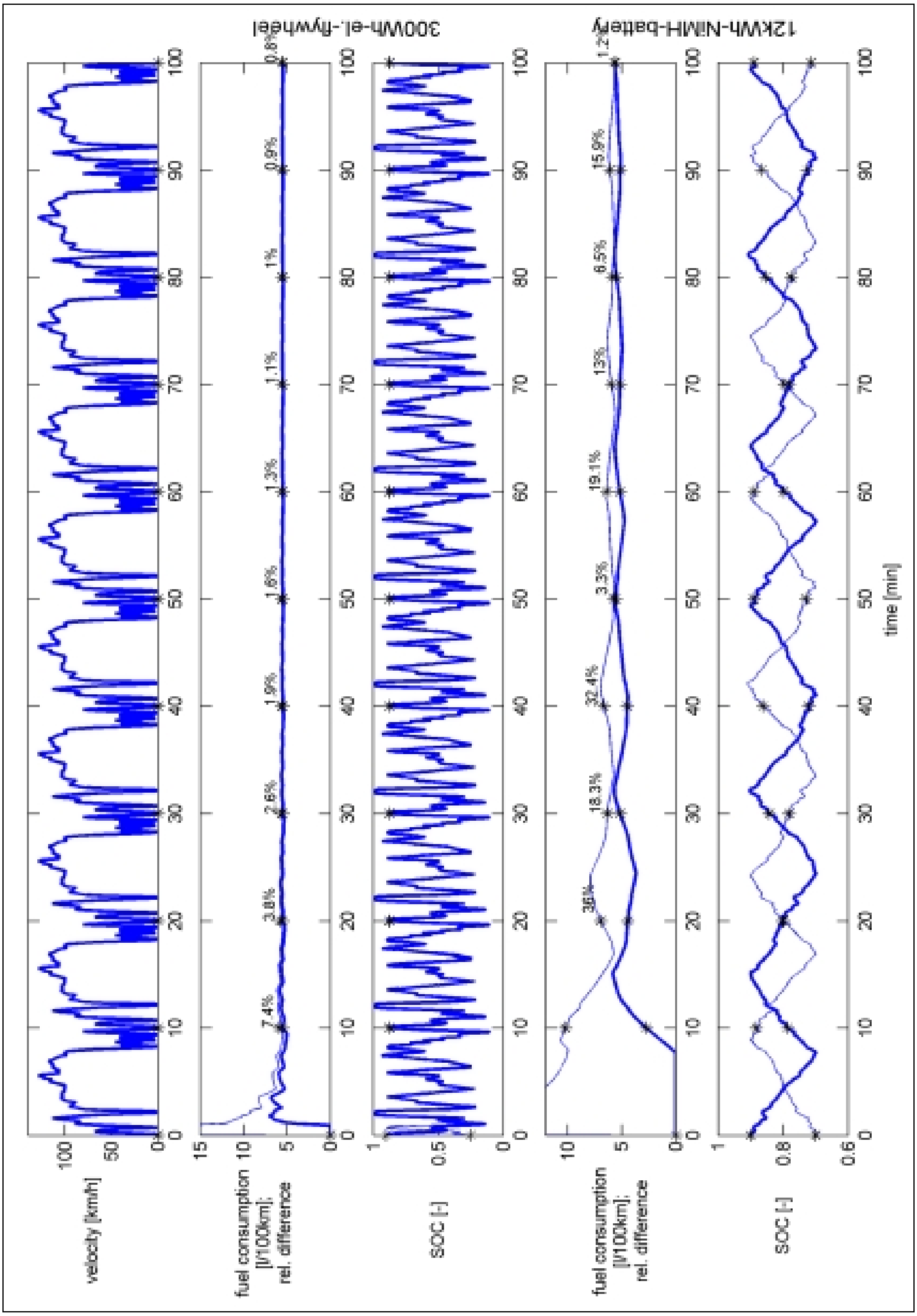


Figure 46: Simulation results for the SHEV with battery or flywheel in US06 driving cycle

Figure 6, page 15

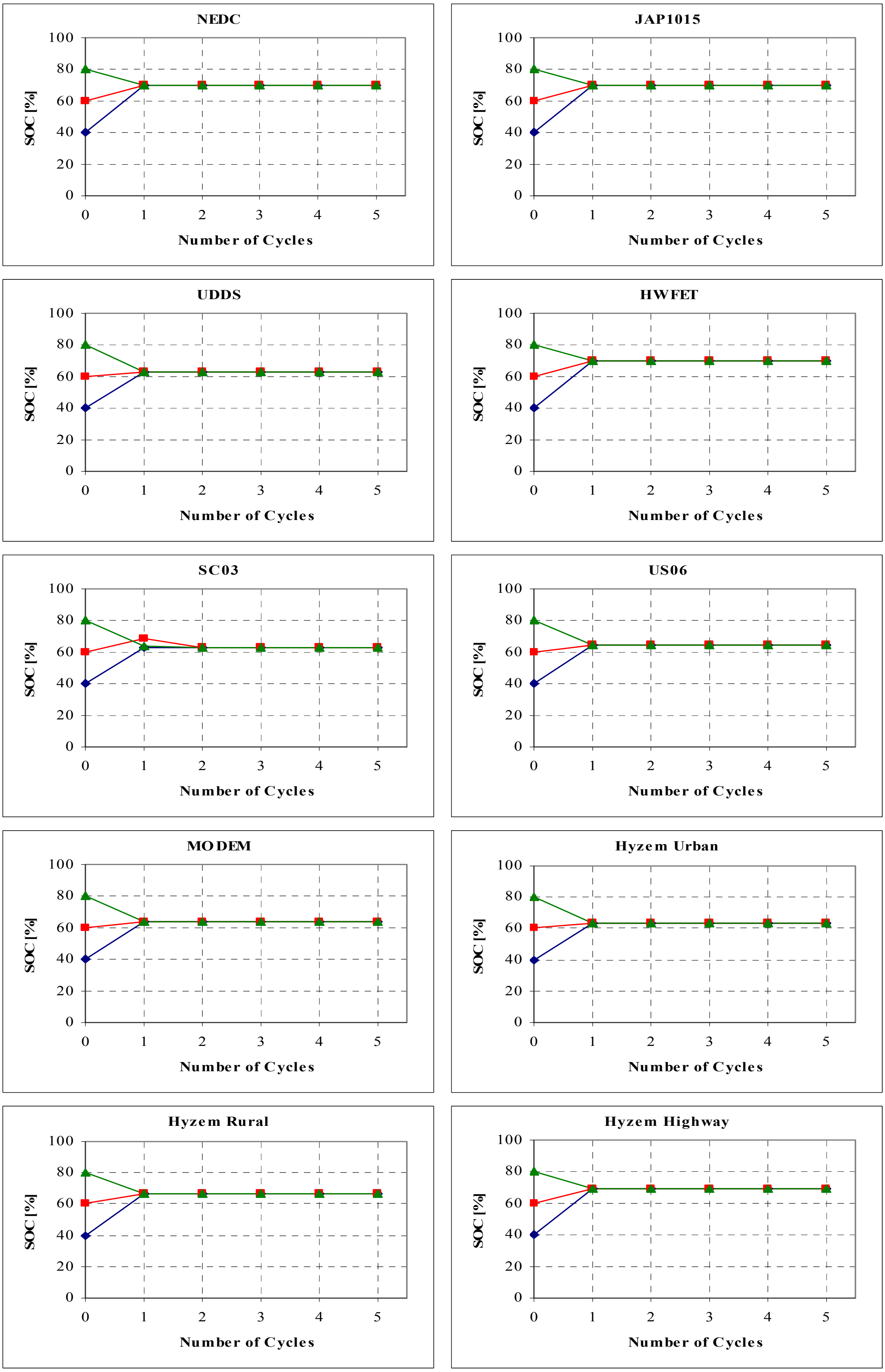


Figure 47: The influence of different initial SOC for LD SHEV on 10 different cycles

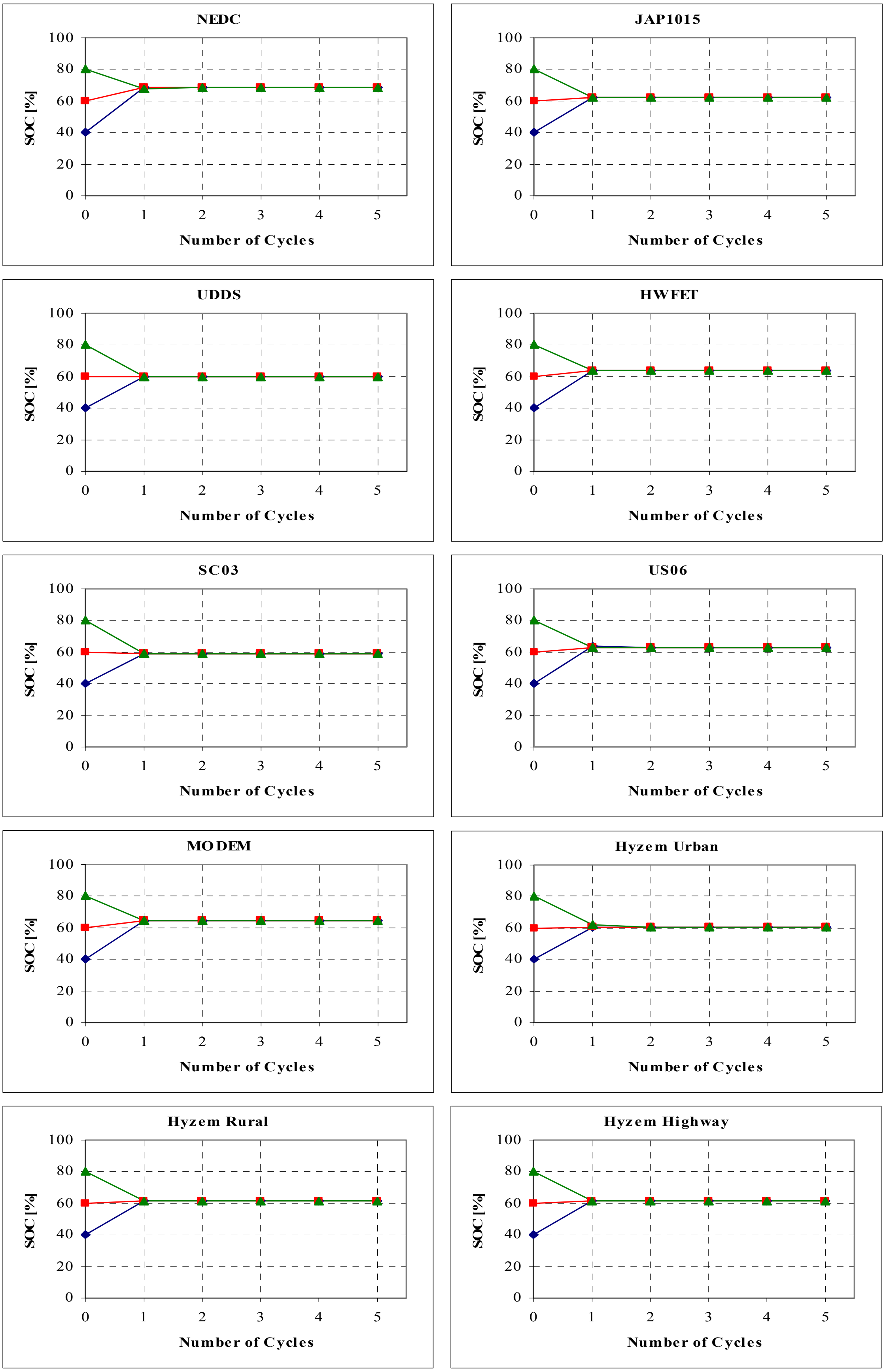


Figure 48: The influence of different initial SOC for LD CHEV on 10 different cycles

Figure 7, page 16

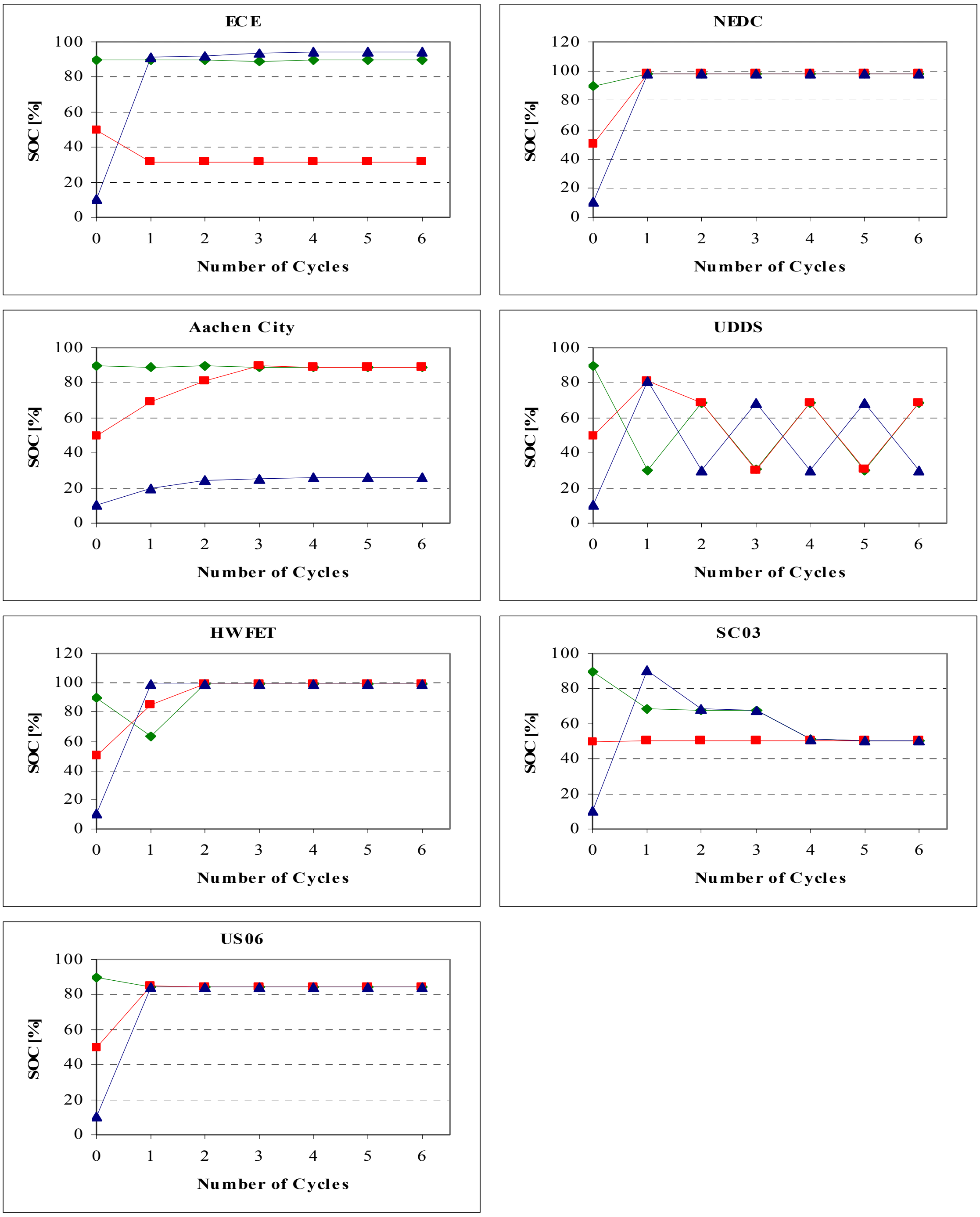


Figure 49: The influence of different initial SOC on the SOC history for a LD PHEV with flywheel storage system

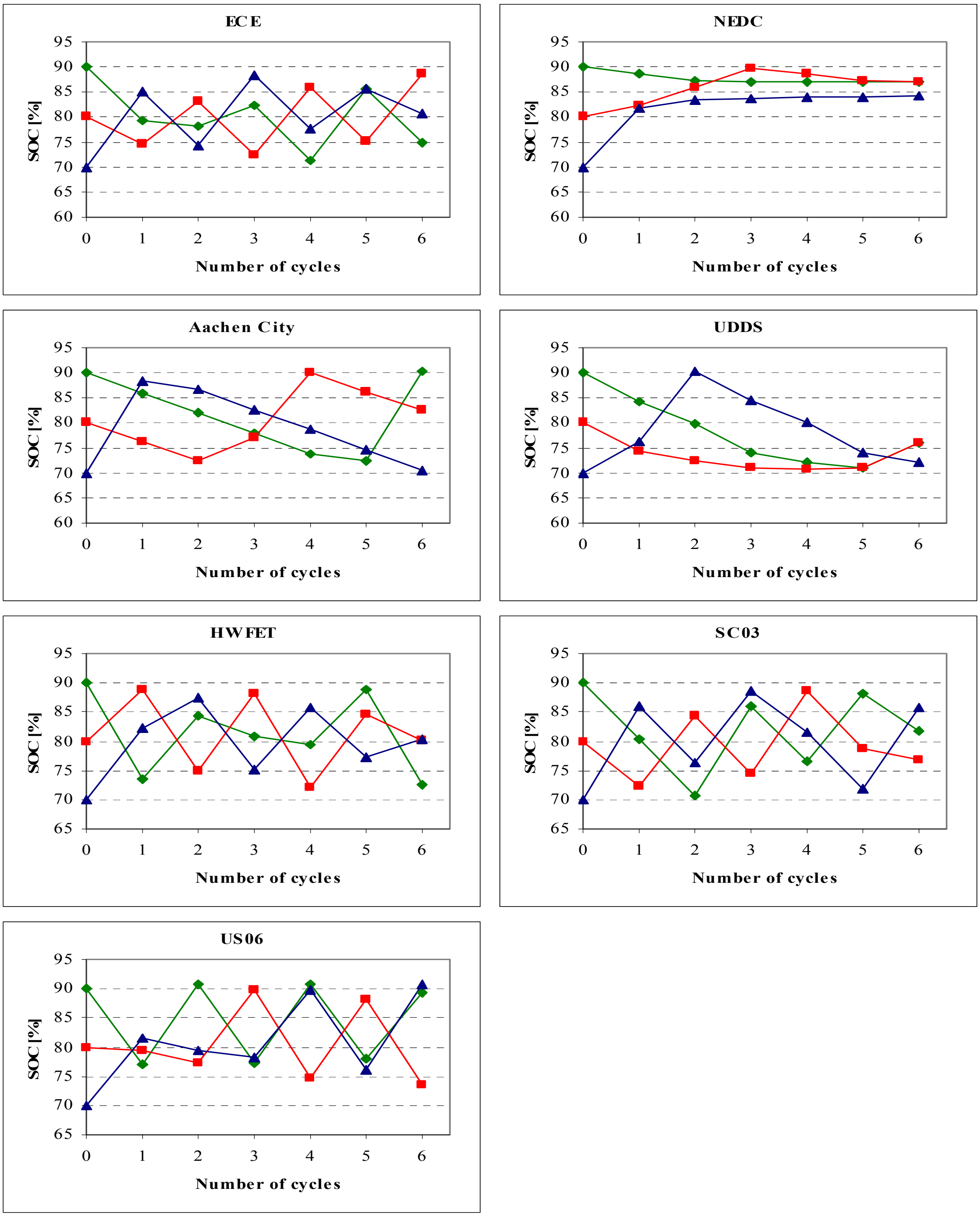


Figure 50: The influence of different initial SOC on the SOC history for a LD PHEV with battery storage system

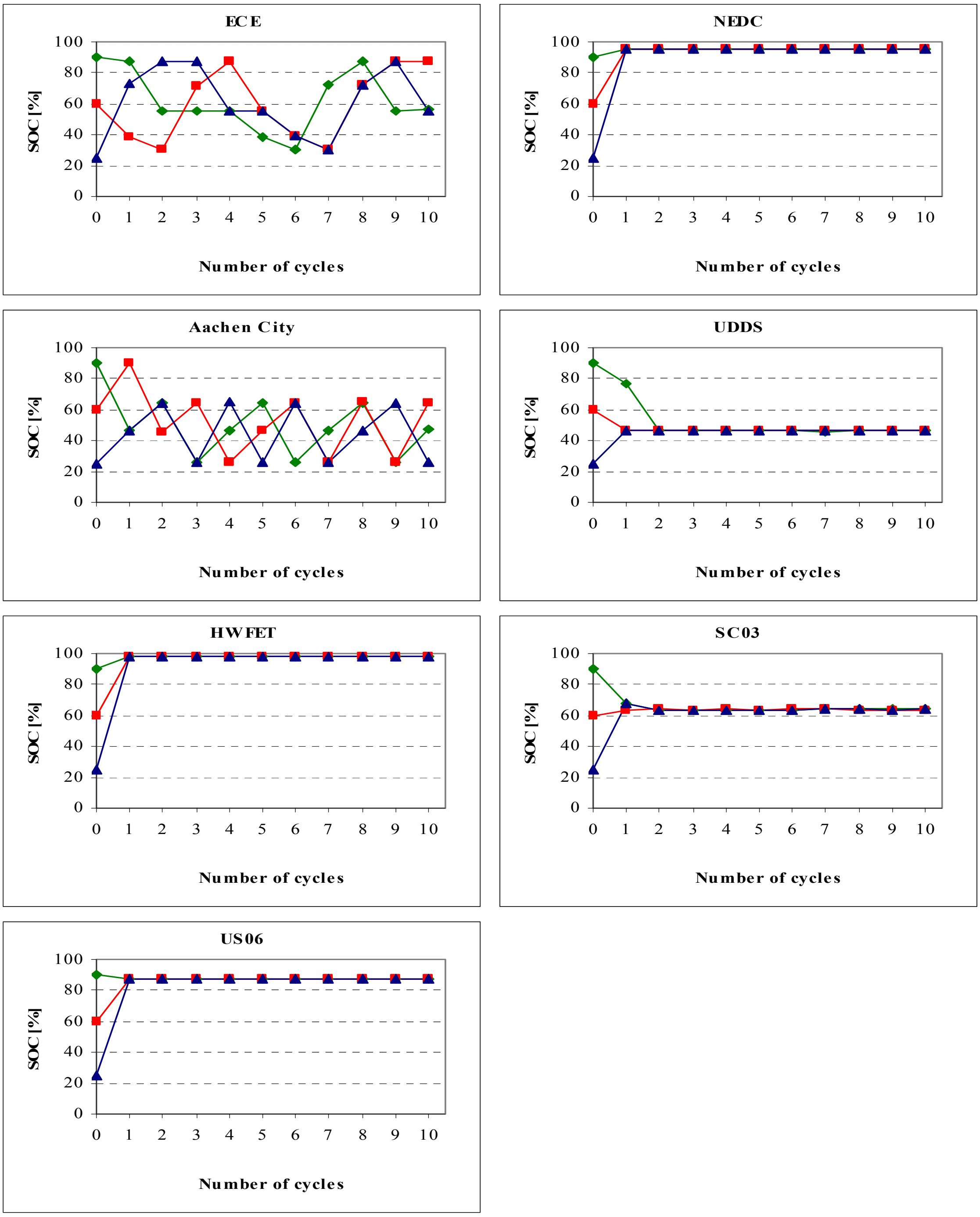


Figure 51: The influence of different initial SOC on the SOC history for a LD SHEV with flywheel storage system

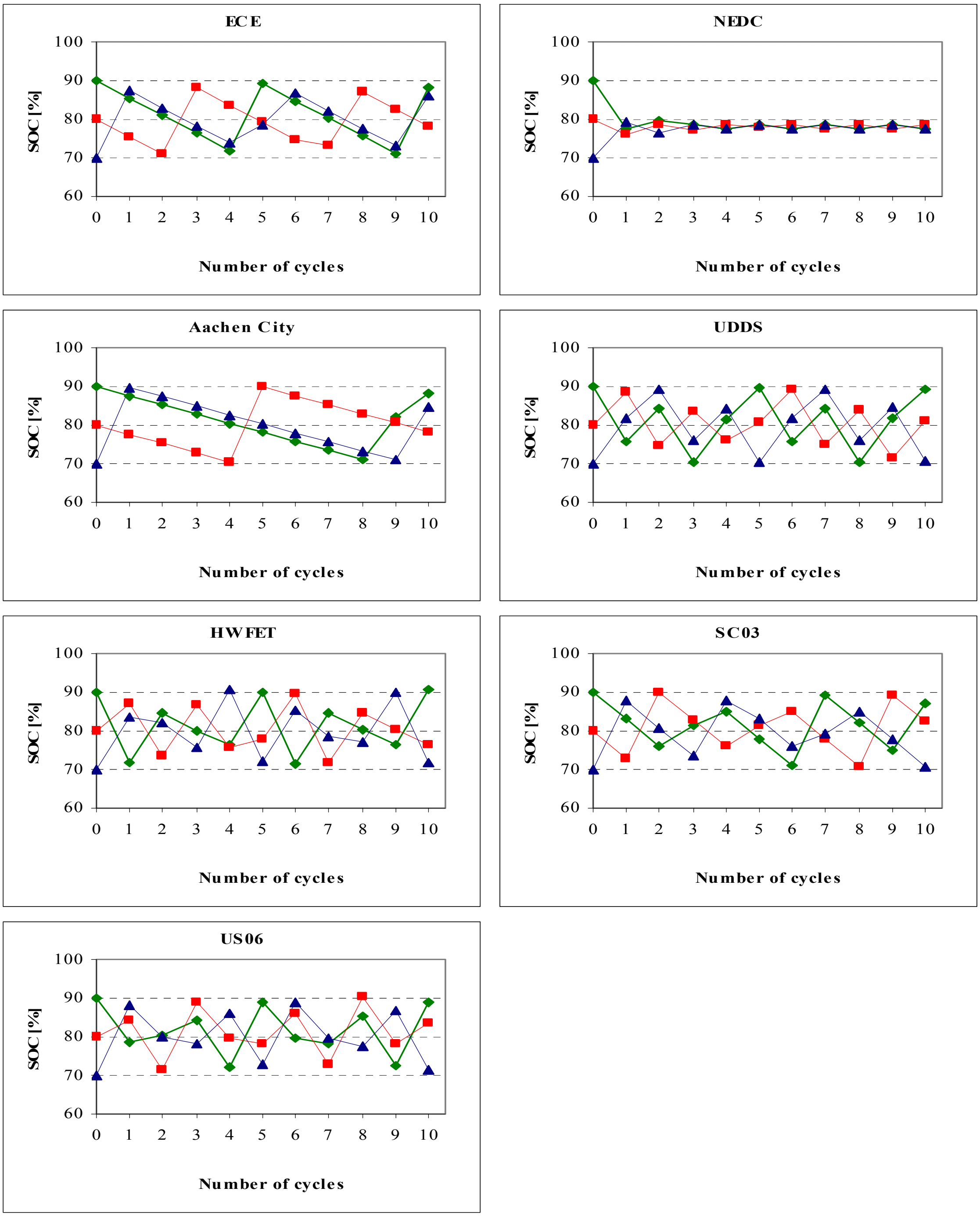


Figure 52: The influence of different initial SOC on the SOC history for a LD SHEV with battery storage system

Figure 8, page 17 Battery: □ 6.5 Ah ▲ 65 Ah

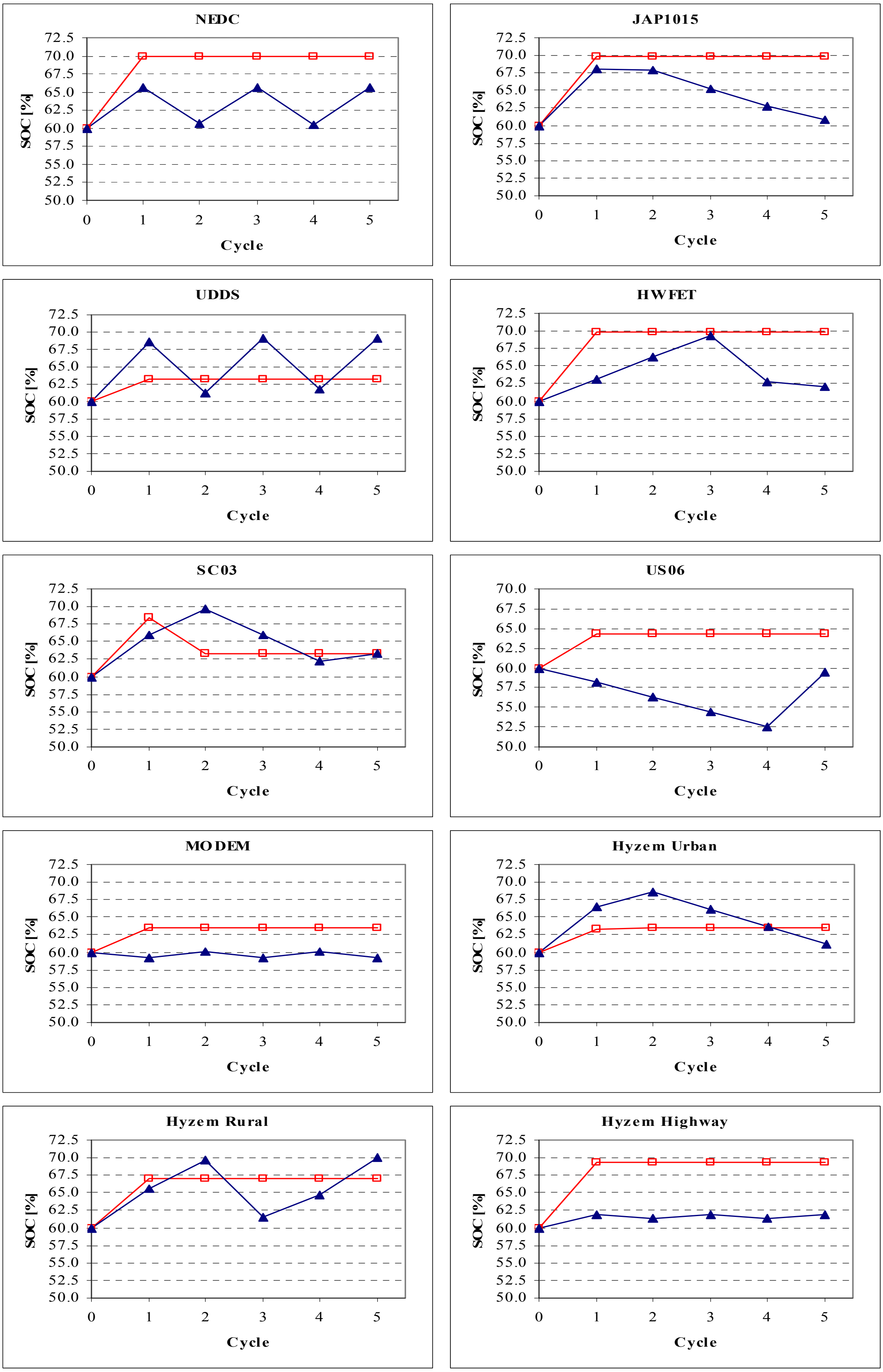


Figure 53: The influence of battery capacity for LD SHEV on 10 different cycles

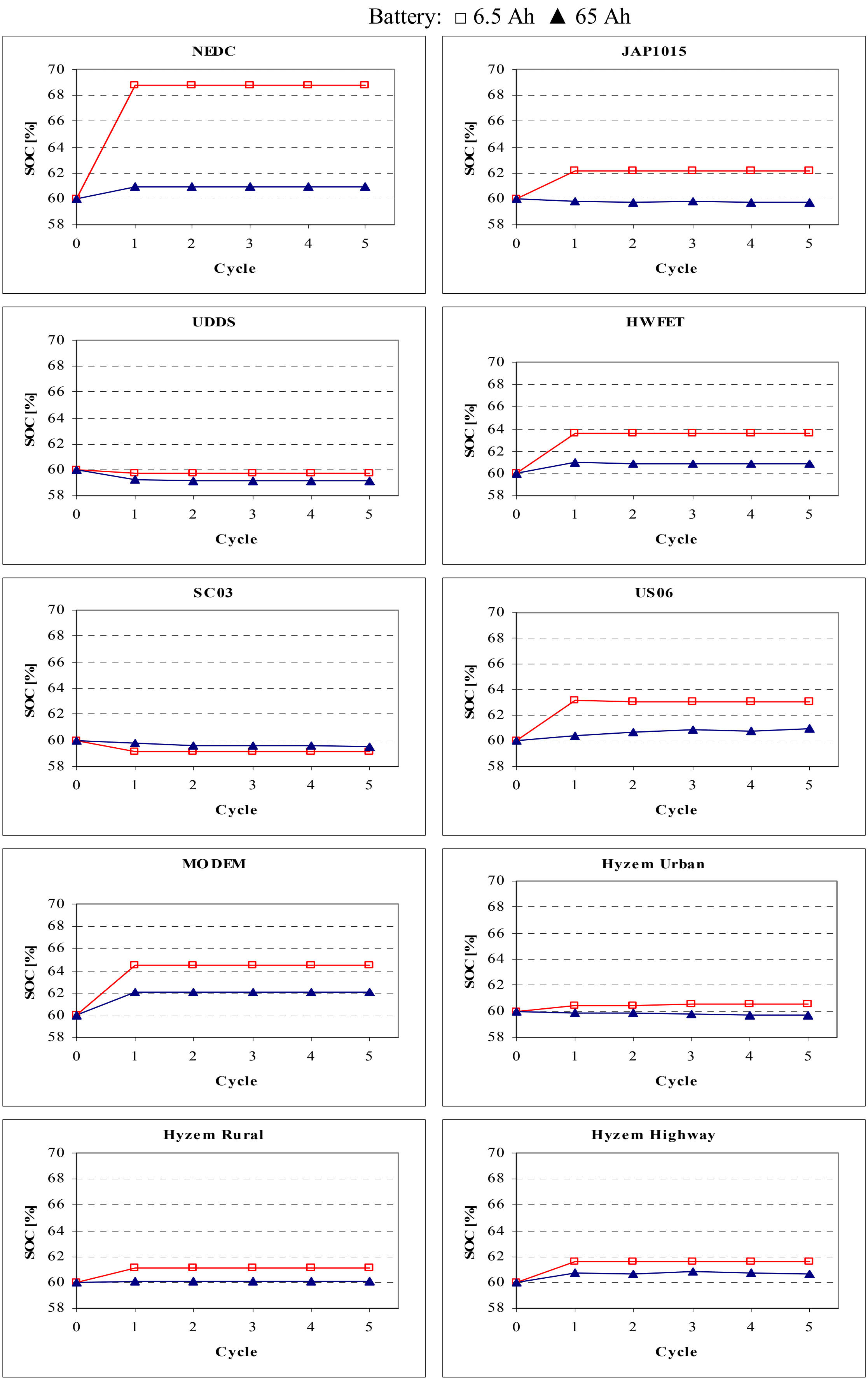


Figure 54: The influence of battery capacity for LD CHEV on 10 different cycles

Appendix C Toyota Prius

In the framework of the MATADOR project, a Toyota Prius was thorougly tested by TNO Automotive. Part of the measurements was the evaluation of the vehicle over six different driving cycles.

C1 The vehicle

The Toyota Prius (Figure 55) is the first series produced hybrid electric vehicle in the world. It was put to the market in Japan at the end of 1997 and will most likely become available onto the US and European market in the summer of the year 2000.
The Toyota Prius is equipped with the THS drive system. THS stands for Toyota Hybrid System. The THS system is a so-called combined hybrid configuration. Figure 56 shows the powertrain lay-out of the Toyota Prius. The technical specifications for the Toyota Prius are listed in Table 19.

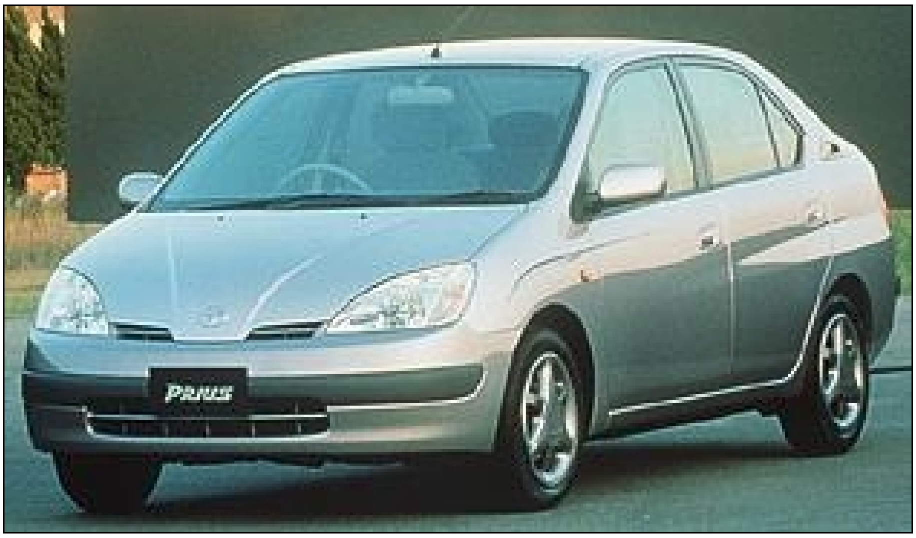


Figure 55: Toyota Prius Hybrid Electric Vehicle

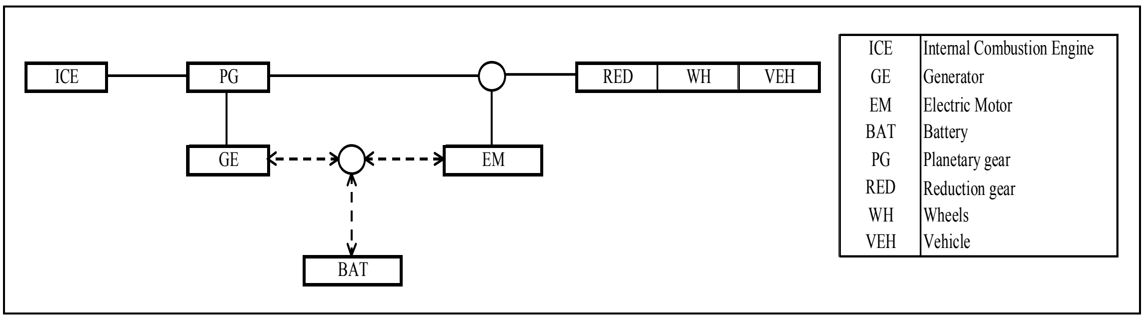


Figure 56: Toyota Hybrid System component configuration

Table 19: Toyota Prius technical specifications

Internal combustion engine		**Reduction gear**	
Type	Otto	gear ratio [-]	3.927
Max power [kW]	43	**Wheels**	
Max speed [rpm]	4000	R dynamic [m]	0.295
Max torque [Nm]	102	Number of wheels (front/rear)	2 / 2
Electric motor		**Vehicle**	
Type	Permanent magnet	Mass [kg]	1240 / 1515[1]
Power (nom/max) [kW]	max 30	C_w [-]	0.3
Base speed [rpm]	940	A [m^2]	-
Generator		**Battery**	
Type	Permanent magnet	Type	NiMH
Power (nom/max) [kW]	-	Capacity [Ah]	6.5
Base speed [rpm]	-	Cell voltage [V]	1.2
Planetary gear		Number of cells [-]	240
gear ratio [-]	-	Internal resistance [mΩ]	-

C2 Measurement procedure

The vehicle has been tested over several different driving cycles. The test cycle was driven in sequences of five with a ten minute rest in between (ignition turned off), see Figure 10. A preconditioning cycle followed by 16 hours of conditioned soak was performed the day before the sequential test.

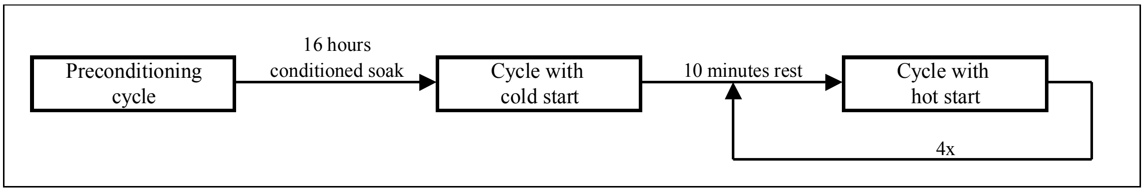


Figure 57: Test sequence used for measurements on a Toyota Prius

Before each cycle the Prius had to be brought into 'Service Mode' in order to be able to test the vehicle on a 2WD rollerbench. On the road the vehicle is driven in 'Normal Mode'. It is assumed that the 'Service Mode' does not affect the drivetrain management, and thus that the results are representative for the vehicle performances on the road.
The measurements have been performed under standard test conditions. For all consecutive cycles the bag emissions (HC, CO, CO_2, and NO_x) were sampled per cycle, and sometimes separate bags were used to divide characteristic phases (e.g. the NEDC was split into the UDC and EUDC). The emission factors are calculated for each phase and for the complete cycle using the actually driven distance on the chassis dynamometer. The fuel consumption (FC [l/100km]), in turn, is calculated from the bag emissions using the carbon balance method (Equation 3). The concentrations of HC, CO, and CO_2 are in g/km and the fuel's density (ρ) is in kg/l.

$$FC = \frac{0.1154}{\rho_{fuel}} \cdot \left(0.866 \times HC + 0.429 \times CO + 0.273 \times CO_2\right) \quad \textit{Equation 15}$$

During the tests the current into and out of the NiMH power battery is measured. From this signal the change of capacity in Ampèrehours (Ah) is calculated by integrating the current. The ΔSOC value is obtained by relating the ΔQ (in Ah) to the maximum battery capacity (6.5 Ah).

C3 Measured and calculated parameters

The following measuring signals were recorded:

Low frequency:

- Speed of the rollerbench, v(t) at 1Hz
- Speed of the ICE, $n_{ICE}(t)$ at 1 Hz
- NiMH battery
  - current (DC), $I_{BATT}(t)$ at 1Hz
  - voltage (DC), $U_{BATT}(t)$ at 1Hz

High frequency:

- Electric motor
  - Phase current (AC), $I_{MOT}(t)$ at 7500Hz
  - Phase voltage (AC), $U_{MOT}(t)$ at 7500Hz
- Generator
  - Phase current (AC), $I_{GEN}(t)$ at 7500Hz
  - Phase voltage (AC), $U_{GEN}(t)$ at 7500Hz

The following signals were calculated:

- Battery power (Equation 16)
- Electric motor power (Equation 17)
- Generator power (Equation 18)
- ΔSOC (Equation 19)

$$P_{BATT}(t) = U_{BATT}(t) \cdot I_{BATT}(t)$$ *Equation 16*

$$P_{MOT}(t) = 3 \cdot U_{MOT}(t) \cdot I_{MOT}(t)$$ *Equation 17*

$$P_{GEN}(t) = 3 \cdot U_{GEN}(t) \cdot I_{GEN}(t)$$ *Equation 18*

$$\Delta SOC = \int_{t=\text{cycle start}}^{t=\text{cycle end}} I_{BATT}(t) \cdot dt$$ *Equation 19*

For all the cycles except the preconditioning cycle the bag emissions of HC, CO, CO_2 and NO_X were measured over the different characteristic phases in each cycle. For example, the ECE was split up into two phases, the UDC (bag 1) and the EUDC (bag 2). The emission factors are calculated for each cycle phase and for the complete cycle using the driven distance on the rollerbench.

$$\text{emission factor}\,[g/km] = \frac{\text{bag emission}\,[g/\text{cycle}]}{\text{cycle distance}}$$ *Equation 20*

With:

$$\text{cycle distance} = \int_{t=\text{cyclestart}}^{t=\text{cycleend}} v(t) \cdot dt \qquad \textit{Equation 21}$$

The fuel consumption was calculated from the emission factors using the carbon balance method:

$$FC = \frac{0.1154}{\rho_{fuel}} \cdot \left(0.866 \times HC + 0.429 \times CO + 0.273 \times CO_2\right) \qquad \textit{Equation 22}$$

C4 Results

The vehicle was driven over 6 different driving cycles:

1. New European Driving Cycle (NEDC)
2. Japanese 10-15 Mode Hot Cycle (Jap1015)
3. US City Cycle (USFTP75)
4. Hyzem Urban
5. Hyzem Rural
6. Hyzem Highway

The results of the calculations for each driving cycle are presented in Table 20.

Table 20: Measurement results for a Toyota Prius

	dQ [Ah/100km]	HC [g/km]	CO [g/km]	CO2 [g/km]	NOx [g/km]	FC [l/100km]
NEDC (UDC+EUDC) (cold)	-	0.02	0.13	132.6	0.05	5.54
NEDC (UDC+EUDC) (hot)	-0.098	0.01	0.03	112.8	0.04	4.71
	0.372	0.01	0.03	112.9	0.05	4.71
	0.462	0.01	0.06	113.4	0.05	4.74
	0.243	0.01	0.05	112.6	0.05	4.71
Japanese 10-15 (cold)	-0.289	0.18	0.70	169.3	0.08	7.13
Japanese 10-15 (hot)	-1.070	0.01	0.09	108.0	0.02	4.51
	-0.175	0.01	0.05	108.7	0.02	4.54
	0.570	0.01	0.03	110.9	0.04	4.63
	-0.061	0.01	0.03	109.9	0.03	4.59
USFTP75 (cold)	0.323	0.04	0.29	126.8	0.04	5.32
USFTP72 (hot)	-1.879	0.01	0.05	104.8	0.05	4.38
	0.275	0.01	0.07	110.1	0.04	4.60
	-0.146	0.01	0.05	109.2	0.05	4.56
	0.269	0.01	0.05	110.9	0.06	4.63
Hyzem Urban (cold)	1.358	0.15	0.98	175.7	0.05	7.42
Hyzem Urban (hot)	-5.445	0.01	0.12	119.2	0.12	4.98
	0.036	0.01	0.12	130.3	0.12	5.45
	0.540	0.01	0.05	129.4	0.11	5.40
	0.306	0.01	0.04	127.4	0.14	5.32
Hyzem Rural (cold)	0.864	0.10	0.72	140.9	0.11	5.94
Hyzem Rural (hot)	-0.371	0.01	0.15	123.6	0.14	5.17
	0.394	0.01	0.08	123.4	0.16	5.15
	0.409	0.01	0.11	123.5	0.12	5.16
	0.409	0.01	0.14	122.6	0.11	5.13
Hyzem Highway (cold)	0.527	0.03	0.22	156.1	0.22	6.53
Hyzem Highway (hot)	0.159	0.01	0.12	147.4	0.19	6.15
	0.096	0.01	0.12	148.0	0.18	6.18
	0.063	0.01	0.20	148.7	0.20	6.22
	0.308	0.01	0.15	149.4	0.17	6.24

Appendix D TNO P2010 Series Hybrid Electric Vehicle

D1 The project P2010

TNO, along with a number of other companies, is currently working on a demonstrator vehicle with an advanced alternatively powered driveline. This project is called '*P2010*', the development of a mid-sized passenger car for the year 2010. On the one hand, the project aims at an important contribution in crash-safety design, while on the other hand the development and introduction of an advanced powertrain are important goals.
The dramatic improvement of passenger-car crash safety in recent decades has tended to come at the expense of extra vehicle weight: the P2010 project aims to make an important breakthrough by improving crash-safety performance in head-on collisions by introducing controlled bending of lightweight S-shaped elements to absorb crash energy. The risk of serious injury to pedestrians is reduced by the advanced lightweight structure of the P2010 bonnet in combination with offsets to under-bonnet components, bringing the P2010 vehicle into line with the stringent requirements for passenger safety being proposed in Europe.
The series hybrid powertrain for the P2010 vehicle consists of a state-of-the-art three cilinder 1.2 litre diesel engine connected to a permanent-magnet generator, an advanced battery, power electronics, and two electric motors (capable of regenerative braking) driving the rear wheels (Figure 58). With this powertrain, optimised by a hybrid controller, fuel consumption will be reduced. Not only that, but because the hybrid powertrain allows the engine to operate in its most efficient range most of the time, the emissions are lower than those of the same engine in a traditional powertrain. In addition, the P2010's NO_x emissions will be greatly reduced by a sophisticated exhaust-gas-after-treatment system. Finally, an advanced continuously regenerative trap (CRT) promises to significantly reduce the emissions of particulates, thus allowing the vehicle to comply with the stringent California ULEV emission standards.

The hybrid control strategy determines the operating conditions for the drivetrain components. It controls the drive and regenerative braking power for the electric motors as well as the APU operating point. Herewith the battery condition is constantly taken into account.
The APU operating point is determined on the basis of the requested wheel power (60 s. moving average) and the battery's State-of-Charge. The control strategy is designed to keep the SOC within a predefined SOC window. At each SOC, the APU operating point therefore is determined in the controller (Figure 59).

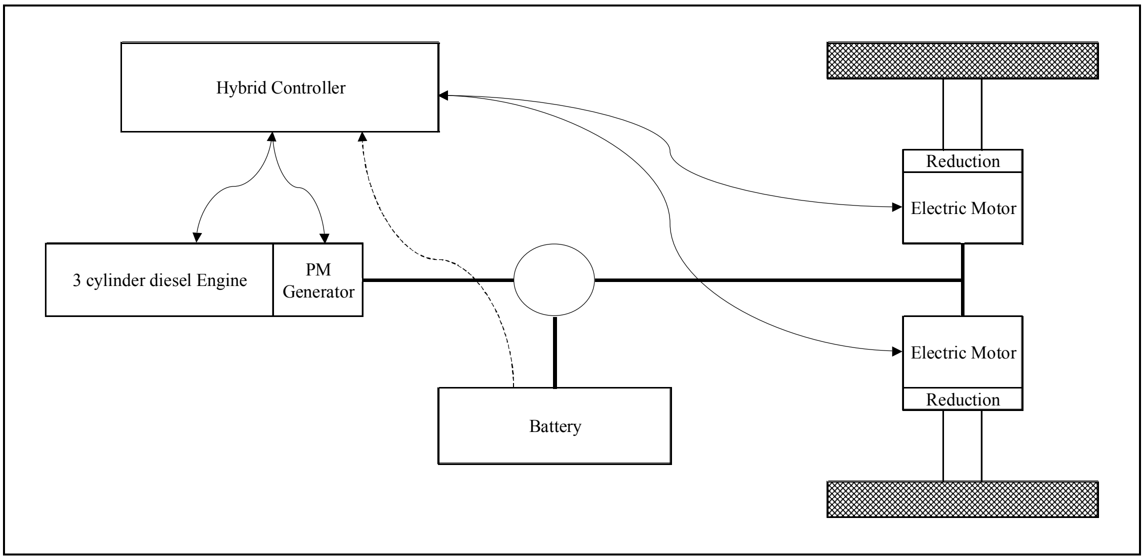


Figure 58: *P2010 Series Hybrid Electric powertrain structure*

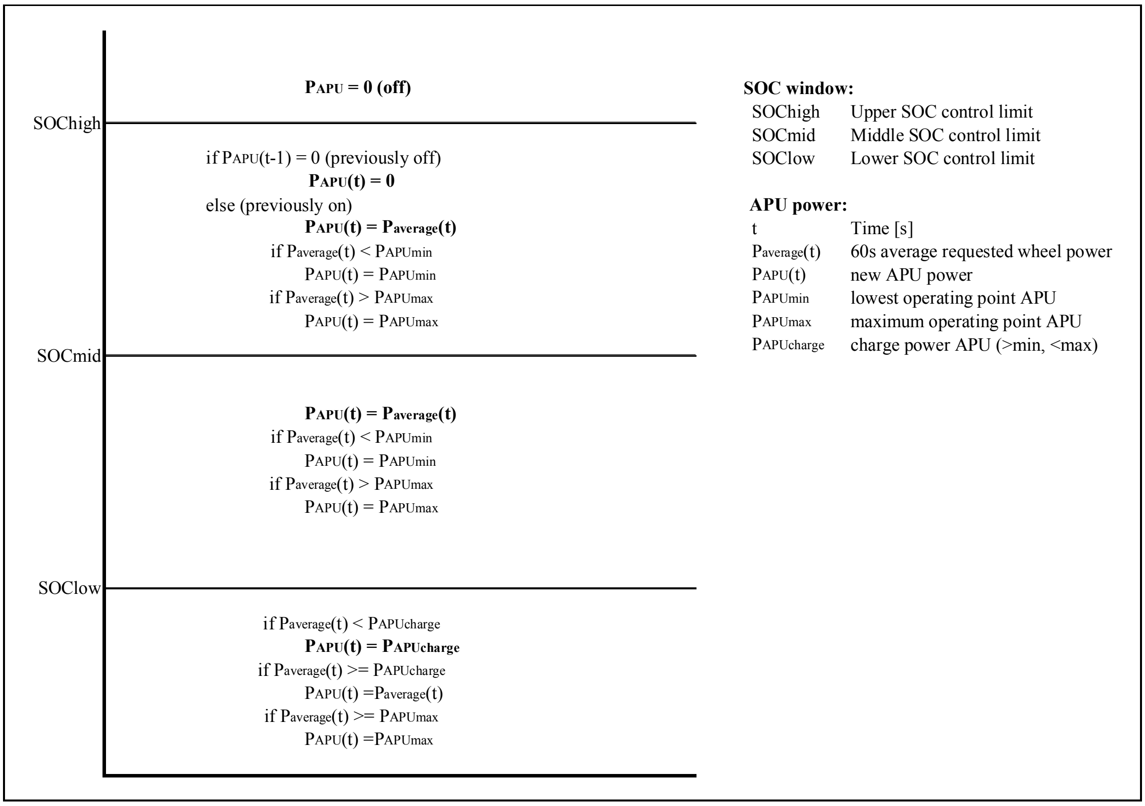


Figure 59: *P2010 APU control strategy*

D2 Specifications and testrig

For all components specifications have been determined. The main specifications are listed in Table 21. Anticipating the project a testrig has been built for validation of the control strategy and to investigate driveline behaviour. For this pre-study, industrial off-the-shelff components are used to equip the testrig (Figure 60). The substitutes have the same functionality (in order that behaviour and operating characteristics are valid for the final version of the P2010 demonstrator vehicle), yet demands for size and mass are not of importance.

The electric motors used on the testrig for instance, are direct drive. No reduction gear thus is needed to provide the required torque at the wheels. For this pre-study, a conventional lead-acid battery is used. This battery, however, has a (relatively) poor power density, which necessitates the use of a larger pack with a higher total energy content (20 times higher). The control strategy uses a small SOC window for the control of the APU. This SOC window corresponds to a certain energy content of the battery. Since the battery for this testrig has a much higher energy content, this window is adjusted so that the vehicle operates with the same battery energy variation.
Due to problems with the generator and inverter, a DIGATRON is used as replacement. The DIGATRON is an electrical apparatus that can provide energy from and to the grid. It can be programmed to simulate electrical components like batteries or, as in this case, the generator (set). No actual fuel consumption thus can be measured on the testrig at this moment. Instead, the electricity 'generated' by the DIGATRON (output power equal to target generator power) is used to determine the energy consumption.

Table 21 – P2010 component specifications

Engine		**Electric Motor**	
Type	diesel	Type	Induction
P [kW]	45	P nom/max [kW]	18 / 25
PICEmin [kW]	17 @ 1950 rpm	T nom/max [Nm]	80 / 120
PICEmax [kW]	43 @ 4000 rpm	**Reduction gear**	
Generator		i	4.57
Type	Permanent Magnet	efficiency	0.96
P [kW]	45	**Wheels**	
base speed [rpm]	4000	Radius [m]	0.3
Battery		f_r	0.007
Type	NiCd	**Vehicle**	
Capacity [Ah]	9	Mass [kg]	1070
U nom [V]	320	C_w	0.3
Energy [kWh]	2.88	A [m^2]	2

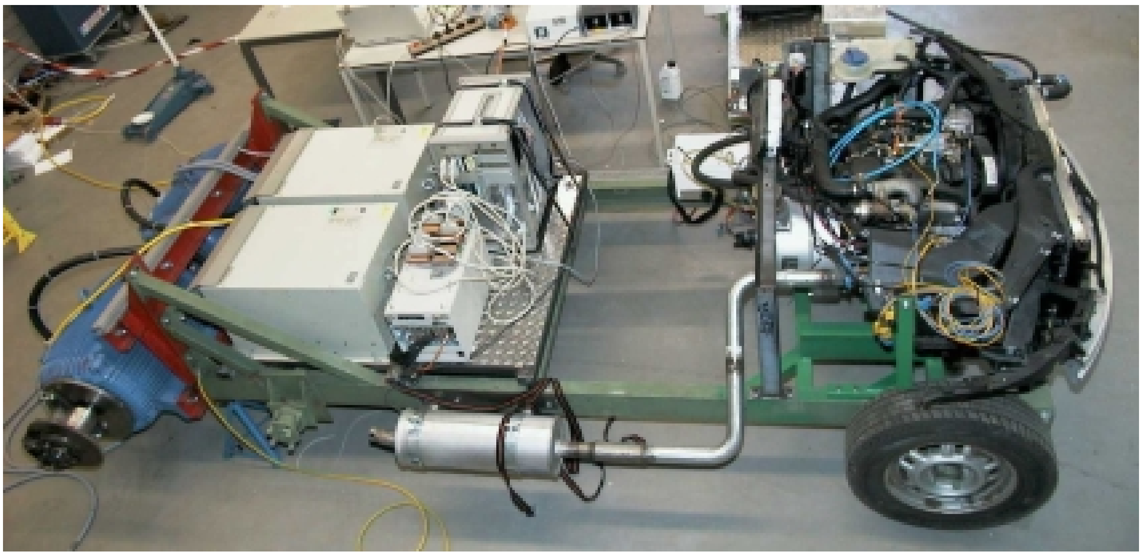
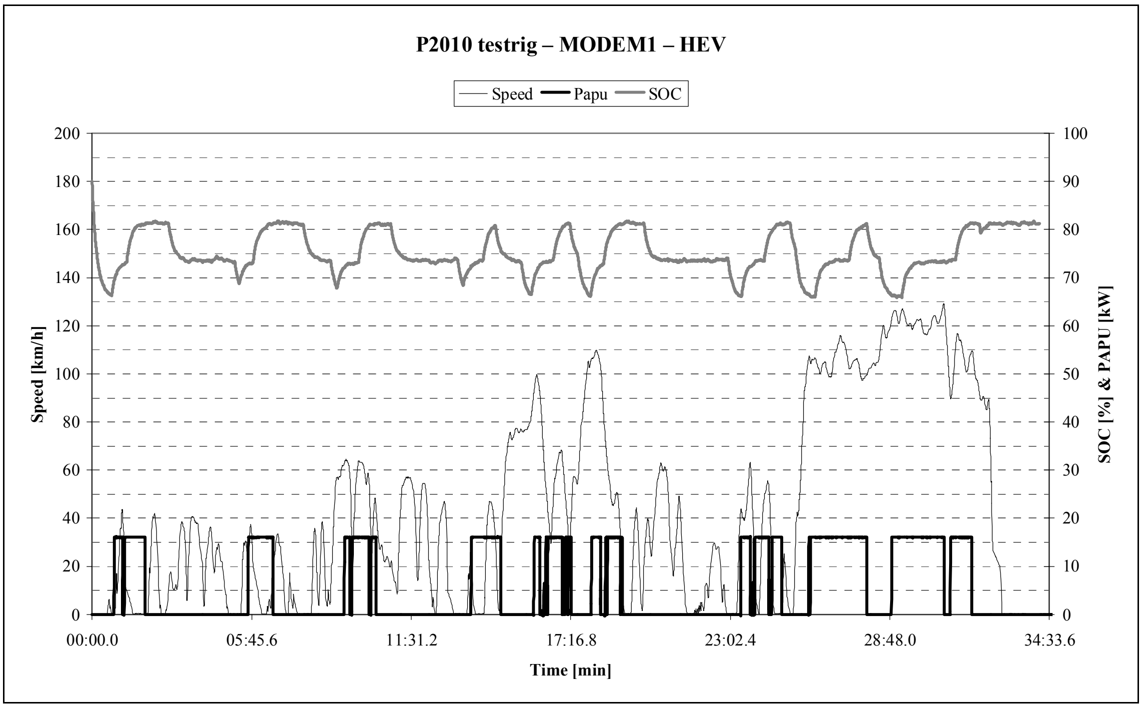


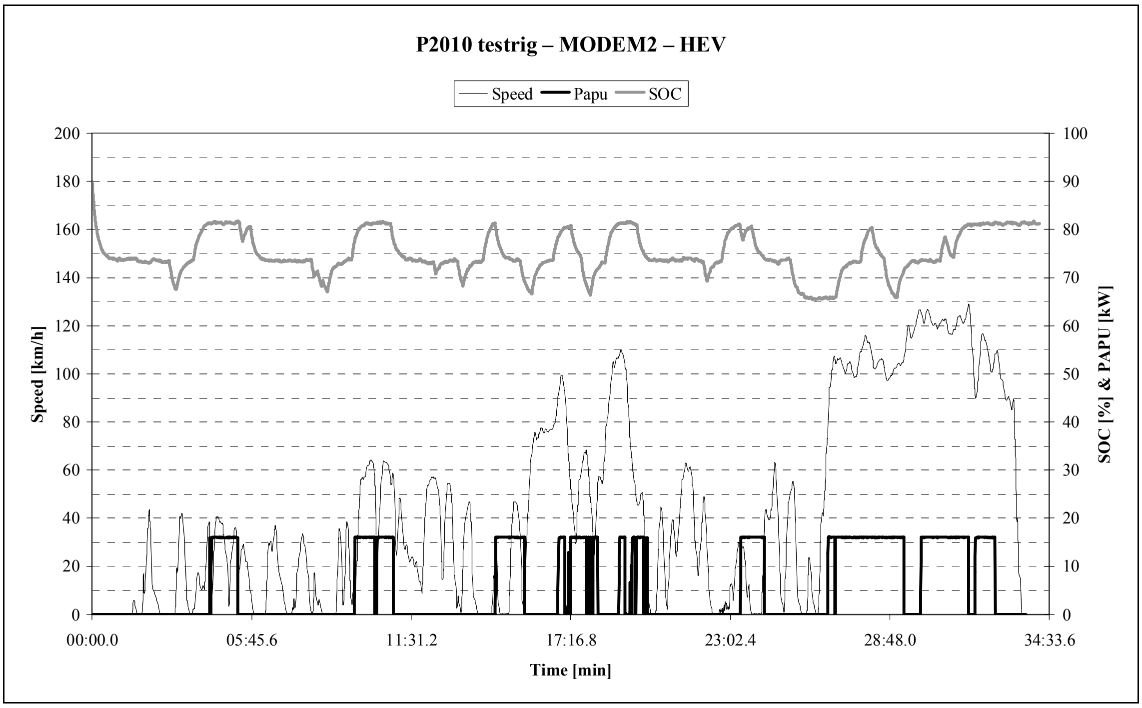
Figure 60: The P2010 testrig (without rear wheel tyres)

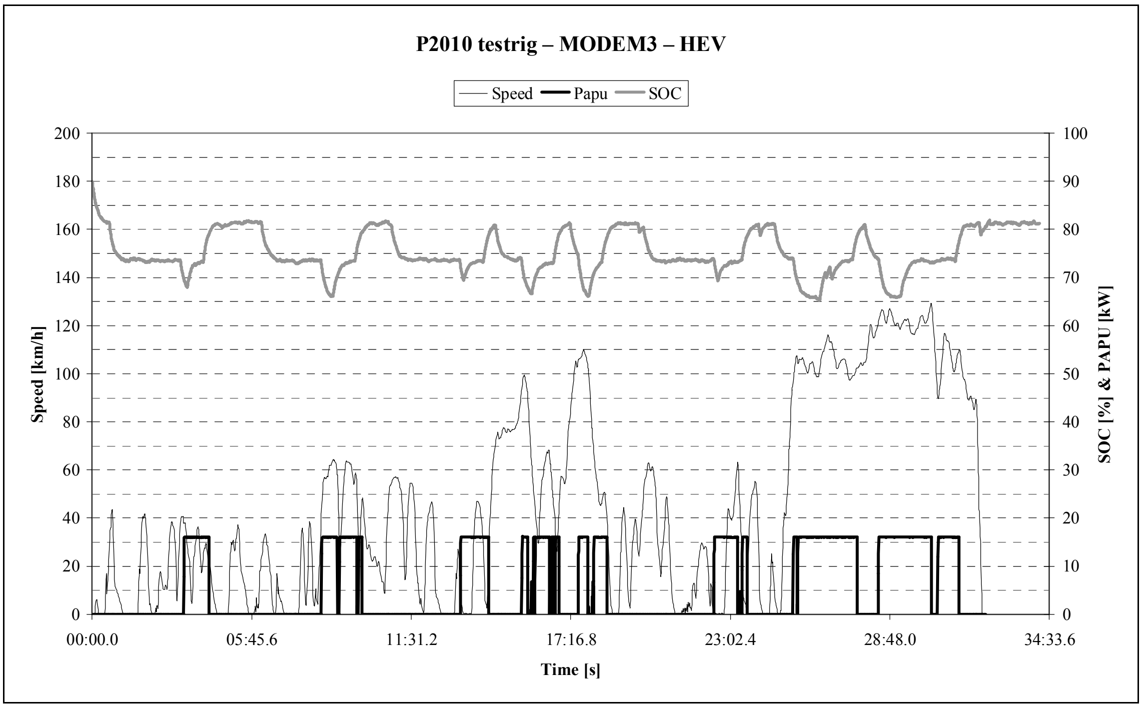
D3 Results

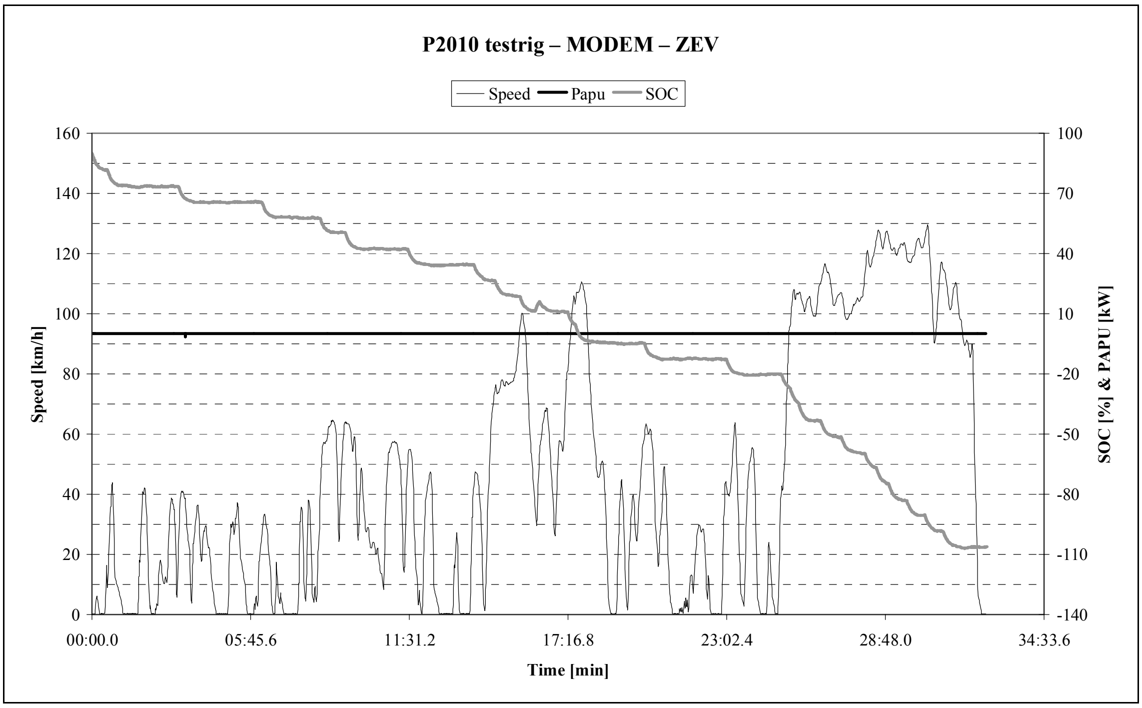
This appendix lists the figures with the speed traces, APU operating profiles, and the SOC history for the performed measurements. The figures are presented in the following order:

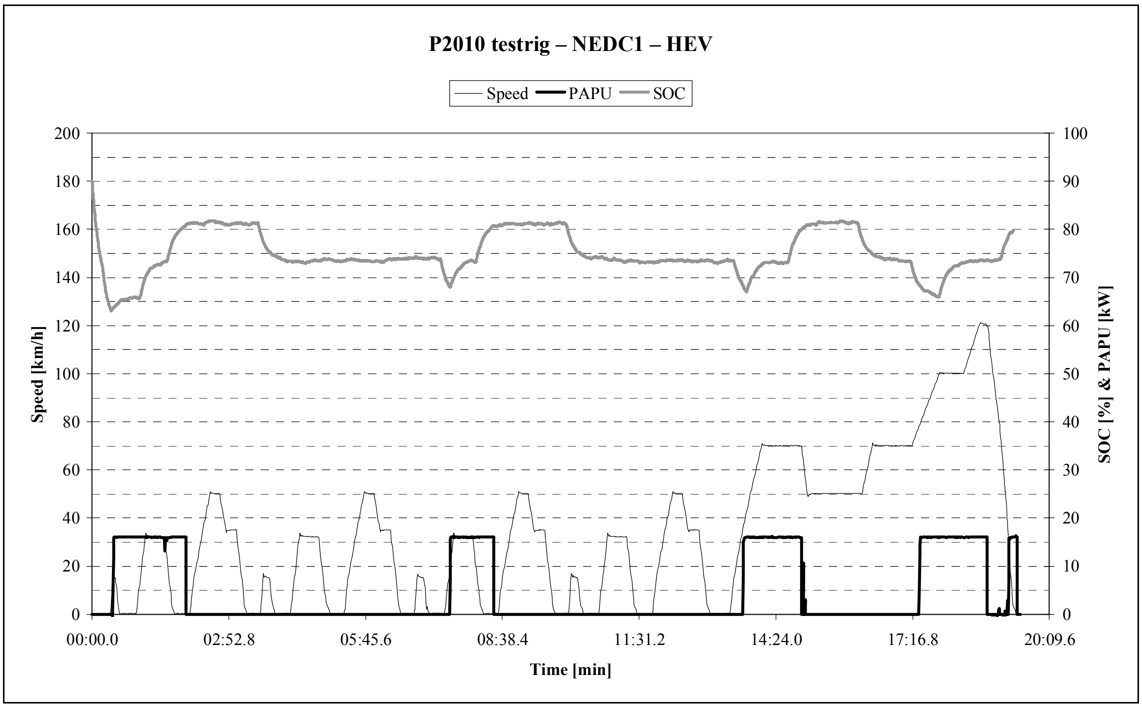
- 1st MODEM cycle, HEV operation
- 2nd MODEM cycle, HEV operation
- 3rd MODEM cycle, HEV operation
- MODEM cycle, ZEV operation
- 1st NEDC cycle, HEV operation
- 2nd NEDC cycle, HEV operation
- 3rd NEDC cycle, HEV operation
- NEDC cycle, ZEV operation
- USFTP75 cycle, HEV operation
- USFTP75 cycle, ZEV operation
- 3 MODEM cycles, HEV operation

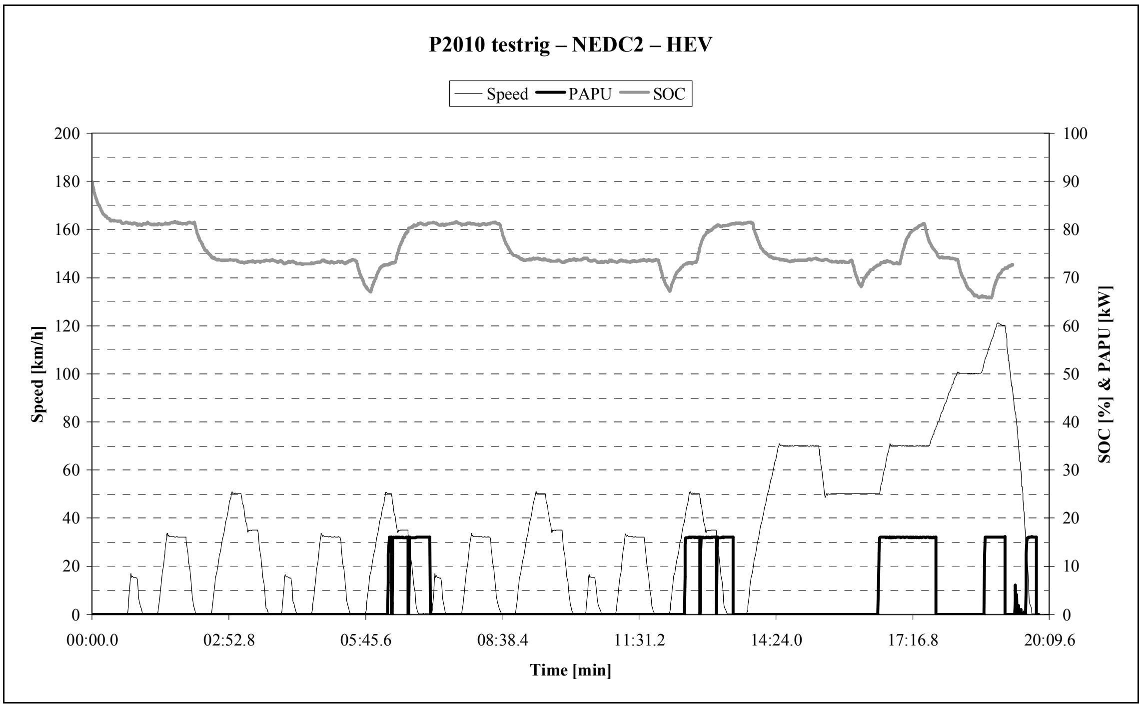


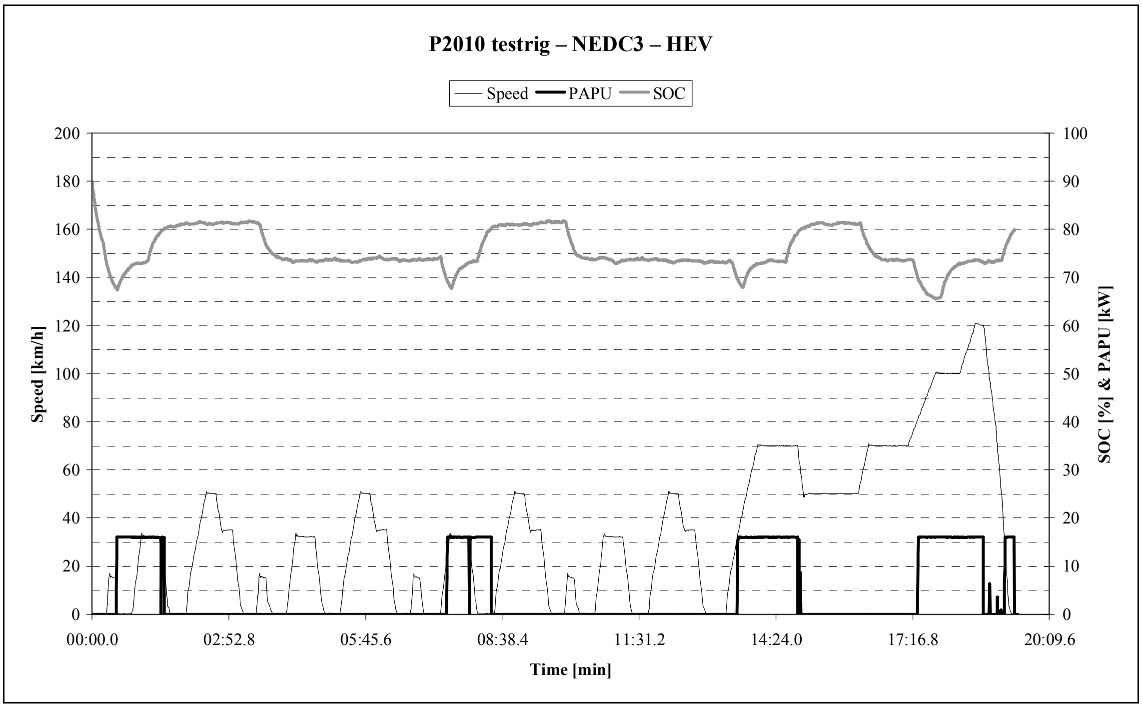

P2010 testrig – MODEM2 – HEV
Speed
Papu
SOC
Speed [km/h]
SOC [%] & PAPU [kW]
Time [min]
00:00.0
05:45.6
11:31.2
17:16.8
23:02.4
28:48.0
34:33.6

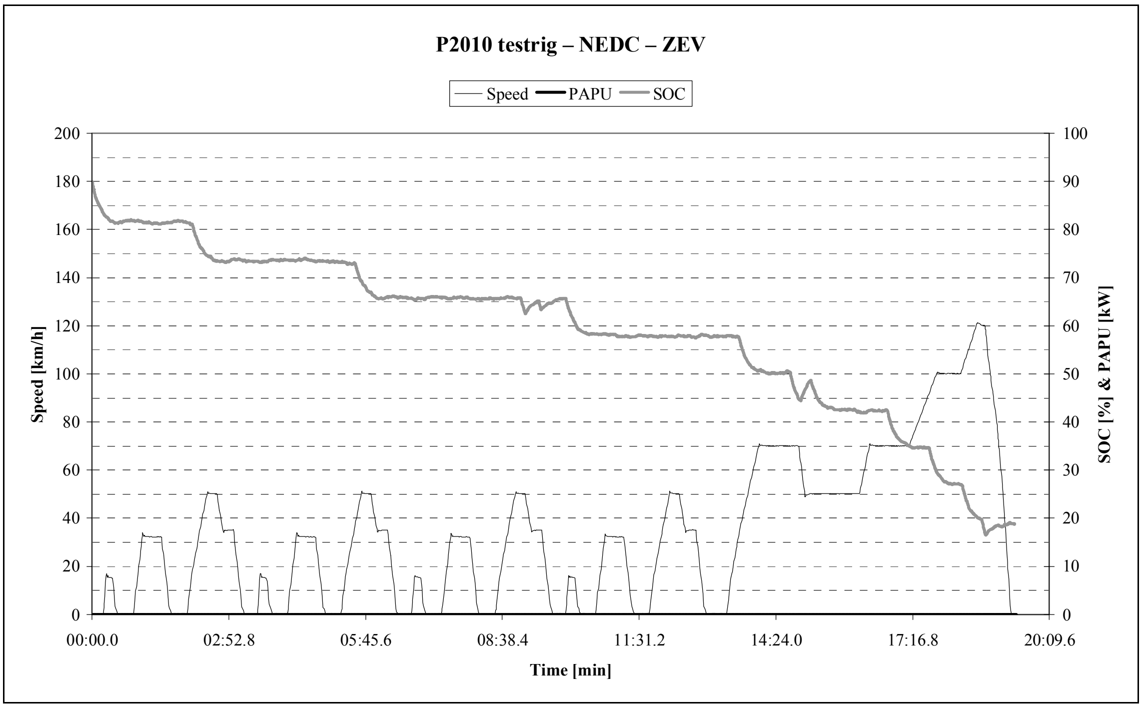

P2010 testrig – MODEM3 – HEV
Speed
Papu
SOC
Speed [km/h]
SOC [%] & PAPU [kW]
Time [s]
00:00.0
05:45.6
11:31.2
17:16.8
23:02.4
28:48.0
34:33.6


P2010 testrig – MODEM – ZEV
Speed
Papu
SOC
Speed [km/h]
SOC [%] & PAPU [kW]
Time [min]
00:00.0
05:45.6
11:31.2
17:16.8
23:02.4
28:48.0
34:33.6


P2010 testrig – NEDC1 – HEV
Speed
PAPU
SOC
Speed [km/h]
SOC [%] & PAPU [kW]
Time [min]
00:00.0
02:52.8
05:45.6
08:38.4
11:31.2
14:24.0
17:16.8
20:09.6


P2010 testrig – NEDC2 – HEV
Speed
PAPU
SOC
Speed [km/h]
SOC [%] & PAPU [kW]
Time [min]
00:00.0
02:52.8
05:45.6
08:38.4
11:31.2
14:24.0
17:16.8
20:09.6


P2010 testrig – NEDC3 – HEV
Speed
PAPU
SOC
Speed [km/h]
SOC [%] & PAPU [kW]
Time [min]
00:00.0
02:52.8
05:45.6
08:38.4
11:31.2
14:24.0
17:16.8
20:09.6


P2010 testrig – NEDC – ZEV
Speed
PAPU
SOC
Speed [km/h]
SOC [%] & PAPU [kW]
Time [min]
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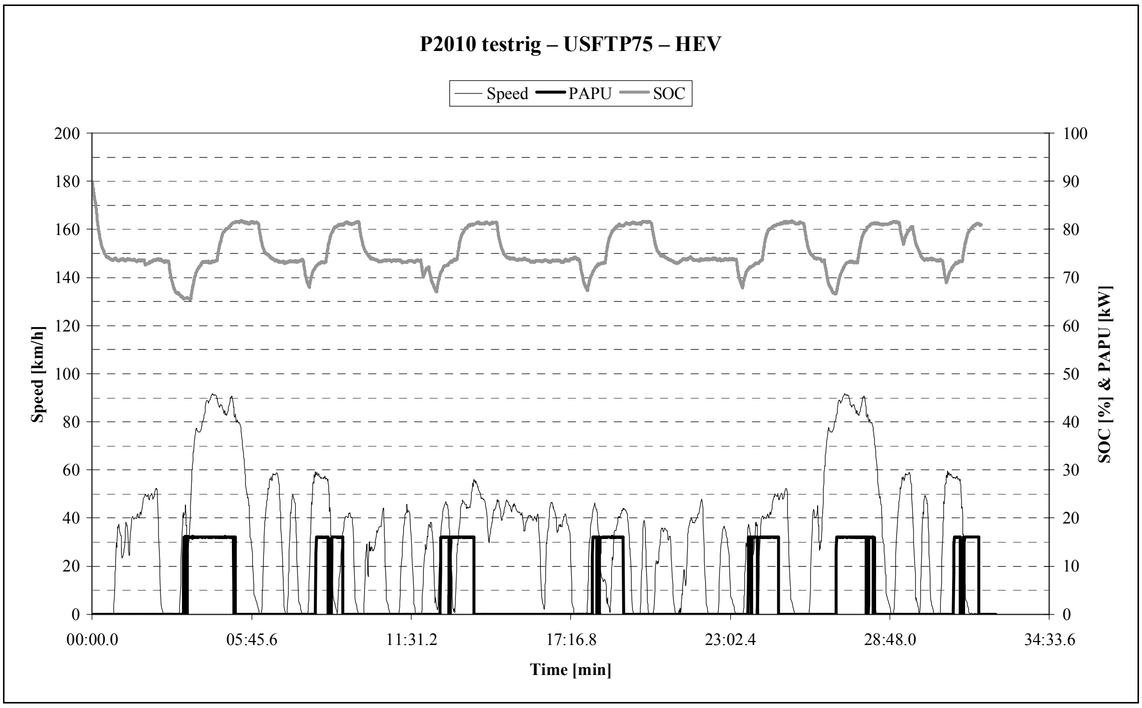
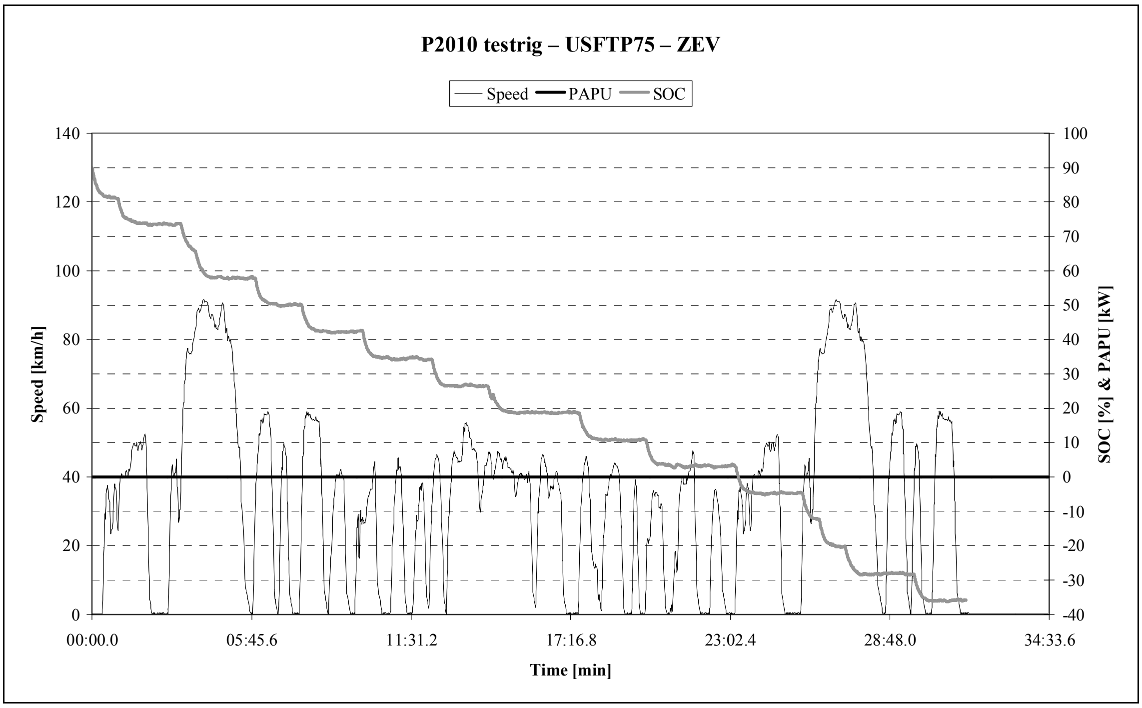
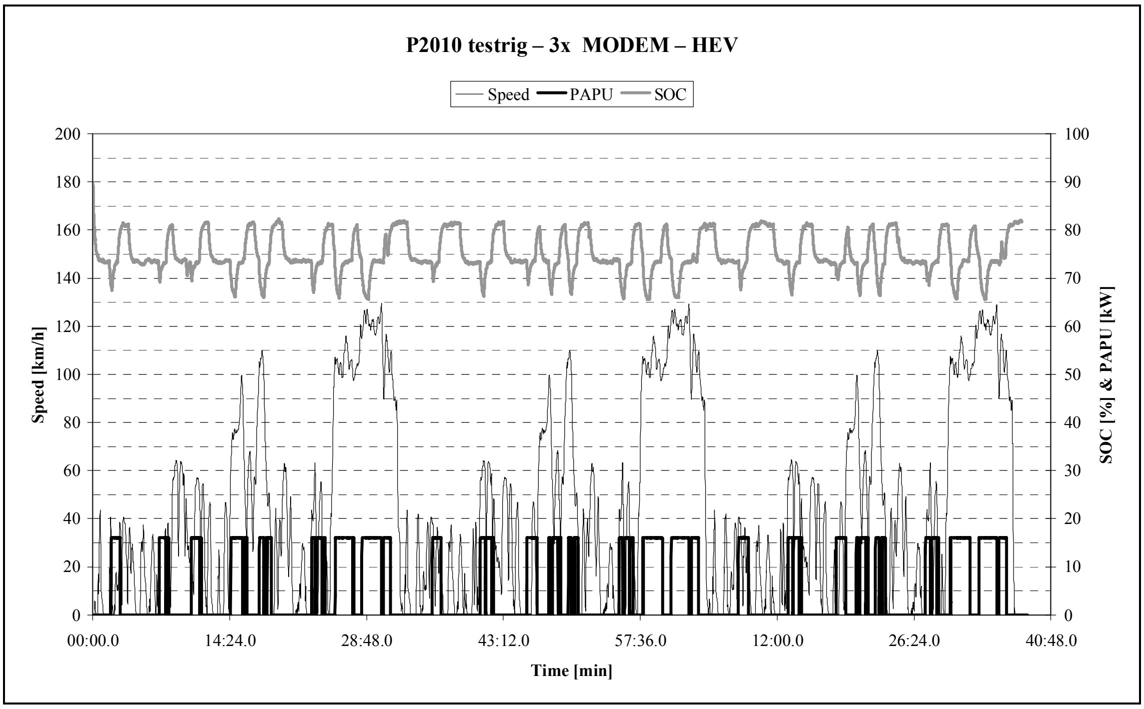
02:52.8
05:45.6
08:38.4
11:31.2
14:24.0
17:16.8
20:09.6


P2010 testrig – USFTP75 – HEV
Speed
PAPU
SOC
Speed [km/h]
SOC [%] & PAPU [kW]
Time [min]
00:00.0
05:45.6
11:31.2
17:16.8
23:02.4
28:48.0
34:33.6


P2010 testrig – USFTP75 – ZEV
Speed
PAPU
SOC
Speed [km/h]
SOC [%] & PAPU [kW]
Time [min]
00:00.0
05:45.6
11:31.2
17:16.8
23:02.4
28:48.0
34:33.6


P2010 testrig – 3x MODEM – HEV
Speed
PAPU
SOC
Speed [km/h]
SOC [%] & PAPU [kW]
Time [min]
00:00.0
14:24.0
28:48.0
43:12.0
57:36.0
12:00.0
26:24.0
40:48.0

Appendix E ALTROBUS

In the framework of the MATADOR project, a series hybrid bus was tested by ENEA, Italy.

E1 The vehicle

The ALTROBUS is developed by the ALTRA society in cooperation with the Ansaldo Ricerche and Fiat-IVECO companies. Two versions of the ALTROBUS were built. The first is 12 meters long, has a weight of approximately 12.8 tons, and can carry about 85 passengers. The other one measures 6 meters, weighs 4.2 tons, and can carry 21 people.

The ALTROBUS is equipped with a series hybrid power train. An electric motor drives the rear wheels. Electric power is provided by a lead-acid battery and a generator set, consisting of an IDI diesel engine and a synchronous PM machine. The control for the generating system is not automated. The driver decides when the engine should be started or shut down.
The vehicle has a range of 150-200 km in thermal mode (engine on) and 20 km in the all electric mode.

A special version of the 6m vehicle was specially designed by ALTRA for ENEA. The drive system is installed on a standard truck chassis in order to give more freedom for experimental purposes. Figure 61 shows the vehicle on the rollerbench at ENEA. The specifications for the ENEA version of the ALTROBUS are listed in Table 22.

Figure 61: ALTROBUS on the ENEA dynamic rollerbench

Table 22: ALTROBUS technical specifications (ENEA version)

Internal combustion engine		**Electric Motor**	
Type (fuel)	IDI diesel	Type	Separately excited DC motor
Displacement (cc)	1204		
Max. power [kW]	24 @ 3600 rpm	Rated power [kW]	22 (1500-4500 rpm)
Rated speed [rpm]	2200 rpm	Rated voltage [V]	192 (Armature)
Regulation	mechanical		85 (Field)
Generator		Max. speed [rpm]	4800 rpm
Type	Synchronous PM	Max. torque [Nm]	172 @ 1200 rpm
Rated power [kW]	10 @ 2200 rpm	Features:	
Rated voltage [V]	220	• DC-DC electronic power converter	
Battery		• Current controlled mode	
Type	Lead acid	• Separate Control of Armature and Field current	
Capacity (C_5) [Ah]	100	• Regenerative braking	
Number of cells	96		
Electronic battery charger		**Vehicle**	
Rated power [kW]	10	LxBxH [m]	6.0 x 2.1 x 2.8
Rated voltage [V]	192	Weight [kg]	3500
Mechanical tranmission		Max. speed [km/h]	55
Type	Fixed reduction gear	Regenerative braking [kW]	15 and 30
Gear ratio	2.26		

E2 Measurement procedure and measured parameters

The test is started with 80% State-of-Charge. ΔSOC is kept between ±5% (75 to 85%).
The available battery capacity is 70Ah at the C_5 discharge rate, instead of 100Ah (manufacturer specification).
The room temperature varies between 10 and 15 °C.

During each test, a set of parameters has been measured and recorded:

1. Vehicle speed
2. Battery current
3. Electric motor current
4. Battery voltage
5. Fuel consumption
6. State-of-Charge
7. Travelled distance
8. Energy for recharging the battery from the mains
9. Test time

Sign convention for several signals:

Generator current:	positive when engine is active
Battery current:	positive during discharge, negative when being charged
Electric motor:	positive when driving, negative during regenerative braking

E3 Results

The ALTROBUS was driven over 6 different cycles. Due to the limitations (maximum speed) only urban parts of the cycles were driven. The following cycles were used:

7x Urban Driving Cycle (UDC, Urban part of NEDC)
10x Japanese 10-15 (only urban part = first 440 seconds)

3x Hyzem Urban
11x MODEM (only slow urban part)
5x UDDS (only stabilised part)
8x Casaccia cycle (Figure 62)

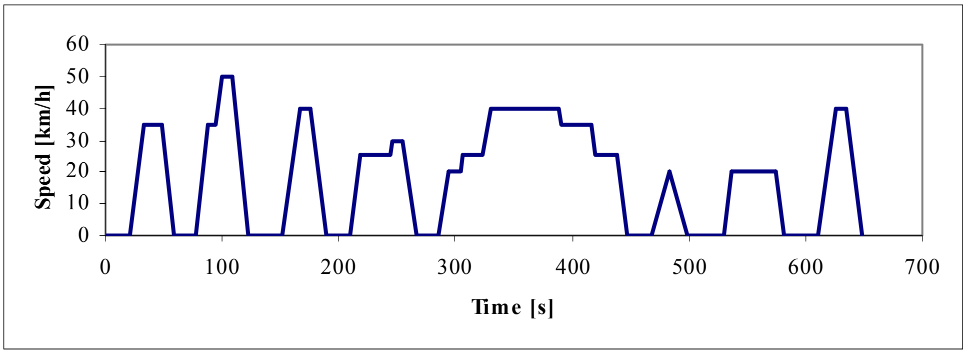
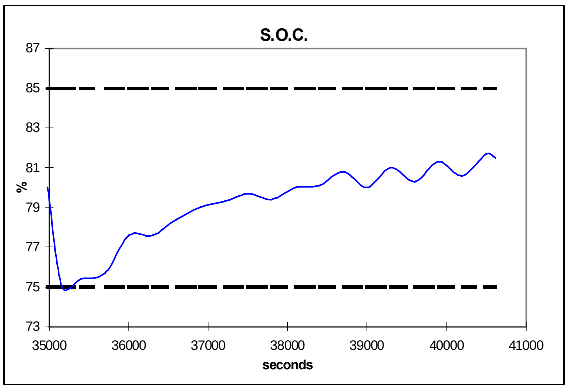
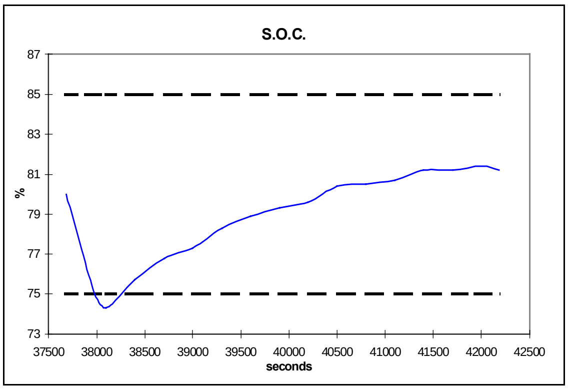


Figure 62: Speed trace of the ' Casaccia driving cycle'

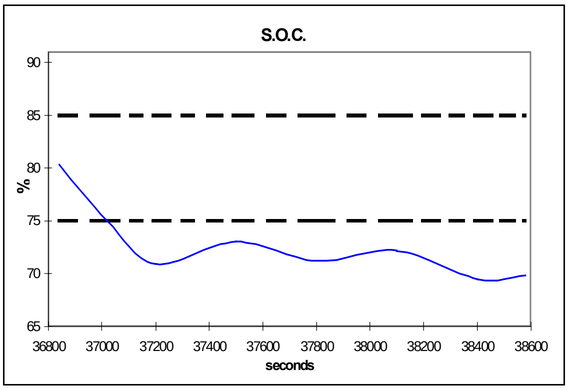
Not all cycles are driven without difficulties. Especially with higher speeds, the vehicle sometimes was not able to reach the desired speed. On the Hyzem Urban cycle the vehicle turned out to be charge depleting and the test was stopped after three cycles since the battery voltage had become to low. In Figure 63, the SOC history for each sequence of cycles is presented.



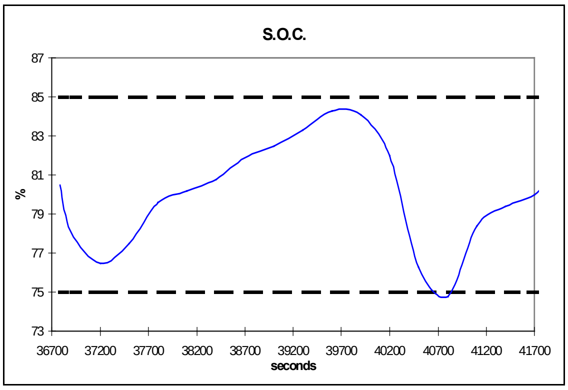
7 times UDC



10 times Japanese 10-15



3 times Hyzem Urban



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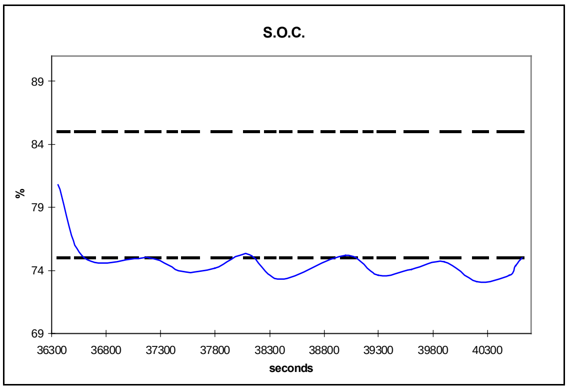

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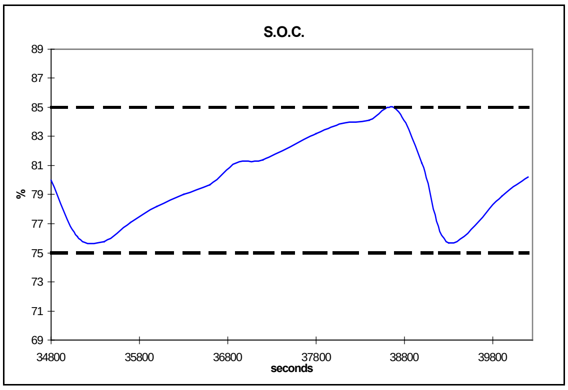
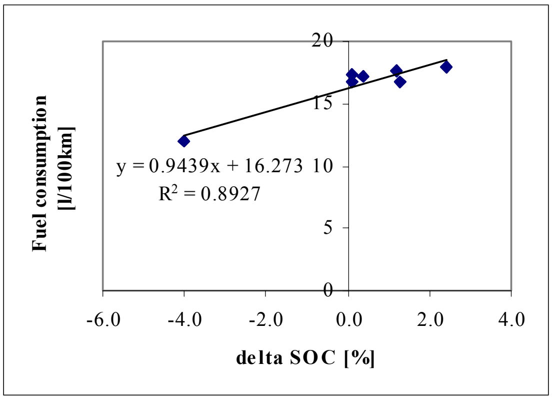


8 times Casaccia

Figure 63: SOC history for the ALTROBUS on 6 different driving cycles



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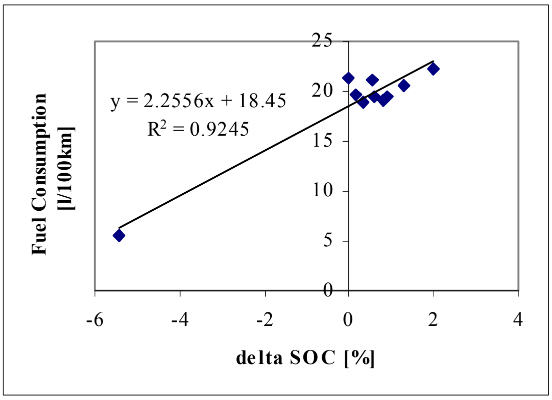
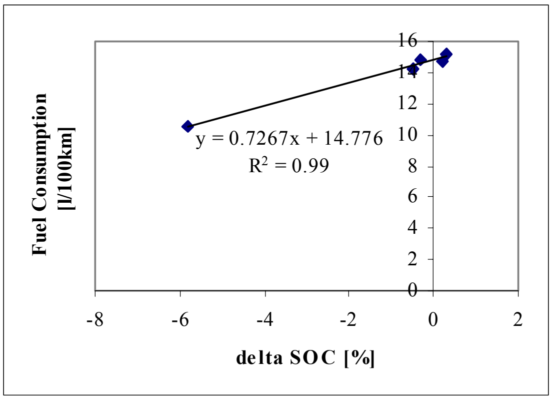


Japanese 10-15



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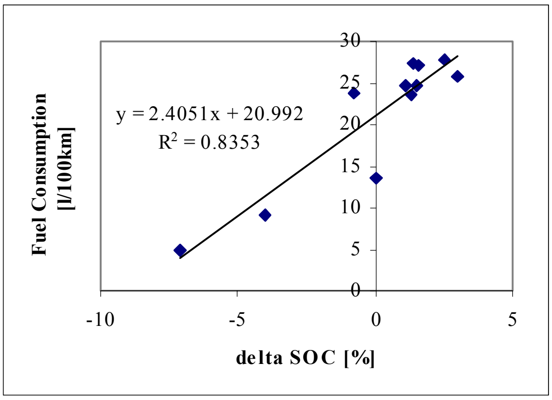

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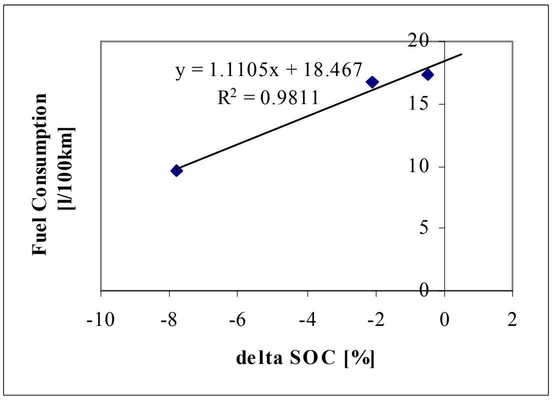

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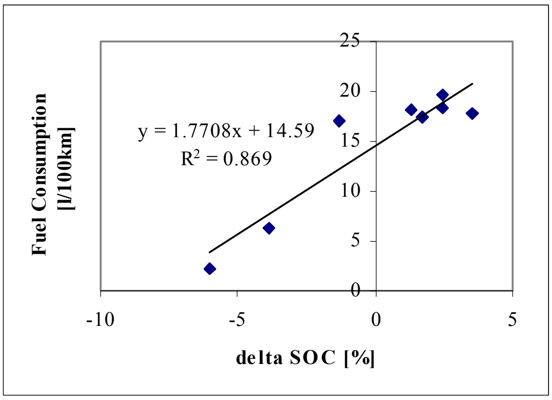

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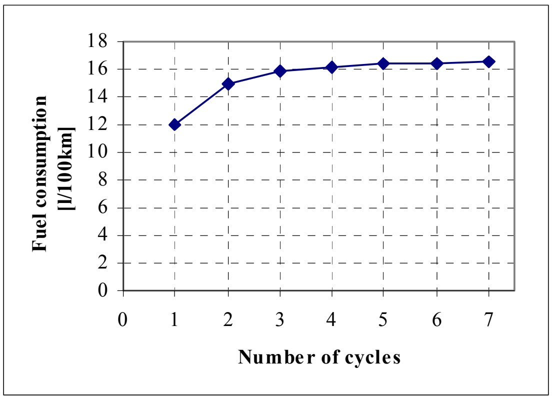
Figure 64: Regression lines for the ALTROBUS over six different driving cycles



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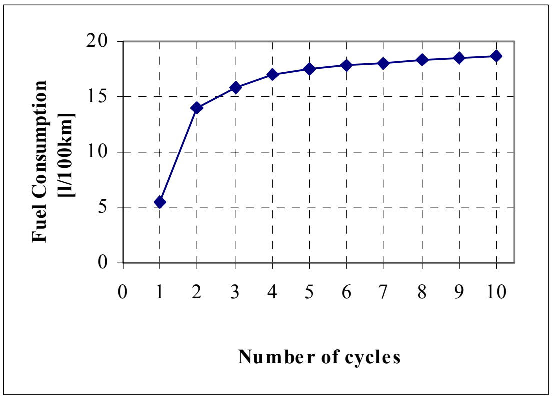

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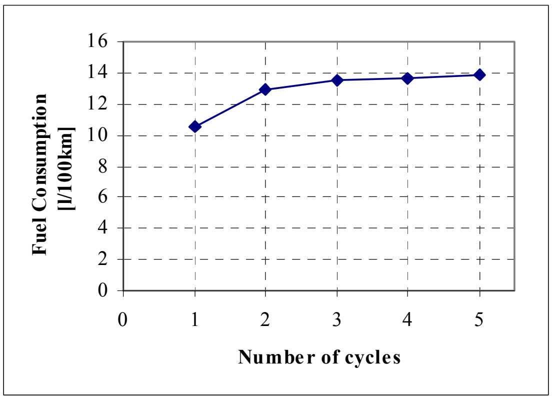

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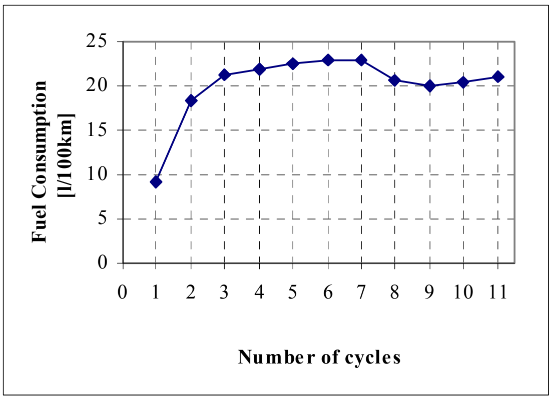

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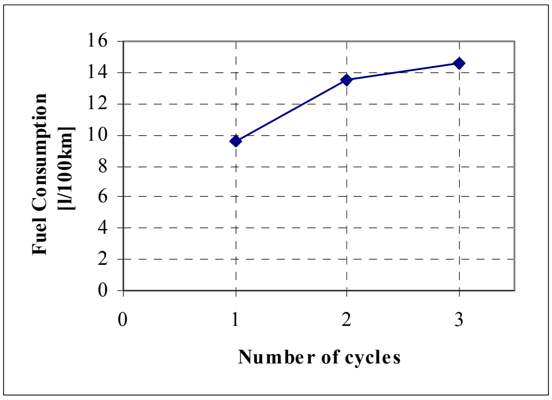

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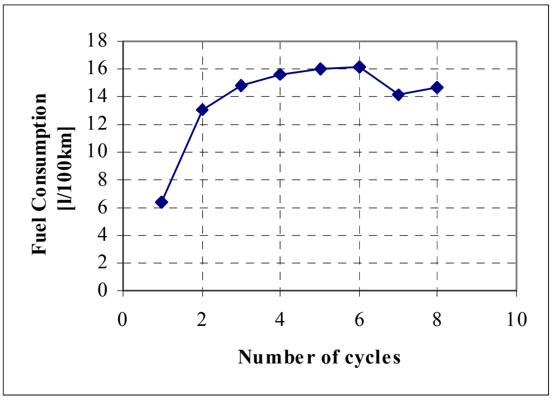

Casaccia

Figure 65: Cumulative lines for the ALTROBUS over six different driving cycles

MANAGEMENT TOOL for the ASSESSMENT of DRIVELINE TECHNOLOGIES and RESEARCH

MATADOR

Contract JOE3-CT97-0081

Task 2:

Testing methods for vehicles with conventional and alternative drivelines

Subtask 2.5

Determination of SOC and ΔSOC in general

ENEA - Advanced Energy Technology Division

20 July, 2000

by
Luciana Cervati (ENEA)
Mario Conte (ENEA)
Luigi De Andreis (ENEA)
Giovanni Pede (ENEA)

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Energy Conservation and Utilisation

Nomenclature

Abbreviations

Ah	Ampere-hour. Unit for electrical charge (and even battery capacity)
AS_I	Asymmetry between battery resistance in charge and in discharge at step current I.
BEV	Battery Electric Vehicle
C	Battery capacity. The electrical charge, in Ah, that a battery can deliver under defined discharge conditions.
CorrCoeff	linear correlation coefficient
C/5	Discharge rate at constant current equal to the battery capacity divided by 5.
Cdl	Double Layer Capacitance
Cp	Parallel Capacitance
Cs	Series Capacitance
CFD	Computational Fluid Dynamics
CH-HEVs	Charge-sustaining Hybrid Electric Vehicles
D.O.E.	Department of Energy
DST	Dynamic Stress Test
ECE15	Cycle profile for vehicle and even battery testing
EIS	Electrochemical Impedance Spectroscopy
Emf	electromotive force
EUCAR	European Car Research Committee
Γ (gamma)	diffusion coefficient
HEV	Hybrid Electric Vehicle
IEC	International Electrotechnical Commission
IU	Charge profile composed by a constant current I phase and constant voltage U phase.
IR	Internal Resistance (Ohmic resistance different from R_{int})
Ni-Cd	Nickel-Cadmium (Alkaline Battery)
Ni-MH	Nickel-Metal hydride (Alkaline Battery)
OCV	Battery Open Circuit Voltage
OCV^{dch}	Battery Open Circuit Voltage at the end of discharge
OCV^{ch}	Battery Open Circuit Voltage at the beginning of charge
Qext	Extracted electrical charge. Amount of electrical charge delivered or extracted by the battery.
Rct	Charge Transfer Resistance
R_{int}^{ch}	battery internal resistance during charge
R_{int}^{dch}	battery internal resistance during discharge
Rp	Parallel Resistance
Rs	Series Resistance
S	generic 'source term' CFD equations
SFUDS	Simplified Federal Urban Driving Schedule
SG	Specific Gravity (of battery electrolyte)
SOC	Battery State Of Charge
SOC*	Corrected SOS, defined as the extracted charge referred to the actual available charge (%).
SOH	Battery State Of Health
SOV	State of Voltage

Contents

1 Introduction

Task 2 of the MATADOR Project (**Ma**nagement **T**ool for the **A**ssessment of **D**riveline Techn**o**logies and **R**esearch, EU-contract JOE3-CT94-0081) is aimed at developing test methods for homologation and evaluating conventional and alternative vehicles and propulsion systems. These testing methods should also allow for a comparative assessment and benchmarking of such technologies. The testing methods, considered in Task 2, are restricted to the determination of energy consumption and emissions of various vehicles and powertrains. The definition of such testing procedures is strongly affected by the vehicle configuration, the required fuels and the specific driving patterns which may be real or simulated on test benches. In addition, the introduction of alternative technologies and fuels may pose measuring problems when compared with conventional vehicles and standardised procedures. Investigation and critical evaluation of technical issues in relation to the various technologies is the main scope of Task 2, from which specific recommendations for modified or new testing and measuring methods are derived.

The determination of the State of Charge (SOC) of electrochemical batteries is of great importance, both for stationary storage systems and for electric (EVs) and hybrid electric (HEVs) vehicles. Knowing the SOC permits an energetic flux management in order to extend the service life of the batteries, makes possible the correct dimensioning of the storage system and, as a consequence, a noticeable reduction of the energy consumption and cost. As far as the determination of energy consumption and emissions of HEVs in testing procedures is concerned, the SOC knowledge and, more significantly, its variations (ΔSOC) become one of the most important issues, because there are significant effects of such SOC changes but they are hardly measurable. It is well known that during testing of HEVs, data from repeated driving cycles are expected different as the battery SOC normally changes. Different approaches have been proposed to solve such a problem. One method for the determination of HEV energy consumption is the restoring of initial conditions at the end of the test, measuring the real consumption: in the final battery recharge, ΔSOC is forced to zero, requiring an accurate measurement of such a parameter. In addition, the reading of battery SOC meters (commonly, Ah-meters or similar) available on the vehicle is often unreliable: this aspect may complicate the testing methods with respect to those of conventional ICEV, because additional sensors and measurements (e.g., battery voltage and current) may be required.

In both EVs and HEVs testing, the battery efficiency depends on the actual SOC and then the driving patterns may greatly affect the measured data for energy consumption calculations. Finally, the lack of experimental data for such vehicles makes simulations a powerful tool for the calculation of various types of vehicles and for the determination of representative parameters, such as SOC and ΔSOC, affecting vehicle performances.

In conclusion, the measurement or determination of SOC is a critical task, which is hard to accomplish accurately. The continuous definition and development of new, more advanced methods and equipment to monitor in real use the battery SOC are a clear demonstration that the problem of SOC accurate determination is far to be completely solved. In the framework of the MATADOR project, there was no intention to face directly the problem by proposing novel solutions, but more simply and usefully to survey the existing methods and verify their applicability in vehicle testing methods. The use of the variation of SOC (ΔSOC), if accurately determined, seems adequate for most testing methods. The Ah-counting or monitoring is a simple and widely used method to perform such measurement. This method has various attractive features: practically independent of the battery type, largely available at commercial level in a variety of products, ease of installation. On the other side, there are some limitations that must be clearly identified and evaluated to improve accuracy in vehicle testing methods. In addition, the use of battery models for the calculation of various battery parameters, including SOC and ΔSOC, may be appropriate in simulation tools for verifying the accuracy of ΔSOC determination and correcting test measurement results. Some of the foreseen limitations of Ah-counting have been also experimentally investigated for a lead-acid battery by means of an extensive testing activities aimed at verifying the non-reversible situations and performance declines and determining the impact on SOC values.

This document reports about the work done to survey the problem of SOC and ΔSOC determination in general and recommends correction methods to improve accuracy and reduce limitations of Ah-counting. The first part contains the results of the survey of the literature on various methods developed for SOC and ΔSOC determination. Battery models, along with those proposed by IKA and TNO, are thoroughly analysed, with focus on accuracy, simplicity and, when possible, differences with Ah-counting. A critical description of the bibliography is presented in Appendix A.

The second part describes the experimental activities and analyses significant parameters and methods affecting the SOC determination. Moreover, the considerations on lead-acid batteries have been extended to other battery types. Finally, recommendations and general conclusions are presented.

2 SOC and ΔSOC Determination: basic considerations

SOC definition is based on the extracted charge (Q_{ext}) and on the available capacity (C) as in the equation (1), where the available capacity is sensibly influenced by the operating conditions like temperature, discharge regime, state of health of the battery and recent history.

$$SOC = 1 - Q_{ext}/C \qquad (1)$$

ΔSOC is the variation of SOC during driving test cycle. This variation seems sufficiently accurate to be used in testing methods to minimise the uncertainties related to the measurement or calculation of the actual battery SOC. For charge-sustaining HEV, the measurement or calculation of the energy consumption requires the accurate assessment of the final value of SOC and its variation with respect to the initial one (ΔSOC). For testing purposes, the best condition would be a final battery state with SOC exactly equal to the initial one (ΔSOC=0). In case of impossibility to reach this condition, it is necessary to measure ΔOSC and determine the energy consumption associated to such variation.

A more direct method for ΔSOC determination is to totally discharge the battery during its functioning in order to measure the residual capacity. As far as testing procedures are of concern, this method becomes more costly and lengthy because has a significant impact on current standard test procedures: battery parameters must be measured and the duration of each test is increased. Consequently, battery models have been developed with the aim to calculate it, in alternative to direct measurements (Ah-counting). Battery can be represented as an electric circuit characterised by parameters and analytic relations that make useful the equation (1). Other models have been developed, based on the measurement of suitable parameters, such as the open circuit voltage, the internal resistance or impedance and the instantaneous change of voltage in fixed operating conditions.

Complex techniques based on physico-chemical models have been proposed in the frame of computational fluido-dynamics: battery is considered from a microscopic point of view, i.e. describing the porous electrodes in details, the local diffusion phenomena and so on. Direct measurement of some parameters and their mathematical or empirical relationships with the SOC have been proposed: the specific gravity of the electrolyte (hard to measure on-line and in dynamic conditions), humidity of electrode active massive or non-destructive techniques. Furthermore, devices and models based on neural networks or other logic systems have been developed.

In the following short review, models have been classified into four groups:
1. Static electrical models
2. Dynamic electrical models
3. Physico-chemical models
4. Logic models.

2.1 Static electrical models

2.1.1 Peukert's model and its following corrections

Available capacity shows an inverse dependence on discharge current; the empirical equation developed by Peukert in 1897 may be extended from constant current discharge to different conditions, defining an average discharge current I_m during the considered discharge time (t). Peukert's equation is:

$$I_m^p \cdot t = C \tag{2}$$

where C and p are constants to be determined from discharge tests. The value of p is close to 1 for small current densities and close to 2 for high current densities. The Peukert's equation is applicable as an interpolation formula for intermediate currents. Three kinds of corrections are considered to improve the reliability of this equation: a temperature correction, an ageing factor and two ore more p-exponents, depending on current range.

As far as temperature is concerned, one of the largely accepted corrections [1] is the following:

$$C = [1 + (T\text{-}30°) \cdot 0.008] \cdot C_n \tag{3}$$

With this expression, capacity variations of 0.8% for degree centigrade are expected. With regard to the ageing correction, J.Lee, S. Lee and Nam Gong recently proposed [2] a correction factor A_f, able to account for the 20 % capacity changes during the service life of a battery (according to the value declared from constructors). SOC expression is modified as follows:

$$SOC^* = (SOC - A_f)/(100 - A_f) \tag{4}$$

$$A_f = Ah_{ref} - Ah_{cyc} / Ah_{ref} \tag{5}$$

Ah_{ref} is the maximum deliverable capacity during the whole life of the battery; Ah_{cyc} is the voltage-based estimated capacity obtained from constant load discharge curves at different cycle numbers. With this correction maximum errors are reduced to 3 %, in all the considered cases. Song, Kim and Oh [3] suggested another correction: dividing discharge current range in two or more regions where different p-exponents are measured or calculated. For example, for a 50-Ah lead-acid battery, the discharge range can been divided in a 5/20 A range (where p_1 is utilised) and 20/75 A range (where p_2 is used). In the first range the maximum error is lower than 2 %, while in the second range never exceeds 9 %.

In spite of these corrections, Peukert's model is unable to well fit high current discharge rates and recuperation effects due to relaxation phenomena. In 1954 another model was developed by Hoxie [4], also available in a more recently improved version, in order to solve these problems.

2.1.2 Hoxie's model

This model was aimed to determine the positive plates number NP, required for a given load demand. Such a number was calculated by an empirical equation, based on Peukert's discharge curves. The following equation given the NP number:

$$NP = \Sigma_j (A_j - A_{j-1} / K_j) \tag{6}$$

where A_j is the discharge current in period j, K_j is the fictive discharge current for discharge time t_j, and t_j is the total time diminished of the time spent in the j-interval.

Hoxie's model was modified [5] to determine the residual capacity of a fixed number of NP. In this model, K_j was obtained by evaluating t_j. The evaluation is iterated until the right side of the equation corresponds to the fixed NP-value.
This procedure is time consuming. To reduce the calculating time, de Kreuk, Meijer and van Duin (TNO - Netherlands) [6] suggested to divide the discharge time into a finite number of periods considered at constant current at an average value of the discharge rate. If an intermediate charge takes place, a new sequence starts, counting for the relaxation process in current calculation. Introducing a temperature factor, (a second order polynomial in T), thermal effects are considered in the available capacity. Differences between the estimated residual capacity and the measured one is in all the considered cases smaller than 5 %.

2.1.3 Shepherd's polarisation model and its development

In 1965 Shepherd suggested a battery scheme as a Thevenin equivalent circuit. In order to determine discharge voltage, V*, in the low polarisation cases, the following expression is utilised:

$$V^* = OCV - k \cdot Q / (Q - I \cdot t) - R_{int} \cdot I \quad (7)$$

where k is the polarisation parameter, OCV the open circuit voltage, Q the active deliverable material rate and R_{int} the internal resistance

On-load voltage is equal to the difference between the open circuit one, Ohmic voltage drop and a polarisation term. In 1984 Vissher [7] modified this model for high polarisation cases: a Tafel's expression of the polarisation parameter k, as a function of the SOC and the discharge rate, was suggested.

Gassing reaction was also considered, by means of the charge efficiency. Starting from this model, a simulation program was developed and tested on driving cycles, counting for braking recuperation. Results with a maximum error of 7 % with respect to the measured data were obtained.

2.1.4 Other Thevenin equivalent circuit

Regarding the battery as an electric bipole other simple models have been developed, which consider the internal resistance and the electromotive force as SOC functions (
Figure 1). The electromotive force is described by means of a linear, logarithmic or polynomial function, usually the same for both charging and discharging processes. Internal resistance may be different during charging or discharging operations: sometimes it contains two parts [8][9], an Ohmic (relevant on a short time) and a diffusion resistance (relevant on a long time).

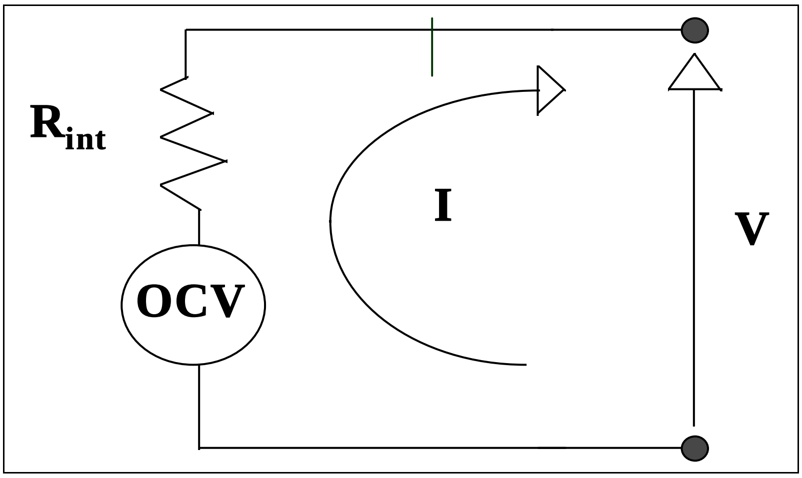

Figure 1: Thevenin's equivalent circuit

TNO Battery Model. The battery model used by TNO Automotive Laboratory in its vehicle simulation code is based on the Thevenin's model, corrected by the Peukert's discharge curves. The model input is the battery power (P_b) profile, and the battery current is obtained by means of the internal resistance and the open-circuit voltage corresponding to the given SOC, solving the equation:

$$R_{int} \bullet I^2 - OCV^{*} \bullet I + P_b = 0 \qquad (8)$$

R_{int} dependence from SOC is supposed to be linear, both in charge and discharge operation: this seems to be one of the main problems of the TNO model. In fact, with such assumptions, the ability to estimate the SOC at extreme regions (0-20 %; 80-100%) can be very poor. The real values of internal resistances in such conditions are quite different, and a parabolic SOC function better matches internal resistance changes. Figure 2 shows the variation of the internal resistance during charge with DOD, measured in ENEA Test activities. The different lines refer to various distances, in km, travelled by the EV, starting from 0: the parabolic trend of the curve is rather evident, excluding the last one, which corresponds to the battery end-of-life.

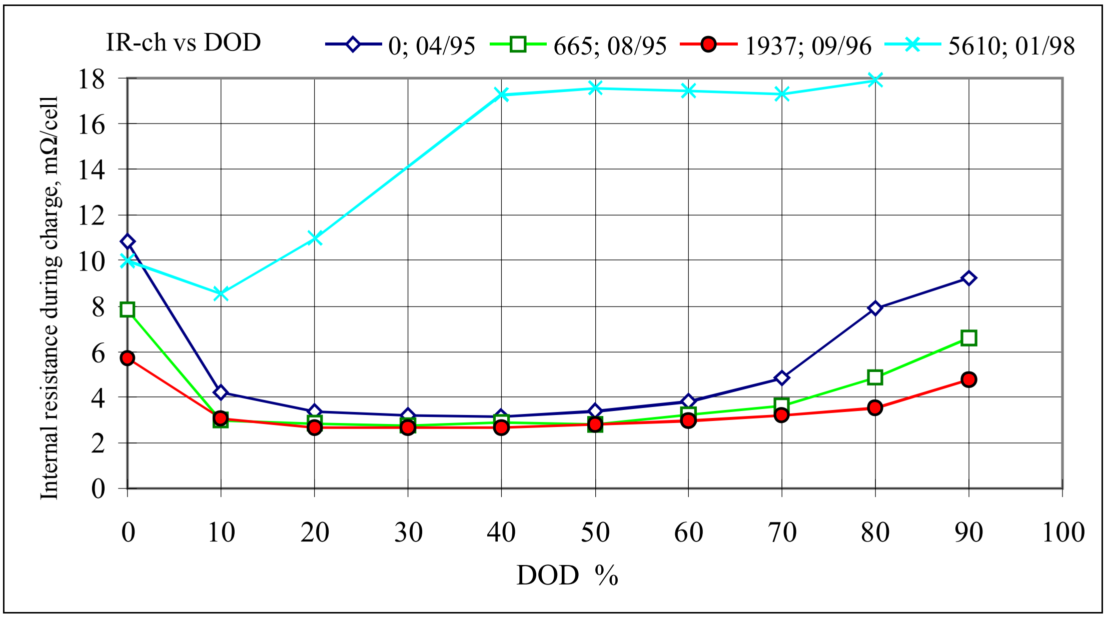

Figure 2: Internal resistance during charge in function of DOD at various service life

Furthermore, OCV values with varying SOC are supposed to be well calculated from a 5^{th} order polynomial equation, with coefficients derived from the manufacturer discharge curves, like the R_{int} linear coefficients.

IKA Battery Model. Another battery model has been used by IKA in its vehicle simulation codes. The battery model, described in Appendix B, is applied to lead-acid and Ni-MH batteries and is based upon an electrical equivalent circuit. The model has various simplifying assumptions that limit the applicability of the model (valid only for lead-acid batteries):

1. The internal resistance normally depends on many parameters (SOC, temperature, discharge current, ageing, type of cycling). The direct correlation between battery internal resistance ($R_{internal}$) and SOC is acceptable, particularly when the discharge current is constant and very close to the measured value and when the battery is almost fresh (without ageing effects).
2. $R_{internal}$ varies during charge and discharge phases, particularly at extreme SOC (O or 100%). The assumption is quite reasonable when the battery works far from such extreme states. The introduction of the $R_{internal}$ curve in function of SOC during charge may help improving the model during charge.

In case of Ni-MH the model seems to be limited to working SOC window far from extreme states. Moreover, there is a clear behaviour of alkaline batteries (Ni-Cd and NI-MH) with ageing: the capacity can be evaluated with a small error by measuring the resistance (with only a charge current pulse).

Consoli has proposed another similar model [10], where the OCV is evaluated after a rest period of a few minutes, considering separately charging and discharging processes. Because of the internal resistance variations for different battery ampere-hour capacity, the nominal capacity is utilised as inverse factor to define a universal SOC function. Experimental constant current discharge curves are well fitted by the simulation results, except for the final part of the discharge process. Consoli has used equations 9, 10 and 11 for its calculations.

$$OCV = f(SOC) = A_1 + B_1 \cdot SOC \quad (9)$$

$$R_{int} = f(SOC, R_o) = R_o \cdot (A_2 + B_2 \cdot SOC) \quad (10)$$

$$C = t \cdot I^p \quad \text{(Peukert)} \quad (11)$$

Experimental tests have been carried out at ENEA to validate Consoli model with two different batteries (both Sonnenschein batteries with a capacity of 50 Ah and 160 Ah, respectively). Figure 3 compares the equation coefficients for the two batteries, while Figure 4 and Figure 5 show how the calculated results fit the experimental data in estimating the OCV.

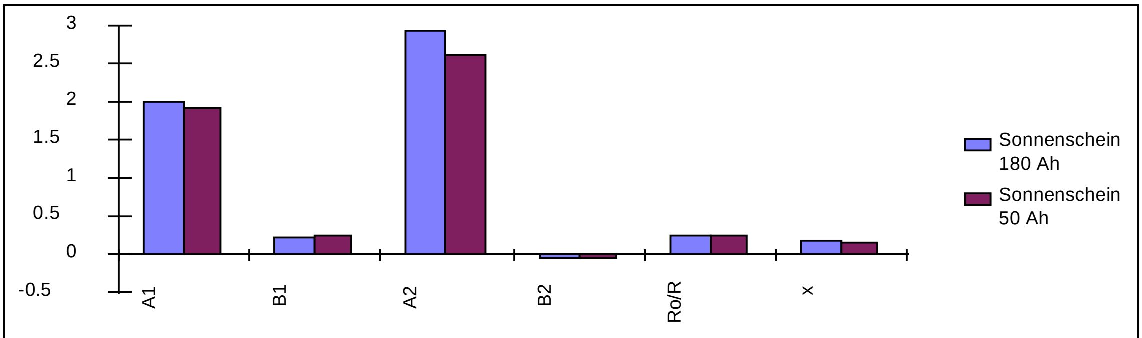

Figure 3: Coefficients for equation (9), (10) and (11) for two batteries

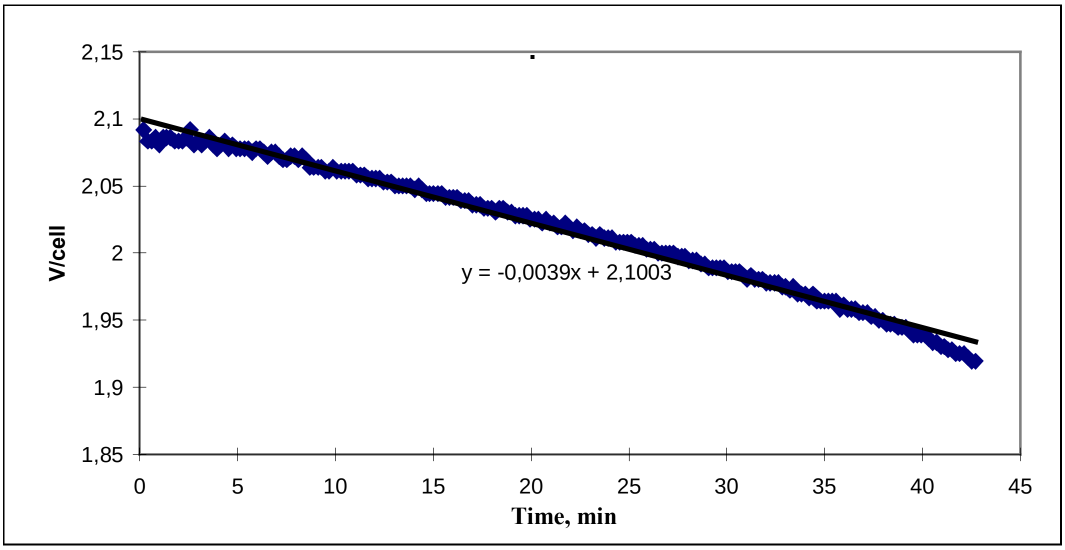

Figure 4: Battery voltage vs. Time for a 160-Ah Sonnenschein during a C/5 discharge

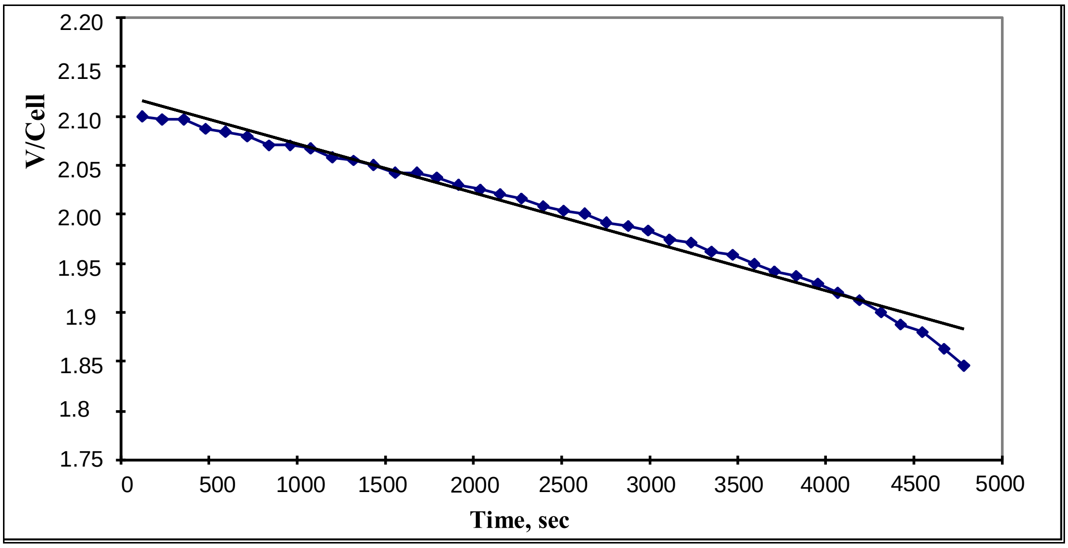

Figure 5: Battery voltage vs. Time for a 50-Ah Sonnenschein during a C/2 discharg

The accuracy of all these models to simulate 'on-road' operating conditions in electric vehicles is very limited. They cannot be usefully utilised with real current or power profiles, Moreover, they do not take into account the variation of the efficiency, internal resistance and capacity. With constant current steps the estimated capacity matches quite well the measured one, while on driving cycles they are not able to follow transients and recuperation effects. In spite of this, these static models are very useful in total vehicle simulation programs (i.e. SIMPLEV, HEVA, and so on). In order to obtain better results in the description of the operating behaviour of the battery, dynamic models have been developed. Consequently, SOC and DSOC determination is affected by a significant error when factors such as temperature, rapidly varying charging /discharging profiles and ageing, must be considered, as in BEVs and HEVs.

2.2 Dynamic electrical models

2.2.1 Giglioli and co-workers model

The model developed by the Pisa University with ENEA and ENEL [11] attempts to characterise the main electrochemical reactions with electrical equivalent circuit elements. Resistive, capacitive and inductive elements are needed to describe various polarisation reactions like charge transfer, double layer effects and diffusion processes. Analysing the transient behaviour with step current pulses, it is possible to identify the different time constants for each effect. In the model the battery current is the model input, battery voltage is the output, the electrical charge delivered by the battery and three current components (gassing, polarisation and diffusion current) are the state variables. The electromotive force, Emf, E (equilibrium voltage at open circuit) is obtained from the following expression:

$$E = OCV + K \cdot T \cdot \ln SOC \qquad (12)$$

where K is a constant coefficient, available from voltage measurements at a given SOC value and T is the electrolyte temperature. In order to define the SOC, the available capacity dependence from temperature and discharge rate (I_{dch}) is needed; a four parameters capacity equation is proposed, able to account for Peukert discharge curves, with temperature corrections.
Many versions [12][13] of the model have been developed up to include both charge and discharge operation and gassing. For most cases, simple external measurements are required: battery current and voltage and ambient temperature.
Figure *6* schematically sketches the most recent model with the main involved characteristics and parameters. It must be noted that this representation of the battery model is only for readability, because the model to take into account dynamic variations of main parameters is strongly non-linear. This is somehow considered in Figure 6: all the electric parameters (resistors, capacitors, e.m.f., gassing branch) are not constant but function of other model quantities. This consideration may only give an idea of the difficulty in using such model in vehicle simulation programs: solving sets of extremely non-linear and differential equation may create problems of convergence of the complete vehicle model.
This model has a dynamics of fourth order, the state variables being:

- battery stored charge (actually the quantity Q_e, called «extracted charge» and measured so that it equals 0 in case of a fully charged battery)
- battery electrolyte temperature θ
- currents I_1 and I_2 shown in Figure 6.

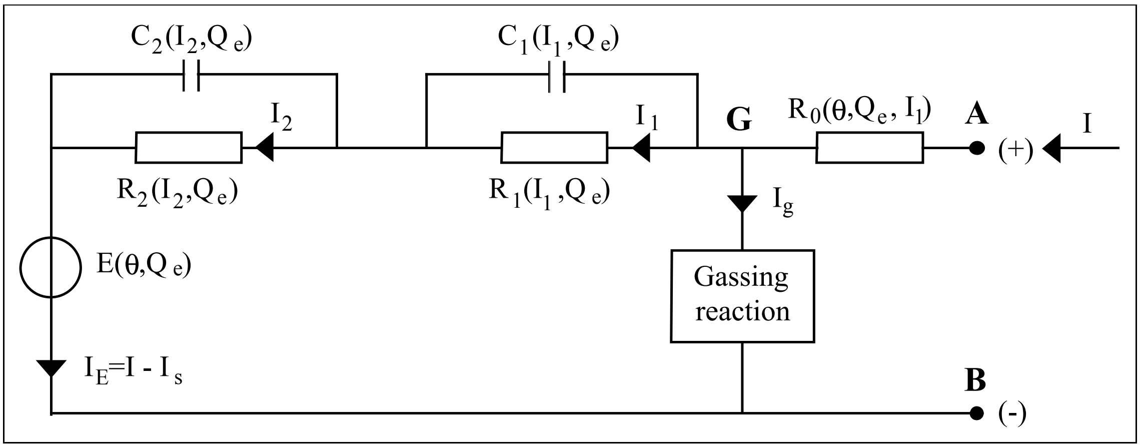

Figure 6: A circuit representation of the considered battery model

Resistance and capacitance parameters are obtained from battery response at step discharge current; gassing reaction as an irreversible effect is also taken into account. Ageing effects are not calculated and the above capacity parameters need to be updated time-by-time depending on the service life of the battery. The model has been applied in various devices used as SOC indicators or, more properly, as battery management systems (BCO= Battery Charger Observer, Battery Supervisor).

The device, based on this model, shows a good accordance with the measured data, with errors lower than 7%, obtained in bench and road tests on any lead-acid battery technology. Measurement simplification of the input parameters and model algorithms are needed in order to develop reliable and cheap SOC indicators.

2.2.2 Randles Ershler model

In dynamic models the internal resistance has been more properly turned into the electrochemical impedance, considering capacitive, resistive and inductive effects [14]. The main electrochemical reactions are described, by means of electric network elements: double layer capacitance, charge transfer resistance, diffusion impedance, electrolyte and contacts resistance and inductance . The electrochemical impedance is function of frequency. The input signal may be a sinusoidal voltage or current (with potentiostatic or galvanostatic measurements). For current input, in order to ensure linear conditions, the current has to generate a voltage change smaller than 10-20 mV/cell.
The frequency analysis permits the identification of different internal processes: in the low frequency range diffusion effects are dominant, while in the high frequency range Ohmic effects are the most relevant. State of charge (SOC) and state of health (SOH) dependence of the network parameters were extensively analysed in a lot of theoretical and experimental studies (references [15] through [23]). The main results are summarised hereafter:
SOH dependence on the impedance is evident, in particular to the inverse of the impedance, the conductance. It suggests a conductance-based failure prediction test [24];
No monotone SOC functions have been identified between the impedance different parameters. Nevertheless lead-acid batteries show impedance variations of about 100 % with residual capacity.
The classical measuring instruments (Solartron Frequency Response Analyser and electrochemical interface) are too expensive and complicated to be directly applied as SOC indicators and even as component in vehicle models.

2.2.3 Non linear impedance

Some experimental and theoretical studies suggest keeping the battery in non-linear conditions, utilising high current or correspondent voltage input values. Gas generation caused by current charge pulses makes the charge impedance higher than the discharge one in the same SOC conditions.
In galvanostatic measurements [25][26], the asymmetry between charge and discharge impedance is shown to be a monotone SOC function. This phenomenon suggested to develop an SOC indicator device.
In potentiostatic conditions [27] frequency distortion effects on the harmonics of the current response are analysed with sinusoidal alternating perturbation voltage. The second order harmonics appears to be a linear SOC function. A device has been developed, based on such non-linear effects. These effects on the SOC determination will be more in-depth described in the paragraph on experimental results.

2.3 Physico-chemical models

2.3.1 Fluido-dynamics models

As far as previous described dynamic models keep a macroscopic point of view, in electrochemical models a microscopic description has been attempted. Electrode-electrolyte interface processes are governed by the Butler-Volmer equations, mass transport (diffusion, migration and convection) equations and local change in the electrode porous nature [28][29][30].
On the basis of CFD (Computational Fluid Dynamics) techniques, processes have been summarised in the following equation, where Φ may represent different function as the potential, the concentration, phase fraction, and so on.

$$\partial\Phi / \partial\tau + \nabla \bullet (v \Phi) = \nabla \bullet (\Gamma \bullet \nabla\Phi) + S \qquad (13)$$

The second term describes the convection process, the third is the diffusion process and S is the generic 'source term', containing terms that cannot be expressed in the other two terms; Γ is the diffusion coefficient. Initial conditions are defined by SOCs. Constant current or constant power charge/discharge profiles are the side conditions. Computer simulation programs have been tested on EV driving cycle (SFUDS, DST). Accounting for the computing complexity and duration, these models are used to improve battery construction techniques rather than for SOC assessment and vehicle simulations.

2.4 Logic models

2.4.1 Fuzzy logic

Models have been developed in order to avoid the analytic difficulties due to non-linearity of the circuit network expressions. Any deviation of the initial data causes estimation errors of the SOC. Instead of solving the mathematical equations, these kinds of models are based on logic relationships between the acquired data. Fuzzy inferences with self-tuning algorithms are utilised, measuring selected parameters and deducing by means of listed tables and inference techniques an SOC assessment.
In a recent paper [31], Singh, Fennie, Reisner and Salkind proposed an ammeter and an impedance-based SOC indicator. Despite the evident simplicity of these two systems, errors in all considered cases (lithium-ion batteries, lead-acid, Ni-Cd, Ni-MH) never exceed 10 %.
Also ageing correction may be reproduced with a good accuracy, as in the recent study published by Sun, Tan, Xie and Song [32]. In this paper, by measuring the current and voltage, during discharge or recharge process, a fuzzy inference principle lets to estimate the SOC related to the 'actual capacity', instead of the nominal capacity.
Such logic techniques seem to be able to simplify, without accuracy losses, the parameter dependence of the residual capacity. More experience is still needed to optimise the use of such approach.

2.4.2 Neural networks

Neural networks are generally divided in two families: back propagation and Kononen networks. The latter ones are able to associate an output to any initial conditions similar to a known input-output pattern couple; they are also able to 'recognise' data like images, sounds and so on. The former type is able to create a dynamics, starting from an input and leading to a preliminary known output, improving itself in the 'self-tuning' phase. After this first phase, the network is able to simulate an output, starting from acquired data, without any external information about the real dynamic equations of the problem.

Back propagation networks can tune themselves in order to estimate battery SOC values with a quite good accuracy. In recent years, some devices have been proposed, with the aim to assess actual capacity or to develop SOC indicators. The features of such software instruments seem to promise a high accuracy level.

3 Variation of SOC and ΔSOC with various battery parameters

The survey of SOC assessment methods gave a wide selection of methods to be used for estimating the battery State-Of-Charge (SOC) or its variation. More than Ah-monitoring or counting, internal resistance or impedance measurements seem to be more accurate to determine the SOC in several conditions, even considering the ageing effects. In fact, many models and devices do not account for parameter variations with ageing during the whole battery service life. To verify the effects of significant modifications of the battery performances, due to various factors (temperature, ageing, discharge regimes, and so on), an experimental study has been performed by means of 4 series-connected lead-acid modules (Dryfit Sonnenschein with gelled electrolyte and with a capacity of 50 Ah at 12 V). The testing activity was mainly aimed at investigating how SOC and Ah-counting could be corrected in order to include the modifications in the measured or calculated values. The results for a lead-acid battery are not immediately transferable to other battery types, but indications and extrapolations may be derived considering that lead-acid batteries probably represent the most intriguing system to be analysed.

3.1 Experimental background

Preliminary indications and results were obtained during long battery tests, even including road tests of BEVs. Chief battery parameters (capacity, efficiency, internal resistance and other characteristics) resulted strongly affected by various operating conditions and status of the battery, such as: temperature, discharge rate, rated capacity, depth-of-discharge (DOD) and ageing. Surely, deep discharge (at about DOD = 80%) cycles modify main battery parameters, which should be updated from time to time. For example, the available capacity at constant current discharge is subject to 20 % variations for some lead-acid battery types. There is an increase of capacity during first cycles (10-20 cycles, reaching a maximum value of about 120 % of the nominal capacity) and then a significant decrease after 70-100 cycles, until to reach the end-of-life point (about 70 % of the nominal capacity). This result has been confirmed at constant current discharge rates and controlled operating conditions. In real use of a storage battery, this dependence from the cycle number (whenever at the same final value of the SOC) is quite difficult to assess. Figure 7 shows ageing effects on capacity for 14 lead-acid modules. The capacity test is performed at three different current rates, during the normal vehicle utilisation.

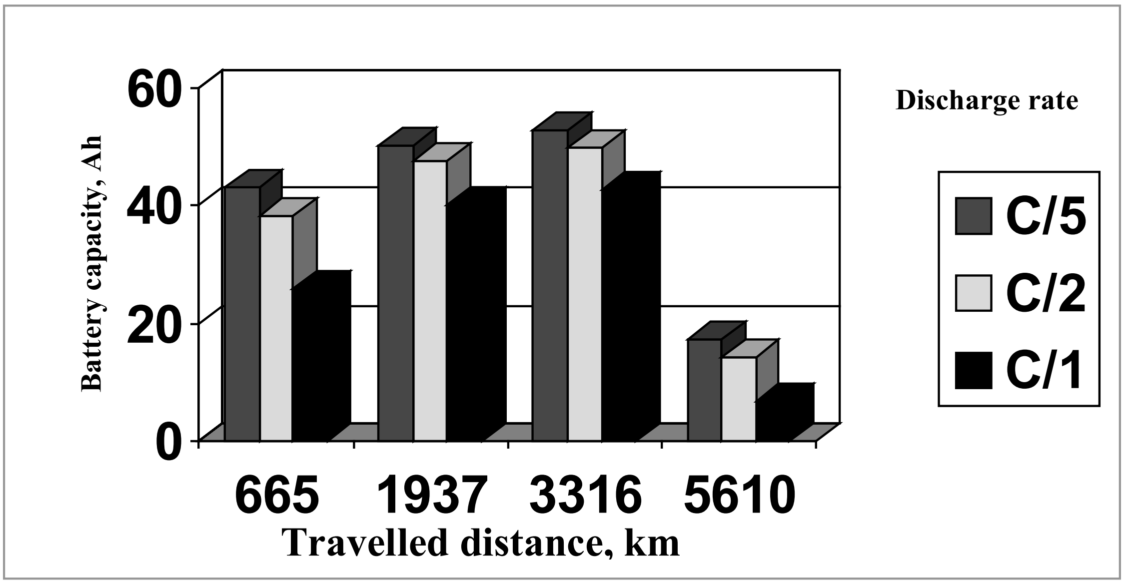

Figure 7: Capacity variation during the service life of 14 lead-acid modules

The Internal Resistance (IR) is subject to greater variations in the final part of the battery service life. The cycle number dependence of IR is non-linear and strongly affected by other parameters like temperature, SOC, current rate. In Figure 8, IR variations with ageing are plotted for the same gelled electrolyte modules (the travelled distance refers to BEV used for cycling the batteries in road tests and monitored at defined time intervals).

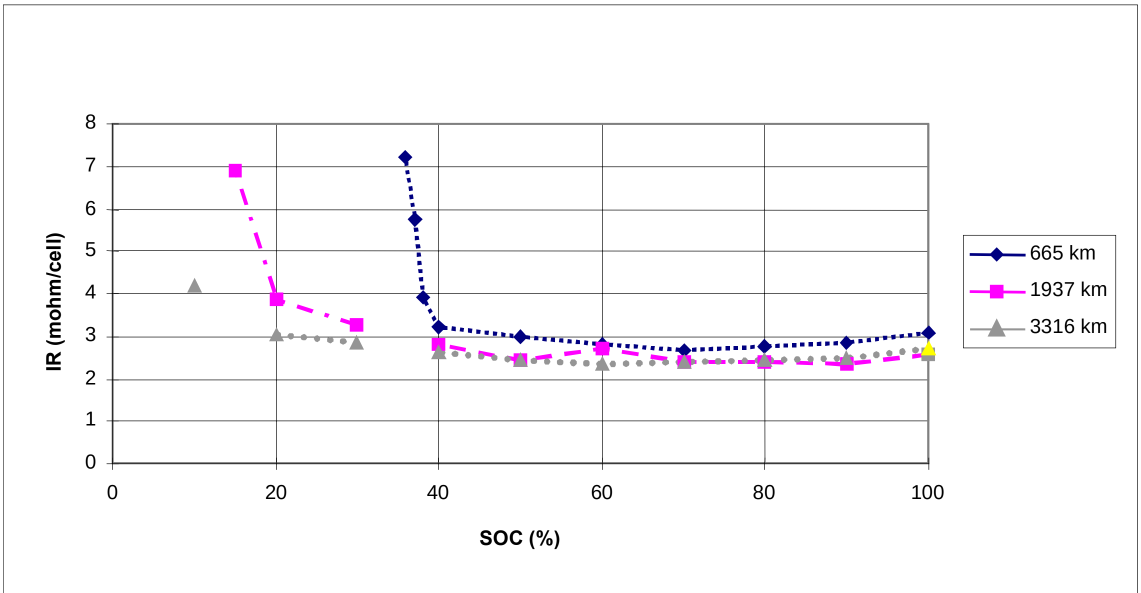

Figure 8: Internal Resistance of a lead-acid battery as SOC function for different travelled distances

In order to take into account the 'history' of the battery in the description of such parameter variations, it is suggested to refer to a new parameter, called State Of Health (SOH) of the battery. This parameter, used instead of the cycle number, is defined as the real available capacity at C/5 discharge rate divided by the nominal capacity C_{nom}.

$$SOH = C_{real}/C_{nom} \quad (14)$$

The battery temperature and the ageing mainly affect such parameter, by modifying the capacity actually achieved and available. The SOC is defined by means of the extracted charge Q_{ext} and the nominal capacity.

$$SOC=1- Q_{ext}/C_{nom} \qquad (15)$$

3.2 Test equipment and plan

Three parameters are continuously measured at different SOC and SOH values: the Open Circuit Voltage (OCV), the internal resistance offered from the battery at discharge pulse steps (R^{dch}_{int}) on different intervals of the relaxation time, and the asymmetry between charge and discharge internal resistances at step current values (I) greater than C/1 (AS_I). The asymmetry is defined as the ratio of the charge internal resistance to the discharge internal resistance at a defined current rate (I). During the test work, various internal resistances have been defined and used. Their differences are apparent from the test results, but their definitions will be given in the final test report.

The knowledge of such three parameters may allow a more accurate determination of SOC and SOH for a given battery. It may be possible successively to extend this method to different battery types, with the appropriate correction factors.

Tests have been performed in a climatic chamber, at temperatures varying between 3 and 40 °C. The life cycle variations of the module parameters have been analysed by performing a selected parameter check up every 25 deep discharge cycles (ECE15 Urban). The parameters to be checked have been asymmetry (at 6-75-100 A), discharge internal resistance, OCV (open circuit voltage) and capacity at C/5. Varying temperature and ageing conditions, the same tests have been performed until the performances of one of the module declined: after about 100 cycles.

Table 1 and Table 2 resume the test bench and the test sequence applied during the life cycle test on the battery.

Table 1: Test Bench and battery description

Batteries	4 gelled-electrolyte lead-acid modules - Dryfit Sonnenschein - 50 Ah-12V
DC- Power Supply	HP6032A (0-60 V; 0-50 A; 1000 W)
Electronic Load	HP5060A (0-60 V; 0-50 A; 0.25-10000 Hz)
Poer meter	Yokogawa VT1030
ELTRA Cycler	E-8094
Climatic Chamber	Angelantoni
Data acquisition system	Keithley 500
Digitising Oscilloscope	Tektronics TDS420A

Table 2: Basic test procedure performed at different SOH values

Test	Current profile
Standard Discharge (C/5)	I= 10 A / cut off voltage = 1.67/cell
Standard Charge (IU)	I=10 A + V= 2.35V/cell until I<0.5 A
Standard Discharge (C/5)	
Standard Charge (IU)	
OCV vs. SOC (3h resting period)	(I=10 A for ΔSOC=10%; 3 h resting period) until total discharge
Standard Charge	
Asymmetry in $R_{int}^{ch}/R_{int}^{dch}$ at high current rate	(I=+/- 75 A (20 s);180 s resting period; I=+/- 100 A; I=10 A for ΔSOC=10%) until total discharge
Standard Charge	
Internal Resistance at low current rate (R_{int}^{dch})	(I=6A; 180 s. rest. Period ; I=10 A for ΔSOC=10%) until total discharge
Standard Charge	
25 Urban ECE15 Cycles	Current profile deduced as in the EUCAR Procedure

The test sequence described in Table 2 has been repeated at different temperature values, varying between 3°C and 40°C. The SOH was calculated at the second C/5 discharge tests and was varying in the range 0.5 - 1.05 %.
The total number of equivalent deep discharge cycles (SOC = 20%) is 190 (equivalent to about 10.000 km). Only one module showed degradation after 100 cycles and was studied separately from the others in the remaining cycles (until an SOH of 50% was reached). The SOH of the other three modules was about 90 %.

3.3 Test results

3.3.1 Capacity at constant current rate and ageing effects

As suggested in IEC - 'International Electrochemical Commission Publication' No 25, 1987 (*), a temperature correction coefficient is introduced in the capacity calculation:

$$C_{C/5} = [1 + (T\text{-}30°C)\ 0.008]\ C_{nom} \qquad (16)$$

Tests performed between 3 and 40 °C revealed a temperature effect, different from the expected one. Instead of a temperature correction coefficient 0.8 %/°C, we obtained a value of 0.3%/°C. Table 3 presents the test results.

Table 3: Temperature dependence of the capacity variation, performed on the 4 lead-acid modules. On the right side, there is the temperature correction coefficient.

Capacity (C/5) (Ah)	Temperature (°C)	ΔC/T (%/°C)
48.3	23	
49.3	30	0.30%
45.2	3	
46.6	13	0.30%
51.4	40	
46.5	3	0.30%
33.5	23	
32	3	0.15%

Another parameter affecting the capacity is the number of deep discharge cycles. The term *deep* applies when a DOD higher than 70% is considered. In IEC battery test procedures, for life cycle test, a deep cycling refers to a variation of DOD between 0 and 80%. Testing the batteries with ECE15 urban deep discharge cycles, the capacity variations obtained are quite similar to those corresponding to constant current discharge cycles. Between the 70^{th} and 100^{th} cycle, the capacity (in function of the number of cycles) achieves its maximum value, slowly decreasing in the subsequent cycles. The capacity function is presented in Figure 9. The temperature correction coefficient of 0.3% has been utilised referring to the nominal temperature, in order to correct the available capacity obtained in different conditions.

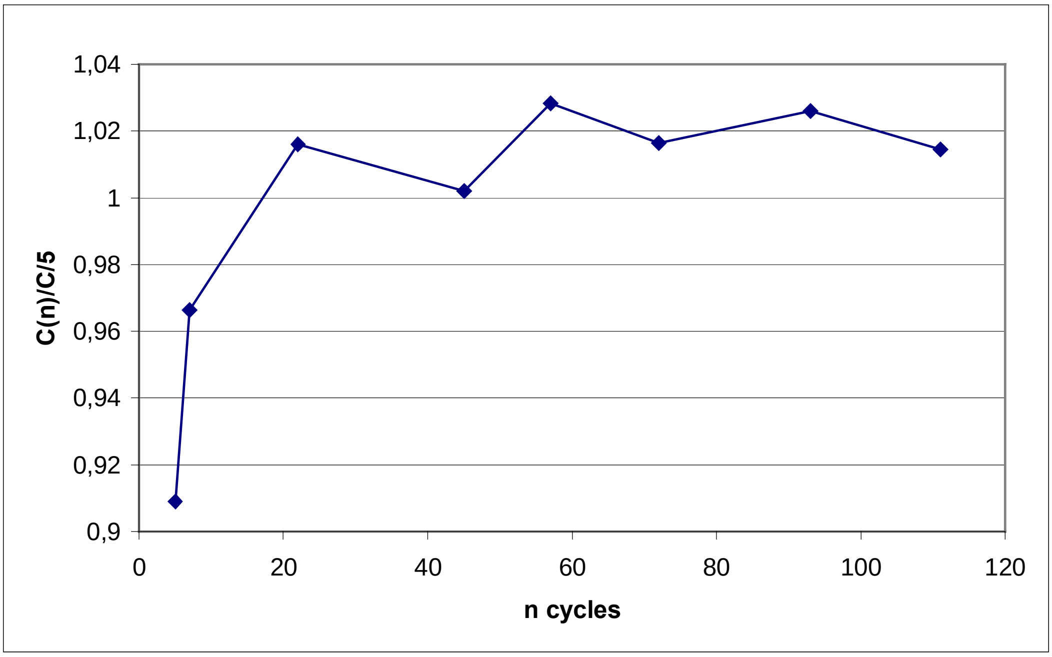

Figure 9: Capacity (C/5) versus deep discharge cycle number (ECE15 urban cycles)

3.3.2 Open Circuit Voltage as SOC and SOH function

The OCV dependence on SOC is described as a polynomial of third degree. It is referred to OCV measurements after a 3-hour resting period.
Waiting for a 10-hour resting period, the OCV shape becomes quite linear (Figure 10), suggesting a linear SOC dependence, due to a capacitance effect with a 10-hour time constant. It will be assumed as reference a resting period lower than 10 hours, because of test rapidity

requirements. During every deep discharge cycle, OCV has been recorded after half an hour, and every 20 deep discharge cycles a parameter check up has been executed, with a 3-hour resting period for the OCV measurement in function of SOC and SOH.

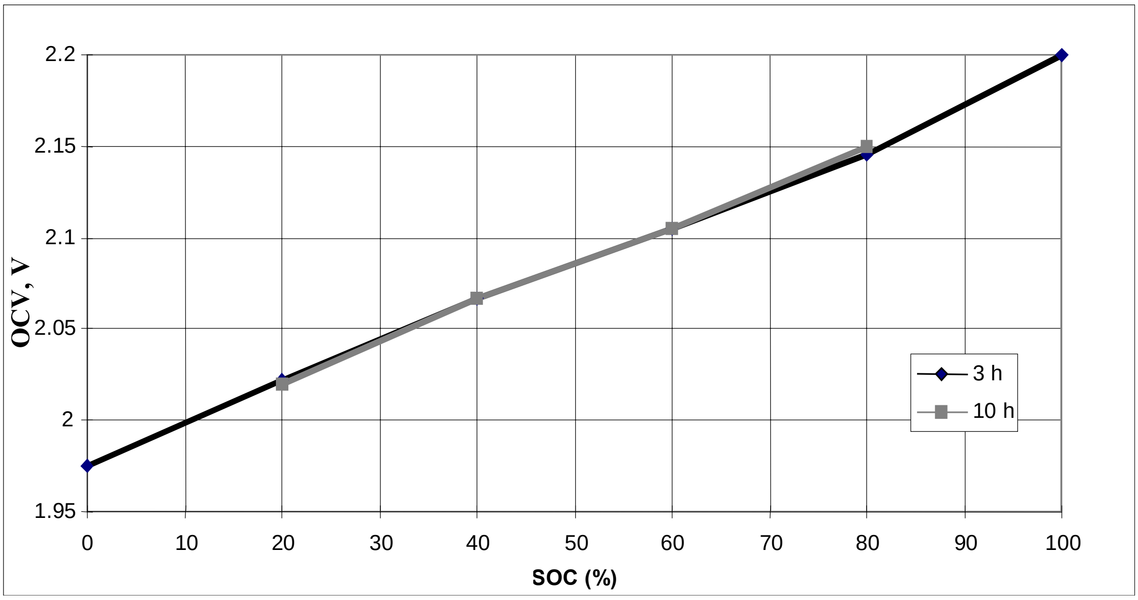

Figure 10: OCV versus SOC at different resting periods (3 hours and 10 hours)

OCV shows a good correlation with SOH only when the batteries are in good conditions. It is shown for three different battery packs, in Figure 11(a), (b), and (c).

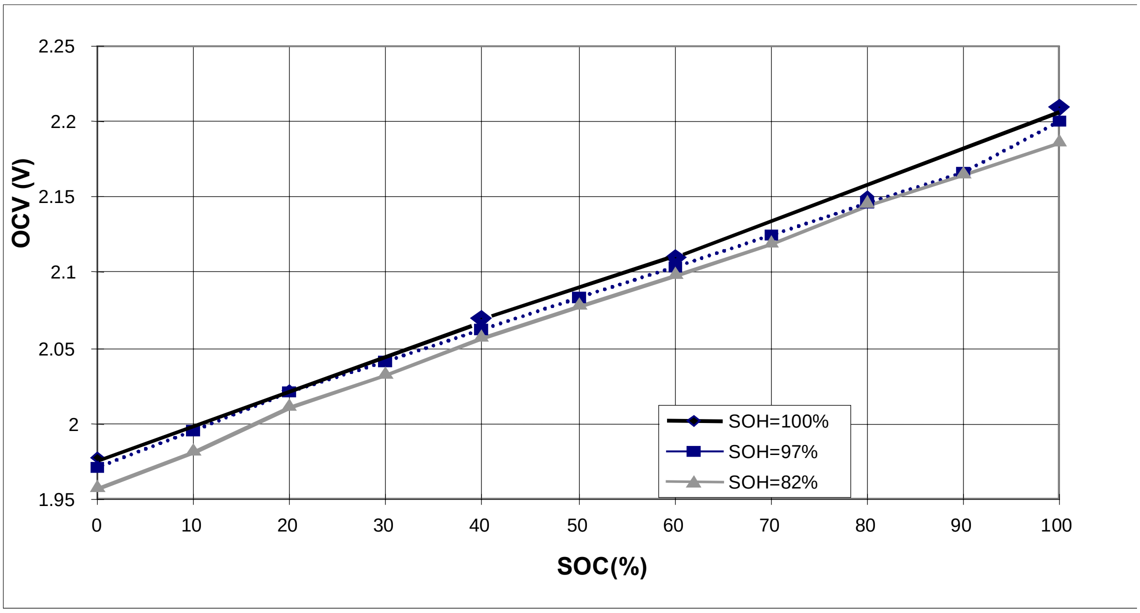

Figure 11a: OCV versus SOC and SOH for 4 gelled-electrolyte lead-acid modules

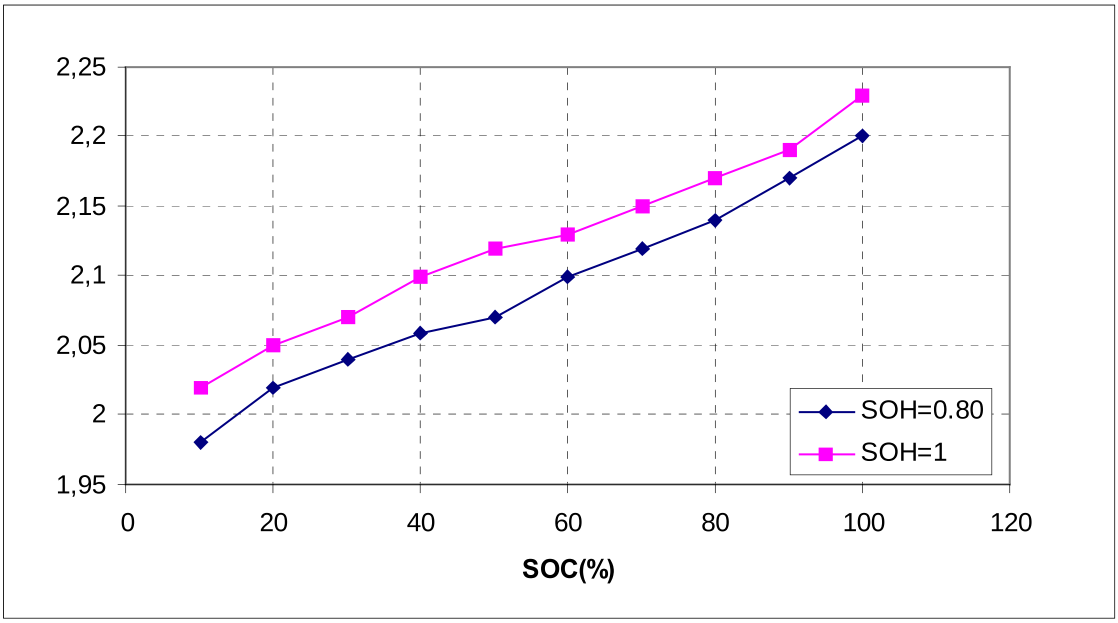

Figure 11b: OCV (SOC, SOH) for different Dryfit Sonnenschein modules

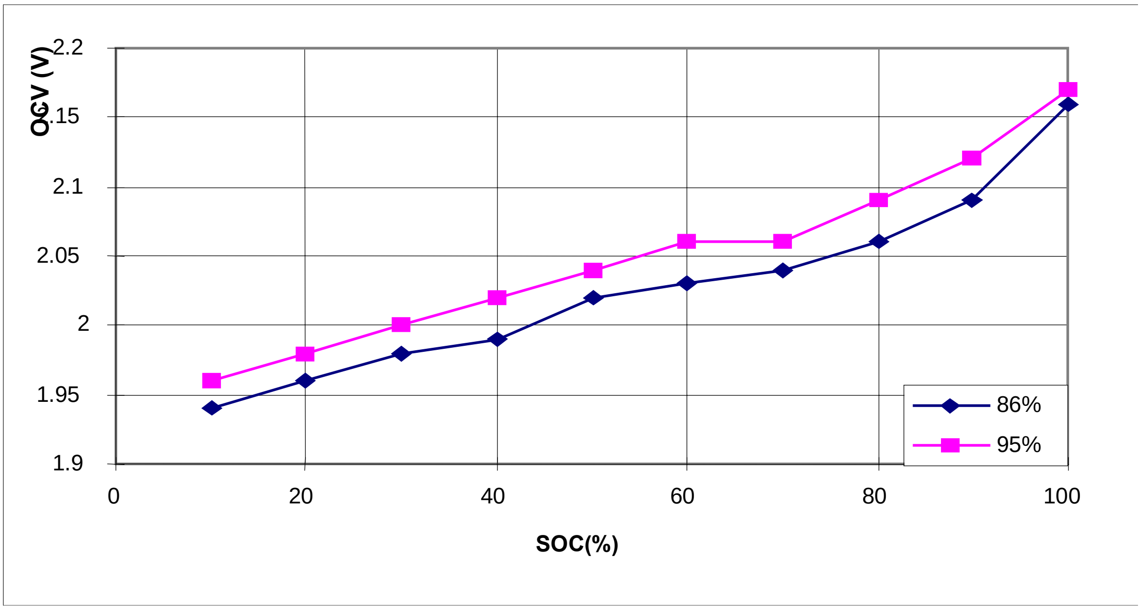

Figure 11c: OCV (SOC, SOH) for lead-acid modules, Tudor - 175 Ah - 6V (previous ENEA test data)

Probably, in such conditions the factor more affecting both SOH and OCV is the temperature. When ageing effects become more important (for example with the aged module), a temperature increase is not sufficient to achieve a higher SOH value, in spite of the OCV increase. The correlation between OCV and SOH is then strongly affected by temperature effects. Tests with aged modules are still needed to achieve better results.

3.3.3 Internal Resistance at low current rate as SOH and SOC functions

Internal resistance as discharge limit indicator

The R^{Int}_{dch} variations with SOH are given in Figure 12. Voltage is sampled with a frequency of 500 Hz during 5 seconds after the load setting off (the voltage value after 1 second is considered in the voltage variation calculation). The discharge current rate is fixed at 6 A.

It may be possible to identify the SOC value that characterises the deep discharge limit. When the extracted charge is greater than 20 % of the available capacity, internal resistance rises quickly; as it is represented in Figure 7, such point may translate during the service life, reaching greater SOC values when the battery is in worst conditions (SOH becomes inferior to 1). In Figure 13, the internal resistance has been measured according to the EUCAR procedure (discharge current rate = 50 A) on other gelled modules, and the Ohmic resistance is plotted.

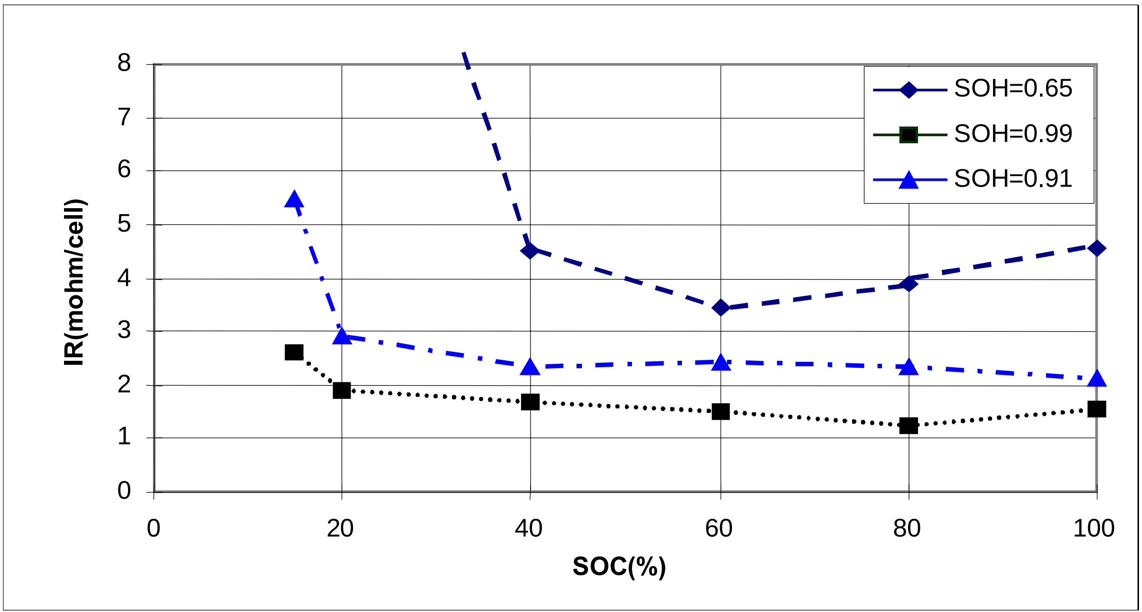

Figure 12: $R_{int\ dch}$ as SOC function at different SOH (for the 4 Dryfit modules under test)

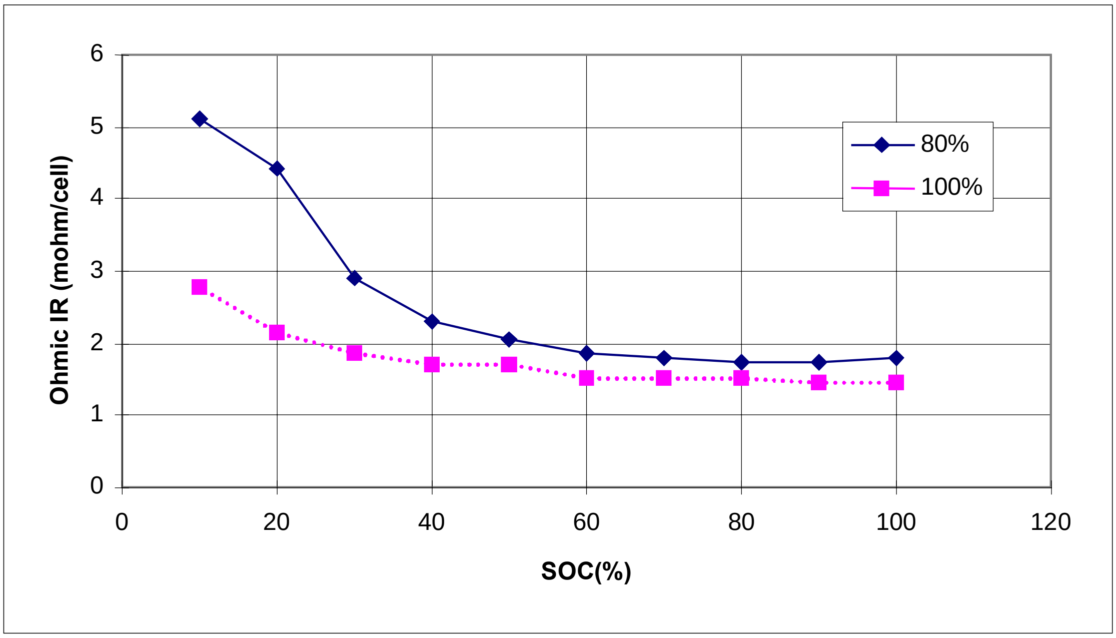

Figure 13: Discharge Ohmic resistance (EUCAR procedure) as SOC function at different SOH (for other Dryfit modules)

Internal Resistance as SOH function.
As shown in Figure 12, R^{Int}_{dch} is strongly affected by SOH. When the battery is almost fully charged, the temperature mainly determines its value, while in the lower part of the SOC range only the ageing effects become important. The linear correlation coefficient (CorrCoeff) between SOH and R^{Int}_{dch} at different SOC values shows that the dependence is inverse (CorrCoeff is negative); its low values suggest that the correlation may be non-linear (Figure 14).

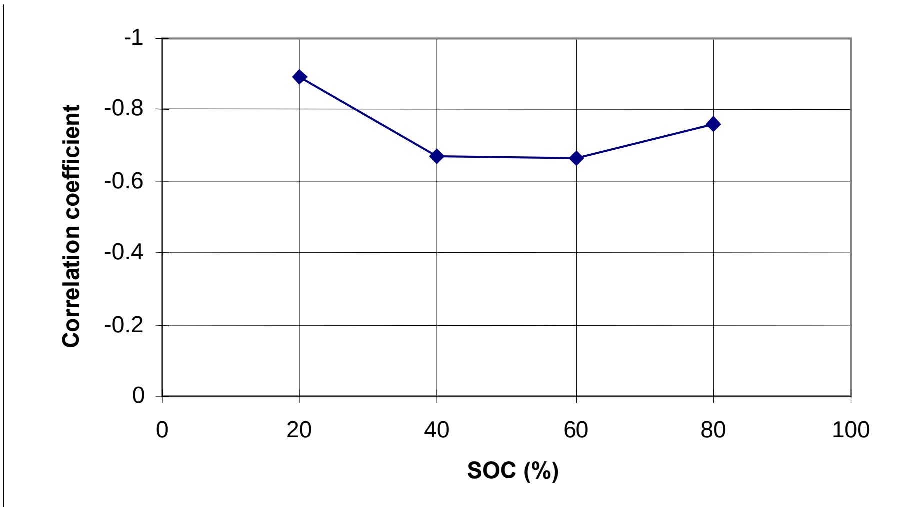

Figure 14: Correlation coefficient between R_{Int}^{dch} and SOH at different SOC values, based on 10 different tests (SOH in the range 0.65-1.04)

3.3.4 Internal Resistance at high current rate and asymmetry in charge and discharge

At low current rates the asymmetry has been investigated as SOC function, in different conditions of temperature, SOH and time interval of voltage measurement (after the load setting off). It revealed to be quite constant, near to the value $AS_I = 1$.
Increasing the current rate, until values greater than C/1, AS_I assumes a different shape: for high SOC values (greater than 50 %) it is a good SOC indicator. Temperature and SOH appear quite unimportant in the AS_I variation.
Tests performed with I=75 A and I=100 A (voltage is recorded 30 sec after the load setting off) are plotted in Figure 15 and Figure 16. With the equipment utilised, a higher value of the current rate is not possible, but until I=100 A., the asymmetry between charge and discharge increases with the current rate.

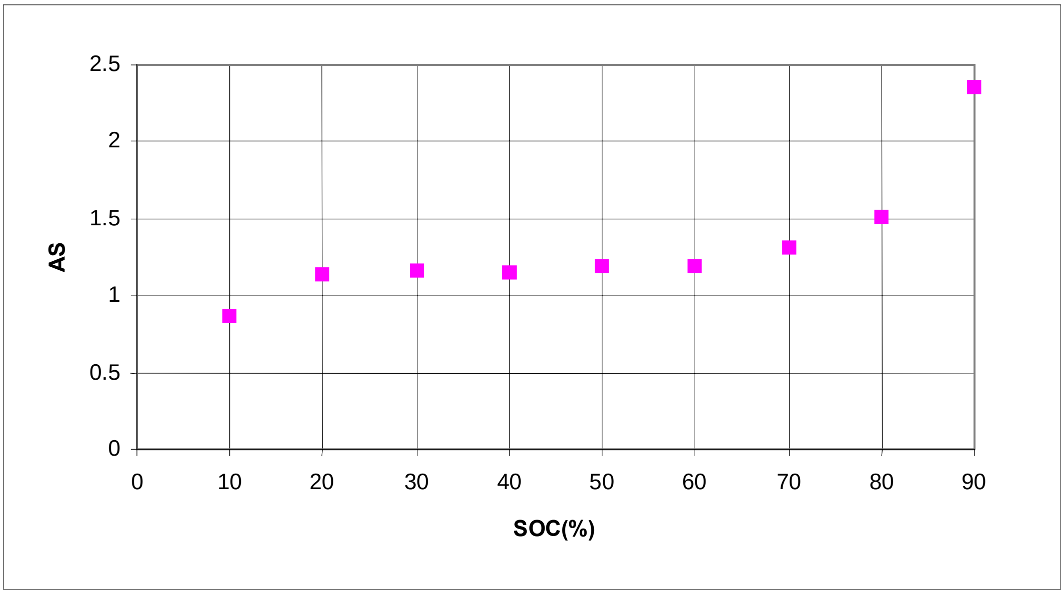

Figure 15: Asymmetry between charge and discharge internal resistance at 75 A (SOH=0.97)

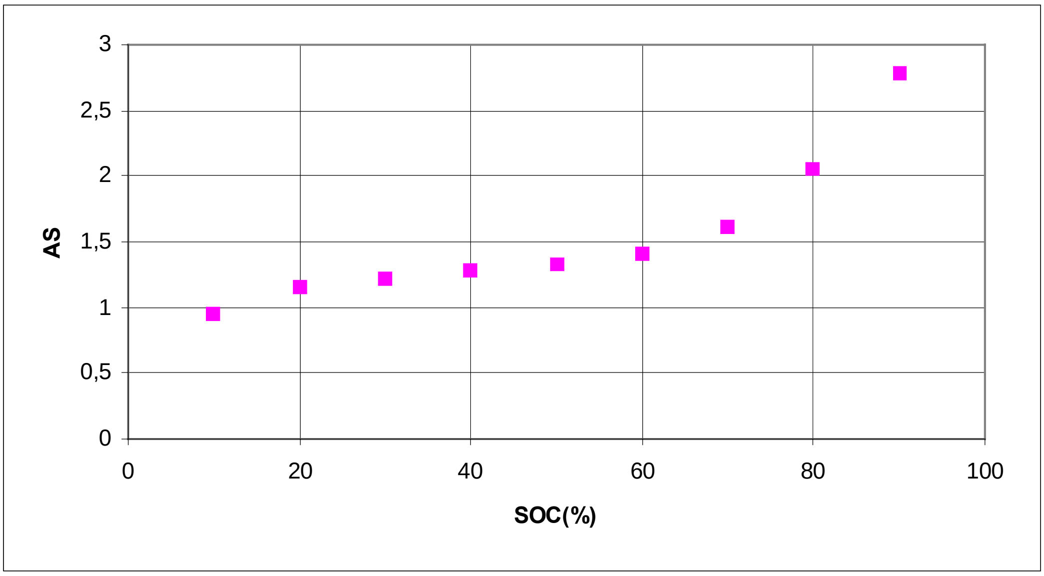

Figure 16: Asymmetry between charge and discharge internal resistance at 100 A (SOH=0.97)

4 Considerations on different battery technologies

As far as other battery types are concerned, no experimental studies have been directly carried out to extend the results obtained on the lead-gel modules. Nevertheless some observations may be pointed out based on the survey of literature (Appendix A).
Ni-Cd, Ni-MH, Li-ion, Zn-air and sodium sulphur batteries, as major candidates for BEVs and HEVs applications, have been considered. As the D.O.E. of the United States of America published in 1999, the expected life of different battery types is resumed in the Table 4.

Table 4: Expected life of different storage technology

Battery technology	Expected Life in Cycle Number
Lead Acid	200-600 depending on the technology
Ni-MH	600
Ni-Cd	2000
Li-ion	1200
Li-polymer	600
Zn-air	400 equiv. to 120.000 km, or to 960 Ni-MH cycles

The internal parameter variation with ageing is peculiar of every different technology, as far as the temperature and discharge rate dependence of the available capacity. However, some results can be extracted from more than 30 articles and summarised in the following point:

1. A universal SOC indicator based on simple electric models may be designed, storing in the internal memory the characteristics of the different battery technologies and adapting the correction factor (like temperature coefficient and the OCV and IR dependence from the SOC).

2. The Randles Erschler model, based on EIS studies, may be adapted to the different battery types, varying suitably the resistance and capacitance parameters.

3. Also the SOC indicators based on logic models may be extended to different battery technologies, allowing different initial settings that enable the reference to different storage data.

Regarding to Ni-MH and Ni-Cd, many papers deal with impedance analysis. In spite of the non-linear SOC dependence of the impedance module and phase in the lead acid modules, in the nickel batteries the impedance phase angle and other Randles Ershler parameters are linearly related to the SOC.
For such batteries, several devices based on fuzzy logic utilise the impedance technique as SOC meter.
Also the SOV technique, proposed for the charge sustaining HEVs, has been adapted to NiCd and Ni-MH batteries, with good results.

Finally, with the exception of Zn-air modules where the mechanical substitution of the metal electrodes establishes a quite different approach, for the other battery technologies considered the same problems are individuated, related to the lead-gel modules on ΔSOC determination by means of a simple Ah-counting. Ageing and temperature effect may not be neglected and the internal impedance or resistance monitoring may be a good SOH indicator.

5 Conclusions and recommendations

Problem definition

Accurate determination of the SOC is a fundamental problem for most battery types and for specific applications, particularly under transient conditions in which charging and discharging modes are frequently involved. Many methods are investigated and proposed: Ah- counting, internal resistance, specific gravity, open circuit voltage, voltage derivative, impedance analysis, and so on. Each of these methods presents advantages and drawbacks, which make it hard to find a general method/device which suits avery battery and every working conditions. For testing purposes, particularly for HEVs, it seems sufficient to determine the ΔSOC, and, possibly, be sure that ΔSOC=0 at the end of the test sequence. This determination can be done by using an Ah-meter, when irreversible phenomena occurring in the battery can be avoided or neglected. Literature survey and experimental activities, described in this document, show that is apparent that the Ah-counting is not a reliable and accurate way to measure the SOC and ΔSOC in any vehicle working conditions and state of the battery. One basic aspect is that the coulombic efficiency of the various batteries varies at different charging/discharging rates and with battery ageing. The measured values of SOC (or ΔSOC) may be different from the real values up to 20-30%, giving a wrong indication to the drivers and a bad reference for testing purposes. For lead-acid batteries, the strong variations of many parameters, including SOC and ΔSOC, have been experimentally verified. The study of the correlation between some significant parameters (internal resistance, temperature, OCV) and the SOC (and SOH) can then suggest an ageing effect correction to the SOC and ΔSOC assessment. Temperature effects need to be carefully considered both for OCV and R_{int}^{dch} variations. Tests on different gelled electrolyte modules are needed, in order to verify the possibility to extend such procedure to other lead-acid battery technology and also to other battery types. The literature behind this experimental work and analysis clearly demonstrates the work still needed to solve this problem. The determination of SOC and ΔSOC is not only useful for evaluating the accuracy of testing procedure, but also for battery models useful for (hybrid) electric vehicle simulation.

SOC determination for testing purpose and battery models

More than 90 articles have been analysed in order to provide a survey of methods and devices about the evaluation of the state of charge for different battery models and uses. Error estimation was also indicated, whenever the data were available from the experimental tests. From such analysis the main results are:

1. A large research work on logic models and devices (fuzzy logic and neural networks) is underway. The SOC estimation method may vary (impedance techniques, characteristic curve techniques, Ah-counting, on-load voltage control) and has been applied to different battery technologies, with good results.

2. There are various attempts to apply the EIS (electrochemical impedance spectroscopy) results to simplified devices. Such method, in spite of a sophisticated and expensive technology, is an affordable tool for SOC determination, meaningful for the battery SOH and operating conditions.

3. It is difficult to define a largely accepted ageing correction factor to the electric models, meanwhile for temperature and current rate effects on available capacity some correction factors have been identified.

Referring to EIS applications, in order to develop methods to correct the Ah-counting, some impedance technique results are:

1. internal impedance and internal resistance are strongly affected by battery ageing.
2. at high current rate, impedance is in non-linear conditions. In this case an asymmetric behaviour between charge and discharge internal resistance is more evident than at low current rate. Such asymmetry is dependent on the SOC.

While the impedance analysis requires sophisticated instrumentation and the data analysis requires complex non-linear least squares methods, internal resistance monitoring is proposed as on-line technique useful to the battery ageing.

Finally, as far as charge sustaining hybrid electric vehicles (CH-HEVs) are concerned, an interesting State Of Voltage (SOV) battery controller has been proposed. The aim is not to predict the end of effective charge, but to maximise 'power processing efficiency and capability while maintaining some degree of charge balance over time'. The SOV control method shifts the battery SOC towards levels, which offer high power cycle efficiencies.

Battery models analysis

The literature survey on models, methods and devices for the SOC and ΔSOC evaluation has considered various battery models. They have been divided in four groups:

1. static electrical models,
2. dynamical electro-chemical models,
3. physico-chemical models, and
4. logic models.

The first and last groups are most useful for the SOC determination and for a ΔSOC computing. The first group includes both coulometric (Ampere-hour counting) and OCV measurements. A combination of these two monitoring techniques is often utilised in order to correct the Ah-counting, strongly affected by the rate of discharge, the duration of resting periods, as well as temperature and ageing effects. OCV measurements avoid the accumulation of errors of the Ah-counting with a periodical correction.
Although the OCV shows a little dependency on the temperature and the history of a battery, it needs a long stabilisation period after the load is turned off. A three-hour resting period is usually considered necessary (EUCAR procedure) for full stabilisation, but it is unsuitable in common vehicle use. For this reason the OCV technique does not provide a good and continuous indication of the SOC, particularly in BEVs and HEVs.
The second and the third group of battery models are quite sophisticated and not useful for on-board SOC-indicators; nevertheless monitoring techniques, such as the electrochemical impedance measurement, underline the importance of ageing effects in the internal parameter variations.
The logic models will be a simple and economic solution to the SOC determination problem: up to now, they need some improvements and more experimental tests.

As regards to the electric models, some simulations have been performed with a simple Thevenin's equivalent circuit. The battery is represented as an electric dipole, characterised by an OCV and IR, both dependent on the SOC of the battery. SOC is calculated integrating the current rate (Ah-counting) and correcting the integral sum with suitable coefficients depending upon the discharge current rate as in the Peukert's equation.
Such a model is able to reproduce only constant current discharge profiles, providing the battery voltage measured at the battery poles. In real driving profiles the results are not satisfactory.
Its importance lies in the possibility to represent a universal model for different battery technologies.

Furthermore, the main effects neglected in such description are the temperature and the ageing effects; in the ΔSOC computing the actual capacity cannot be substituted with the nominal capacity value. The temperature affects the actual available capacity for about 0.8%/°C, while the ageing effect has been quantified in a maximum variation of ±20 % of the nominal capacity.

Experimental tests

On the basis of the literature survey and with the MATADOR goals in mind, experimental tests have been performed. The aim has been to investigate possible corrections for Ah-counting and electrical models for simulations, as well as the battery State Of Health (SOH) evaluation, in the simple electric models. In order to investigate the ageing effect, a test procedure, which considers the whole service life of the batteries, has been designed.

Capacity variation with ageing (cycling)

Figure 17 clearly shows the variation of the actual battery capacity with cycling (the curve refers to a lead-acid battery). This behaviour may cause the maximum error in the ΔSOC evaluation when the battery is at the end of the service life. Considering a charge variation of 10 Ah for a 50 Ah module, the ΔSOC of 30% (even if very rare and undesired) may be underestimated up to 20 %, in the extreme cases of a battery fully degraded with a real capacity of 35 Ah (70% of the nominal one).

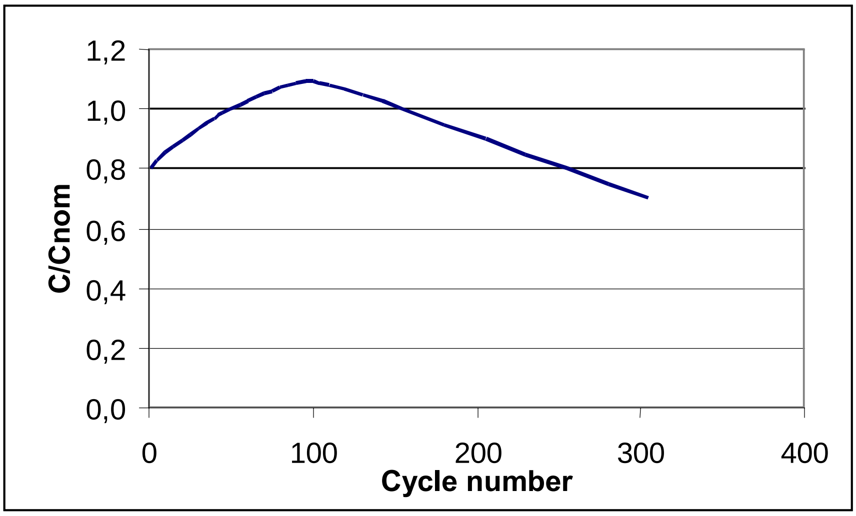

Figure 17: Capacity versus deep discharge cycle number for lead-acid modules

Discharge Internal Resistance as SOH indicator

The discharge internal resistance obtained at low current rate (6A) was named R_{int}^{dch}. This parameter as function of SOC depends on the temperature of the test in the first part of the discharge period, until the voltage drops to about 80% of the actually available capacity. Such temperature dependency is monotonous, but non-linear.

When the modules are almost completely discharged, the R_{int}^{dch} increases quickly from 5 to 10 times the initial value. This resistance variation is strongly affected by the SOH of the battery: the continuous monitoring of R_{int}^{dch} provides an indication of the residual capacity in the final part of the SOC range, also when a discharge at constant rate is no longer possible.

In Figure 18, R_{int}^{dch} is plotted as SOC function and at different SOH.

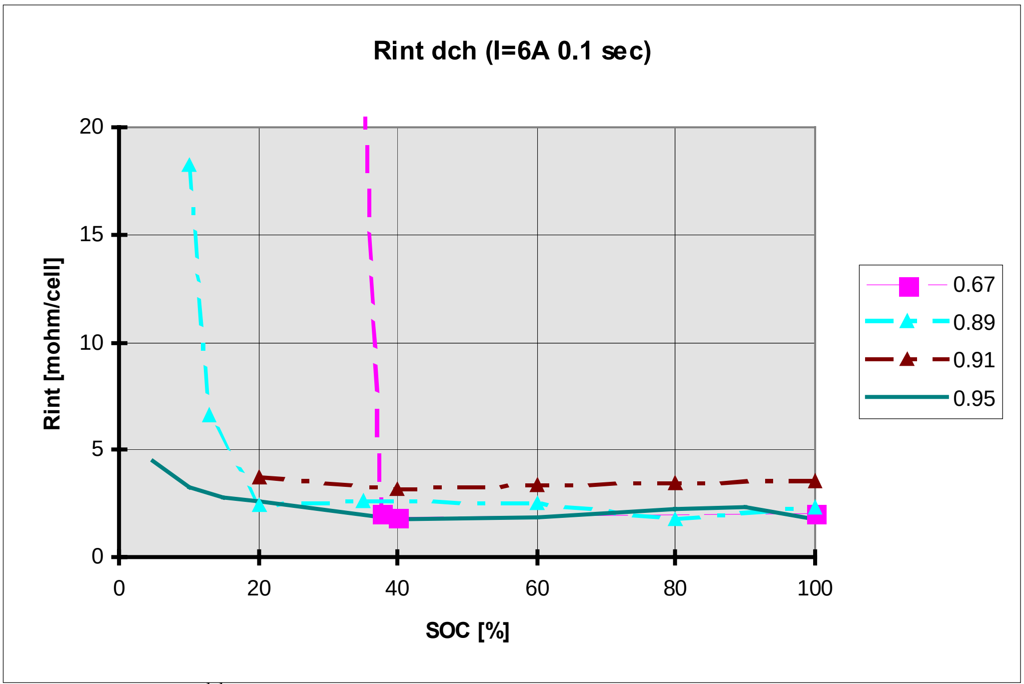

Figure 18: R_{int}^{dch} at 6A current pulses, in the SOC range 0-100 %; the SOH of the modules is varying between 0.67 and 0.95

R_{int}^{dch} is proposed as SOH indicator, interrupting the discharge when the resistance change exceeds 1 mOhm/cell in ΔSOC=10 %. The extracted charge, corresponding to such a discharge limit, will be considered as 80 % of the available capacity in the actual operating conditions. It is then possible the calculation of a '*corrected* ' SOC, indicated as SOC*, defined as the extracted charge referred to the actual available charge. For example, if the SOH of a 50 Ah-module is deduced from the resistance monitoring as 80% and the extracted charge during the functioning is measured as 25 Ah, the corresponding SOC* will be 62.5 % is spite of 50%. The SOC* is more conveniently used instead of SOC, which is referred to the nominal capacity.

Asymmetry and OCV as SOC function*

Monitoring charge and discharge internal resistance at high current rate ($R^{ch}_{I(A)}$ and $R^{dch}_{I(A)}$ respectively) the asymmetry between them is a monotone function of the SOC, weakly affected by temperature effects.
At current rates lower than or equal to C/1, the asymmetry $AS_{I(A)}$ as SOC function is quite uniform and equal to 1 ($R^{ch}_{I(A)} = R^{dch}_{I(A)}$), at high current rates it may be considered a good SOC indicator in the range 50-100 % of the SOC.
Tests have been performed at 75 A and have been corrected with the ageing effects by using the SOC* as state of charge and state of health indicator.
Furthermore OCV with a resting period of three hours after the load setting off has been measured for different temperature and SOH conditions; neglecting the temperature dependency that has shown to be quite complex (non-linear and non-monotone), the SOH effects may be considered by representing OCV versus SOC*.

Battery efficiency

The charge/discharge efficiency varies with SOH and SOC of the battery. Table 5 presents overall efficiency with deep discharge, using a current profile (ECE15) on the four lead-acid modules in different state conditions.

Table 5: Constant current discharges at C/5 rate and following IU-recharges

Ah dch	Ah ch	Efficiency
-41.05	47.89	85.7%
-42.65	53.43	79.8%
-45.72	49.67	92.0%
-49.36	53.26	92.7%
-50.73	55.29	91.7%
-51.41	58.97	87.2%

Furthermore, the charge/discharge efficiency depends on SOH. Table 6 presents charge/discharge efficiency at various SOH.

Table 6: Ah discharged and Ah charged on deep discharge (final SOC=20%) performed on ECE15 cycles

Ah ch	Ah disch	Efficiency	SOH
-40.379	43.65	92.5%	0.96
-39.99	43.46	92.0%	0.96
-39.949	43.37	92.1%	0.96
-39.929	43.36	92.1%	0.96
-39.906	43.45	91.8%	0.96
-39.698	43.89	90.4%	0.96
-39.469	44.88	87.9%	0.96
-39.47	43.25	91.3%	0.96
-39.31	43.8	89.7%	0.96
-39.401	44.16	89.2%	0.96
-39.446	42.09	93.7%	0.92
-39.348	41.66	94.4%	0.92
-39.361	41.69	94.4%	0.92
-39.113	41.65	93.9%	0.92
-39.22	41.65	94.2%	0.92
-39.243	41.66	94.2%	0.92
-39.288	41.58	94.5%	0.92
-39.231	41.51	94.5%	0.92

Recommendations for simulation models and testing

In the framework of the MATADOR Project, SOC and ΔSOC determination is of great importance for testing and comparing electric and hybrid vehicles. In the SubTask 2.5, an analysis on determination methods and devices is pointed out as an essential tool for energy consumption computing. The hypothesis not to take into account the capacity variations in the ΔSOC determination seems to be inadequate to the general purpose of hybrid and electric traction. Particularly for assessment of technologies in real operating conditions, the ageing and efficiency aspects ought to be taken into account.
Starting from the most accepted techniques to estimate the SOC and the battery capacity prediction, the integration of current in time (Ah-counting) requires correction factors in order to account for ageing and temperature effects. OCV, IR and asymmetry between charge and discharge resistance are proposed as ageing indicators; experimental tests have been performed only on lead-gel modules, but IR variations due to ageing of the batteries are common to other battery technologies. The overall results of the literature analysis and test work direct to some recommendations for battery simulation models and ΔSOC determination.

Simulation models

The use of simulation models for batteries may help to correct the Ah-counting and improve accuracy in energy consumption determination. The advantage of using models is twofold: increased accuracy in SOC and ΔSOC assessment and better determination of other parameters (current and voltage) needed to calculate energy consumption, if not directly measured. Main problems are shortly described and addressed.

There are significant variations of battery behaviour with the operating condition (temperature, ageing, and discharge current), easily detectable with the monitoring of the internal resistance at low current pulse.

Proposal:
1. Electrical models can be used, but they must include a parabolic function for the calculationof the internal resistance (IR).
2. The definition of a corrected SOC (SOC*) provides useful information on the state of health of the battery pack.
3. The asymmetry between charge and discharge resistance (at high current pulse) can be a useful and more precise SOC indicator (the OCV after a three-hour resting period may be used as verification test). For OCV at high discharge rates, it is more realistic to use a 3rd order polynomial function.

Recommendations for ΔSOC determination in testing procedures

The ΔSOC evaluation is performed accounting for the Ah-capacity drawn from the battery pack and the Ah-capacity provided to the pack during recharge or by the ICE during the vehicle operation.
The ΔSOC is obtained dividing the total Ah-counting by the nominal capacity of the storage battery. A related problem is the calculation of the electrical energy associated with the measured ΔSOC, when different from zero.
The main limits of such method are:

1. The total Ah-counting refers to the nominal capacity, which can be different from the actually available capacity, because the battery capacity varies with the battery ageing, the operating temperature, the discharge current rate, and so on.

2. The battery charge and discharge efficiencies change with SOC and are not considered in the Ah-counting, which assumes the efficiency constant and equal to 1. The available capacity at the end of the operation (or test sequence) depends upon the operating point into the SOC range during which the battery has been charged or discharged.

3. Batteries, other than lead-acid types, require further investigation to clearly identify other correction factors. For example, NiCd batteries deteriorate mainly because of electrolyte losses. Their capacity can be determined with a small error by measuring the internal resistance IR (with a charge current pulse) and using the following equation: $Q_{ext} = a \ln(IR) + b$, where Q_{ext} is the extracted capacity, IR is the internal resistance, and a and b are constants.

For the first problem, exclusively the nominal capacity variations due to the ageing effect are considered, in order to quantify the importance of neglecting such an aspect. As an example, a lead-acid battery subjected to constant current deep discharge cycles (SOC=20%) can be considered.

For the second problem, the control strategy of HEVs (at least the battery management unit) may impose that the storage system is operated in a fixed SOC range, maximising the battery efficiency and limiting significant variations during charge and discharge phases.

As a practical recommendation and proposal to solve such accuracy problems, which are online with the current trend of verifying performances at varying age (distance travelled) of any vehicle, a periodic test (e.g. every 50.000 km), should be performed. Such test should be aimed at updating the values of chief parameters related to ageing effects (e.g. battery capacity versus temperature and rates) and ΔSOC determination.

References

[1] International Electrochemical Commission Publication No 254, 1987

[2] J. Lee, S. Lee, E. Namo Gong, in EVS 15 - Bruxelles 1998

[3] S. Song, K. Kim, S. Oh, in EVS 13 - Osaka 1994

[4] E.A. Hoxie AIEE Transactions 73 (2), 17

[5] L.E. Unnewehr, IEEE 1979

[6] C.W: de Kreuk, C.A.M. Meijer, P.J. van Duin , XVI Int.Power Sources Symposium 1988

[7] W. H. Vissher, Int. Power Sources Symposium Committee, Leatherland., UK, p.525

[8] Buonarota, P. Menga, V. Scarioni, in 'L'Energia Elettrica', No 7-8 1987

[9] F. Bonanno, S. Musumeci, A. Raciti in Poroc. of SPEEDAM, Symposium on Power Electronics, Capri Italy 1996

[10] Politecnico di Torino (Dip. Ing. El.) and University of Roma, 'la Sapienza' (Dip. Ing.El.), Study Report for ENEA, April 1997.

[11] R. Giglioli, P.Pelacchi, V. Scaroni, A. Buonarota, P. Menga, 33rd international Power Sources Symposium 1988.

[12] R. Giglioli, G. Zini and M. Conte. 3rd Third International Conference on Batteries for Utility Energy Storage, Kobe, Japan (March 1991).

[13] M. Ceraolo, R. Giglioli, G. Pede, G. Casavola, M. Conte. S. Granella, EVS-15, Bruxelles, 1998.

[14] M. L. Gopikanth, S. Satthyanarayana, in J. A. Electrochem. 9 (1979) pp. 369-79

[15] S.A: Ilangovan, S. Satthyanarayana, in J. A. Electrochem.22 (1992) pp. 456-63

[16] J. Jindra, M. Musilva, J. Mhra, in J.P.S. 37 (1992) pp. 403-409

[17] V.V. Visvanathan, Salkind, Kelley, Ockermann, in J. A. Electrochem. 25 (1995) pp.716-728

[18] V.V. Visvanathan, Salkind, Kelley, Ockermann, in J. A. Electrochem. 25 (1995) pp.729-39

[19] M.J. Hlavac, D. Feder in INTELEC 1995 - /th International Telecommunication Energy Conference p. 284-291

[20] P. Mauracher, E. Karden, in J. P. S. 67 (1997) pp.69-84

[21] J.P. Diard, B. LeGorrec, C. Montella, in J.P.S. 70 (1998) pp. 78-84

[22] H.L. Wiegmann, R.DF. Lorentz, EVS 15 Bruxelles 1998

[23] F. Huet in J.P.S. 70 (1998) pp.59-69

[24] D.O. Feder T.G. Croda, K.S: Champlin, S.J. McSahne, M.J. Hlavac in J.P.S. 40 (1992)

[25] Le Pioufle, J. F. Fauvarque, P. Delalande in Eur, Phys. J. AP (1998), pp.2 257-265

[26] E. Karden R.W: DEDoncker in EVS 15 Bruxelles 1998

[27] S. Okazaki, S. Higuchi, S. Takahashi in J. Electrochem. Soc. Vol. 132 n.7, (1985)

[28] U. Teutsch in Telescon 1994 Berlino

[29] W.B. Gu, C. Y. Wang in J. Electrochem Soc. Vol. 144 N.6, (1997)

[30] E. Karden P. Mauracher F. Shoepe in J.P.S. 64 (1997) pp.175-180

[31] P. Singh, C. Fennie, Jr and D. Reisner, A.J. Salkind in EVS 15 Bruxelles 1998

[32] L. Sun, X. Tan, F. Xie, C. Song in EVS 15 Bruxelles 1998

Appendix A Commented bibliography on battery models

One of the actions in SubTask 2.5 activities has been the collection and preliminary analysis of literature related to the area of the determination of SOC and ΔSOC. The scope of this survey has been twofold: on one side, to identify battery models that can be usefully applied in simulation models of EVs and HEVs; on the other side, to verify the existence of SOC or ΔSOC estimation devices or methods alternative to ampere-hour measurements. Moreover, the methods/devices were also analysed in terms of the level of accuracy and parameters that may more affect SOC or ΔSOC estimations. The survey has been carried out looking at the in-house bibliography at ENEA and also through the use of the literature databases to which ENEA library is connected. As a consequence of such investigations, only part of the selected papers is effectively currently available, but the paper copies of some useful references have been ordered. In a revised version of such bibliography survey, planned for the final report, the overall list will be fully analysed. For such reason some of the references are not described or analysed. Whenever possible, the abstracts or a direct description of the references have been included.

To assist in accessing the information hereafter collected, a simple classification has been adopted: the literature is listed according to the searching keywords. Three main classes have been searched: 1) modelling of EV and HEV in which references to battery models were mentioned; 2) battery models for SOC determination; and, finally, 3) commercial or prototype devices mainly developed for SOC measurement or estimation. Of course, the work has mainly been focused on the second and third class of bibliography, while the first one has been only used for identifying problems and connections. Furthermore, some abbreviations and acronyms have been used to simplify the description. Finally, the critical results of such survey are reported in other working documents and reports, specifically addressing the models for SOC determination, the experimental verification of some of them and their applicability in simulation codes.

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Table of contents based on searching keywords

<u>A. Introduction: HEV and EV Control</u>

A.1 Computer Modelling of the automotive energy requirements for internal combustion engine and battery electric-powered vehicles
J. R. Bumby, P. H. Clarke, I. Forster, IEE Proceedings Vo. 132, Pt. A, No. 5 September 1985
Keywords: HEV and EV control.
Availability: Printed

A.2 Optimisation and control of a hybrid electric car
J. R. Bumby, I. Forster, IEE Proceedings, Vol. 134, Pt. D, No.6, November 1987
Keywords: HEV and EV control.
Availability printed

A.3 Life cycle cost evaluation of Electric/Hybrid vehicles
W.W. Marr, W. J. Walsh, Energy Conversion Management vol. 33, No. 9, pp. 849-853, 1992
Keywords: HEV and EV control.
Availability: printed

A.4 Modelling of battery-PWM-converter-PM synchronous motor for vehicle drive-chain
A. Makki, A. AH-Jaco, A. Jammal, G. Grellet in European Power Electronics Chapter Symposium p. 449-52 - 1994
Keywords: HEV and EV control.
Availability: required (INSPEC)

A.5 Adaptive control of the unique Mobility EV drive system to account for time-varying battery parameters
C. Kopf, IEEE 1995
Keywords: HEV and EV control.
Availability: printed

A.6 A switching logic controller for a HE/ICE vehicle
D.L. Buntin, J.W.Howze in Proceeding of the 1995 American Control Conference vol.2 p.1169-75 - 1995
Keywords: HEV and EV control.
Availability: required (INSPEC)

A.7 A rule-based energy management strategy for a series hybrid vehicle
N. Jalil, N.A: Kheir, M. Salman, in Proceedings of the 1997 American Control Conference - 1997
Keywords: HEV and EV control.
Availability: required (INSPEC)

A.8 State of charge estimation of sealed lead-acid batteries used for EV
A. Kawamura, T. Yangihara in 29th Annual IEEE Power Electronics Specialist Conferences p.538-7 vol. 1 - 1998
Keywords: HEV and EV control.
Availability: required (INSPEC)

A.9 Development of test procedures for the evaluation of vehicles with electric, hybrid and fuel cell power trains
R. Smokers, R. Bady, M. Conte, L. Buning, K. Meier-Engel, Bruxelles, EVS 15, 1998
Keywords: HEV and EV control.
Availability: printed

A.10 The use of computer simulation in the evaluation of electric vehicle batteries
W. B. Gu, C.Y. Wang, B.Y. Liaw in Journal of Power Sources 75 (1998), pp. 151-161
Keywords: HEV and EV control.
Availability: printed

A.11 The Battery Management System for Electric Vehicle based on Estimating Battery's States
Li Sun, Xinde Tan, Fuchun Xie, Chunli 4, in EVS 15, Bruxelles 1998
Keywords: HEV and EV control.
Availability: printed

A.12 Solving measurement and evaluation problems in the development of test procedures for vehicles with electric, hybrid and fuel-cell power trains.
R. Smokers, S. Ploumen, Synopsis for EVS 16 (1999)
Keywords: HEV and EV control.
Availability: printed

****

B. Batteries: Models

1. A comparative evaluation of battery models for electric vehicle simulation
L.E. Unnewehr, Ford Motor Company, IEEE 1979
Keywords: Battery - Models
Abstract:
Starting from the comparison of different previous models (Hoxie Modified Model, Exxon Model, Airesearch, Ford, JPL Model) at the level of terminals voltage and of capacity variations, different available values of predicted capacity and module parameters (internal resistance, self-discharge, etc) are discussed.
A universal model is proposed that justifies different battery behaviour; the scheme is simple. It is constituted by a voltage generator E_v, an internal resistance R, current I, terminal voltage E_t and the required or supplied vehicle's power P. Electrical current is determined by means of P, E_v and R; the next step is calculation of Et.
Availability: printed

2. Impedance parameters and the state-of-charge. I Nickel-cadmium battery
S. Sathyanarayana, S. Venugopalan, M.L. Gopikanth in Journal of Applied Electrochemistry 9 (1979), 125-139
Keywords: Battery - Models
Abstract:
An Electrochemical Impedance Spectrum analysis is performed to investigate SOC dependence of the model parameters (Rs, Rp, Cs, Cp, etc..). Dealing with Ni-Cd batteries, low frequency domain (5-30 Hz) is more interesting: The impedance module, the Rs and Rp as SOC functions, are examined with the aim to determine the electrical model. The impedance module is mostly affected from diffusion effects. Series capacitance, parallel capacitance and impedance phase are parameters sensible to SOC variations. The latter one seems to be a monotone function of SOC.
Availability: printed

3. Impedance parameters and the state-of-charge. II Lead Acid Battery
M. Gopikanth, S. Sathyanarayana in Journal of Applied Electrochemistry 9 (1979) 369-379
Keywords: Battery - Models
Abstract:
A different frequency range is examined to investigate internal processes of lead-acid batteries: charge transfer and diffusion process mostly affect the impedance between 15 and 100 Hz. Impedance phase, series capacitance and parallel capacitance show a parabolic shape as SOC functions; a minimum value is reached at about SOC=50 %.
Availability: printed

4. Influence of temperature and ageing on the measurements of internal parameters of lead-acid accumulators (in Italian)
N. Polese, A. Bernieri, C.Landi, E.I. Noviello, C.N.R. - Università di Napoli
Keywords: Battery - Models
Abstract:

Starting from a Randles model, with Warburg impedance described as a parallel Rct-Cdl, model parameters are obtained applying current step pulses to the modules, with an accuracy of 2%. Transient behaviour analysis leads to define other parameters, such as the virtual resistance, polarisation voltage, etc; all parameters are investigated as SOC functions. As a final result, the most useful parameter seems to be the *integrated voltage*, defined as the integral of the difference between the *relaxation* open circuit voltage and a reference voltage value measured at the beginning of the relaxation. With a life accelerating technique, this function versus ageing and temperature is observed. A prototype device for SOC assessment is suggested.
Availability: printed

5. Decay indexes of advanced lead-acid accumulators during accelerated cycle life testing 8in Italian).
C. Landi, N. Polese - Department of Electrical Engineering - University of Napoli, A.34 (1980)
Keywords: Battery - Models
Abstract:
In order to test different batteries in limit conditions for PV plants, accelerated procedures have been executed; the deterioration process velocity is strongly dependent from temperature, electrolyte density and other parameters. Between 40 and 50 °C the capacity reached a maximum, and then decreases to lower values; in addiction to capacity other parameters are used as ageing indicators. Different battery structure are examined (tubular, flat, with antimonium, and so on.). The experimental work was partially described in this paper, because s more than 2000 cycles for the best kind of batteries were examined.
Availability: printed

6. Internal resistance measurement as a decay index of lead-acid batteries (in Italian)
C. Landi, Report 45 C.N.R., Università di Napoli, Centro di studio sui calcolatori ibridi (1981)
Keywords: Battery - Models
Abstract:
Attention was focused on internal resistance, after a review of the main indicators of failure for lead-acid batteries. The report describes recent and classical measurement techniques, both in d.c. and a.c. The influence of parameters, like electrolyte temperature, density and SOC, on the internal resistance values, is discussed.
An experimental testing part is developed, concerning lead acid batteries for photovoltaic plants (University of Napoli). It seems possible to detect the failure status of a module by means of parameters available during operations.
Availability: printed

7. S.O.C. characteristics of the lead-acid battery
W. Visscher Preprint from the 14th Intern. Power Sources Symposium 1984
Keywords: Battery - Models
Abstract:
Starting from a Shepherd model for low polarisation conditions, the author suggests a model able to work in high polarisation conditions. Simulation results are tested on normal operation EV condition, taking into account the braking recuperation effects. Tests are performed on Varta 6-Volt modules, in a temperature range between 7 and 27 °C. The achieved accuracy is greater than 7 %.
Availability: printed

8. An electric model for discharge and recharge af lead-acid batteries, developed for industrial applications
A. Buonarota, P. Menga, V. Scarioni, in 'L'Energia Elettrica' N.7-8 1987
Keywords: Battery - Models
Abstract:

The Thevenin equivalent electric circuit of a battery contains in this model a voltage source and two resistive components, an Ohmic and a diffusional one. A PV plant storage system is simulated and the comparison with experimental data accounts also for charging process, assessing the charging efficiency and the ageing effects.
Availability: printed

9. Battery model of charge and discharge processes for optimum design and management of electrical storage systems
R. Giglioli, P. Pelacchi, V. Scaroni, A. Buonarota, P. Menga, 3rd International Power Sources Symposium, 13-16 June 1988, Cherry Hill p.756-761
Keywords: Battery - Models
Abstract:
Two branches of the internal process description are developed: one is reversible and the other irreversible. Thermal balancing is also considered in the mathematical model implementation. Starting from manufacturer information, some parameters are previously measured, with step current profiles: both charging and discharging curves are fitted. Constant current profiles are simulated because the experimental comparison is based on data from a PV plant storage system.
Availability: printed

10. Estimation of power-energy plots for secondary batteries
F. R. McLarnon, E.J. Cairns, Albert R. Landgrebe, 3rd International Power Sources Symposium Cherry Hill, New Jersey, June 1988
Keywords: Battery - Models
Abstract:
A rapid and convenient method can be used to estimate power energy plots, or correlate and extrapolate experimental data: the relationship utilised contains power, energy, voltage and capacity values for low-rate discharge. This method may be used for comparisons between different systems, evaluation of different device designs and estimation of parameters.
Availability: printed

11. Estimation of the residual capacity of maintenance-free lead acid batteries. I. Identification of a parameter for the prediction of SOC.
R.T. Barton, P.J. Mitchell, in Journal of Power Sources 27 (1989) pgg. 287-295
Keywords: Battery - Models
Abstract:
Availability: printed

12. The Impedance of Sodium-Sulphur cells at very low frequencies
P.J. Johnson in Journal of Power Sources 32 (1990), pp.63-70
Keywords: Battery - Models
Abstract:
In the frequency range of $10^{-5} \div 10^{3}$ Hz, measurements are carried out with a Solartron 1250 frequency response analyser and a Solartron 1286 electrochemical interface operating in potentiostatic mode. The Sodium sulphur cells used were constructed in the CSP (Chloride Silent Power) laboratories; for this kind of battery, the rate of internal heat generation is strongly influenced by the internal impedance, depending by SOC and frequency. Below 10 mHz, the battery exhibits Warburg behaviour; below 0.4 mHz the impedance rises sharply, because of concentration polarisation of the sulphur electrode, controlled by diffusion processes. This behaviour is analysed in terms of an equivalent circuit, and the significance of the resulting values for the parameters of the circuit is discussed.
Availability: printed

13. Impedance studies of internal cell welds in automotive lead/acid batteries
Z. Stoynov, B. Savova-Stoynov, T. Kossev, in Journal of Power Sources, 30 (1990) 301-307.
Keywords: Battery - Models
Abstract:
Improvement of battery design is the main aim of this article: testing instrument and procedures are described. Attention is paid to the quality of welds, responsible of many battery failures. Studies have been carried out on internal cell welds on two types of plates groups, of standard and deliberately inferior technology. Small (55 Ah) and large (135 Ah) sizes are taken under examination. Real impedance part correlates well with the d.c. measurements; self-inductances of the welds are different, varying in both value and behaviour. A quality control equipment based on impedance measurements can be derived, for improvement and field adjustment of the weld technology.
Availability: printed

14. Conductance testing compared to traditional methods of evaluating the capacity of VRLA batteries and predicting state of health.
D.O. Feder, T.G. Croda, K.S. Champlin, S.J. McShane, M.J. Hlavac - Journal of Power Sources 40 (1992)
Keywords: Battery - Models
Abstract:
Traditional methods of SOH measurements (SG, OCV, and so on) are not always available for sealed lead-acid accumulators.
A method based on conductance/capacity relationship of the battery is proposed (tests are performed for a telecommunication plant, with 1000 Ah-modules). Correlation coefficient between conductance and discharge time until the cut off voltage value is contained in the range 0.75/0.95, with varying discharge rates and cut-off voltages.
Availability: printed

15. Impedance characteristics of sealed lead/acid cells during galvanostatic charge.
J. Jindra, M. Musilovà, J. Mrha in Journal of Power Sources 37 (1992) pp. 403-409.
Keywords: Battery - Models
Abstract:
Oxygen evolution at the positive-electrode affects the impedance value during the final part of charging; impedance rises, as shown in the test results. In the low frequency range, a SOC dependence of the imaginary impedance is revealed, due to the capacity change of the negative electrode.
In the second phase of the charging process and in the overcharge case this effect is more relevant. A single cell-test is performed, both in galvanostatic and in potentiostatic modes.
Availability: printed

16. Impedance parameter of individual electrodes and internal resistance of sealed batteries by a new nondestructive technique
S.A. Ilangovan S. Sathyanarayana, in Journal of Applied Electrochemistry 22 (1992) 456-463
Keywords: Battery - Models
Abstract:
Galvanostatic discharges, with very low current rates (C/2000 A where C is the nominal capacity) for very short periods, permit an almost linear test regime, with SOC variations lower than 0,01 % and with Randles parameters (Rct e Cdl) practically constant. Such parameters are defined separately for anode, cathode and electrolyte/separator. Testing conditions allow the simplification of neglecting diffusion effects and self-induction phenomena. Main objectives of the work are the design optimisation of the battery and the possibility to identify the decay processes.
Availability: printed

17. A mathematical model for Lead-Acid Batteries
Z. M. Salameh, M. A. Casacca, W. A. Lynch, IEEE Transaction on Energy Conversion, Vol. 7, No.1 March 1992
Keywords: Battery - Models
Abstract
The described model considers self-discharge, internal resistance, temperature, overvoltage phenomena and the variation of the storage capacity. The charge and discharge processes are represented by diodes after resistances that simulate the circuit: self-discharge resistance, internal resistance during charge, internal resistance during discharge, overvoltage resistance during charge and discharge. A set of non-linear equations is used to describe the model. A BASIC program integrates currents with an iterative process in order to obtain the waveform of the capacitor voltage (overvoltage and battery capacitance). The model is tested by using experimental data with two different duty cycles. No details are given about the experimental part and the error analysis.
Availability: printed

18. Statistical analysis of the error function in the determination of the S.O.C. in lead-acid batteries
C. Armenta-Deu, T.Donaire Madrid, in Journal of Power Sources, 39 (1992) 95-105
Keywords: Battery - Models
Abstract:
The method for SOC estimation uses the correlation between the electrolyte specific gravity and the voltage of a reference cell connected to the cell under investigation. The error analysis, derived from simulations with model and compared with some experimental data, aims at defining a probability related to the estimation error. The error is thus connected to the uncertainty of the variation of the specific gravity, added to a certain value linearly depending on the S.O.C. and the charging and discharging efficiency. The maximum error achieved was of 8%, while the statistical distribution of the error shows a negligible probability to obtain an error higher than 2.2%. A correction factor of $\pm$ 0.022 (with a risk factor of 0.1 %) of the simulation results is then proposed. Experimental tests have been carried out on PV plants with high and low discharge regimes.
Availability: printed

19. Tests de duree de vie sur des accumulaters au plomb pour vehicules electriques.
A. Borghetti, C.A. Nucci, in VP/CV(Véhicules 'Propres' -'Clean Vehicles') 15-19 November 1993 La Rochelle
Keywords: Battery - Models
Abstract:
The aim of this work is to study the influence of charging and discharging procedures on the performances and life of the lead acid accumulators: the influence of deep-discharge is discussed, and parameters other than capacity are studied as possible ageing indicators. Results of the research carried out on tubular-plate lead-acid accumulators for EV are reported. A linear correlation between the logarithm of life-cycle and depth of discharge is found; the terminal end-of charge voltage measured during equalising charges decreases with ageing.
Availability: printed

20. Variables that influence results of impedance testing for valve regulated cells
G. J. Markle in INTELEC 93 - 15th International Telecommunications Energy Conference p.444-8 USA 1993
Keywords: Battery - Models
Abstract:

This paper demonstrates the effects of two variables that influence measured internal cell impedance values: SOC and temperature. Both influences have an inverse effect on the internal impedance that decreases as the cell is subjected to proper float charging and/or elevated temperatures. The popularity of this test technique has been propelled since the advent of the sealed VRLA batteries, and an understanding of the data that must be collected to correlate the findings must be attained. Data presented represents tests on VRLA cells of both gelled and absorbed electrolyte technologies.
Availability: Catalogue JPS 60 (1996)

21. Impedance testing - is it a substitute for capacity test?
G. Alber M.W. Migliaro in INTELEC XVIth International Telecommunications Energy Conference p.245-9 USA 1994
Keywords: Battery - Models
Abstract:
Capacity tests are used to reliably determine lead acid battery capacity. The results of the capacity tests are used to evaluate whether the battery can continue in service or need to be replaced. Unfortunately, many batteries do not receive regular capacity tests. This occurs because of perceptions that: the test is difficult to perform; it takes too much time; the battery is too important to be removed from service for a test; the test is too costly, and so forth. Measurements of impedance (or conductance, or internal resistance) are useful in detecting weak or failed cells and probably to replace capacity tests. This paper shows that internal resistance rather than impedance is the parameter more important to measure. The changes in cell impedance as the cell ages are also analysed. Finally, a discussion of published results of impedance testing to date is presented.
Availability: required (INSPEC)

22. An empirical nickel-hydrogen battery model
H.H.Rogers, S.J. Stadnick, T.M. Pemberton, in 29th Intersociety Energy Conversion Engineering Conference p.81-5 vol.1 - USA 1994
Keywords: Battery - Models
Abstract:
Availability: required (INSPEC)

23. Determination of impedance parameters of individual electrodes and internal resistance of batteries by a new non-destructive technique. 2. Theoretical approach
S.A. Ilangovan in Journal of Power Sources, 50 (1994) 33-45
Keywords: Battery - Models
Abstract:
A general framework is defined, with the aim of improving battery constructive techniques, failure prediction and expected life. Based on Randles model, the simulation model does not account for inductive effects and for diffusional phenomena. A galvanostatic non-destructive technique is described, at very high current rate. Model is implemented on Fortran 77, and 3% average errors are provided.
Availability: printed

24. A mathematical model for float operation of VRLA batteries.
U. Teutsch in Telescon 94, Berlin, 1st International Telecommunication Energy Special Conference p.89-96, Germany 1994
Keywords: Battery - Models
Abstract:
In uninterruptable power supplies, the battery is floating and continuously charged at low voltage to avoid gradual self discharge.

Describing lead-acid battery behaviour in float conditions taking care of the transient periods, Computational Fluid Dynamics (CFD) methods are utilised to solve a set of non-linear differential coupled equations. The general equation is of diffusional-convective kind ($S + \nabla (G\nabla\Phi) = \nabla (v\Phi) + \delta\Phi/\delta t$).
The main aim is not the SOC evaluation, but the reproduction of discharge and charge processes, taking into account the main elements of the electrochemical kinetics. Simulation results reproduce with accuracy the experimental data, but there is not an error analysis.
Availability: printed

25. Methos of estimating deterioration of lead acid batteries using pulse discharge and charge characteristics
T. Ogata, K. Takano, M. Kohno and K. Yoshida in INSPEC: B9503-8410E-006 Electronics and Commun. in Japan, Part I (Communications), 77 (1994) 1-10.
Keywords: Battery - Models
Abstract:
Availability: required ()

26. Performance measurement and reliability of VRLA batteries
D.O. Feder in Intelec 95 7th International Telecommunications Energy Conferences p.22-8 - USA 1995
Keywords: Battery - Models
Abstract:
This paper provides a brief review and the level of understanding of some of the aspects of VRLA battery technology which determine performances and are potentially life limiting. It underlines the complex interrelationships involved and highlights their impact in narrowing the optimal 'window' for VRLA cell design, process and application. It describes how the search for a suitable technology to allow determination of the state of health (SOH) of VRLA batteries has resulted in the largest published capacity performance data base ever created for any type of industrial stationary lead acid battery. It then presents the results of actual discharge capacity tests on more than 24000 VRLA cells, describes the extent of premature failures discovered, the obvious implications on VRLA battery reliability, and the success of conductance and impedance techniques in detecting cell failure.
Availability: required (INSPEC)

27. Development of a battery runtime prediction algorithm and a methos for determining its accuracy
W. Ross, P. Budney in Intelec 1995 7th International Telecommunications Energy Conference p.277-283
Keywords: Battery - Models
Abstract:
Johnson Controls Battery group has developed a battery performance algorithm which provides an accurate runtime prediction via continuous battery monitoring. The Energy Eye algorithm is based on a mathematical model that describes the batteries' relative SOC as a function of voltage and discharge rate. Each battery design used with the algorithm has a unique set of mathematical constants derived from a comprehensive testing regime. The algorithm provides an accurate runtime prediction with stable output under constant and dynamic loads. Its compatible with continuous monitoring and updates battery performance using readily measurable battery information. The algorithm also possesses a learning capacity to provide improved predictive capability, with an accurate and conservative prediction in the critical time frame near the end of discharge.
Availability: required (INSPEC)

28. Effect of state of charge on impedance spectrum of sealed cells, Part I: Ni-Cd cells
V.V. Viswanathan, A.J. Salkind, J.J. Kelley, J.B. Ockerman in Journal of Applied Electrochemistry 25 (1995) 716-728
Keywords: Battery - Models
Abstract:
This paper follows after many years the first experimental work of the authors; a systematic analysis of the whole frequency range (0.002/250 Hz) on impedance is proposed.
SOC dependence of impedance phase angle, of the series capacity and of the parallel capacitance is shown to be monotone, in the low frequency range. The Imaginary impedance results to achieve a minimum value in the whole frequency range, impeding its utilisation as SOC indicator.
Availability: printed

29. Effect of state of charge on impedance spectrum. Part II: lead acid batteries
V. V. Viswanathan, A. J. Salkind, J.J. Kelley, J.B. Ockerman, in Journal of electrochemistry 25, (1995) 729-739
Keywords: Battery - Models
Abstract:
In order to continue the experimental work shown in paper 28, alternating current impedance spectroscopy was performed on sealed lead-acid batteries; the frequency range is prolonged to the lowest values (about 10μHz).
In addition to the previous considerations on the impedance parameters useful to determine the SOC, the same evaluations are presented for this kind of batteries, starting from Randles model:
1. Ohmic resistance decreases with the increasing of SOC
2. transfer charge resistance increases with the increasing of SOC
3. double layer capacitance increases with the increasing of SOC.
Availability: printed

30. VRLA battery monitoring using conductance technology
M.J. Hlavac, D. Feder, in INTELEC 1995 - 7th International Telecomunications Energy Conference p. 284-291
Keywords: Battery - Models
Abstract:
Availability:

31. Testing and evaluation of tubular positive lead acid batteries
P.R. Roberge, J.P. Salvador, in Proceedings of the 10th annual Battery Conference on Applications and Advances p.1407-151 USA 1995
Keywords: Battery - Models
Abstract:
The possibility of using lead-acid batteries in tandem with fuel cells in applications such as submarine propulsion requires a strong understanding of the transient behaviour of the lead-acid battery. A simple yet accurate method of describing the response at a given SOC is as a resistor capacitor model. Preliminary testing supports the model's ability to describe the voltage response to load changes at a given SOC. Furthermore, analysis of the steady state characteristics of the cells supports claims in the literature that the charge transfer resistance is partially a function of the inverse of the current. Once complete, the empirical relationship describing the circuit elements will be a useful tool to monitor the gassing effects during pulse charging.
Availability: required (INSPEC)

32. Internal resistance behaviour of Zebra batteries.
J. Angloher A. Prassek, U. Wagner in ETZ vol. 117 p.12-15 1996
Keywords: Battery - Models
Abstract:
The behaviour of ZEBRA batteries differs significantly from that of other battery systems in inter-charge processes. The quantity of energy fed back or topped-up is available irrespective of the S.O.C. in the following discharge at low internal resistance and high voltage. This makes possible to increase the degree of utilisation of the system under dynamic loads.
Availability: required (INSPEC)

33. High Power batteries
C. H. Dustmann in REE, Revue de l'Electricité et de l'Electronique - Iss no1, p.26-30 Jan. 1996.
Keywords: Battery - Models??
Abstract:
Availability: printed

34. A Contribution to lead-acid battery modelling for Urban Electric Vehicle applications.
Abstract:
Availability: under search

35. Determination of an aging factor for lead-acid batteries. I Kinetic aspects.
C. Armenta-Deu, T. Donaire in Journal of Power Sources, 58 (1996) p. 123-33
Keywords: Battery - Models
Abstract:
The capacity of Lead-acid batteries decreases with the number of cycles. This process is known as ageing.
The reduction of capacity affects only the operation time but also the performance of the accumulator and of the system attached to the battery. One of the main procedures affected by the battery ageing is the determination of the S.O.C. In this paper a parameter called 'ageing factor', which represents the reduction of the available energy in lead/acid batteries, is introduced. A non-destructive method to predict the ageing factor, based on the effective reduction in electrolyte specific gravity for a fully charged battery with the number of cycles, is then described. The predicted values are in good agreement with experimental data, the associated error being lower than 9 %.
Availability: printed

36. Numerical modelling of coupled electrochemical and transport processes in lead-acid batteries
W.B. Gu e C.Y. Yang in Journal of Electrochemical Society, Vol. 144, No. 6, June 1997
Keywords: Battery - Models
Abstract:
Considering separately charging and discharging process, this model describes the electrochemical kinetics and the mass transport, and the convection effects due to acid stratification. This technique is quite sophisticated. It is a Computational Fluid-dynamics (CFD) method developed in order to solve many coupled non-linear differential equations. Transient behaviour is included. The complexity of this model makes it useful for deep comprehension of the internal phenomena or for developing a particular recharging technique, rather than for SOC assessment.
Statistical error analysis is not totally developed, except for three experimental cases, where a good accordance between simulation results and experimental data is obtained.
Availability: printed

37. Electrochemical modelling of lead-acid batteries under operating conditions of electric vehicles
E. Karden, P. Mauracher, F. Schoepe, in Journal of Power Sources 64 (1997) 175-180
Keywords: Battery - Models
Abstract:
Electrochemical models are divided in two main groups: macro-homogenous models and 'of single electrode pore':
The authors apply a former model, tested with high current discharge. The battery analysed is a Dryfit Sonnenschein module (160 Ah). The single module is examined and divided in four parts: two porous electrodes, the gelled electrolyte and the separator.
The main problem is the Ohmic resistance, which is greater in the simulated model results than the experimental values.
Availability: printed

38. Modelling of local conditions in flooded lead/acid batteries in photovoltaic systems
D.U. Sauer in Journal of Power Sources 64 (1997), p.181-171
Keywords: Battery - Models
Abstract:
A model is set up for a time-dependent description of currents, polarisations, SOC and acid concentration with high spatial resolution in a flooded lead-acid battery. The detailed description of all relevant parameters for the battery under real operating conditions allows using the results obtained under well-characterised laboratory conditions for different ageing effects. Model of acid stratification, vertical current distribution in the electrode and description of polarisations, concentrations and SOC in the porous electrodes are necessary for any ageing model. First results show very severe conditions for the lower part of the electrode under typical operating conditions in the photovoltaic power supply systems. The work aims at a quantitative ageing model for batteries in such systems.
Availability: printed

39. Dynamic modelling of lead-acid batteries using impedance spectroscopy for parameter identification
P. Mauracher, E. Karden in Journal of Power Sources 67 (1997) 69-84
Keywords: Battery - Models
Abstract:
The battery model calculates terminal voltage as a function of current and time. The model, based on a Randles equivalent circuit, describes lead acid battery with an immobilised electrolyte (Sonnenschein dry-fit 6V-160 Ah). The differential equations are solved in the frequency domain. The non-linear dependence on current and frequency of the circuit elements is described. Three different experiments were conducted in order to verify the model: the deviation between measured and simulated voltage is smaller than a few millivolts, corresponding to an error that never reaches the value of 1 %.
Availability: printed

40. A review of impedance measurements for determination of the SOC or SOH of secondary batteries
F. Huet, CNRS, France - Journal of Power Sources 70 (1998) 59-69
Keywords: Battery - Models
Abstract:
A lot of experimental and theoretical studies upon impedance measurements and techniques are discussed: conductance and internal resistance measures are also described. Investigation about the kinetics of the battery are described, in order to individuate circuits parameter and relationships with state of charge and state of health of the battery. The experimental works are referred to lead acid and Ni-Cd batteries. The conclusions are mainly:

1. in the frequency range 10-100 Hz (Ohmic resistance dominant) the temperature is negligible
2. lead acid batteries exhibit resistance variations of about 100 % with residual capacity.
3. Ni-Cd batteries exhibit lower variations, difficult to use.
4. a standardisation of measurements is needed
5. as SOH test and failure prediction test, impedance is a good candidate.

Availability: printed

41. A Fuzzy Logic Approach to SOC Determination in High Performance Batteries with Applications to Electric Vehicles
P. Singh, C. Fennie, Jr. and D. Reisner, A. J. Salkind - EVS 15 Bruxelles septembre 1998
Keywords: Battery - Models
Abstract:
Without complex mathematical models, fuzzy logic is utilised for SOC assessment. For NiMH batteries, impedance parameters at two values of the current perturbation frequency are analysed as cycle number functions.
The frequency selected values are 1 kHz and 0,4 Hz, accounting for Ohmic and diffusion process.
Two functions suitable for ageing and SOC assessment are proposed, as a combination of the real and imaginary part of the impedance.
Availability: printed

42. High Efficiency Battery State Control and Power Capability Prediction
H.L.Wiegmann, R.D. Lorenz, University of Wisconsin - Madison EVS 15 Bruxelles September 1998
Keywords: Battery - Models
Abstract:
Starting from hybrid vehicle requirements, a battery state regulator is proposed, based on voltage rather than charge control. A power capacity prediction technique is developed, by means of a Randles modified model. Assessment of model parameters is obtained by means of a recursive technique with the LS method. The introduction of non-linear elements in the electric equivalent circuit may improve the simulation results, as far as the introduction of diffusion parameters. Battery model is quite universal and sophisticated.
Availability: printed

43. EIS study of electrochemical battery discharge on constant load
J.P. Diard, B. Le Gorrec, C. Montella , Ecole Nationale Supérieure d'Electrochimie de Grenoble, in Journal of Power Sources 70 (1998) 78-84.
Keywords: Battery - Models
Abstract:
Developing a new method to measure the impedance of battery during discharge, the authors discharge Ni-Cd and sealed lead-acid batteries on a constant load, under current perturbation. Battery impedance was measured in the frequency range 6500Hz/ 50 mHz, with a Solartron 1250 frequency Analyser. The results are compared to that obtained with the classical modulated current method. The results show that the impedance measured with the constant load is the same of impedance measured with a constant current. High capacity and low impedance batteries need a current greater than the maximum value that the regulation system could supply. The impedance diagrams (the Nyquist diagrams) are realised for different values of SOC.
Availability: printed

44. A Dynamical Model of VRLA Batteries in EV Operation Based on Electrochemical Impedance Spectroscopy
E. Karden, R.W. De Doncker, Aachen, Germany. EVS 15 Bruxelles 1998
Keywords: Battery - Models
Abstract:
High current rate is simulated (non -linear dynamics) on the whole variation range of SOC. The proposed model, able to describe the battery behaviour in such conditions, has to be a non-linear one.
A modified Randles model is proposed, with changes in the Warbourg Impedance (diffusion impedance). Results are compared with EIS data in the frequency range from 7.5 kHz to a few μHz.
Testing is performed on gelled electrolyte lead-acid modules, Dryfit Sonnenschein (12 V/1.2 Ah) with galvanostatic tests. Nyquist diagram is plotted; real and imaginary impedances are represented as frequency functions.
Availability: printed

45. Non-linear behaviour of electrochemical generator in static converters. Detection of SOC (in French).
B. Le Pioufle, J.F. Fauvarque, P. Delalande in Eur. Phys. J. AP 2, 257-265 (1998)
Keywords: Battery - Models
Abstract:
In this paper the non-linear behaviour of electrochemical cells submitted to high level current is investigated. Gas creation caused by current charge pulses, leads to higher impedance of the cell. A battery SOC indicator is then proposed. Combination of data provided by response to different current pulses permits to give an accurate SOC indication.
The asymmetric response to charge and discharge pulses of quite high current is dependent from the SOC. This phenomenon is the basis of the ‘ transitory impedance’ use to detect the SOC. An experimental indicator test-bench for lead-acid battery is finally proposed: the discharge mode is taken into account in the algorithm.
Availability: printed

46. Experiences of Residual Range Estimation of Electric Vehicles Powered by Lead Acid Batteries
M. D. Prattichizzo, P. Romano, F. Smargiasse (Università di Pisa - ENEA-Advanced Energy Technology Division) EVS 15 Bruxelles, September 1998
Keywords: Battery - Models
Abstract:
The paper deals with the on-line estimation of the residual range (the expected distance to be travelled) of EVs. An algorithm is introduced to estimate the battery residual charge by using a sophisticated electrical model. Some road tests with an onboard prototype showed accuracy in the estimation of the SOC and residual charge lower than 10%.
Availability: printed

47. A computer model for the determination of the residual capacity of the lead acid batteries
C.W.de Kreuk, J.A.M. Meijer, P.J. van Duin TNO, Preprint for the 16th Intern. Power Sources Symposium
Keywords: Battery - Models
Abstract:
The model due to Hoxie is known to give very accurate results for the calculation of the SOC of lead-acid batteries. In order to utilise this model in a computer program bypassing the large number of calculation required by the iterative character of the model, the authors adapted Hoxie model by dividing the discharge time into a limited number of periods each with a

constant current. With a high capacity traction battery (12 kAh) charge/discharge sequences were performed taking into account temperature and ageing effects. The TNO model demonstrated accuracy better than 4 %.
Availability: printed

48. Non stationary impedance analysis of lead-acid batteries
Z. Stoynov, B. Savova-Stoynov, T. Kossev. in Journal of Power Sources (?)
Keywords: Battery - Models
Abstract:
Complex nature of the processes involved in impedance studies (non-linearity, quasi irreversible regime, multiparameter processes, distributed parameter on both macro and micro scale,...) makes it necessary to simplify the model. The first problem is the linearisation of the circuit parameters, choosing a.c. signal values; the non-stationary state of the battery is a more serious difficulty, also because is interesting to operate on-line. The quasi-stationary approach is selected and the error introduced is discussed, depending on frequency, amplitude, 'frequency by frequency' mode of measurements. Experimental apparatus is constituted by a Solartron 1174 Frequency Response Analyser, a standard interface connection to a central computer and a 'home-made' power galvanostat (30 A, 20 V).
Crystallisation process and porosity of the electrodes are discussed by means of the Nyquist diagrams
Availability: printed

49. An electrochemical impedance spectroscopy method for prediction of the State of Charge of a NiMH battery at open circuit and during discharge.
K. Bundy, M. Carlsson, G. Lindbergh, A. Lundqvist in Journal of Power Sources 72 (1998) p.118-125
Keywords: Battery - Models
Abstract:
A multivariate method for predicting SOC from electrochemical data of a NiMH battery is presented. Partial Least Square (PLS) regression in used to evaluate electrochemical impedance spectra and predict SOC. A Solartron 1255 Frequency Response Analyser and a Solartron 1287 electrochemical interface were used in galvanostatic measurements. Impedance spectra were sampled at different SOC, on the frequency range 239/0.6 Hz and in open-circuit conditions or during continuous discharge (in the range 0.2/0.8 C). During discharge, on the DC current an AC current signal is superimposed ; the impedance dependence from SOC become more evident looking at the real part only. With increasing SOC, the real part of Z is seen to decrease, except at 100% of SCO. The predictive capability tested by multivariate analysis was as low as 7 %, and smaller in the range 10-100 % of SOC.
Availability: printed

50. Dynamic State Battery Model with Self-Adaptive Aging Factor for EV and HEV Applications
J. Lee, S. Lee, E. NamGong in EVS 15, Bruxelles 1998
Keywords: Battery - Models
Abstract:
Model has been developed to calculate S.O.C. with respect to usable energy under dynamic load conditions: by understanding the relationships among power loss, load, temperature and SOC within a battery. It is possible to calculate the SOC evaluating usable remaining energy by means of temperature, content of charges within the battery and discharging power itself. Effect of degradation of capacity (variation of about 20%) due to ageing has been accounted in the development of the model: measuring the voltage at given discharging power and cycles, the influence of ageing can be estimated. The calculated values of SOC differ from those measured

only by 1-2 % if ageing correction factors are considered. Only discharging process is described, not accounting for any efficiency variations during charging reactions.
Availability: printed

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C. Batteries: Devices for SOC assessment

51. A new battery S.O.C. Indicator especially for use in Electric Vehicles
C. Bader in Proceedings of 9th Symposium Non Mech. Electr. Power Sources 1975
Keywords: Battery - Devices for SOC assessment
Abstract:
To indicate the available energy supply for electrochemical storage batteries, a measuring unit has been developed which indicates the behaviour of the battery during charging and discharging. By simulating the essential physical characteristics, the unit employs measurable quantities such as voltage, current and the temperature of the energy source. The numerical data of the simulated functions refer to a lead-acid battery, but the unit can be equally well employed for other types of batteries by changing coefficients appropriately.
Availability: printed

52. Device for the on-line dynamic estimation of the lead-acid battery SOC (in Italian)
3E Ingegneria, ENEA, ICET S.p.a.
Keywords: Battery - Devices for SOC assessment
Abstract:
Electrochemical storage systems are used in stand-by and on-line operating conditions: in the former case the risk is not to reach the available energy required when it needs, because of electrolyte stratification or other effects of large pauses. In the latter case problems are connected with battery life and efficiency: a dynamic on-line SOC estimator with a no-destructive technique is proposed to solve this problem.
The BCO, Battery Charge Observer provides a temperature and SOC estimation, measuring battery voltage current and ambient temperature by means of external sensors. Communication to the controller of charge/discharge processes and to the computing external unit (Master) is allowed by an electronic interface. Accuracy in the SOC estimated values were quite high: the BCO showed errors smaller than 3 %.
Availability: printed

53. Battery State of Charge Determination in Photovoltaic Systems
R. Weiss, J. Applebaum Tel Aviv, Journal of Electrochemical Society, September 1982 , vol 129,No 9, pp.1928-1933
Keywords: Battery - Devices for SOC assessment
Abstract:
The ability to determine the battery SOC in a system at any time is very important from system design point of view. Knowing the SOC continuously makes system energy management possible. In addition for a stand-alone PV system the required battery capacity can be more accurately determined. The present study introduces a new on-line method of battery SOC determination in a working PV system. The proposed method is based on extending the known open circuit voltage-charge relation to the operating battery voltage charge relation and combining it with the ampere-hour accounting method for finite periods of time and averaging out random measurement errors. Error analysis leads to errors smaller than 12 %.
Availability: printed

54. Microprocessor-based device for the automatic control of the charge and discharge processes in lead-acid batteries (in Italian)
M.Pallacordi, G. Salvagni - FARE /RTI (84) 1 ENEA Internal Report.
Keywords: Battery - Devices for SOC assessment
Abstract:
Battery life-time is strongly influenced by temperature effects, overcharging (gas production during charge), and deep discharge. The system proposed controls three parameters: current, temperature and Depth Of Discharge - DOD. It was designed for a wind energy plant, installed in the ENEA Casaccia research centre and produced by Riva Calzoni. The device can be easily adapted to other energy production plants. The DOD upper limit was fixed at 70 %, operating temperature limit at 45 °C, current upper limit was provided by the 'ampere-hour law' Imax = C_{nom}. - C_{istant}. (Expressed in ampere).
Each 2 hours the system updates a counter recording battery ageing up to 14 years; each 30 seconds voltage and temperature are acquired in order to detect maximum charge (if there are no significant voltage variations in a period of one hour, reaching of maximum charge is obtained)
Availability: printed

55. An instrument for determining the charge level of lead storage batteries
W. Schleuter, H.P.Schoner, W. Steffens, G. Wille in Elektrotech. and Maschinenbau (EuM) 102 1985 pp.82-7.
Keywords: Battery - Devices for SOC assessment
Abstract:
Availability: Catalogue JPS 60 (1996)

56. Experimental Battery SOC indicator for armoured fighting vehicles
J.E. Cooling Loughborough Univ. UK Surf. Technol. 24 (1985) pp.15-28
Keywords: Battery - Devices for SOC assessment
Abstract:
Availability: Catalogue JPS 60 (1996)

57. Second order harmonic in the current response to sinusoidal perturbation voltage for lead-acid battery, an application to a S.O.C. Indicator
S. Okazaki, S. Higuchi, S. Takahashi in Journal of Electrochemical Society, Vol 132, No. 7, July 1985 pp. 1516-1520
Keywords: Battery - Devices for SOC assessment
Abstract:
In order to develop indicators of SOC for EV, emergency power supplies and SLI batteries, distortion of the current response to sinusoidal alternating perturbation voltage has been qualitatively measured as a function of SOC for lead acid batteries. The input amplitude chosen is quite high, greater than those used for ordinary impedance measurements. The second order harmonic of the current response shows a linear dependence with SOC. It was also clarified that, compared to other parameters of the indicator, such as terminal voltage, concentration of sulphuric acid, and so on, this parameter is less influenced by other factors during practical operation, such as discharge current and rest time.
Availability: printed

58. Charging and S.O.C. indication of lead-acid batteries
D.A.G. Pedder, UK, in Electric Vehicles Developments Vol. 6 No 3, July 1987 pp. 102-105.
Keywords: Battery - Devices for SOC assessment
Abstract:
In stand-by applications is necessary that power is available when the main sources fails and with traction the system must carry out the specified duty between recharging operations.

Correct charging and maintenance will prolong battery life and increase reliability with consequent saving in both capital and operating costs. The ideal SOC indicator operates with the battery in use and would not depend upon knowledge of the past history of the battery use. Some techniques of evaluation are described (ampere-hour meter, based on internal resistance, on specific gravity measurements,...). A related subject is battery state of health but techniques enabling easy detection of failing batteries are not yet available.
Availability: Catalogue JPS 60 (1996)

59. A low-cost battery supervisory device for use with VRLA batteries
S.J. Bengtsson, K.A. Landqvist in Proceedings of INTELEC'88 10th International Telecommunications Energy Conference 1988, San Diego, pgg.398-402
Keywords : Batterie - Dispositivi
Abstract:
Availability: Catalogue JPS 60 (1996)

60. Use of modelling Lead/Acid battery operation for the development of a SOC meter.
D. Meyer , S. Biscaglia, in Proc. of the tenth E.C: Photovoltaic Solar Energy Conference, April 1991 Lisbon, pp.1209-13
Keywords: Battery - Devices for SOC assessment
Abstract:
Availability: Catalogue JPS 60 (1996)

61. Battery control Unit with S.O.C. indicator.
A. Jossen, A. Bosch, H.P. Hones, H. Karl, G. Lehner, G. Saupe A. Zahir, in Proc. of the tenth E.C: Photovoltaic Solar Energy Conference, April 1991 Lisbon, pp.1012--15
Keywords: Battery - Devices for SOC assessment
Abstract:
Availability: Catalogue JPS 60 (1996)

62. The Application of software package 'heavy' to battery simulation for Electric Vehicles
M. Jayne A Mistry C Morgan, in Proceedings of the 24th ISATA International Symposium on Automotive Technology and Automation, Firenze 1991
Keywords: Battery - Devices for SOC assessment
Abstract
The HEAVY (Hybrid Electric Advanced Vehicle System) component library includes three battery subroutines which are based on three different modelling techniques. The resulting three models were developed by Bozek, Lee, Martin, Heldt and Canders. The first does not provide a voltage model of the battery, the second does not provide a temperature and current dependence of the diffusion processes, the last one does not take into account for battery recuperation effects but has the advantage of being easily implemented. All the models are tested on the same duty cycle and the second one result inadequate to deal with realistic situations. Results of the three models are discussed, and the conclusion is that other models are more useful for more in-depth representation of battery behaviour.
Availability: printed

63. SOC Indicator for lead-acid batteries in EVs
Hongsheng An, E.K. Stefanakos in VP/CV (Véhicules 'Propres' -'Clean' Vehicles) 15-19 November 1993 La Rochelle
Keywords: Battery - Devices for SOC assessment
Abstract:
Two methods are pursued in order to develop an accurate SOC indicator: 1. Rate-dependent Capacity approach; 2. Model-based approach. The former is cheaper and easier, but

improvements are still needed; the latter works well only under specific conditions: In this paper an algorithm that adaptively computes the SOC of lead acid batteries under different discharge profiles is presented. The accuracy reached is better than 10 %.; the model is self-calibrating using only voltage measurements (two methods are presented: SOC calibration by specific gravity measurements and by battery equilibrium voltage). Temperature effects are also taken into account, by means of temperature compensation.
Availability: printed

64. IBC, an intelligent battery controller.
R. de Crecy, C. Glaize, in VP/CV(Véhicules 'Propres' -'Clean' Vehicles) 15-19 November 1993 La Rochelle
Keywords: Battery - Devices for SOC assessment
Abstract:
Because of heterogeneity of batteries, the key feature to answer the SOC indicator need is an independent measure of voltage on each battery. SOC evaluation is provided by ampere-hour measurements, with some coefficients that allow taking into account the discharge-rate. The device works on lead-acid and Ni-Cd batteries. Data recording is executed with three different memorisation forms: an 'annual logic', a 'week logic' and an 'hour logic'. A mini-charger is controlled by IBC, in order to avoiding weaker module degradation.
Availability: printed

65. Simulation programme of vehicles
T. Walter, H. Kahlen, in VP/CV(Véhicules 'Propres' -'Clean' Vehicles) 15-19 November 1993 La Rochelle
Keywords: Battery - Devices for SOC assessment
Abstract:
Within the framework of the Joule II programme funded by the Commission of the European Communities a modular interactive simulation programme, Drive Train Simulator (DTS), is being developed. The programme allows the comparison of different drive trains in electric, hybrid and thermal vehicles, at the level of performances, of energy consumption and of exhaust emissions. With predefined drive-cycles (ECE, FTP,...) the program calculates the energy demand at the level of the wheels, taking into account the vehicle characteristics (aerodynamic drag coefficient,....) to obtain the longitudinal forces that apply on the vehicle. Some examples of application are provided.
Availability: printed

66. BATLOG: an intelligent battery monitoring system
R. Kiessling, in Telescon 1994, Ist International Telecommunication Energy Special Conference p.219-23 Germany 1994
Keywords: Battery - Devices for SOC assessment
Abstract:
This paper discusses a battery model implemented into a monitoring system, which can provide all the necessary information for: actual S.O.C. and available capacity of the full battery. Capacity deviations for single cells or modules from the average; early warning for potential cell/module failure; complete history for failure mode analysis; on-site and remote central data storage; graphic evaluation of battery and cell/module behaviour; prediction of residual service life.
Availability: required (INSPEC)

67. State of charge indicators (batteries)
T.B. Atwater in 1994 IEEE MILCOM, Conference Record p.203 vol.1 - USA 1994
Keywords: Battery - Devices for SOC assessment
Abstract:
Prediction of capacity remaining in used batteries is important information to the user. Each year millions of dollars are spent on batteries for use in portable electronics equipment. In order to maintain readiness, users currently replace batteries on a conservative schedule. This practice results in the waste of approximately 40 % of the available battery capacity every year. Knowledge of the capacity remaining in used batteries results in their better utilisation. Capacity remaining is a complex function of current drain, temperature and time: a continuous internal mean of determining remaining capacity is desirable. These internal methods require extensive calibration and in many cases are difficult to implement. The pursuit of a universal S.O.C. indicator has been elusive due to the variation in behaviour of battery systems. Different methods for predicting remaining capacity are presented with the application to different battery systems.
Availability: required (INSPEC)

68. Noninvasive lead-acid battery monitoring
T.L. Churchill, J.S.Edmonds, C.T.Feyk in Power Quality '94 Proceedings of the 7th International Power Quality Telecomputer Infrastructure Conference p.137-151 - 1994
Keywords: Battery - Devices for SOC assessment
Abstract:
A successful four-year R&D effort has produced true, robust, multiparameter, on-line condition monitoring every cell in lead-acid wet-cells battery banks. State and trend parameters measured outside each cell jar include electrode utilisation (SOC), specific gravity, fluid level, internal temperature, current path integrity (Delta V across cell and post joints at I=C/8), maintenance current and cell voltage. Bank voltage and bipolar bank current are also measured. Optical coupling techniques safeguard bank ground isolation
Availability: required (INSPEC)

69. Assessment of lead acid battery SOC by monitoring float charging current
K.D. Floyd, Z. Noworolski, J.M. Noworolski, W. Sokolski, in INTELEC - XVIth International Telecommunications Energy Conference p.602-8 USA 1994
Keywords: Battery - Devices for SOC assessment
Abstract:
Availability: required (INSPEC)

70. Battery Diagnostic and Charge Equalising system BADICHEQ
W. Retzlaff, J. M. Ambrosio, in EVS 12 - 1995 , pp. 524-533
Keywords: Battery - Devices for SOC assessment
Abstract:
Badicheq is a microcontroller based on-board battery management unit, which combines single battery voltage measurements including battery history monitoring and individual battery recharging (Mentzer-microprocessor), by means of a small integrated charger. Non-destructive charge equalisation, electric fuel gauge indication and general monitoring are the main characteristics; the consequences are eliminating of drying-out and over-heating failures, yielding the minimum charge time and obtaining high efficiency of the charge process. The model is based on Peukert's law and takes into account the role of temperature. Errors smaller than 5 % are obtained. In the future the system may be extended to Ni-Cd and other battery types.
Availability: printed

71. Methods for measuring internal resistance of batteries
I. Sajfar in Proceedings of the 37th ELMAR International Symposium p.311-315 Croatia 1995
Keywords: Battery - Devices for SOC assessment
Abstract:
The paper deals with several methods for defining the internal resistance of batteries. It also surveys the methods specified in standards BS 6290 Part 1 and IEC 89 Amd. 1. The measurement method that provides the best results for a high-Ohmic distribution with transient limitation is recommended. The results are confirmed by measurements performed in the power supply circuit interrupted by a fuse. The dependence of internal resistance on the SOC of the battery obtained by various methods is discussed.
Availability: required (INSPEC)

72. Development of an on-board charge and discharge management system for EV vehicles
J.Alzieu, P.Gagnol, H. Smimite in Journal of Power Sources 53 (1995) 327-333
Keywords: Battery - Devices for SOC assessment
Abstract:
The main characteristics of the device are: battery life recording, short and long term information storage, charge monitoring. A fast charging algorithm for VRLA batteries has been developed, with which up to 50 % of the range can be reached in 20 minutes. Communication with a 23 kW charger is established trough an ISO 9141 interface. The influence of fast charging on cycle life is now under investigation during in-vehicle testing.
Availability: printed

73. NiMH and NiCd battery management
in Microprocessor and Microsystems 19 (1995) p. 165-174
Keywords: Battery - Devices for SOC assessment
Abstract:
To allow the high performance of battery packs using high capacity rechargeable cells, Philips has developed a range of highly integrated single-chip battery management circuits which safely control fast charging and indicate the state of charge of NiMH or NiCd batteries.
Availability: required (INSPEC)

74. Development of a S.O.C. meter for lithium manganese dioxide cells and batteries
A. Nimberger, R. Schwartz, A. Roza, H. Yamin, in Power Sources 15 - 19th International Power Sources Symposium p.478 - 1995
Keywords: Battery - Devices for SOC assessment
Abstract:
To replace rechargeable nickel-cadmium batteries with primary lithium batteries, Israeli Defence Forces adopted for various military applications various different lithium batteries. Recently the authors completed the development of a prototype SOC meter for 2/3 AA size Li MnO_2 cells; research then began upon a SOC meter for multicell battery intended for use with equipment such as the PRC-624 and GVS-5. During the first phase of this development, several method have been evaluated and a correlation was found between several electrical features and residual capacity. Refinement of the chosen method was accomplished, to obtain better accuracy and reliability. The results obtained on lithium-manganese dioxide cells are shown.
Availability: required (INSPEC)

75. Battered no more! (Intelligent batteries) - Li-ion batteries
N. Bowen, D. Patkar, in New Electronics vol. 29 p.21-2 Findlay 1996
Keywords: Battery - Devices for SOC assessment
Abstract:
Implementing an intelligent battery charging system can reduce the risk of damaging batteries extending their working life. The author describes intelligent battery charging circuitry for Li-ion batteries. It is used for various purposes. The first is the accurate determination of available energy within the battery, also known as fuel gauging The second purpose of intelligent battery circuits is to provide an additional layer of protection for the charging of a battery. Li-ion batteries are intolerant of over-charging and over-discharging potentially to a dangerous extent. For that reason, manufactures use several back up layers of protection: The management battery system discussed here provides one of these redundant layers of protection by monitoring battery voltage, temperature, current and SOC.
Availability: required (INSPEC)

76. Rechargeable zinc air batteries market and technology overview
M. Schimpf in Wescon/93 Conference Record (Cat. No 93RC0500-9) 1996
Keywords: Battery - Devices for SOC assessment
Abstract:
Availability: required (INSPEC)

77. On-board battery management system BADICOaCH
W. Retzlaff in EVS 13 - 1996, pp.666-671
Keywords: Battery - Devices for SOC assessment
Abstract:
Upon the experience of the Badicheq system, this new system utilises the same kernel. The hardware features are individual block voltage measurement, charger control outputs, total discharge protection, SOC display and PC interface, driver outputs for miscellaneous functions (fans, pumps). The software features are: battery model for SOC, calculation generation of complex recharge profiles and recording of historical data. The error obtained is lower than 10 %; the system is a low cost and small size alternative to Badicheq. Installed in 5 vehicles, the system showed a good accuracy, even at winter temperatures. Installation is done in a few hours; problems due to high interference from the three-phase drivetrain are detected in one of the 5 cases.
Availability: printed

78. A New Design of a battery Management System Including a Range Forecast
D. Heinemann, D. Naunin EVS 14 USA 1997
Keywords: Battery - Devices for SOC assessment
Abstract:
In order to equalise the module behaviour is necessary to take into account the S.O.C: of each module; a Battery Management System (Battmobil) has been developed, with other aims like supervising the process of discharging, avoiding the module to get deep-discharged, and prolonging the lifetime of the battery. The structure is decentralised; the modules are communicating via the CAN-bus. The system is described in all the parts; also the test bench, Battlab, and his components are shown. To give a prediction of the remaining capacity, the system utilises fuzzy logic; also the ageing of the battery is taken into account, with a neural network system.
Availability: printed

79. Improvement of intelligent battery controller: S.O.C. indicator and associated functions
J.Alzieu, H. Smimite, C. Glaize in Journal of Power Sources 67 (1997) 157-161
Keywords: Battery - Devices for SOC assessment
Abstract:
Electricité de France (EdF) tested a few hundred of vehicles for several years. The need of a battery management system emerged from the testing. An Intelligent Battery Controller was developed: rapid and normal charge monitoring, data recording, SOC indication and help for maintenance are the main features. The system is quite simple. SOC range is divided in three parts, the first based only on temperature and current range measures; the second and the third phased on polarisation's measures of the individual cells. The full-capacity value is periodically re-estimated during discharge.
The gauge described in this paper is the result of collaboration between the Montpellier II University and EdF, R&D division.
Availability: printed

80. Noninvasive measurement of battery state-of-charge.
W.A. van Schalkwijk in Proceedings of the Symposium on batteries for portable applications and E.V. p.574-82 1997
Keywords: Battery - Devices for SOC assessment
Abstract:
Availability: required (INSPEC)

81. A rule-based energy management strategy for a series hybrid vehicle
N. Jalil, N.A. Kheir, M. Salman, in Proceedings of the 1997 American Control Conference (Cat. No. 97CH36041) pp.689-693, Vol. I
Keywords: Battery - Devices for SOC assessment
Abstract:
A rule-based control and energy management strategy for a series hybrid vehicle is presented. The strategy is based on splitting the power demand between the engine and the battery such that this power sources are operated at high efficiency . The power demand is estimated as the output of a high gain PI controller that controls the longitudinal acceleration of the vehicle. The focus was to improve the fuel economy of the vehicle by suitable power assignment to the power sources. The power split is controlled by the values of selected variables: the power demand itself, the driver's acceleration command and the status of S.O.C. of the battery. Simulation results showed improvement in fuel economy over the 'thermostat' strategy. An improvement of 11% in the urban cycle and of 6 % in the highway cycle have been achieved for a series HEV driven by a 40 kW diesel engine and a 60 kW lead acid battery.
Availability: required (INSPEC)

82. Evaluation of S.O.C. Indicator. Approaches for EVs
A.F. Burke E66 n.88341- Conf-880741 (?)
Keywords: Battery - Devices for SOC assessment
Abstract:
Studies of battery management systems (BMS), including SOC algorithms, were performed in the battery Test and Vehicle Dynamometer Laboratories at the INEL. The evaluating SOC algorithms indicated that the capacity rate dependent and adaptive approaches to determining SOC yielded RMS errors between the indicated and actual SOC of less than 10 % if battery temperature and ageing effects are not dominate. The BMS tested are not sufficiently accurate and reliable to permit their use as the primary means of charge control during the various INEL test programs. Considerable progress has been made in the development of BMS, but further work is needed before the system can be used with confidence in either the charge or discharge modes without careful attention from the user.

Availability: printed

83. Update Status of EDF's R&D Studies on Batteries for EV: batteries assessment, on board management, lithium-polymer battery
P. Gagnol, S. Lascaud, Berckmans, L. Capely, H. Smimite, J. Alzieu - EVS 14 , USA 1997
Keywords: Battery - Devices for SOC assessment
Abstract:
Electricité de France tested an EV float of several hundreds of vehicles, with lead-acid, nickel-cadmium and polymeric-Lithium batteries. The 'battery management' system is based on an IBC, Intelligent Battery Controller, developed by EDF together with IES, Intelligent Electronic Systems. During the first phase the system provides a simple coulomb counting; during the second phase voltage changes due to current variations are measured. A temperature correction factor,
an ageing factor and the discharge rate relationship are contained in the final phase of BMS' functioning. Resting periods are also taken into account as recuperation effect, with an exponential decay shape. No error analysis is provided.

84. S.O.C. Indicator for the Lead-acid batteries
J.L.Weininger , J.L. Briant in Journal of Electrochemical Society, vol. 129 No. 11 24092412
Keywords: Battery - Devices for SOC assessment
Abstract:
A state of charge indicator has been successfully tested in sulphuric acid solutions corresponding to different states of charge. The device is based on a solid-state electrochemical humidity sensor (beta alumina humidity sensor). The large variations of sensor impedance with humidity allow the use of the sensor as SOC indicator: the device could find applications as a fuel gauge in electric vehicles and a s a monitor and control in battery chargers.
The sensitivity increases as the frequency of the monitoring AC signal decreases, although the total impedance increases. Repeated tests demonstrate an accuracy of 10 %, considered sufficient for the battery applications.
Availability: printed

85. Using a pulse technique and measured resistance to evaluate the capacity of trickle-charged nickel/cadmium cells.
N. Kato, T. Ogata, T. Hirai , H. Hirota Tokyo, in Journal of Power Sources 69 (1997) 89-96.
Keywords: Battery - Devices for SOC assessment
Abstract:
The use of a pulse current technique to evaluate capacity of trickle-charged Ni-Cd batteries is investigated. Telecommunications equipment and future telecommunication systems running on optical networks require this kind of storage system to monitor the operating conditions. An internal resistance-based method is proposed, under charge current pulses.
A linear relationship between the logarithm of resistance and the capacity of the cell is observed. For deteriorated cells a high correlation coefficient is detected with current pulses in the range 0.1/1.0 C, with pulse width < 10 ms. In the capacity range of more than 50 % of nominal capacity, an error smaller than 10 % is obtained, with nominal capacity in the range 1.6/1.8 Ah.
Availability: printed

86. Progress towards a 20 Ah/12 V electrically rechargeable zinc/air battery
S. Muller, F. Holzer, O. Haas, in Proceedings on the Symposium of batteries for portable applications and EV.
1997
Keywords: Battery - Devices for SOC assessment
Abstract:

This paper describes first steps in the development of a lightweight and low-cost 12 V/ 20 Ah electrically rechargeable zinc-air battery. The wettability of the pasted Zn-electrode and the catalytic activity of the bifunctional oxygen diffusion electrode have been optimised by using cellulose additives of different length and some catalysts of different particle size. In the first stage of development the electrodes where tested in 2.5 Ah monopolar cells with moderately alkaline electrolyte. In the second stage, electrodes having larger active areas were successfully developed. Deep discharge cycles at different currents were carried out for monopolar cells with nominal capacities of up to 15 Ah. The course of the charge and discharge voltages of a battery consisting of two cells that were connected in series was measured.
Availability: required (INSPEC)

87. Electric fuel Zincair system: zinc regeneration update
J.R. GoldsteinN. Lapidot, M. Ague, I. Nekton, M. Given, in Proceedings on the Symposium of batteries for portable applications and EV. 1997
Keywords: Battery - Devices for SOC assessment
Abstract:
Electric fuel has developed a high specific energy refillable zinc-air battery for EV, in which discharged zinc plates are rapidly replaced with charged plates using mechanised means. The discharged plates after removal from the battery are recycled to charged plates in an alkaline zinc electrowinning process at a local site. the system is being tested for use in fleet operation in a number of demonstration programs, and regeneration pilot plants have been built in Israel, Italy and Germany. The paper describes and updates the regeneration process with particular emphasis on improvements in the anode material used in the zinc electrowinning cell. Selection of the anode materials having a low over-voltage for oxygen evolution, that are stable with time in the alkaline electrolyte, provide lower electrowinning cell operating voltages, increasing the overall system energy efficiency of the battery.
Availability: required (INSPEC)

88. The Electric Fuel/sup TM/zinc-air mechanically rechargeable battery system for EV.
B. Koretz, Y. Harats, J.R.Goldstein, M.Korall in New Promising Electrochemical System for rechargeable Batteries. Proceeding of the NATO Advanced Research Workshop.
Keywords: Battery - Devices for SOC assessment
Abstract:
The electric fuel limited refillable zinc-air battery system is currently being tested in a number of EV demonstrations projects, the largest of which is a field test of zinc-air postal vans sponsored chiefly by Deutsche Post AG (the German Post Office). The zinc-air battery is not recharged electrically but rather is refuelled trough a series of mechanical and electrochemical steps that will require a special infrastructure in commercial application. As part of the German Post Office field test program, EF designed and constructed a pilot zinc anode regeneration plant in Bremen, Germany. This plant is capable of servicing up to 100 commercial vans per week.
Availability: required (INSPEC)

89. Recent advancement in Zinc-air batteries,
F.G.Will, in 13° Annual Battery Conference on Applications and Advances (CAT No 98TH8299) 1998
Keywords: Battery - Devices for SOC assessment
Abstract:
Availability: required (INSPEC)

90. Ongoing tests on the electric fuel/sup (R)/ zinc-air battery for EV
J. Goldstein, B. Koretz, in 13° Annual Battery Conference on Applications and Advances (CAT No 98TH8299) 1998
Keywords: Battery - Devices for SOC assessment
Abstract:
The electric fuel zinc-air battery system is being tested in fleet programs throughout Europe, with the programs in various stages. In Germany, Sweden and Italy, vehicles powered by the Electric Fuel zinc-air battery system are being tested in demonstration drives. In the Netherlands a new programme is getting
Availability: required (INSPEC)

91. The real life of a lead-acid battery during an EV endurance test
M. Conte, M. Pallacordi, M. Romanazzo in EVS 15 Bruxelles 1998
Keywords: Battery - Devices for SOC assessment
Abstract:
The work reported in the paper describes the road test of a Panda Elettra until the end-of-life of the lead.acid battery. Several dedicated tests are described and results analysed over a full range of about 20,000 km. Particularly, energy consumption and correlation among nominal range and real ones under various working conditions.-
Availability: printed

92. An Optimised SOC Algorithm for Lead Acid Batteries in Electric Vehicles
Muneret, Caumont (Oldham - France); Le Moigne (Ecole Centrale de Lille) EVS 15 Bruxelles settembre 1998
Keywords: Battery - Devices for SOC assessment
Abstract:
This article proposes a new coulometric approach to calculate the SOC of a lead acid battery in EV. The main existing algorithms have 2 major defects leading to unacceptable inaccuracies: a SOC definition not adapted to EV applications and the non-optimal use of static performances of the accumulator. In order to improve these weak points, a new algorithm is proposed, giving the percentage of residual capacity at a reference current with a new approach. Indeed the reference current is fixed and linked to the performances of the vehicle; the Ah virtually discharged at this reference current are obtained by applying statistical equivalence coefficients to the real current profile. In all cases studied the error respect to the real discharges has been lower than 5 %.
Availability: printed

93. Regeneration of Zinc anodes for the electric fuel (R)/zinc-air refillable EV battery system
B. Kortez, J.R. Goldstein, in IECEC-97 Proceedings of the 32^{th} Intersociety Energy Conversion Engineering Conference (Cat. No 97CH36203)
Keywords: Battery - Devices for SOC assessment
Abstract:
Availability: required (INSPEC)

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Most recent acquisitions

94.New Dynamical Models of Lead-Acid Batteries
M. Ceraolo,
Keywords: Battery – Models
Abstract:

Simulating electrochemical batteries by means of electric circuits is a well-known technique; in this paper it is utilised trying to find an electrical model able to interpolate battery voltage behaviour, instead to reproduce the single parts of the storage unit. The implementation of a third order model is developed in detail; the electric network contains a parasitic branch to simulate water electrolysis that occur at the end of the charge. Three resistance and one capacitance are the reversible branch parameters; in order to reproduce the difference between charge and discharge behaviour at different SOC values, a SOC-dependent resistance deviates part of the current on the parasitic branch. The model has been validated by means of many lab tests made on different types of lead-acid batteries; flooded, gelled, valve-regulated. Several parameters are to be identified; some parameters can be taken as constant for all the batteries built with the same technology.
Availability: printed

95. A Battery Management System for optimised Control and Diagnosis of Traction Batteries in EVs and HEVs
D. Heinemann, D. Naunin, TU Berlin, in EVS 16 Beijing 1999
Keywords: Battery - Models
Abstract:
After the presentation of BattMobil on EVS14 in Orlando, the authors redesign the system in order to make it able to manage advanced batteries in EV and HEV. The Battery Management System (BMS) has been adapted to NiMH, Li-Ion and lead-gel batteries, keeping all different modules in their operating limits. Battery temperature is controlled, and a load balancing as well as a thermal balancing is performed, what guarantees the same operating conditions for all cells/modules. Battery diagnosis capability have been improved, measured data and error messages are stored and can be used by diagnosis software on a PC. The BMS BattMobil I can be used as a test bench, when an external load is connected to the traction battery.
Availability: printed

95. EV Battery Management System with Fuzzy Expert Diagnosis
Xiaomin Sun, Yufei Zhong, Guoguang Qi , Zaiqing Nie, Tshinghua University, in EVS 16 Beijing, 1999
Keywords: Battery - Models
Abstract:
Another parameter is proposed in order to provide information about the breakdown, hidden trouble and maintenance of the battery; the battery State Of Running (SOR). The evaluating algorithm proposed for SOR is based on three characteristics of a single module: voltage current and temperature. Also an indication of remaining capacity is provided by this expert system, able of real time fuzzy diagnosing of the battery.
Availability: printed

96. Approach for proper battery adjustment for HEV Application
A. Szumanowski, G. Bursaglino, in EVS16 Beijing, 1999.
Keywords: Battery - Models
Abstract:
As far as hybrid vehicles are concerned, engines fuel consumption and battery energy alterations should be determined simultaneously, minimising fuel and electricity consumption. The paper present a method of resolving this problem by proper adjustment the battery in the general case using experimental data and mathematical modelling. The battery adjustment method can be resumed in the following steps: 1. Selection of experimental data for the storage system (Internal resistance data and voltage charging -discharging data; 2. the model of electromotive Force related to one cell; 3. the model of transitory efficiency during charge and discharge; 4. the definition of a dynamic approach to SOC factor of a battery; 5. the calculation of minimum energy capacity of battery connected with its nominal current; 6. the limitation of zone of

alterations of the battery SOC. Calculation have been performed for 1300 kg mass passenger car and repeatable standard ECE15 driving cycle.
Availability: printed

97. Battery Parameterisation System: Generic battery evaluation for electric vehicles.
E. Barsoukov, J. H. Kim, K. S. Hwang, Korea Kumho Petrolchemical Company, in EVS16 Beijing, 1999
Keywords: Battery - Models
Abstract:
The aim of this paper is to combine electrochemical models and simplified electric ones, to provide a universal, economic and time-efficient way to simulate battery behaviour. Parameters of the model are determined from the experimental impedance spectrum; the non-linear circuit obtained provides an on-load response reproduced by means of electronic circuit simulator (like SPICE). Different type of batteries are examined (NiCd, Li-ion, NiMH) and calculation of pulse response is performed in order to investigate the transient conditions.
Tests on SFUDS current profiles are used for lead acid batteries and Li-ion batteries; an average deviation inferior to 1 % is found in all examined cases.
Availability: printed

98. Neural Networks: a proper approach to the energy management problem
M. Stoll, in Procs. 10th E.C. Photovoltaic Solar Energy Conference, Lisbon 1991
Keywords: Battery - Models
Abstract:
*******************+
Availability: printed

99. Artificial Neural Network simulation of battery performance
C. C. O'Gorman, D. Ingersoll, R.G. Jungst, T.L. Paez in Procs 31st Hawaii International Conference on System Sciences, 1998
Keywords: Battery - Models
Abstract:
***********++
Availability: printed

100. Fuzzy logic enhanced electrochemical impedance spectroscopy (FLEEIS) to determine Battery State of charge
P. Singh, C. Fennie and D. Reisner in Procs. 34th IECEC, Vancouver 1999
Keywords: Battery - Models
Abstract:
While the amp-hour counting neglects ageing effects, imminent battery failure and weakness of a battery in a string, electrochemical impedance spectroscopy (EIS) is the basis for a fuzzy logic state-of –charge meter. Combining the fuzzy logic analysis technique with battery impedance measurements at only one or two frequencies, the authors obtain a SOC assessment without having to perform the additional intermediate step of obtaining equivalent circuit parameters. Both the state of health and the state of the charge of the battery are determined; $LiSO_2$, NiMH and lead acid batteries are examined. On the lead acid modules, the real component of impedance at 0.65 and 1030 Hz is monitored during a predefined driving cycle until the total discharge. On the NiMH cells the impedance changes with SOC are too low for a useful device; stringing several cells in series may solve such problem.
Availability: printed

101. Measurement of maximum charge and discharge powers of a NiMH battery for HEVs
Yi-Fu Yamg, Toyota corporation, in Journal of Power Sources 75 (1998) 19-27.
Keywords: Battery - Models
Abstract:
The determination of the maximum acceptable charge power and power output is of special significance in the development of HEVs; at a current level as high as the maximum, the charge efficiency can reach 100 %. Theoretically, the maximum acceptable charge power and power output can be defined as those relating to the maximum current levels before the occurrence of any side reaction. A new method has been developed to measure the maximum currents for NiMH batteries in HEVs. The method involves three steps: a measurement of the transient voltage vs. current relation during charge or discharge by a sequence of pulse currents; the calculation of the overall battery internal impedance at different times and current magnitudes; the determination of the maximum current from the minimum point of the internal impedance. This method is based on the principle that, with increasing current level, mass transport becomes the rate-limiting step. Impedance and voltage vs. current at different SOC values are analysed. Experimental results show that the maximum current strongly depends on the battery SOC and also on the battery structure
Availability: printed

102. A clear logic: fuzzy logic determination of battery SOC - a powerful tool for battery management
C. Fennie, Jr. and D.E. Resiner, P.Singh, in Electric &Hybrid Vehicle Technology , 1999, p.116-122
Keywords: Battery - Models
Abstract:
The SOH is one of the essential characteristics to be known to describe the battery functioning condition. Between the techniques commonly used to measure SOC, only the electrochemical impedance spectroscopy (EIS) provide information about the SOH: to reduce the acquired data to a simple scalar output, fuzzy logic is proposed as a powerful tool. In comparison to neural networks, fuzzy logic is easier and cheaper; nevertheless they can work together using the neural network to identify the membership functions and the rule set of the fuzzy logic system.
Applications to LiSO2 and NiMH are shown, in addiction to the lead-acid field. The fuzzy logic methodology does not rely on an explicit mathematical description of the fundamental electrode process; equivalent circuit models are not assumed.
Availability: printed

Appendix B IKA Battery Model

The properties of a traction battery are modelled in the Battery module. Battery current, bus voltage and state of charge are calculated with the electrical power coming from electric motor, generator and auxiliary devices.
The bus voltage is calculated with the open circuit voltage of the battery, the internal resistance and with the battery current according to the formula:

$$U_{bus} = U_0 - R_{internal} \cdot I$$

To calculate battery current, in this formula bus voltage is substituted according to the relationship between voltage, electric power and current:

$$U_{bus} = \frac{P_{elec}}{I}$$

Battery current is then being calculated with the resulting square equation:

$$I = \frac{U_0}{2 \cdot R_{internal}} - \sqrt{\left(\frac{U_0}{2 \cdot R_{internal}}\right)^2 - \frac{P_{elec}}{R_{internal}}}$$

Both in the calculation of bus voltage and battery current the opening voltage as well as the internal resistance are used. They are integrated in the module as state of charge dependent lookup tables. For a NiMH-battery these lookup tables are shown in Figure B-1.

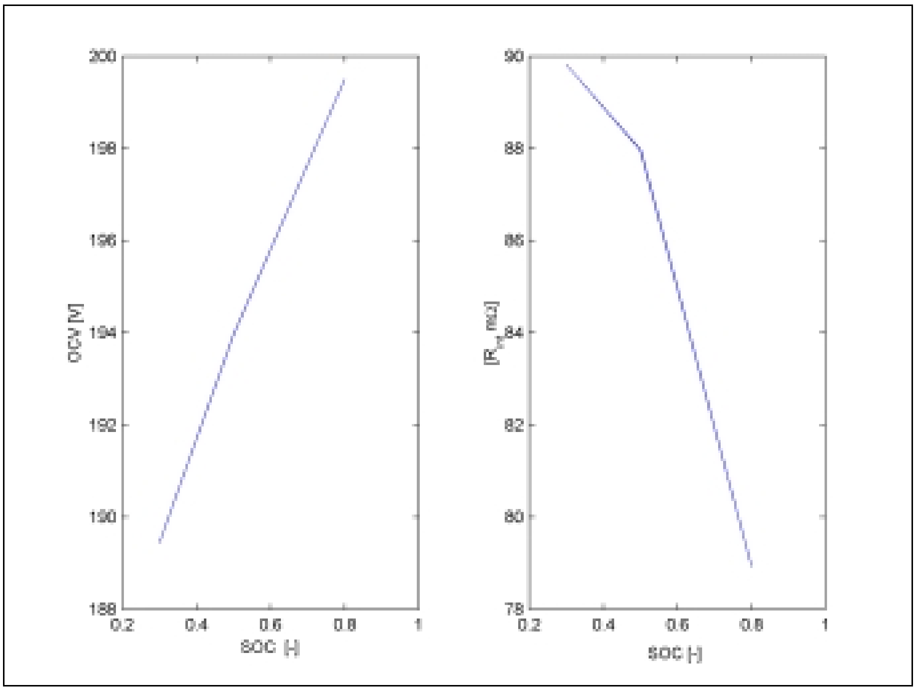

Figure B-1 Open Circuit Voltage and internal resistance as a function of state of charge for a NiMH-battery

For this battery, SOC (state of charge) is calculated with the battery current and the nominal capacity according to the following formula:

$$SOC = SOC_{initial} - \frac{I}{C_{nominal}} \cdot dt$$

For lead-acid batteries however, the actual capacity strongly depends on the discharge current. Therefore, this formula is supplemented with a current-related correction factor:

$$SOC = SOC_{initial} - k \cdot \frac{I}{C_{nominal}} \cdot dt$$

In case of discharge, k is calculated as follows:

$$k = 1 + f \cdot I$$

f is determined with data from the battery manufacturer. Looking at the SOC relationship, it becomes clear that SOC over-proportionally drops with increasing discharge currents, respective that the battery supplies more energy when discharged with smaller currents. To get the inverse effect in case of charging, a degressive increase of state of charge when charging with higher currents that is, and at the same time assuring a steady curve of actual capacity $C_{nominal}/k$, k is calculated according to the formula:

$$k = e^{f \cdot I}$$

OCV and internal resistance as a function of state of charge as well as the current-dependent curve of actual capacity are shown in Figure B-2.

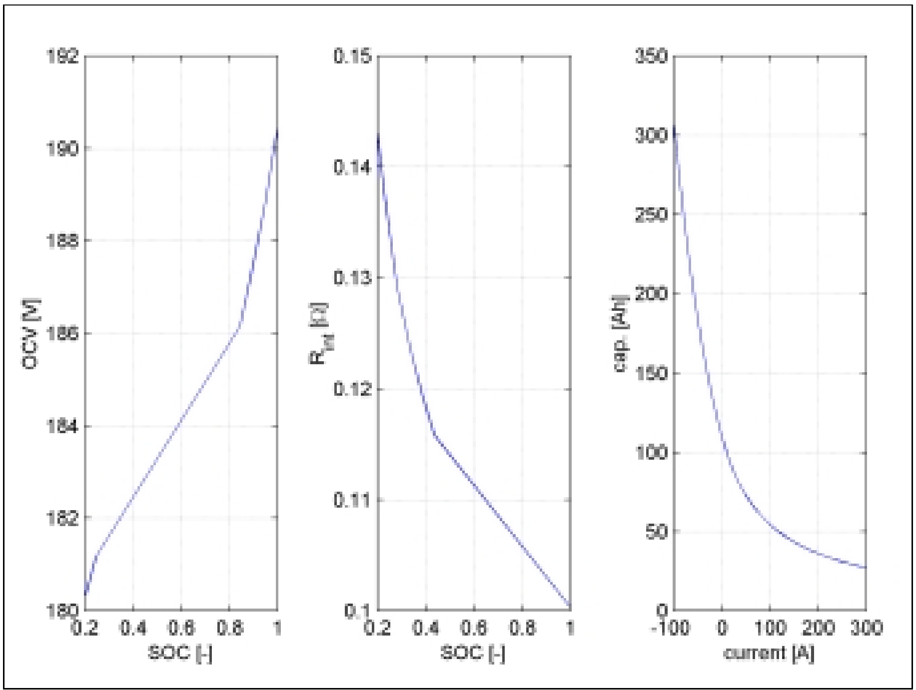

Figure B-2: Open circuit voltage, internal Ohmic resistance and corrected capacity C_0/k for a lead acid battery

MANAGEMENT TOOL for the ASSESSMENT of DRIVELINE TECHNOLOGIES and RESEARCH

MATADOR

Contract JOE3-CT97-0081

Task 2:

Testing methods for vehicles with conventional and alternative drivelines

Subtask 2.6

Comparing electricity and fuel consumption

TNO Automotive

20 July, 2000

by
Richard T.M. Smokers (TNO Automotive)

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THE COMMISSION OF THE EUROPEAN UNION
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Energy Conservation and Utilisation

Nomenclature

Abbreviations

BEV	Battery Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
HEV	Hybrid Electric Vehicle
ICEV	(Conventional) Internal Combustion Engine Vehicle
LCA	Life-Cycle Analysis
MATADOR	Management Tool for the Assessment of Driveline TechnOlogies and Research
TNO	Netherlands Organisation for Applied Scientific Research
ZEV	Zero Emission Vehicle

Contents

1 Introduction

In the context of Task 2 of the MATADOR-project (Management Tool for the Assessment of Driveline Technologies and Research, EU-contract JOE3-CT97-0081), research is carried out in support of the development of test procedures for electrically propelled road vehicles and vehicles with other alternative drivelines. The definition of testing procedures for determining energy consumption and emissions of vehicles with different drivelines requires the evaluation of technical aspects, specific of each vehicle technology. Furthermore, the development of testing procedures that allow for a comparative technical benchmarking of different vehicle powertrains is an even more complicated task, because the performance of each technology could be significantly different (alternative fuels, hybridisation, combined energy sources), asking for various measuring needs. Key issues have been addressed and are evaluated in terms of their impact on testing methods.

For comparing energy and emission performance of vehicles with different propulsion systems the consumption of different energy carriers (in most cases fuel and electricity) must be brought on a comparable basis. For evaluating charge depleting hybrid vehicles this is even more necessary as they consume both fuel and electricity. The general approach is to compare primary energy consumption and total (= direct + indirect) emissions, taking into account all energy losses and emissions in the various well-to-wheel energy chains. This requires an estimation of energy efficiencies and emissions up-stream in the energy chain, for which various methods are available. These methods, however, may lead to very different results. Also results are generally different for different regions of the world and depend heavily on the assumptions and defined boundaries of the study. Detailed studies will give scientifically correct numbers, but these are applicable only to the specific cases under study. International R&D, on the other hand, requires generally accepted numbers to establish a benchmarking that is valid world-wide. This clearly poses a dilemma that can not be resolved within the scientific realm. Policy decisions on an international level are required to come to a solution.

The subject of comparing electricity and fuel consumption has not been studied in detail by the MATADOR-project. Task 2 concentrates on methods for vehicle testing. Overall technology assessment methodologies are considered out of the scope of this Task. However, the Task 2 members do wish to draw attention to this subject as it is a crucial element in defining procedures for comparative testing of vehicles with different drivelines. This report describes the different available methods in general, discusses some advantages and disadvantages, and highlights the choices that have to be made at a political level to come up with an appropriate solution.

2 Problem identification

In Task 2 of the MATADOR-project test methods for battery-electric, hybrid-electric and fuel cell electric vehicles are investigated in relation to the existing test methods for conventional, internal-combustion engine vehicles . All these vehicles consume energy and directly or indirectly produce emissions. Different vehicles use different input energy carriers, and some vehicles even have multiple input energy carriers. ICEVs may be fuelled by gasoline or diesel or by alternative motor fuels such as LPG, CNG, LNG, alcohols or DME. The batteries of BEVs are charged with electricity from the grid. Charge sustaining HEVs run on conventional or alternative motor fuels. FCEVs either use hydrogen or, with the help of an on-board fuel processor, run on e.g. methanol, gasoline, natural gas or some other fossil or synthetic carbon-based fuel. Charge depleting HEVs use both fuel and electricity in a ratio determined by the power train configuration and the way the vehicle is used.

Development of vehicles with alternative power trains in general serves one or more of the following three different goals:
- reduction of emissions that directly or indirectly cause harmful effects to the environment and the health of human beings on a local or regional scale;
- reduction of the emissions of greenhouse gases, in particular of CO_2;
- reduction of the consumption of oil or energy in general, either to conserve world-wide fossil fuel resources or to decrease a nations dependency on imported oil. The latter argument is especially emphasised in the US.

Additionally also noise reduction and a reduction of the use of materials or of substances that are harmful to other environmental compartments than air may be important environmental goals.

In order to assess and compare the potential benefits of different technologies and to benchmark the performance of different technologies, that are in a prototype or (pre-)commercial stage, it is necessary to quantify energy consumption and emissions in a uniform and unambiguous format. Ideally a single environmental index could be used in which all energy and environmental aspects are expressed in the same unit. Such an environmental index should comprise the following two aspects:
- all energy and environmental impacts resulting from the production, use and disposal of the vehicle (cradle-to-grave analysis)
- all energy and environmental impacts resulting from the mining, production and distribution of the input energy carrier(s) and their conversion to mechanical energy on board the vehicle (well-to-wheel analysis).

This, however, is a complicated solution. In practice it is preferred to work with less comprehensive definitions of the system boundaries and to express energy consumption and the emissions of different chemical substances separately in straightforward units (e.g. l/100 km or MJ/km and g/km). The defined system boundaries and the methodology used to quantify the energy and emission parameters will depend on the purpose for which the results are used.

Quantifying energy consumption and emissions of vehicles is generally necessary for a wide range of purposes:

R&D purposes:
- comparing driveline efficiencies of vehicles with different propulsion technologies and different input energy carriers;

Scientific purposes:

- comparing the overall energy consumption and emissions of vehicles with different propulsion technologies and different input energy carriers (in a well-to-wheel analysis);
- comparing energy consumption and emissions of vehicles under different driving circumstances;
- determining emission factors for use in air quality models or emission monitoring on a national or international level.

For R&D or scientific purposes the researchers involved basically have the freedom to define their own methodology and system boundaries in relation to nature of the research questions that are to be answered, as long as their definitions and assumptions are clearly reported. Nevertheless the international discussion, both on the scientific and on the political level, would greatly benefit from the use of uniform definitions and methodologies.

User and market related purposes:

- determining the fuel (or better: energy) costs as part of the operational costs of vehicles;
- marketing of vehicles by manufacturers on the basis of fuel efficiency or environmental performance.

Manufacturers have a responsibility to present honest and correct information to customers. It is therefore in the interest of customers that communication about energy consumption is transparent. Already now one sees confusion in the public discussion in relation to the fuel consumption of conventional vehicles. Fuel consumption of gasoline and diesel cars is in both cases expressed in l/100km, but the energy content of a litre of gasoline is significantly different from that of a litre of diesel (32.2 MJ/l for gasoline and 35.9 MJ/l for diesel). In a similar way also the resulting CO_2-emissions are different. In comparing BEVs to ICEVs the kWh's charged from the grid are sometimes expressed in gasoline-equivalents without specifying or even taking into account the efficiency of electricity production.

Legal and policy purposes:

- homologation testing to certify that vehicles comply with legal emission regulations;
- determination of fiscal or other policy incentives to promote the implementation of clean and energy-efficient vehicles.

This aspect is the most important of all as the exact definition of regulations or policy incentives has a profound impact on the types of technologies that will be marketed by manufacturers. A well known example is the Californian ZEV-mandate, the definitions of which -until some time ago- excluded all vehicles except BEVs from gaining ZEV-credits, regardless of their actual impact on the local air quality. For a long time this has forced large car manufacturers to focus on the development of BEVs. Currently, however, a general consensus has been reached that BEVs will only be applicable to specific niche markets and that a much greater overall reduction of energy consumption and emissions can be reached with advanced ICEVs, HEVs or FCEVs.

In CEN-context currently a test procedure for hybrid vehicles is in preparation, that includes procedures for measuring fuel and electricity consumption of charge-depleting hybrids. A procedure for measuring the electricity consumption of BEVs has already been established. However, in the way they are defined, European emission regulations are unable to deal with vehicles that consume electricity as an input energy carrier. This means that such vehicles can only obtain type approval by exception, which in future may become a factor that discourages manufacturers from marketing these vehicles for large-scale use.

If in the near or longer-term also European regulations on energy consumption would be established, the matter of defining test procedures and ways to deal with comparing the use of different input energy carriers becomes even more important. Defining energy consumption limits in litres or grams of fuel per 100 km (as implicitly done in the present discussion on the 3 litre vehicle consuming 3 l/100km) only makes sense if separate limits are defined for all possible fuels. Such a definition would, however, disregard the source of the energy carrier (fossil, nuclear or renewable) and the CO_2-emissions both at the vehicle level and in the energy chain. Depending on the actual policy goals that are pursued (e.g. reducing greenhouse gas emissions or the dependency on imported oil) also limits defined in MJ/km or in grams of CO_2 per km should be considered, either in- or excluding indirect energy losses and emissions.

The next chapter will briefly discuss different methodologies for assessing the (indirect) energy losses and emissions from electricity production and other energy chains.

3 Assessing indirect emissions and energy losses

3.1 Defining system boundaries

The first and most crucial step in an assessment of indirect emissions and energy losses is the definition of the system boundaries. Which parts of the energy chain and the product life cycle are taken into account and which are not? A system is characterised by the processes that are included, but also by a geographical location or region and a time horizon for which the data are intended to be valid. It is, of course, well known that the emissions from electricity production are different for different countries, depending on the national electricity generation mix. The same is true for process emission from e.g. refining or coal mining in different countries.

3.1.1 Well-to-wheel analysis

From a scientific point of view a complete well-to-wheel analysis should include:

- mining of raw energy carriers (oil, coal, natural gas, uranium, renewable sources)
- transport of raw energy carriers
- processing of raw energy carriers
- conversion of raw energy carriers to final energy carriers:
  - production of fuels in a refining process
  - generation of electricity
- distribution of final energy carriers
- transfer of final energy carrier to vehicle:
  - gas station
  - charging station
- conversion of final energy carriers to propulsion energy on-board the vehicle

Energy losses and emissions occurring in the various parts of the energy chain need to be assessed. Basically this is a global system definition.

The energy carriers that are directly fed to the vehicle are often referred to as final or secondary energy carriers and the consumption of those energy carriers is expressed as final or secondary energy consumption in MJ of energy content of those energy carriers used to drive a certain distance. Raw energy carriers are also referred to as primary energy carriers. Taking all efficiencies in the energy chain into account a vehicle's energy consumption van be expressed in terms of the energy content of the primary energy carriers that are consumed to produce the fuel or electricity that is used to drive a certain distance. This is called primary energy consumption.

Quantifying emissions and energy losses, however, is more difficult for some steps than for others. Emissions of mining may not be accurately measured in certain countries. Also the mix of locations from which a country or conversion plant receives its primary energy carriers may vary strongly in time as a result of the dynamics of the world market for these energy carriers. Furthermore, it often does not make sense to simply add up the emissions of a specific substance occurring in one part of the chain with those occurring in another part of the chain. HCs emitted by cars in an urban environment have an impact on urban air quality and human health, but those emitted by a bulk carrier on the ocean do not. On the other hand CO_2-emissions do add up globally. Moreover, certain parts of the energy chain may be outside the influence sphere of the policy level for which the study is made. For the definition of a national policy on e.g. acidification or urban air quality it is not relevant to quantify the sulphur emissions from flaring in Saoudi Arabia.

For these reasons it is often justified or even necessary to define stricter system boundaries. One option is to exclude the mining and transport of raw energy carriers. In that case the system boundary can be placed at the border of a country or region (e.g. EU), so that indirect emissions and energy losses are only accounted for as far as they occur within those geographical boundaries. In this case mining and transport is not included for energy carriers that are imported, but these steps are included for raw energy carriers that are mined inside the considered region. Instead of a geographic boundary also a technical boundary can be chosen. It is e.g. possible to draw the system boundaries around the plants that convert raw energy carriers into the final energy carriers (fuels or electricity) that are used by the vehicles under study. In that case the refineries and electricity generation plants are included, but mining and transport of raw energy carriers is not.

3.1.2 Life-cycle analysis (LCA)

A life cycle analysis (LCA) at least includes three major phases of a product's life cycle:

- production phase (production of materials, manufacturing of components and vehicle manufacturing)
- use phase (driving the vehicle)
- disposal phase (scrappage, waste disposal and or recycling)

The terms direct energy consumption and direct emissions refer to the use phase. Energy consumption and emissions in the production and disposal phase are called indirect energy consumption and indirect emissions.

A complete LCA includes a well-to-wheel analysis as the energy inputs and emission outputs of all steps in the life cycle are considered. This includes complete energy chains for the production of motor fuels or electricity as well as the energy chains for the various processes in the production and disposal phase (e.g. for the production of steel or the recycling of plastics).

Carrying out a complete LCA is a very complex and time-consuming process. It requires huge databases with energy and emission information concerning all process steps in the product's life cycle. The problem with these databases is that they are largely filled with information from publicly available sources. As companies generally do not release sensitive information on their actual energy consumption and environmental impacts, this means that the data in the public domain are generally quite old. In practice this often means that environmental impacts are overestimated as modern plants are generally claener than old ones, due to environmental legislation. A good LCA, therefore, can only be made in cooperation with all industries involved in a product's life cycle. For an assessment of the environmental benefits of new technologies that are currently in the R&D or demonstration phase it is often not possible to generate data on the production and disposal processes as these processes are not yet in operation or not even designed. In that case expert guesses have to be made which, of course, add significantly to the overall uncertainty in the outcome of the LCA.

In comparing vehicles with different power trains it is often justified to exclude the production and disposal phases from the analysis. This depends on the one hand on the share of the direct energy consumption and direct emissions in the total energy consumption and emissions and on the other hand on the differences between the power trains with respect to energy consumption and emissions in the production and disposal phases. Vehicles with different power trains may to a large extent (e.g. as share of total vehicle mass) be composed of the same or similar components (body, wheels, drive shafts, interior, etc.). In that case the differences in energy consumption for manufacturing will be relatively small.

3.2 Methods for attributing indirect emissions and energy losses

For each step or process in the energy chain or the life cycle indirect emissions and energy consumption have to be attributed to a unit of energy output (e.g. g/MJ, g/kWh or MJ/MJ). This can be done in two different ways:

3.2.1 Incremental emissions and energy losses

Especially for electricity production the energy sources from which the electricity, which is consumed at a certain location, is generated vary strongly in time. At night most electricity is produced by base-load installations powered by e.g. coal, nuclear energy or hydro-energy. During the day electricity is produced by medium and peak-load installations using e.g. natural gas or oil. In terms of emissions and conversion efficiency it therefore makes a big difference whether an electric vehicle is charged at night or at day-time. Besides daily fluctuations there may also be seasonal fluctuations. The “incremental emissions and energy consumption” method attributes indirect emissions and energy consumption by assessing which power plant it is that produces the extra kWh’s that are consumed by an electric vehicle that is connected to the grid on a certain moment in time. This can be done with detailed load models of the electricity generation system of a certain region. A similar approach can be followed for other energy carriers. For transport fuels, of course, the temporal correlation between production and consumption is less strong (due to the buffering function of storage and distribution), but also here seasonal variation may occur. Moreover, if the introduction of a new technology increases the demand for a certain energy carrier by such an amount that a new energy production plant needs to be build, then the “incremental method” prescribes that the emissions and energy consumption of the, often more modern and thus much cleaner and more efficient, new plant are attributed to the new technology that causes the extra demand.

The “incremental method” has several disadvantages:

- It requires detailed assumptions about the total additional energy demand (in terms of quantity and temporal distribution) as a result of the introduction of a new technology. This requires a scenario approach and complex modelling of the energy system. For battery-electric vehicles it is crucial to make a good estimate of the amount of overnight charging (including or excluding load management to avoid peak demand in the early evening) in comparison to the amount of energy consumed by day-time (opportunity) charging.
- Modelling the energy system (including emissions) works well when the energy system is centrally planned and controlled, and when most energy consumed in a certain region or country is also produced in that region or country. This was the case in most European countries until a few years ago. Currently the electricity market is being liberalised, which means that imports and exports will cover a greater part of the demand and supply volumes. As a result it becomes much more difficult –or even impossible- to trace the origin of a specific kWh consumed at a specific time and location. In that case the seeming scientific or theoretical correctness of the method is counteracted by the practical uncertainties introduced as a consequence of a complex reality.
- The “incremental method” can be applied to scenario outlooks that study the impacts of introducing a new technology in the near or more distant future. That future will, however, not only see the introduction of e.g. electric vehicles but also of other new, electricity consuming technologies such as heat pumps. When the increased electricity demand requires the implementation of new electricity generation plant it becomes an arbitrary choice to attribute the most cleanly or efficiently produced additional kWh’s to one or the other newly introduced technology.

3.2.2 Average emissions and energy losses

A more practical, but less scientific method to attribute indirect emissions and energy consumption is the "average method". In this method the total emissions produced by a certain energy production system (be it electricity generation or oil refining) in e.g. one year, and the total energy inputs consumed in that same period, are divided by the energy output in that same period. In this way average factors for calculating the indirect emissions (g/MJ) or energy input (MJ/MJ) can be generated that are representative for the average production in that period.

This is a rather straightforward method that eliminates a lot of uncertain assumptions (in terms of penetration rates of new technologies and time distribution of the energy demand) at the expense of some scientific accuracy. This method can also be applied to a liberalised market as the average yearly share of imported energy and its sources can be quite easily determined on the basis of import and export contracts.

One drawback of the "average method" becomes apparent when dealing with energy plants that produce more than one output energy carrier. This is e.g. the case for refineries which use a complex, highly integrated combination of processes to produce gasoline, diesel, LPG and other products from raw oil. In this again some system modelling is necessary to attribute different shares of the plants emissions and energy losses to the plants outputs. In the "incremental method" detailed modelling is necessary anyway, so that problem is in principle dealt with.

3.2.3 The role of renewable energy in energy and environmental assessments

Given specified system boundaries the methods described above all calculate the total energy input from different sources into the system necessary to deliver a certain transport performance (when applied to vehicles). These sources may include fossil energy sources (coal, oil, natural gas), nuclear energy and renewable energy sources (e.g. solar, wind or hydro power and biofuels). In the context of energy and environmental policy only the reduction of the use of non-renewable energy and the reduction of net CO_2-emissions are relevant. This means that a comparison has to be made in terms of the direct and indirect consumption of non-renewable energy only, or when the focus is on the greenhouse effect, of the direct and indirect consumption of fossil fuels only. When pollutant emissions are concerned of course all energy sources are relevant as there are always emissions associated with the life cycle of renewable energy sources. The manufacturing of photovoltaic panels e.g. will have various environmental impacts, and vehicles running on biofuels still produce emissions like CO, HC and NO_x.

3.2.4 Comparison of methods

All in all the "incremental emissions and energy consumption" method seems most appropriate for studies with scientific or R&D purposes, as mentioned in chapter 2. The same accounts for well-to-wheel and life-cycle analyses with a more global system definition. These methods provide insight in the complexity of the total system and may clearly illustrate the trade-offs that are inherent in most system changes.

For user or market oriented purposes as well as for practical policy purposes and the definition of regulations the "average emissions and energy consumption" method seems most practical. It generates more generally valid numbers that are not so sensitive to the exact assumptions and definitions used in the study. Also this approach is more easily understood by a large non-scientific audience.

3.2.5 Application of methods to the problem under study

In the context of test methods developed in task 2 of MATADOR the necessity has become apparent of having generally valid conversion factors available for comparing the environmental impacts and energy consumption of different vehicles using electricity and or different fuels as input energy carrier(s). For evaluations that are relevant in an EU policy context conversion factors are required that are valid for the average European situation. In the context of national policy issues, however, also nationally valid numbers are required. Such conversion factors are absolutely necessary for:

- European policy making and emission legislation (e.g. integrating vehicles with alternative powertrains in future emission regulations or in the agreement between EU and EUCAR on the reduction of the fleet-average CO_2-emission);
- Type approval of vehicles with alternative powertrains (in relation to emission regulations);
- National policy making (e.g. fiscal stimulation measures for more environment-friendly vehicles).

This calls for the definition of a unified methodology that may be applied on the EU- and national level. Especially the issue of type approval needs to be resolved at short notice. Several technologies at are the brink of large scale market introduction. The absence or unclarity of emission legislation with respect to alternative powertrains may force manufacturers to develop vehicle configurations that suit the existing homologation procedures, but that are sub-optimal with respect to the reduction of environmental impacts in everyday use.

In essence the following steps should be undertaken by the EU:

- Formulate a practical common methodology for calculating indirect emissions and energy consumption related to the use of road vehicles. This can be done in a project involving European experts on the different aspects of the problem. This project can build on results already obtained by some EU-funded and national projects;
- Establish a formal body (organisation or network) that collects all data necessary for applying the common methodology, and that generates conversion factors on the EU level and on the national level for all energy carriers that are currently used on a significantly large scale (gasoline, diesel, LPG, electricity, and maybe a few more). This body should periodically update the conversion factors to account for changes in the energy supply and demand systems. When new energy carriers are introduced to the market this body should adapt the methodology to include the new fuel and should perform an assessment to generate conversion factors;
- Define appropriate emission legislation and associated test procedures for vehicles with alternative power trains.

In the past decades a large number of studies has been performed using the various methods sketched above to assess environmental and energy impacts of new technologies on a regional, national or EU-level. An concise example of a study on the European level can be found in [1]. A large number of institutes in Europe has gained vast experience in this kind of studies. This means that the EU has a good basis for establishing a common methodology and that enough qualified consultants are available to work with the above proposed body or network.

3.2.6 Comparing different impacts

So far we have only concentrated on expressing the energy consumption of vehicles with more than one input energy carrier in a single number and the energy consumption of vehicles with different input energy carriers in the same unit. This requires including indirect energy consumption to some extent. For a comparison of vehicles then also indirect emissions need to be taken into account. Given a chosen methodology for this comparison the result of comparing tow vehicles will be expressed as a set of numbers for energy consumption (in MJ/km) and the

emissions of different exhaust gas components (in g/km for e.g. CO_2, CO, HC, NO_x, particulates, etcetera). In general one will find that one vehicle scores better on e.g. energy consumption and CO_2 while the other will be better with respect to NO_x or HC-emissions. Comparing these different figures is like comparing apples and pears.
However, large efforts have been made, partly sponsored by the EU, to develop methodologies to also express energy consumption and different environmental impacts in a single unit (e.g. [2,3]). In general there are two approaches for this:

- weighted sum of all impacts on the basis of the severeness of different impacts;
- monetisation: express all impacts in financial terms (a single currency) on the basis of either estimated damage costs or abatement costs.

These methodologies are still in a development phase and have various drawbacks. In the context of this MATADOR-project the use of such methodologies is therefore not considered. Especially for scientific purposes and overall environmental policy making it may be useful to adopt these evaluation methods. For the more restricted and more short-term purpose of emission legislation, test procedures and homologation it is not necessary to compare environmental impacts among each other.

4 Conclusions and Recommendations

Conventional vehicles and vehicles with alternative powertrains consume energy (fuel and/or electricity). Most of them also produce emissions while driving. For an honest comparison of technologies not only the direct energy consumption and direct emissions during driving need to be considered, but also the indirect emissions and energy losses occurring e.g. in the production of fuels and electricity as well as in the manufacturing and disposal of vehicles. In general quantifying and comparing overall energy consumption and emissions of vehicles with different powertrains is necessary for:

1. R&D purposes
2. scientific purposes
3. user and market related purposes
4. legal and policy purposes (including emission regulation and homologation)

For purposes 1 & 2 researchers have the freedom to choose the system boundaries and the methodology according to the needs of the study. Unification, however, would benefit international scientific discussions. Especially purposes 3 & 4 require a simple and clear procedure for expressing electricity and fuel consumption in a single unit and for accounting relevant indirect emissions and energy losses in the overall comparison.

Defining system boundaries is an important part of the methodology. This determines to which extent a complete “well-to-wheel” analysis or life-cycle analysis (LCA) is performed. Indirect emissions and energy losses can be attributed to the various steps in the energy chain or life cycle using two main methodologies:

- incremental emissions & energy efficiency
- average emissions & energy efficiency

The first methodology is more scientifically correct, but requires complex modelling of the energy system and detailed assumptions on the size and time distribution of the incremental energy demand. This in itself introduces uncertainties in the results. The second method is more straightforward and eliminates a lot of uncertain assumptions at the expense of some scientific accuracy. In general the “average method” seems most appropriate for generating robust numbers (conversion factors) that have general validity.

The definition of appropriate standardised test procedures for vehicles with alternative powertrains is in progress in Europe and elsewhere. The results of the MATADOR-project contribute to this process. Standardised test procedures are a necessary basis for the definition of emission regulations and possible future regulations on energy consumption. In addition to the definition of measurement procedures, it is of paramount importance to develop evaluation procedures that allow the assessment and comparison of all relevant direct and indirect energy impacts and emissions of vehicles with conventional and alternative powertrains. Inappropriate test and evaluation procedures may lead to the market introduction of vehicles that are sub-optimal with respect to the environmental policy goals.

The following actions are recommended to the EU in order to arrive at useful conversion factors for the above mentioned purposes:

- Formulate a practical common methodology for calculating indirect emissions and energy consumption on the basis of final electricity & fuel consumption at the vehicle level. It should be possible to apply the method both on a European and on a national level. Special attention should be paid to the role of renewable energy sources;
- Conversion factors should preferably be based on average efficiencies and average indirect emissions of electricity production and fuel refining in Europe;

- In comparing the total energy consumption of vehicles with different powertrains only the total consumption of non-renewable energy is relevant. When comparing CO_2-emissions one has to assess the net CO_2-emission, which for e.g. biofuels is relatively low, even though the emissions at the vehicle level are comparable to those for conventional fuels. In comparing pollutant emissions, all energy sources need to be taken into account;
- It seems appropriate to limit the system boundary to the energy input flows to refineries and electricity generation plants in Europe (or in a country if factors are generated on a national level). For fuels and electricity imported from outside Europe average conversion factors may be assessed;
- Establish a formal body (organisation or network) that collects all data necessary for applying the common methodology, and that generates conversion factors on the EU level and on the national level for all energy carriers that are currently used on a significantly large scale (gasoline, diesel, LPG, electricity, and maybe a few more). This body should periodically update the conversion factors to account for changes in the energy supply and demand systems. When new energy carriers are introduced to the market this body should adapt the methodology to include the new energy carrier and should perform an assessment to generate conversion factors;
- Define appropriate emission legislation and associated test procedures for vehicles with alternative power trains;
- Allow each country to define national conversion factors based on the same methodology and data set.

For scientific purposes and for general policy making it is also useful to be able to express the different environmental and energy impacts of a vehicle in a single number in order to compare the overall environment-friendliness of vehicles with different powertrains. Methodologies are being developed for this, but it is considered outside the scope of the MATADOR-project to make recommendations on this issue.

5 References

[1] *Comparison of Energy Consumption and Emissions*, by Bernd Sporckmann, RWE Energie AG, Essen, Germany, on behalf of the UNIPEDE Group of experts on electric vehicles (70.DEVEL), in MobilE, May 1997.

[2] *ExternE Transport*, Final Report, 1998.

[3] *External Effects of Transport, Final Report*, S.P. Mauch and W. Rothengatter, INFRAS/IWW, Zürich/Karlsruhe, 1994

MANAGEMENT TOOL for the ASSESSMENT of DRIVELINE TECHNOLOGIES and RESEARCH

MATADOR

Contract JOE3-CT97-0081

Task 2:

Testing methods for vehicles with conventional and alternative drivelines

Subtask 2.7

FCEV test procedures

ENEA - Advanced Energy Technology Division

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by
Mario Conte (ENEA)
Agostino Iacobazzi (ENEA)
Giovanni Pede (ENEA)

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Nomenclature

Abbreviations

BEV	Battery Electric Vehicle
CEN	European Committee for Standardisation
CORIVAMIA	Italian Research Consortium for low emission vehicles
EUCAR	European Car Research Committee
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
FCHEV	Fuel Cell Hybrid Electric Vehicle
HC	Hydrocarbon
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
PEM	Proton Exchange Membrane or Polymer Electrolyte Membrane
PNGV	Partnership for a New Generation of Vehicles
TC	Technical Committee of the European standard setting body CEN

Contents

1 Introduction

Task 2 of the MATADOR Project (**Ma**nagement **T**ool for the **A**ssessment of **D**riveline Techn**o**logies and **R**esearch, EU-contract JOE3-CT94-0081) is aimed at developing test methods for homologating and evaluating conventional and alternative vehicles and propulsion systems. These testing methods should also allow for a comparative assessment and benchmarking of such technologies. The testing methods, considered in Task 2, are restricted to the determination of energy consumption and emissions of various vehicles and powertrains. The definition of such testing procedures is strongly affected by the vehicle configuration, the required fuels and the specific driving patterns which may be real or simulated on test benches. In addition, the introduction of alternative technologies and fuels may pose measuring problems when compared with conventional vehicles and standardised procedures. Investigation and critical evaluation of technical issues in relation to the various technologies is the main scope of Task 2, from which specific recommendations for modified or new testing and measuring methods are derived.

Fuel Cell Electric Vehicles (FCEV) represents a brand new transport means, which is a typical exemplification of the technical issues encountered in the definition of a specific testing procedure. The starting points for FCEVs considerations about testing methods are the following:

1. FCEVs are available only at prototype level with a few pre-series products;
2. The configurations investigated until now are various and may present testing problems similar to ICEV, HEV and BEV, depending on the system chosen.
3. No standard testing procedure is presently available specifically for FCEVs. Current CEN standards or draft standards only consider BEVs, HEVs with thermal generators and ICEVs.
4. The use of some aspects of existing testing procedures for BEV, HEV and even ICEV may be applied, but seems more reasonable to adapt such testing procedures more specifically to FCEVs.
5. The existing standard setting bodies are currently working on the classification and basic definitions.

This document summarises the work done in the preparation of a proposal for a testing procedure for FCEV. Initially, there was an evaluation of existing testing procedures for BEVs, ICEVs and HEVs that in some cases present common problems with FCEV to be tested. The test procedures for such vehicles will not be described here because they have been already discussed in a previous report, which contains basic considerations on FCEV definitions and testing issues [1]. Three major aspects or problems have been identified and analysed: the classification of FCEV; the specific problem of measuring energy consumption and emissions; the key technical aspects of start up time and heating energy that are somehow similar to that of the cold start of ICEV and HEV and of high temperature batteries in BEV testing methods. The considerations about the measurement of energy consumption and emissions come from contacts with Italian organisations involved in FC development. They also contain the revision of previous considerations about the classification, for testing purposes only, of FCEVs. The conclusions of the document about classifications show a convergence of the ENEA group with the preliminary conclusions of the CEN 301 TC/WG 1 [2]. Finally, the conclusions do not take into account the process underway to improve the measuring methods for conventional and alternative vehicles. For example, there are under discussion revisions of the measurements to be performed in order to take into account other sources of emissions, as the ambient air pollutant content and evaporative emissions.

2 Classification

The initial proposal of FCEV classification was mainly based on the possible configurations (4 in total) of the drivelines. This proposal, reported in the Inventory of Test Procedures [1], has been modified to better meet the needs of the energy consumption and emissions testing methods. It seems reasonable to consider two large categories and then subdivide them in other two subcategories, based on fuel types.

1 ***Category 1 as an ICEV*** (FCEV without energy storage system different from the fuel tank)
  1.1 Carbon-based fuel
  1.2 Hydrogen

2 ***Category 2 as an HEV (FCHEV)*** (FCEV with an energy storage system different from the fuel tank)
  2.1 Carbon-based fuel
  2.2 Hydrogen

Both categories include the direct methanol FC systems.
Figure 1 sketches configurations of FCEVs with two different fuels [3] and with and without reformer.

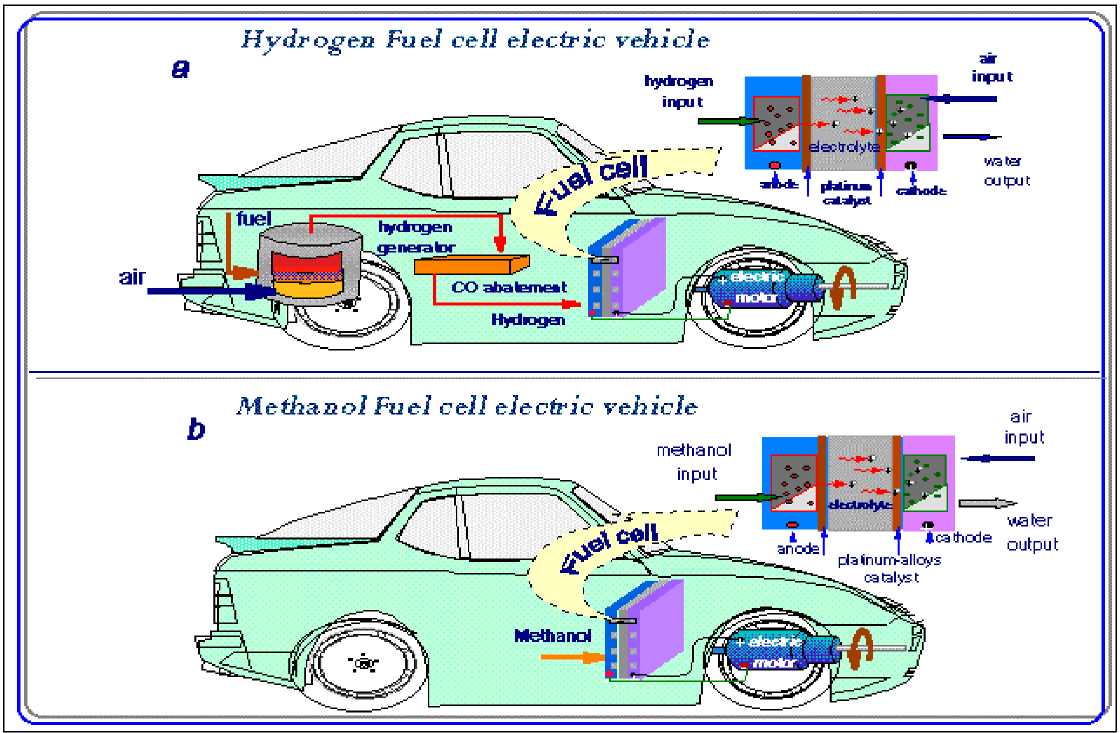

Figure 1: Possible configurations for FCEVs

3 Energy consumption measurements

The present standards for ICEVs and HEVs [4][5] determine the energy consumption by measuring the overall emissions of HC, CO and CO_2. This method is based upon the measurement of the exhaust gases containing carbon and then calculating the fuel consumption by carbon atomic equivalents. As a consequence the energy consumption determination depends on the inlet fuel characteristics. Speaking about FCEVs, three different fuels are presently considered: hydrogen, methanol and gasoline. Schematically for measuring purposes, we can use the proposed subcategories: carbon-based fuels and hydrogen. The following considerations can be extended to the FCHEV for which the electrical energy consumption of the battery (or other storage system) must be added to the calculated value for the *"thermal"* mode according to the proposed standards for HEV.

3.1 Carbon-based fuels

For these fuels, there is no specific evidence of problems in applying the existing standard methods for ICEVs.
Some warnings and attention can be posed in identifying clearly the emission outputs from the generation system. Actually, depending on system configuration, it is possible to have more than one emission outlet: e.g., fuel processing burners and fuel cell stacks. The fuel reformers may treat the reformate gas, that is the fluid which exits from the fuel reformer, in order to reduce excess of catalyst poisoning components, such as CO in methanol reformer. The final overall emissions of the fuel cell generator are very low. Some considerations related to the type and amount of emissions from FC systems are described later when emission measurements are analysed.

3.2 Hydrogen

In this case the method to be applied has to be different from that proposed for ICEV for two reasons.

1. The measurements provided in ICEV standards refer only to carbon-content exhaust gases.
2. The exhaust products to be measured should be water (steam H_2O) and H_2 not used in the reaction. The produced H_2O depends on the consumed H_2 and on both the inlet air composition **and** the humidification process of the reaction gas inside the stack system.

<u>*Recommendation*</u>
The only possible solution seems to be the **direct measurement of the consumed H_2.** Two alternative methods can be envisaged:
1) the measurement of the H_2 needed for the full replenishing of the storage tank or
2) the measurement of the H_2 fed to the FC, by means of a mass flow meter (balance or other device). The second method is already used for testing ICEV and FC systems, while the first method may be somehow influenced by the characteristics of the storage tanks (pressurised vessel, liquid tank, metal hydrides, carbon nanotubes, and so on). The first method can be also more practical than the second one, if an external fuel tank could be used during the test. This last possibility may greatly simplify and also reduce the cost of the test by weighing the tank before and after the test.

4 Emission measurement

According to the above classification and considerations, the emission measurements can be differentiated in relation to fuel type as for the ICEV or HEVs. To better identify the type of emissions and set up the measurement equipment, it is necessary to analyse experimentally the real exhaust emissions mainly from the fuel processor, and, generally, from the fuel cell stack. In case of H_2-fueled EV, there is no need for any regulated emission measurement, since exhaust gases contain only ambient air, water and, in some cases, hydrogen.

4.1 Carbon-based fuel: METHANOL

Table 1 reports the hydrogen-rich gas composition measured (ENEA and CNR-TAE) [6] at the outlet of a fuel processor (steam reforming or autothermal reforming= POX+steam reforming).

Table 1: Outlet gas composition from fuel processor using methanol.

Gas	Range (%)
Hydrogen	65 - 75
Carbon Dioxide	20 - 24
Carbon monoxide	ppm
Nitrogen*	Balance
Methanol (non converted)	ppm - 5 %
Formic Acid	ppm
Formaldehyde	ppm
Methyl formate	ppm
Water	0.5 – 2

*In case of autothermal process

Another source (Johnson Matthey) claims a different dry composition:

H_2: 75 %
CO_2: 25 %
CO: < 5 ppm

The overall noxious emissions of a methanol powered FCEV have been measured by DaimlerChrysler in the NECAR3 prototype vehicle. The measured values are 30% lower than the more stringent EU regulations EURO 4, which will be in place in 2005. This vehicle emits extremely low (near zero) polluting exhausts: 0 CO, 0 NO_x and 0,004 HC [6].

4.2 Carbon-based fuel: GASOLINE

The emissions of a fuel processor, using gasoline as a fuel, depend on the composition of the gasoline: commercial gasoline (Table 3), synthetic gasoline, virgin naphtha, and so on. In practical operations, it is possible to have in the reformed gases all the components contained in the starting gasoline (conversion factor of each component lower than 100%), along with the secondary reaction products, which are strongly dependent on the operating conditions (such as, temperature, type of catalyst and so on).
Nevertheless, Epyx Corporation claims for its processor, fed with gasoline (with no specified composition), the following emissions:

CO: < 5 ppm
HC: < 4 ppm

NO_x: < 1 ppm

Moreover, Epyx declares that SULEV standards are fully met.

According to preliminary tests (CNR-TAE) with a simulated gasoline (a compound of n-octane, benzene), the dry composition (the water content varies between 2 and 5 %) of the hydrogen-rich gas produced by a fuel processor is listed in Table 2.

Table 2: Outlet gas composition from fuel processor using gasoline

Gas	Range (%)
Hydrogen	14-25
Carbon Dioxide	4-9
Carbon monoxide	15-22
Nitrogen*	Balance
NH_3	0-10 ppm
CH_4, methane	0.05-2
C_2H_4, ethylene	0.01-2
C_2H_6, ethane	0.02-0.3
C_3H_6, propylene	0.05-1
C_3H_8, propane	0.01-0.02
C4-C5-C6	0.01-0.6
C_8H_{18}, n-octane	5-15
C_6H_6, benzene	0.01-1

*In case of autothermal process

Table 3: Typical composition of a commercial gasoline [7]

Compound		Molecular Weight	Complete formula	%	Mean %	H_2 Available %	H_2, % (conc.)
Butane	C_4H_{10}	58		9	9	17.24	1.55
Pentane	C_5H_{12}	72		6	6	16.66	0.99
N-hexane	C_6H_{14}	86		4	4	16.27	0.65
Isomeric hexane (2-dimetil butane)	C_6H_{14}	86		8	8	16.27	1.30
Benzene	C_6H_6	78		1.2-4.9	4	7.69	0.30
N-heptane	C_7H_{16}	100		<2	2	16.00	0.24
Xylene	C_8H_{10}	106		<11	11	9.43	1.03
Cyclohexane	C_6H_{12}	84		<2	2	14.28	0.28
Trimetilbenzene	C_9H_{12}	120		<4	4	10.00	0.40
Methyl-t-butyl ether (MTBE)	$C_4H_9OCH_3$	76	$C_4H_{12}O$	0-15	15	15.78	2.36
Toluene	C_7H_8	92		<12	12	8.69	1.04
Ethyl-t-butyl ether (ETBE)	$C_4H_8OC_2H_5$	101	$C_6H_{13}O$	0-7	7	12.87	0.90
T-amyl-methyl ether (TAME)	$CH_3OC(CH_3)_2CH_2CH_3$	102	$C_6H_{14}O$	0-5	5	13.72	0.68
Ethanol	C_2H_5OH	46	C_2H_6O	0-11	11	12.00	1.32
TOTAL						**13.04**	

Available H_2 (H_2 available x concentration) = **13.04 %**

5 Start up time and heating energy

Current test standards assume that the main components (ICE, batteries, and others parts) are tested at their working temperature, according to recommendations of manufacturers and defined pre-conditioning procedures. This condition is quite reasonable for current vehicle configurations and driving cycles. The hybridisation of drivelines, the introduction of a variety of control strategies (enabling even discontinuous operations) and the increasing request of more realistic driving cycles may pose various problems in energy consumption and emission measurements for any vehicle. In the case of FCEVs, this cannot be fully acceptable, because the start up time (cold start), heating energy needs (FCs operate at temperatures above the usual ambient temperature) may significantly affect the FC efficiency, the emissions (when fuel reformers are present) and the energy consumption for heating/cooling FCs. It is thus necessary to evaluate case-by-case, at current state of art and goals of FC technology, what could be the impact on the testing methods.

5.1 Start-up time (cold start)

The goals of major FC programs (PNGV, Italian Program CORIVAMIA) are all in a range of 1-2 minutes of start-up time for the complete generation system, including the fuel reformer. This time refers to a starting working temperature between -40 and -20 °C. This value seems to be obtainable for FC systems fed by pure hydrogen, while the presence of a fuel reformer and different fuels makes more difficult the achievement of such goals.

H_2-fed FCEVs

Test results at ENEA laboratories [8] on a first generation of Ballard FC stack (2.75 kW, 22 V at 70 °C) have shown that FC stacks gave roughly 50% of the peak power at start up at room temperature (20°C), while the full power was reached in about 15 minutes. These results could greatly change with the introduction of the reformer and fuels different from H_2.
More recently, General Motors has announced that new generation fuel stacks have been able to reach full power in 60 seconds (at a temperature of -30 °C) and in 30 seconds at -20 °C [9]. With these values it is apparent that the start up time and the transients do not create a strong impact on energy consumption. For completeness, Chrysler has calculated that, for a hybrid configuration (FC+battery), a one-minute start-up time for the FC system at -40 °C (PNGV goal) implies an energy consumption of about 200 Wh of the battery for propulsion (based on FTP cycle only) [10]. This value is anyhow negligible compared to the total energy consumption in a standardised test sequence.

FCEVs with carbon-based fuels

The situation for such FCEVs may be extremely varying in function of the fuel type and the reformer required. At present stage of development, there are a lot of uncertainties as regards the data of fuel reformers and emissions during transients. Some qualitative considerations can be drawn up:

1. The energy consumption and emissions of the FC generation system are much different from pure H_2 systems, due to the kinetics and chemical reaction efficiency.
2. The start-up time goals remain still valid and applicable to these FCEVs. Consequently, it can be reasonable to extend the same considerations to any category of FCEVs.
3. The effect of transient situations throughout the driving cycle is not significant for energy consumption but, as for HEVs, may be relevant for the emissions.

Experimental data from an onboard methanol reformer, developed by AINSI SEIKI, shows that the concentration of H_2 and CO in gas inlet to the fuel cell stack, after reforming and CO removal, depends on the start up time. The shorter the start up time, the higher is the content of CO and the lower the percentage of H_2 [11]. In terms of energy consumption and emissions, the results show a limited impact.

5.2 Heating energy

PEFCs, the best candidate for transport in a near future, operate at about 80 °C and then need to be heated. Chemical processes involved in FCs during operation are exothermic, and then FCs will be maintained hot whenever the systems are used for long time or even with short standstill periods. In reality, as described above, this FC can work at a reduced power output even at room temperature [12], when no fuel reformers are used. For testing purposes, it is possible to state the following assumptions:

1. The heating energy must not be measured whenever a long continuous working time is considered.
2. The heating energy can become a significant energy loss and then must be measured only when long stand still periods are included in the real operating driving cycles.

6 Conclusions and recommendations

Problem definition

The ongoing development of FCEV creates uncertainties about vehicle classification and definition of measuring and testing methods because of the various fuels proposed, the different fuel cell types, and the various driveline configurations. FCEVs can be similar to ICEVs and HEVs with similar testing problems, but with the main difference of having an onboard energy source (the FC) other than a thermal engine.
The definition of a new test procedure for FCEVs and, subsequently, a standard for measuring energy consumption and emissions presents common aspects to the introduction of a new product with peculiar features, which have been the basic assumption for the analysis carried out in this subtask work:

1. FCEVs are available only at prototype/demonstrator level with a few pre-series products;
2. The configurations investigated until now are various and may present testing problems similar to ICEV, BEV, and HEV, depending on the system chosen.
3. No standard testing procedure is presently available specifically for FCEVs. Current or draft CEN standards only consider BEVs, HEVs with thermal generators and ICEVs.
4. The use of some tests of existing testing procedures for BEV, HEV and even ICEV seems to be applicable, at least for evaluation purposes. For practicality and comparability, it seems wise to look for incremental adaptation to or combination of elements from existing standards.

Three main practical and technical issues have resulted from these preliminary considerations:

1) the FCEVs must be correctly included in the a general classification;
2) the specific needs for measuring FCEV energy consumption and emissions must be defined by, eventually, combining or adapting existing standards for ICEV, BEV, and HEV (with thermal engine); and, finally,
3) the heating energy and the start up time must be analysed to verify whether there are specific features impacting the testing method. Due to the limited availability of experimental results and products, the analysis has been carried out at the major candidate technologies for the fuels (hydrogen, methanol and gasoline), the FC type (proton exchange FC) and configurations.

General classification

The categorisation of FCEV is functional to the definition or to the application of specific testing procedures. The variety of possible fuels and configurations necessitates classification in a systematic way in order to favour the use of specific testing procedure.

Energy consumption and emission measurements

The different fuels and configurations normally require the application of different measuring techniques not always considered in existing (draft) standards. The impact of the problem is relevant particularly when only H_2 is used as fuel. Present standards are exclusively devoted to carbon-based fuels and electricity.

Start up time and heating energy

The problem of start up time is similar to the problem of cold start in ICEVs. Apart from the practical aspect of the vehicle readiness, the impact on the vehicle consumption and emission may be significant depending on the type of fuel and configuration. A one-minute start up time is now considered as the minimum goal of most development programs and has been obtained in FCEV and FCHEV (using battery for the initial vehicle start). Studies have confirmed that a

one-minute start up time may imply a consumption of 200 Wh from the battery when that directly powers the electrical motor. This confirms that the impact of start up time is quite negligible, while results of analysis for the effects on emissions require further research for various configurations and fuels. The main detrimental influence on emissions is expected when a fuel reformer is used.
The energy losses are related to the necessity to heat up the fuel cell stack and the fuel reformer, which normally operate at temperatures significantly higher than the ambient temperature (at minimum 80 °C for PEFC stacks). Chemical processes involved in FCs during operation are exothermic, and then FCs will be maintained hot whenever the systems are used for long time or even with short standstill periods. This FC can work at a reduced power output even at room temperature, when no fuel reformers are used. In general, the amount of energy required for making the FC system fully operational seems not relevant with respect to the energy needed during a standard driving cycle. Further studies are needed to quantify the impact of heating losses.

Status of standard procedures

There is no specific standard in the world considering specifically FCEV test procedures. A few years ago EUCAR proposed a test procedure for FC stacks, which, however, never reached a final version. The European standard setting body CEN (TC 301 WG1), has started working on the classification and basic definitions. The "Part 3: Other electric hybrid vehicles than those fitted with a thermal machine" of the European Standard prEN 1986, under the general title "Electrically propelled road vehicles – Measurement of energy performances" is in abeyance. According to the last recent CEN TC 301 meetings [2], FCEV should be included in future standards prEN 1986-3 (for energy consumption) and in prEN 13444-2 for emissions.

FCEV Classification

Two large categories of FCEVs have been proposed. It seems reasonable to consider two large categories and then subdivide them in two other subcategories, based on fuel types.

1 ***Category 1 as an ICEV*** (FCEV without energy storage system other than the fuel tank)
- 1.1 Carbon-based fuel
- 1.2 Hydrogen

2 ***Category 2 as an HEV (FCHEV)*** (FCEV with an energy storage system other than the fuel tank)
- 2.1 Carbon-based fuel
- 2.2 Hydrogen

Both categories include the direct methanol FC systems.
This classification is consistent with that proposed by CEN 301/WG 1. The main difference consists in the elimination of non-carbon based fuels different from H_2, e.g., hydrazine used in space applications.

Recommendations for energy consumption and emission measurements

<u>Energy consumption</u>
The present standards for ICEVs and HEVs calculate overall energy consumption by measuring the emissions of HC, CO and CO_2. This method assumes the use of carbon-based fuels and the application of carbon atomic equivalents and measured gas emissions for calculating the energy consumption. This method is obviously not applicable when pure hydrogen is used. The considerations are applicable also to FCHEVs.

Energy consumption for carbon - based fuels
The existing testing methods for ICEV and HEVs can be applied without problems. Attention can be given to the possible sources or outlets for emissions. Recent results of prototypes FCHEV and fuel reformer tests confirm very low exhaust emissions. The use of cleaning and exhaust removal systems to improve the quality of the reformate gases before entering the fuel cell stacks must be carefully evaluated in order to consider possible temporary accumulation of exhaust gases.

Energy consumption for pure hydrogen
In case of H_2-fed FCEVs, there is the need to directly measure the consumed hydrogen. In a FC generator, the fed H_2 is partially converted into water (steam water) and partially recirculated, since it is not used in the reactions. The produced H_2O depends on the consumed H_2 and on both the inlet air composition **and** the humidification process of the reaction gas inside the stack system. Two measuring methods can then be recommended: the measurement of H_2 needed to replenish the storage tank, or the continuous measurement of the fuel supplied to the FC stack. The first one seems to be more practical for testing purposes if an external tank can be used.

Emission measurements
The emissions depend on the characteristics of the inlet fuels. There is no need for any regulated measurement, when pure H_2 is used. For carbon-based fuels, the measuring equipment can be set up after an investigation of the composition of the used fuels and the emissions that must be measured. The analysis of fuel compositions of major fuel candidates (methanol and gasoline) and some experimental data show that regulated emissions are very low in absolute values. Existing (draft) standards (prEN 1986-2 and prEN 13444-1) can be applied.

Start-up time and heating energy
The start-up time does not significantly affect the energy losses and emissions, when H_2 is used as fuel. Present goals of major development programs of one-minute start-up time for the FC generator can make this problem negligible for measuring purposes.
The energy losses due to the heating/cooling of the FC stack and reformers vary extremely and depend on driveline configurations and driving cycles. Specific need for measuring such losses can arise only when long standstill periods are part of the driving patterns. For comparative assessment, rather than for homologation, standstill periods and related heating energy should be recorded to improve accuracy and significance of energy consumption comparisons.

References

[1] MATADOR Project- task 2, Inventory of Test Procedures: State of the Art and Problems, Report, 1998.

[2] S. Ploumen, “Meeting CEN TC301/WG1”, minutes for MATADOR, October 1999.

[3] TAE-CNR, “DMFC Activity at CNR-ITAE”, 4^{th} Korea-Italy Joint Symposium on Fuel Cells, October 1999.

[4] CEN/TC301/WG1, prEN 1986-2, July 15, 1999.

[5] CEN/TC301/WG1, prEN 13444-1, July 15, 1999.

[6] Martin, “Recent advances in fuel cells for transportation applications”, EVS-16, Beijing, October 1999.

[7] TAE-CNR, “Emissions for FC stacks”, private communication, December 1999.

[8] S. Galli, Test results of a Ballard FC stack, ENEA private communication, March 2000.

[9] EV Progress, “Fuel cell strides and initiatives on the rise”, vol. 22, No 7, April 1 2000.

[10] C.E. Borroni-Bird, “Fuel cells and other clean power sources”, Chrysler presentation, 1996.

[11] K. Kiryu, O. Tsubouchi, A. Takumi, “Advanced reformer for a fuel cell powered EV”, EVS-15, Bruxelles, October 1998.

[12] R.M. Moore, D.J. Friedman, A.F. Burke, “Fuel cell vehicles: efficiency and emissions”, Commercializing FCVs '97, Frankfurt, October 1997.

MANAGEMENT TOOL for the ASSESSMENT of DRIVELINE TECHNOLOGIES and RESEARCH

MATADOR

Contract JOE3-CT97-0081

Task 2:

Testing methods for vehicles with conventional and alternative drivelines

Subtask 2.8

Driving cycles for LD vehicles

TNO Automotive

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by
Erik van den Tillaart (TNO Automotive)

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Nomenclature

Abbreviations

AC	Alternating Current
APU	Auxiliary Power Unit
BAT	Battery
BEV	Battery Electric Vehicle
CHEV	Combined HEV
CS	Control Strategy
DC	Direct Current
el. Flywheel	Electro mechanical flywheel
EM	Electric Motor
EUDC	Extra Urban Driving Cycle
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
FCHEV	Fuel Cell Hybrid Electric Vehicle
GE	Generator
genset	Generator set (APU)
GVW	Gross Vehicle Weight
HD	Heavy-Duty
HEV	Hybrid Electric Vehicle
HWFET	Highway Fuel Economy Test
Hyz. H.	Hyzem Highway driving cycle
Hyz. R.	Hyzem Rural driving cycle
Hyz. U.	Hyzem Urban driving cycle
ICE	Internal Combustion Engine
ICEV	(Conventional) Internal Combustion Engine Vehicle
Jap1015	Japanese 1015 Hot Mode Cycle
LD	Light-Duty
MATADOR	Management Tool for the Assessment of Driveline TechnOlogies and Research
NEDC	New European Driving Cycle
NiCd	Nickel-Cadmium (battery)
NiMH	Nickel Metal Hydride (battery)
PG	Planetary gear
PHEV	Parallel HEV
PHEVbat	Parallel HEV with battery
PHEVfw	Parallel HEV with flywheel
PM	Permanent Magnet
RED	Reduction gear
SC03	SC03 Air conditioning cycle
SHEV	Series HEV
SHEVbat	SHEV with battery and load-follower strategy
SHEVfw	SHEV with flywheel
THS	Toyota Hybrid System
TNO	(Netherlands) Organisation for Applied Scientific Research
UDC	Urban Driving Cycle
UDDS	Urban Dynamometer Driving Schedule
US06	US06 High Speed / High Load driving cycle
VEH	Vehicle
WH	Wheels

Symbols

A	Frontal area	[m^2]
APU op 1	APU operating point 1	[kW]
APU op 2	APU operating point 2	[kW]
BSFC	Brake Specific Fuel Consumption	[g/kWh]
CO	Carbon mono-oxide emission	[g/km]
CO_2	Carbon dioxide emission	[g/km]
C_w	Air drag coefficient	[-]
E	Energy	[MJ]
		[kWh]
$E_{B,C}$	Energy from charger into batteries during charging	[kWh]
$E_{B,DC}$	Energy from batteries during driving	[kWh]
EC_B	Energy consumption relative to the battery	[kWh/km]
$EC_{B,I}$	Energy consumption relative to the grid	[Ah/10km]
EC_G	Energy consumption relative to the grid	[kWh/km]
E_G	Energy from the grid	[kWh]
$E_{I,C}$	Capacity from charger into batteries during charging	[Ah]
$E_{I,DC}$	Capacity from batteries during driving	[Ah]
F	Failure time	[%]
FC	Fuel Consumption	[MJ/100km]
		[l/100km]
		[l/km]
		[kWh/km]
f_r	Rolling resistance coefficient	[-]
HC	Hydro carbonate emission	[g/km]
I	Current	[A]
i	Gear ratio	[-]
$I_{BATT}(t)$	Battery current	[A]
$I_{GEN}(t)$	Generator current	[A]
$I_{MOT}(t)$	Electric Motor current	[A]
$n_{ICE}(t)$	Engine speed	[rpm]
NO_x	Nitrogen oxide emission	[g/km]
P	Power	[W]
$P_{BATT}(t)$	Battery power	[kW]
$P_{GEN}(t)$	Generator power (electric)	[kW]
$P_{MOT}(t)$	Electric Motor power (electric)	[kW]
$R_{dynamic}$	Dynamic wheel radius	[m]
R_E	EC_G-ratio, relative to EC_G on NEDC	[-]
RPA	Relative Positive Acceleration	[m/s^2]
S_{DC}	Covered distance	[km]
SOC	State-of-Charge	[%]
t	Time	[s]
		[h]
T	Torque	[Nm]
U	Voltage	[V]
U_A	Arithmetic mean average battery voltage during driving	[V]
$U_{BATT}(t)$	Battery voltage	[V]
$U_{GEN}(t)$	Generator voltage	[V]
$U_{MOT}(t)$	Electric Motor voltage	[V]
v(t)	Rollerbench speed	[km/h]
ΔQ	Change in charge content	[Ah]
		[Ah/km]
ΔSOC	Change of State-of-Charge	[%]
		[Ah]
η	Charging efficiency	[-]
ρ	Fuel density	[kg/l]

Contents

1 Introduction

In the context of Task 2 of the MATADOR-project (Management Tool for the Assessment of Driveline Technologies and Research, EU-contract JOE3-CT97-0081), research is carried out in support of the development of test procedures for electrically propelled road vehicles and vehicles with other alternative drivelines. The definition of testing procedures for determining energy consumption and emissions of vehicles with different drivelines requires the evaluation of technical aspects, specific of each vehicle technology. Furthermore, the development of testing procedures that allow for a comparative technical benchmarking of different vehicle power trains is an even more complicated task, because the performance of each technology could be significantly different from each other (alternative fuels, hybridisation, combined energy sources) asking for various measuring needs. Key issues have been addressed and are evaluated in terms of their impact on testing methods.

At this moment, standardised cycles are used for the determination of emissions and energy consumption of conventionally powered Light-Duty vehicles. The use of a rollerbench (chassis dynamometer) to perform vehicle testing has lead to the definition of driving cycles representative of real-life driving patterns as well as stylistic (or “modal”) cycles. The legislative cycle in Europe is an example of such a stylistic speed pattern. This cycle can hardly be considered representative for real-life usage. Since the operating conditions of the vehicle significantly affect the energy consumption and emissions, the need for more realistic driving cycles is currently already expressed.

With the introduction of vehicles with advanced drivelines, like battery and hybrid electric vehicles, the need for more realistic and representative driving cycles probably becomes even more urgent. These kind of vehicles are often developed to give lower emissions and energy consumption under realistic operating conditions, either defined for a general purpose vehicle or for specific applications.

It is expected that, for vehicles with alternative drivelines, the driving cycle characteristics have an even more profound influence on the energy consumption and emissions than for conventionally powered vehicles. Testing of the vehicle under unintended use conditions might boost the emissions and energy consumption, therewith giving a complete misrepresentation of the actual performance. This gives reason for investigating the influence of driving cycle characteristics on the mentioned factors.

In this report existing driving cycles are presented, and by means of simulation and measurement the influence of driving cycle characteristics on driveline behaviour, energy consumption, and emissions is investigated. A comparison between driving cycles can then be made.

The goal of the research discussed in this report is not to determine, nor to present, the (best) driving cycle for the testing of (alternatively powered) vehicles, but just to indicate the effects of different driving cycle characteristics on powertrain behaviour. From this analysis conclusions can be drawn with respect to demands on future testing cycles.

The report ends with the overall conclusions and recommendations, a reference list and the appendices.

2 Existing driving cycles

An important element of the test method to measure exhaust gas emissions and fuel consumption of road vehicles is the test cycle. In this respect, a distinction has to be made between light duty (LD) and heavy-duty (HD) vehicles:

- In the case of light duty vehicles (passenger cars and light commercial vehicles) testing is done with the complete vehicle on a chassis dynamometer that allows the simulation of a trip made with the vehicle. The test cycle in this case is a vehicle driving cycle, defined as a time-speed sequence.
- In the case of heavy-duty vehicles (in principle vehicles above 3500 kg GVW) it was decided to certify engines rather than vehicles. Consequently, the test cycle is set up for an engine on an engine tested. The test cycle in this case is defined as an engine cycle. Testing is done ‘steady state’ or ‘transient’. The steady state cycle consists of the measurement of a series of fixed points in the engine’s speed-torque map. The transient cycle consists of the simulation of a vehicle-based driving cycle on an engine testbed. The test is still engine based as the engine is tested separately, but the results are also directly related to the vehicle driving pattern, since the driving cycle is converted to engine operated points.

There are three basic legislations covering the testing of road vehicles, all using different test cycles:

- The US legislation (sometimes to be divided into the Californian and the US Federal legislation). This legislation is also adopted by Canada, several South American countries and many Asian countries.
- The Japanese legislation. This is mostly limited to Japan itself.
- The European legislation. This is adopted by both West and East Europe and some countries outside Europe.

Besides the legislative test cycles, different real-life test cycles have been developed in order to represent the actual use of vehicles.

This chapter gives an overview of the currently used test cycles for light-duty road vehicles.

2.1 European driving cycle

The New European Driving Cycle (Figure 1, also known as MVEG-A) is a so-called modal cycle, meaning that it consists of straight line elements. The urban part of this cycle (UDC), with speeds up to 50 km/h, was first introduced in 1970. It represents very congested urban traffic. It was not meant as representative of average driving, but rather as a worst case for CO-emission, which was regarded the main problem in those days. This means a low average speed, much idling and low acceleration rates. Additionally, the cycle is built up from fixed modes, leading to relatively low dynamics. In the early eighties, with its growing awareness of acidification, an extra-urban part was added that was loosely based on statistical data regarding extra-urban traffic. This part (EUDC), with speeds up to 120 km/h, was mainly added to enable a meaningful way of measuring NO_x-emission, which is not significant for urban driving conditions. These cycles are still in use to measure emissions in homologation testing. The urban cycle was used in combination with constant speeds of 90 and 120 km/h to measure fuel consumption. Since 1993 the fuel consumption is measured in the urban and extra-urban driving cycle.

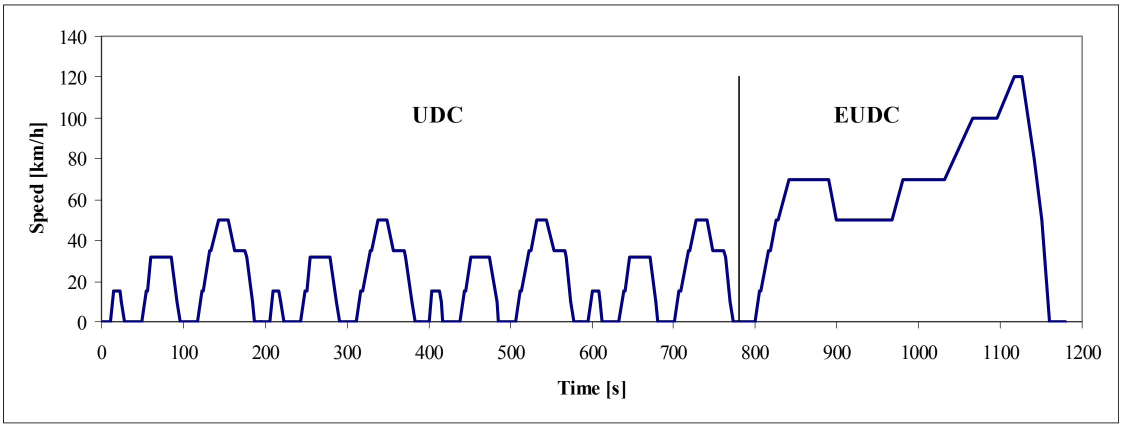


Figure 1: Speed trace of the 'New European Driving Cycle'

At this moment TNO is studying the possibilities to come to a new European driving cycle for the emission testing of light duty vehicles. There is a general feeling that the present European cycle is too outdated to be able to form a basis for emission legislation much longer. There is strong evidence that the emission results measured with this cycle are not representative for those in real life conditions. Experiments have shown that vehicles scoring extremely well in the present test, may show an excessive increase in emissions with a significant rise in the dynamics of the driving behaviour. Additionally, it may be pointed out that it has been found that e.g. the relative comparison of NO_x-emissions of diesel and petrol engined cars is to a large extent influenced by the dynamics of the test cycle used. It should therefore be concluded that even if the present cycle were to give a more or less correct ranking of vehicles with a similar drive train, a better balanced cycle might also improve the mutual comparison of different types of drive trains. This aspect will grow in importance when e.g. hybrid vehicles will appear on the market. As a consequence, a more realistic driving cycle would also produce more realistic emission figures that would enable their use as 'true' emission factors.
At TNO methods for the development of (new) driving cycles have been worked out. For this, extensive background knowledge as well as experimental skills have been gained in the past. More information on the background and development of driving cycles can be found in Appendix A.

2.2 Japanese driving cycles

The Japanese legislation contains several driving cycles (Figure 2 and Figure 3). They are modal in character, and moreover, they reflect the low speed characteristics of Japanese traffic with a highest speed of 70 km/h. The first is the 11 Mode Cold Driving Cycle, which is driven four times. The second is the 10-15 Mode Hot Driving Cycle.

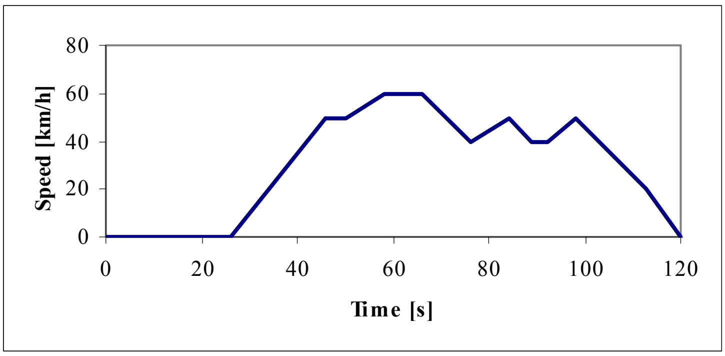


Figure 2: Speed trace of the Japanese `11 Mode Cold Driving Cycle'

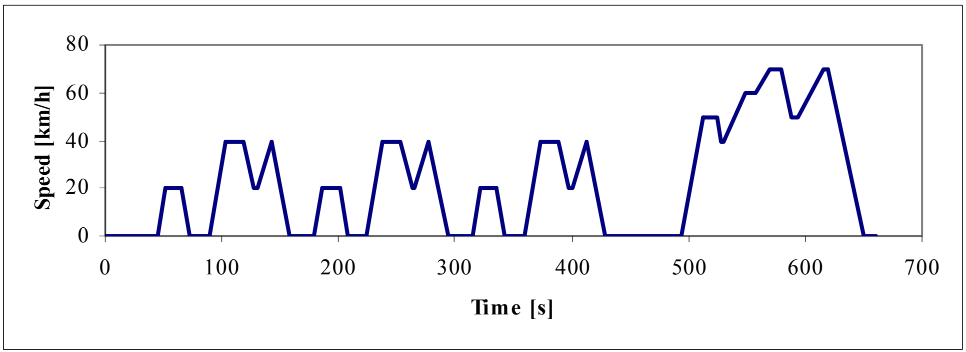


Figure 3: Speed trace of the Japanese `10-15 Mode Hot Driving Cycle'

2.3 United States driving cycles

The US city driving cycle (Figure 4) is essentially an urban cycle (called City Cycle, FTP-75, or EPA III), although with a short piece of urban freeway with speeds of up to 90 km/h. In contrast to the European and Japanese cycles it is the representation of a real driving pattern, a so-called *transient* driving cycle. It is used for emission measurement and fuel consumption measurement. This cycle consists of several phases; a cold transient and cold stabilised part (also known as FTP-72, Urban Dynamometer Driving Schedule (UDDS), EPA II, or LA-4), followed by a 9 to 11 minutes period of hot soak, after which the transient part is driven again (now with hot engine).
The FTP-75 is mainly an urban cycle. Additionally fuel consumption is measured in the 'Highway Cycle' (Figure 5) which is also transient, also with speeds up to about 90 km/h yet has a higher average speed, and therefore is more representative for highway driving.

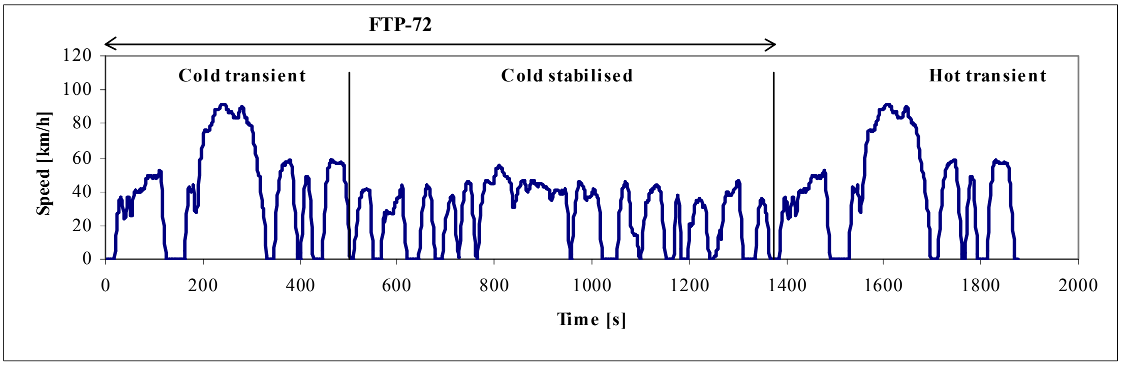


Figure 4: Speed trace of the `FTP-75 City Driving Cycle'

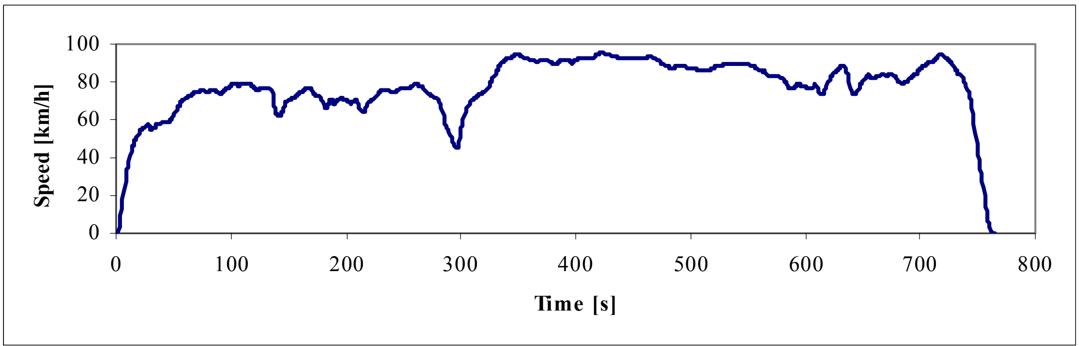


Figure 5: Speed trace of the `Highway Fuel Economy Test'

An additional test procedure with separate emission standards will be phased in for passenger cars and light commercial vehicles from the year 2000. The main purpose is to include the use of air conditioning in the legislation, as well as to introduce higher speeds and higher loads into a driving cycle. Therefore, the test procedure consists of two extra driving cycles: the SC03 Air Conditioning Driving Cycle (Figure 6) and the US06 High Speed/High Load Driving Cycle (Figure 7).

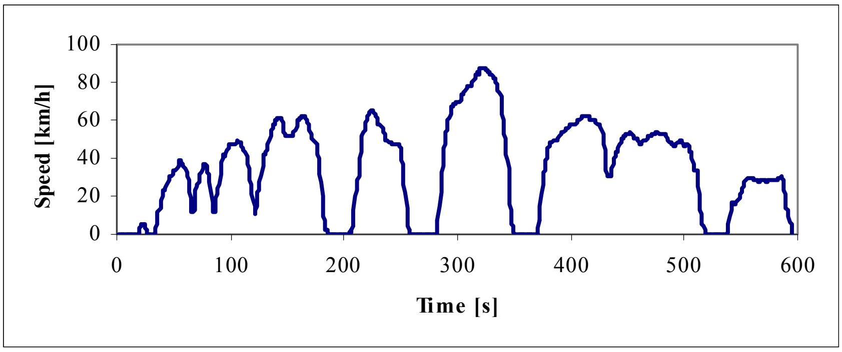


Figure 6: Speed trace of the `SC03 Air Conditioning Driving Cycle'

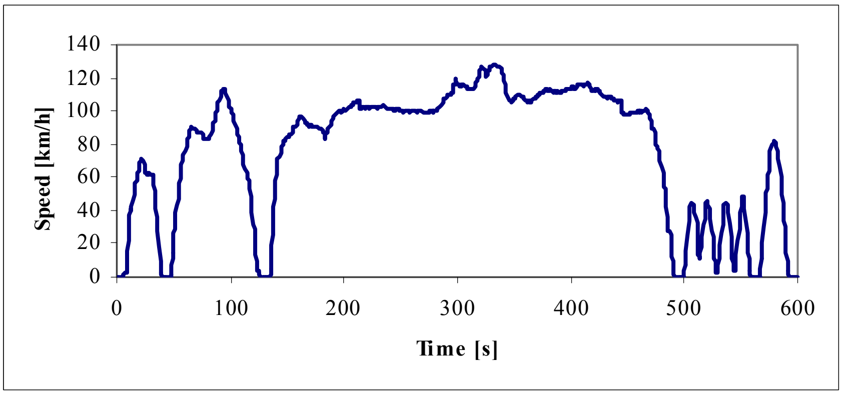


Figure 7: Speed trace of the `US06 High Speed/High Load Driving Cycle'

2.4 Real-life driving cycles

Besides the legislative driving cycles, different real-life driving cycles have been developed in order to represent the actual use of passenger cars and/or vans. They are always based on real driving data, sometimes measured in specific situations like for example traffic jams or urban goods distribution (with vans). The cycle can also represent an average traffic situation in, for example, the Netherlands. Although these cycles do not have an official status, some of them are well accepted and are used for different research purposes in different projects, mostly in addition to one or more legislation cycles.

An example of such cycles is the MODEM driving cycle. This cycle (Figure 8) is developed by INRETS in France, and is based on large scale driving behaviour measurements in three European countries in the framework of the DRIVE - project "Modelling of emissions and consumption in urban areas - Modem" [1]. As can be seen from the figure, the driving cycle consists of four parts: a slow urban, a free flow urban, a road (rural driving) and a highway part.

Similar to the MODEM Driving Cycle are the HYZEM cycles [4]. These too are developed by INRETS. More and newer recorded driving patterns were used to set up three distinct cycles, each covering a specific operating area. The three Hyzem cycles represent Urban, Rural, and Highway traffic conditions (Figure 10).

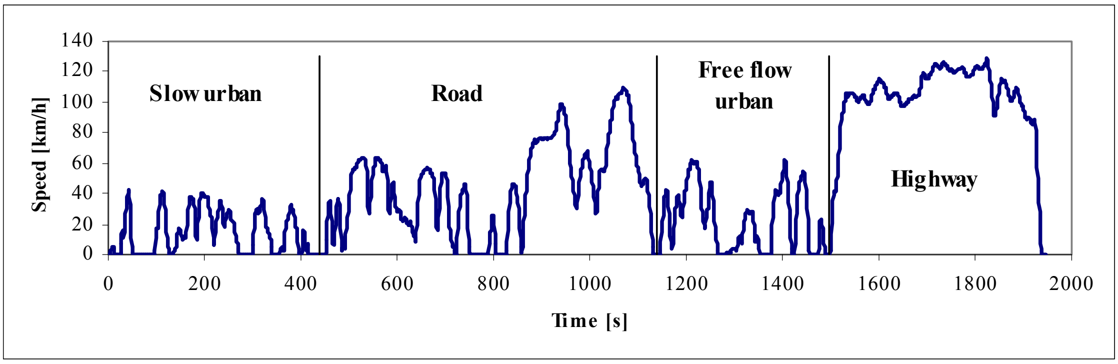


Figure 8: Speed trace of the `MODEM Driving Cycle'

Many other speed profiles are used by research institutes too. TNO, for instance, has developed several real-life cycles representing different driving styles. Normal, aggressive, and smooth driving styles are available. IKA has a driving pattern based on measurements in the Aachen (inner) city (Figure 9) which thus is an urban cycle. ENEA (Italy) also has recorded a speed pattern in a city from which a modal speed pattern called Casaccia City cycle (Figure 11) has been derived.

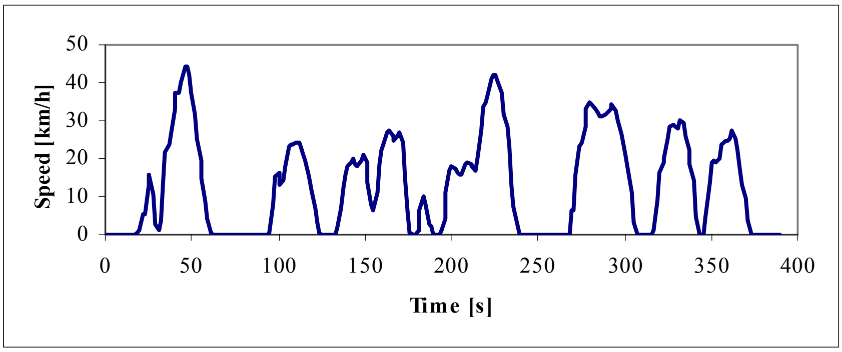


Figure 9: Speed trace of the `Aachen City Cycle'

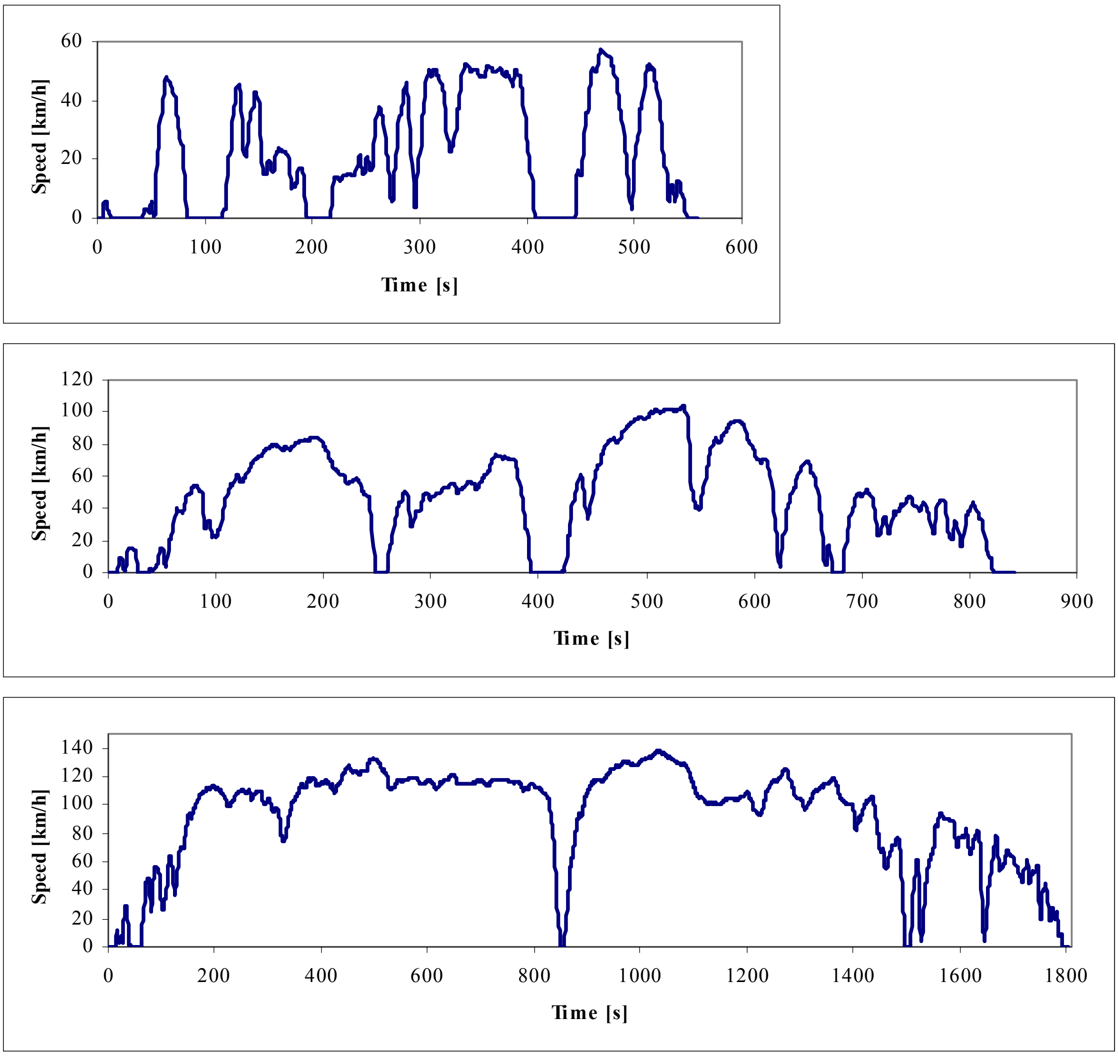


Figure 10: Speed traces of the `Hyzem Urban' (top), 'Rural' (middle), and 'Highway' (bottom) Driving Cycles'

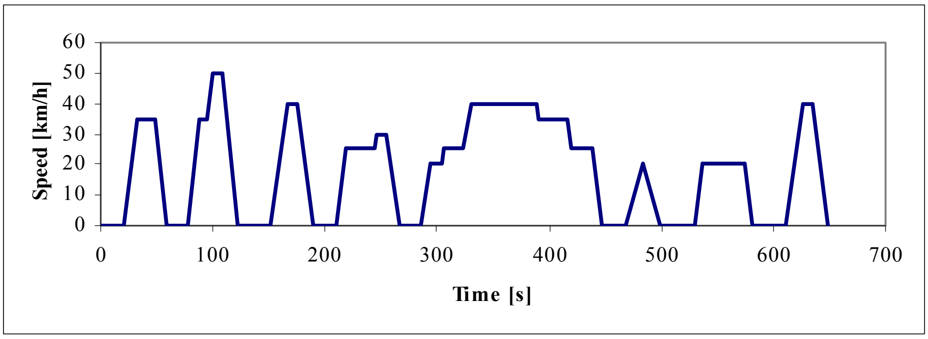


Figure 11: Speed trace of the 'Casaccia City Cycle'

2.5 Comparison of driving cycles

In the previous sections a large number of driving cycles for Light-Duty vehicles has been presented. Each cycle has its own characteristics and application area (Europe, Japan, USA). In Appendix A, Table 6 lists parameters that are used to identify the characteristics of a driving cycle. For the driving cycles presented in this chapter, the main parameters have been calculated and are listed in Table 1.

Table 1: Light-Duty Driving cycle parameters

Driving cycle	Time [s]	Distance [m]	Maximum speed [km/h]	Average speed [km/h]	Maximum acc / dec [m/s^2]	RPA [m/s^2]
New European Driving Cycle (NEDC)	1180	11007	120	33.6	1.04 / 1.39	0.12
Japanese 10-15 Mode Hot Cycle (Jap1015)	660	4171	70	22.7	0.79 / 0.83	0.17
US City Cycle (USFTP-75)	1877	17762	91.2	34.0	1.89 / 1.81	0.18
USFTP-72 / UDDS	1372	11986	91.2	31.4	1.89 / 1.81	0.19
US Highway Cycle (HWFET)	765	16507	96.4	77.4	1.43 / 1.48	0.07
SC03 Air Conditioning Cycle (SC03)	594	12887	88.2	34.9	2.28 / 2.73	0.22
US06 High Speed/High Load Cycle (US06)	600	5760	129.2	77.2	3.78 / 3.08	0.22
MODEM cycle	1946	25121	128.7	46.5	3.19 / 2.42	0.19
Hyzem Urban	559	3470	57.2	22.3	2.19 / 2.06	0.28
Hyzem Rural	842	11224	103.4	47.9	2.42 / 4.61	0.22
Hyzem Highway	1803	46205	138.1	92.2	3.19 / 4.03	0.13
Aachen City Cycle	390	1396	44.3	12.85	2.72 / 2.67	0.29
Casaccia City Cycle	649	3224	50	17.9	0.97 / -1.07	0.13

The average speed and RPA are parameters that together provide information that enables a judgement on the demands of a driving cycle in terms of energy at the wheels. A mutual, qualitative, comparison of different driving cycles can be made. Figure 12 shows the RPA values plotted versus the average speed for the driving cycles listed in Table 1. In general, higher RPA and higher average speed require higher power and energy. What directly is found in Figure 12 is that the (old) legislative cycles (black markers) have lower RPA and average speed than more recently developed driving cycles as, for instance, the Hyzem driving cycles (based on real-life driving patterns). This indicates that driving behaviour has changed over the years, and that the old cycles are no longer representative for current traffic conditions. The Hyzem cycles show that each operating condition has its own specific combination of RPA and average speed. Urban driving is characterised by low (average) speed and relative high acceleration, while highway driving has low RPA and high average speeds.

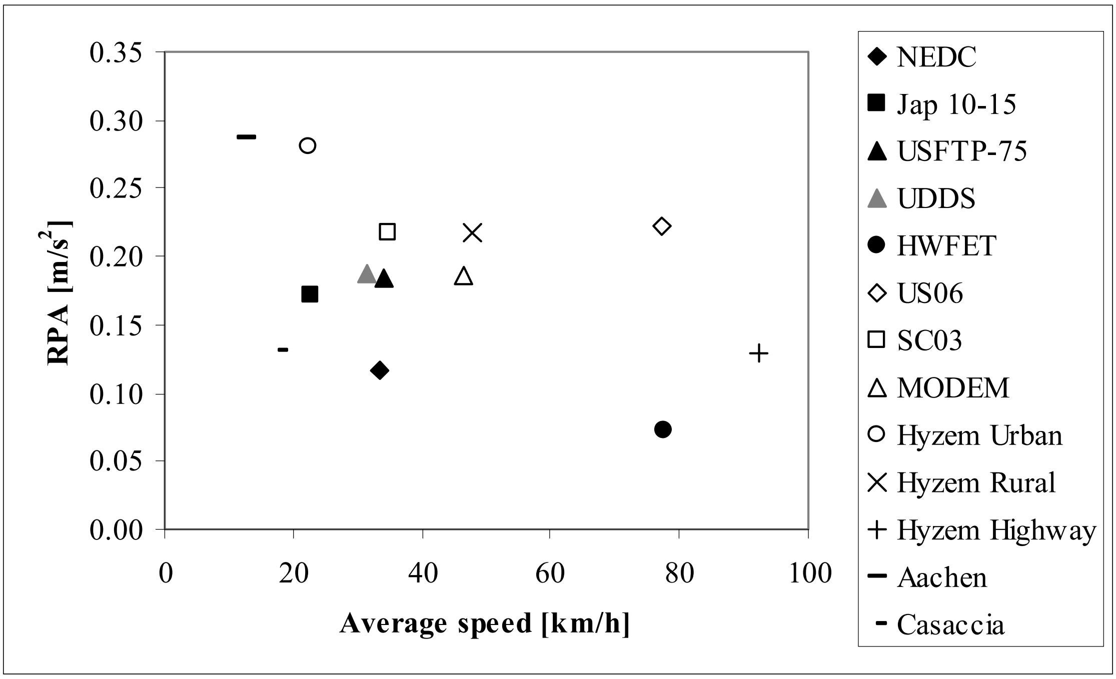


Figure 12: RPA versus average speed

3 Expected influence of the driving cycle characteristics on emissions and energy consumption

3.1 Background

The main goal of a standardised driving cycle for approval testing of road vehicles is to provide a reliable basis for an honest ranking of different engines and technologies, relative to each other as well as to the limits that are set by the government. As explained in paragraph 2.1, the European driving cycle dates back to the early 70's and 80's. In those days, the available engine technologies were quite comparable. Therefore, there was no need to have a representative driving cycle, as ranking was implicitly guaranteed by the fact that different engines showed quite similar behaviour. Instead of representativity, driving cycles were focused on displaying effects of worst case situations. Nowadays, more propulsion systems with different operating principles are being used. In addition, even two physically identical engines may produce different emissions, only because of a difference in engine management systems. This calls for representative driving cycles, that characterise real-life conditions as close as possible, as the only fair basis for comparison is the actual load of the engine itself.

3.2 Parameters of influence concerning conventional propulsion systems

Conventional Otto engines are currently all equipped with a closed-loop three-way catalyst. In steady state operation, they ensure very low emissions. However, if the driver shows very dynamic driving behaviour, emissions will depend on the way in which the management system can deal with these rapid load changes (the so-called 'dynamic effect on emissions'). Any dissimilarity between a driving cycle and real-life operating conditions may therefore easily result in a deviation of measured emissions. Figure 13 represents the emissions for the same route, driven in a smooth and an aggressive driving style. It is obvious that there is quite a strong relationship between driving behaviour and the resulting emissions.

Another point for bringing dynamics into the driving cycle is for reasons of comparison of different technologies. Figure 14 shows the difference in measured NO_x-emissions of a petrol, indirectly injected diesel, and directly injected diesel vehicle for the European and the more transient MODEM driving cycle (see paragraph 2.4). This example clearly illustrates that the comparison of emissions for different kind of engines and technologies depends on the dynamic characteristics within the driving cycle applied to measure them. The current European approval driving cycle is of a low dynamic level. A new driving cycle should therefore include dynamics representative of real-life driving patterns.

Fuel consumption is to a large extent proportional to the mean power demand at the wheels. Figure 13 shows the influence of an aggressive driving style on the emissions. The fuel consumption correlates to the CO_2-emission. The required energy at the wheels for an aggressive driving style is higher, but the energy is partly produced at a higher efficiency since the engine is operated at higher loads. Furthermore, current fuel injection systems are quite sophisticated, so they can deal with dynamic driving behaviour in a proper way and minimise the dynamic effects on fuel consumption.

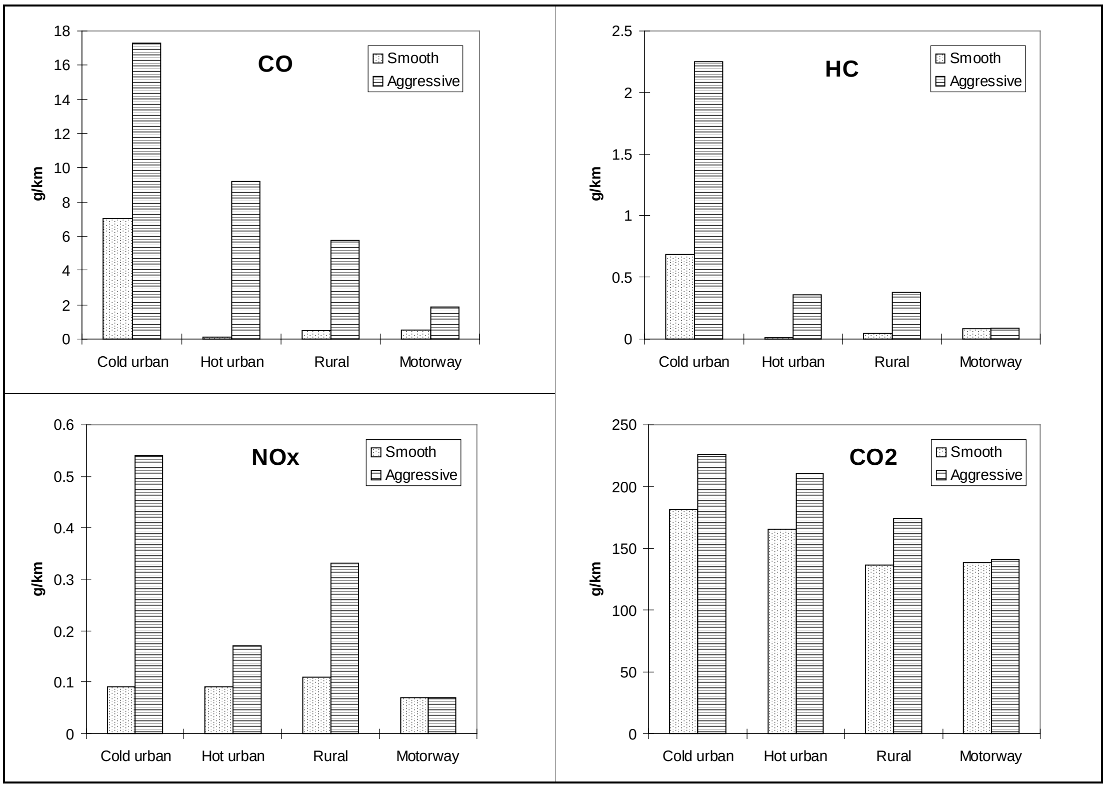


Figure 13: *Example of the influence of 'aggressive' (extremely dynamic) driving behaviour*

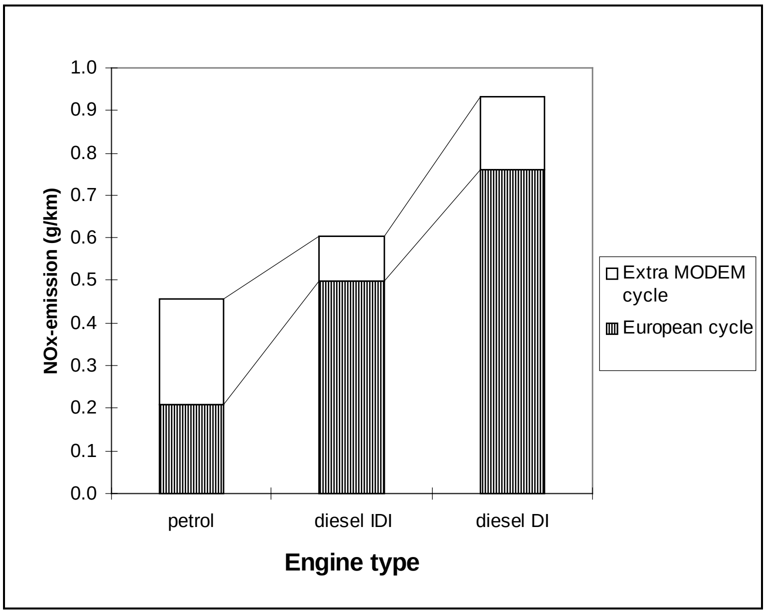


Figure 14: *Influence of driving cycle on NO_x-emission. The marker 'Extra MODEM cycle' represents the extra emissions resulting from the difference in dynamics between the European and MODEM driving cycle*

Another point of interest concerns the cold start effects. Some time is needed for the engine and catalyst to reach their normal operating temperatures. During this time, emissions are increased to such an extent, that they form a considerable part of the measured emissions over the whole driving cycle. It therefore is very important to establish representative driving patterns just after the cold start, in order to determine the actual time needed for the catalyst to heat up, and the extra emissions produced during this process.

In the European legislative testing, this effect was initially ignored as the driving cycle started with 40 seconds of engine idling during which the emissions were left out of the measurement. From the year 2000 together with the introduction of the EURO-3 emission limits, cold start is included in the test procedure by simply leaving out the 40 seconds idling prior to the cycle start. Figure 15 illustrates the emissions produced by a petrol vehicle, including the cold start in the European driving cycle. As the driving cycle during the first 200 seconds is repeated three times, the period from 200 until 400 seconds represents what the emissions would have been if the test was started with a hot engine. Compared to the cold start, especially HC and CO emissions show a spectacular reduction. It is therefore very important to include the first part of the driving cycle in a representative way.

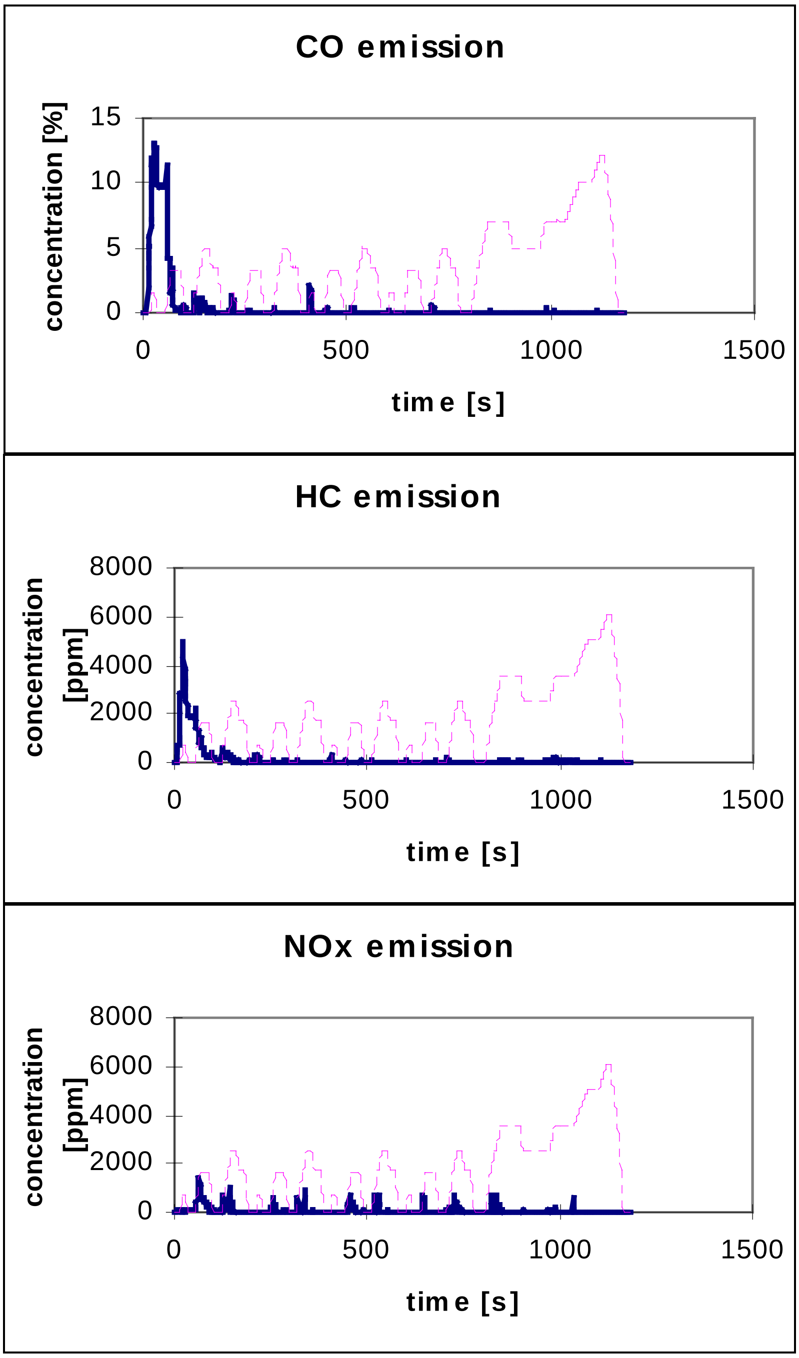


Figure 15: Emissions of a Volkswagen Golf 1.8 during the European driving cycle including cold start (ambient temperature 7˚C)

3.3 Parameters of influence concerning electric and hybrid propulsion systems

Electric and hybrid propulsion systems appear in different configurations, with a variety of applied components, and various control strategies. Important parameters of influence will be illustrated for the case of a series hybrid propulsion system.

One of the major advantages of a series electric hybrid propulsion system is its ability to regenerate braking energy. A driving cycle with large periods of constant speed will underestimate this property, where a highly dynamic cycle may depict the hybrid propulsion system too positively. Once again, dynamics prove to be very important for reasons of representativity. This also means that within a driving cycle special attention needs to be given to the distribution of distances driven in urban areas, rural areas and on motorways.

The primary engine of a series hybrid propulsion system is usually operated in a limited number of points of its engine map, where fuel efficiency and emissions are favourable. Power control is partly provided by switching the engine on and off. Engines of conventional propulsion systems are operated in all parts of the engine map, because they need to deliver the exact amount of power requested by the driver, together with a certain engine speed. They are therefore more dependent of the driving cycle, where a hybrid propulsion system will respond more proportional to the average requested power. If for instance the mean power demand of a driving cycle is lower than the real-life situation, a conventional propulsion system will be loaded in lower parts of the engine map, thus producing other emissions (usually higher), and fuel efficiency (usually worse). The series hybrid, however, can just drive more distance in the electric mode. It will produce proportionally less emissions per kilometre, with a proportionally lower fuel consumption. Consequently, both propulsion systems can only be objectively compared if the driving cycle is representative for real-life situations.

The effect of cold start emissions may be of more importance with hybrid vehicles compared to conventional propulsion systems. Where conventional vehicles will only have a cold start at the beginning of the driving cycle, the power unit of hybrid vehicles can be switched on and off at any point during the cycle. The effect on emissions are clear when nothing is done to incorporate cooling down of the engine and catalyst. If this behaviour is to be taken into account, again propulsion systems can only be fairly compared on the basis of a representative driving cycle. In this respect, representatively also refers to the length of the driving cycle.

Hybrid vehicles have not yet been tested extensively, so only few data is available. The above described parameters of influence suggest that probably emissions and fuel consumption of a hybrid vehicle are less susceptible to driving cycle parameters than a conventional propulsion system. The other way around is also possible, as the configuration and control strategy of hybrids can be optimised for a specific application (e.g. urban driving), so that emissions and energy consumption may increase if the vehicle is driven over a cycle that is not representative of the vehicle's intended use. Thus, the need for a representative driving cycle remains, as measured data needs to be comparable.

In the following Chapters, the research on the behaviour of vehicles with alternative powertrains over different cycles and the influence on for instance energy consumption is presented.

4 Simulation results

Many simulations have been conducted to study the behaviour of vehicles with alternative drivelines over different cycles. Information on the vehicle models can be found in the Subtask 2.2 report. The main parameters are listed in Appendix B. In Subtask 2.4 many of those simulation results are used to investigate influences of ΔSOC on the determination of energy consumption and SOC behaviour. The same simulation results are used here to study the effect of different driving patterns on powertrain behaviour, energy consumption, and other related aspects. Several previously presented figures are represented here to determine and illustrate cycle related aspects.

4.1 SOC behaviour

LD Simulation 1

- *Model(s):* LD SHEV, CHEV, FCHEV
- *Simulation aspect:* SOC history over consecutive cycles
- *Parameter variation:* Driving cycle

The LD hybrid vehicle models were simulated over five consecutive driving cycles. During the simulations the battery's SOC was monitored. The initial and final value is shown in Figure 16.

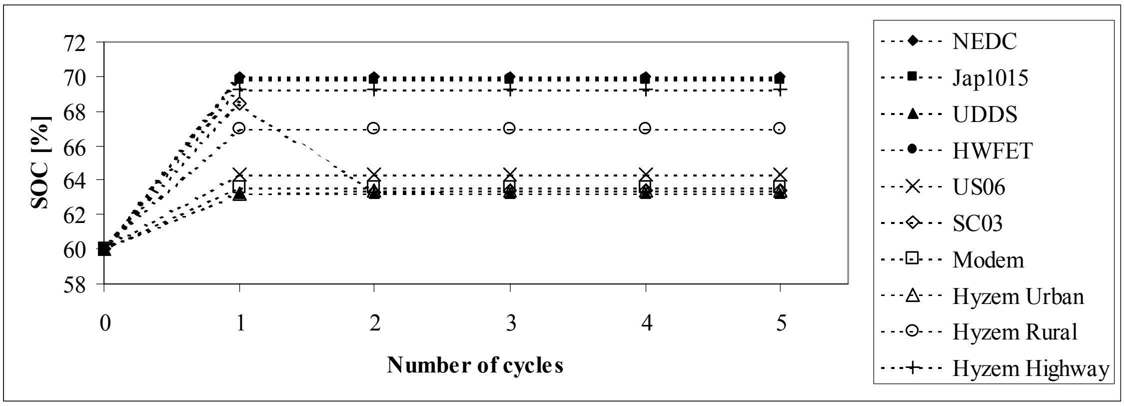


Figure 16: Influence of driving cycle; initial and final SOC for LD SHEV with APU 2 over 5 consecutive cycles

Within one or two cycles an equilibrium is reached, i.e. initial and final SOC are the same. Apparently some time is needed for the vehicle to adjust to the load pattern of the driving cycle. Despite the fact that on all cycles an equilibrium is reached, the influence of the driving cycle cannot be neglected. The SC03 cycle needs one additional cycle to come into balance. This is possibly the result of an 'unfavourable' initial SOC for this cycle, in combination with the short length and duration. It therefore cannot be excluded that these kind of results might also have been obtained on the other cycles, when those are started with a different SOC. Although simulations with different initial SOC have also been performed, the vehicle models (LD SHEV, CHEV, and FCHEV) with their current dimensioning did not give other results (Appendix C).

LD Simulation 2
- *Model(s):* PHEVfw, PHEVbat, SHEVfw, SHEVbat
- *Simulation aspect:* SOC history over consecutive cycles
- *Parameter variation:* Driving cycle

These models too were simulated over a number of different driving cycles. For all simulations started with the middle value for initial SOC, the initial and final values over a cycle are plotted. Figure 17 shows the result for the series hybrid vehicle model with a flywheel. For the other models the graphs are included in Appendix C.

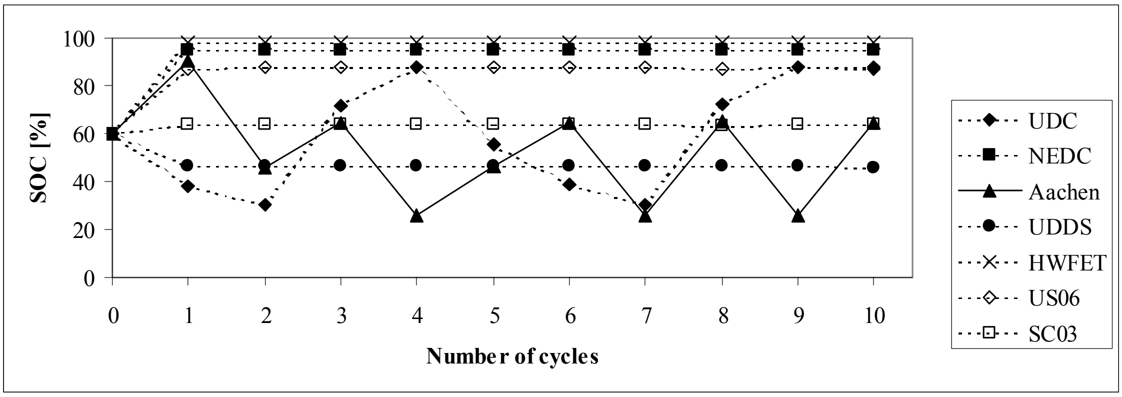


Figure 17: Influence of driving cycle; initial and final SOC for 'SHEVfw' model

Clearly, the State-of-Charge does not settle into a single cycle period for all driving cycles. This is especially valid for the 'short' cycles (UDC and Aachen city). The SOC does settle into periodic behaviour after several cycles have been driven though, as can plainly be seen for the Aachen city driving cycle. On this cycle, the SOC period is two driving cycles, while it is one for several of the other speed patterns. For the other models, the same kind of behaviour is found. The models with battery show that a SOC period of a (large) number of cycles can be the result.

4.2 Energy consumption

LD Simulation 1
- *Model(s):* LD BEV, SHEV, CHEV, FCEV, FCHEV
- *Simulation aspect:* Energy consumption
- *Parameter variation:* Driving cycle

The energy consumption over all driving cycles is derived from the simulation results. Since different vehicle types are investigated, the energy consumption instead of fuel consumption is calculated (for obvious reasons of comparison). The BEV consumes electrical energy only. Its energy consumption is derived from the change of State-of-Charge over the cycle with respect to nominal maximum energy content (max kWh on the basis of nominal capacity and voltage). The efficiency of a charging device or that of a power plant thus are not included. For the (charge sustaining) hybrid vehicles the energy consumption is calculated from the fuel (gasoline) used over the cycle. When necessary, ΔSOC correction is applied by means of linear regression (ΔSOC correction methods are discussed in the Subtask 2.4 report). The energy consumption of the FCEV is measured much like a conventional vehicle, since this vehicle also uses fuel (Hydrogen) only.

For each driving cycle the energy consumption figures for each vehicle are shown in Figure 18. It might seem very inviting to rank the different vehicles mutually. On the basis of the figures in Figure 18, this however is not allowed, because vehicle models are not validated and the energy consumption is calculated at the vehicle level (for EVs the emissions are produced at the power plant). Figure 18 is used to illustrate the differences between cycles, and only generally between vehicles.

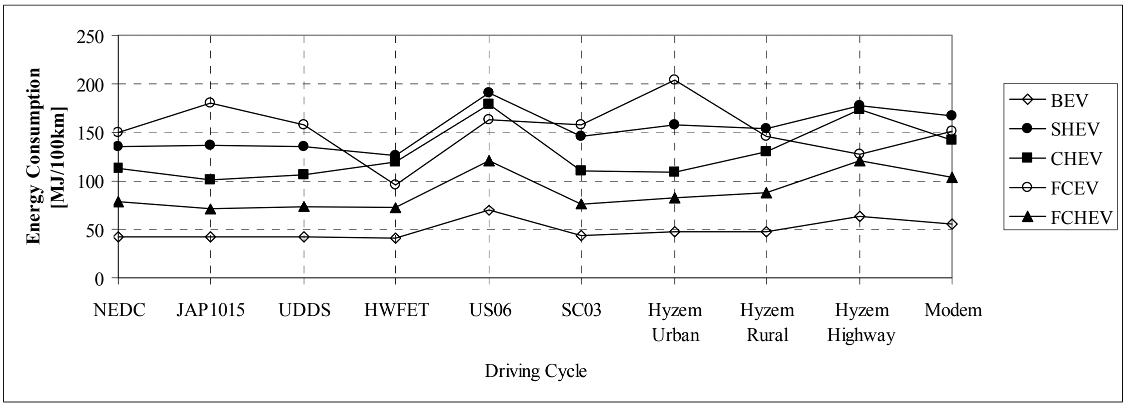


Figure 18: Energy consumption for the LD vehicle models over different driving cycles

Considering all cycles, it is clear that the cycle has profound influence on the energy consumption of a vehicle. This is no surprise, as different cycles will also have differing energy requirements per kilometre. Comparing the energy consumption patterns for the different vehicles on each of the simulated cycles, several things in Figure 18 attract attention:

- In general, quite similar behaviour is found for most drivelines. "Ups and downs" are found for the same sequences of types of driving cycles (e.g. for HWFET-US06-SC03, which show a rise followed by a decrease of the energy consumption).
- However, the driveline behaviour still is cycle dependent. For one driveline the energy consumption increases, while a decrease can be found for another powertrain. As an example, the energy consumption of the SHEV and CHEV over the HWFET (with respect to the UDDS) is looked at. The response of drivelines on a driving pattern thus is dependent on the specific configuration (structure and dimensioning).
- Even more, completely different behaviour can appear, and as a result mutual ranking of the drivelines varies. The FCEV gives the proof, that entirely different results are possible. This vehicle seems to give strongly deviating "random" values. An explanation can be found by comparing the FCEV and FCHEV, as the first is a pure fuel cell electric vehicle and the second a fuel cell hybrid electric vehicle. The operating strategy for the fuel cell in both vehicles is different. In the FCHEV the fuel cell mainly operates stationary at its highest efficiency and sometimes at its maximum power output, while the battery is used to absorb or provide peak powers. In the FCEV, however, the fuel cell power output is directly related to the road-load and consequently is operated transiently over its entire power range. Figure 19 shows the efficiency curve for the applied fuel cell system. Especially for low powers (less than 10% of the maximum fuel cell power) small differences in operating points already give distinctly different efficiencies. In case of the FCEV, equipped with a 90 kW fuel cell system, the power output during the cycles lies at low powers, causing differences between cycles to be clearly visible.

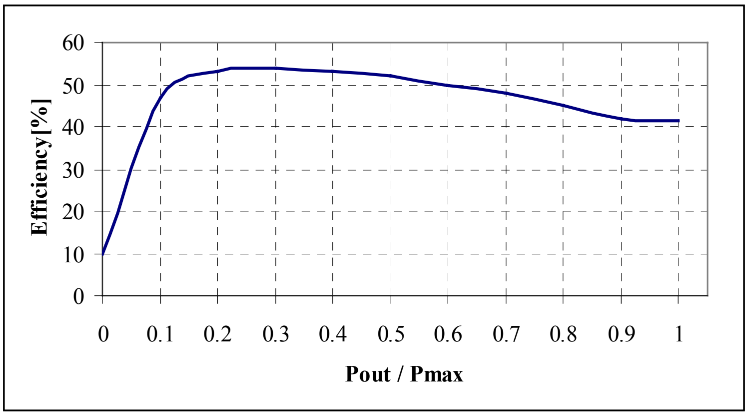


Figure 19: Fuel Cell system efficiency curve

It has been remarked before that each cycle has a different load pattern and consequently has a different energy requirement at the wheels. To demonstrate this, the energy consumption is plotted versus the propulsion energy at the wheels for these vehicle models (Figure 20), as well as versus the average (cycle) speed and RPA (Figure 21 for BEV, Appendix C for other models). Since all vehicles have exactly the same mass and resistance factor, the energy at the wheels for a specific cycle is also the same. The energy consumption can vary, because of the differences in efficiency of components and energy distribution from the source to the wheel.

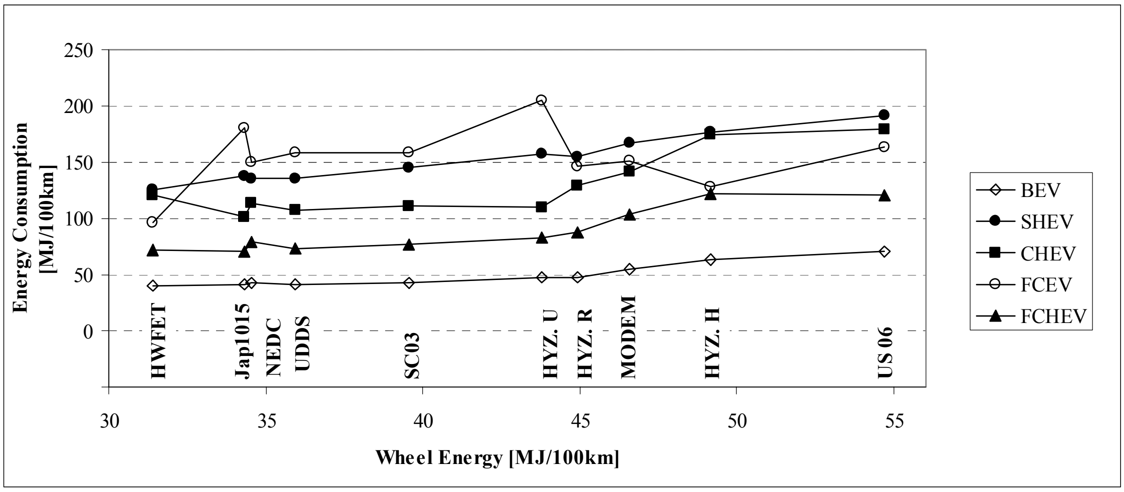
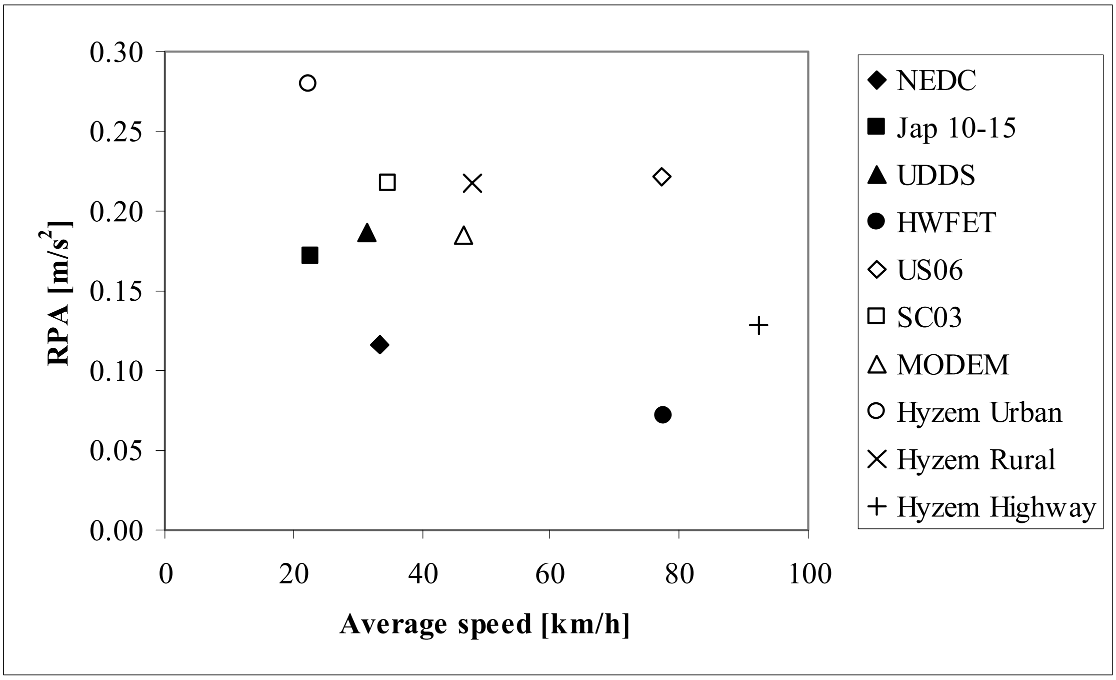


Figure 20: Energy consumption versus wheel energy for five driveline models

The general trend that can be read from Figure 20 is that more demanding driving cycles also give higher energy consumption figures. These two parameters however do not necessarily have a linear relationship, as can be seen in the top figure. The mutual ranking strongly fluctuates. The FCEV again shows strongly varying results, which can be explained with the same arguments as before.
The stable energy consumption of the BEV is in contrast with the changes of the FCEV energy consumption. With increasing energy requirement, energy consumption also increases in an almost linear way. The battery power is also directly dependent on the road load, just as the fuel cell power. The reason for the differences between these two drivelines is probably caused by the fact that the (large) battery has an efficiency that is almost independent of the power output. The increasing energy consumption does indicate that (battery) losses are higher in more demanding cycles, yet the overall battery efficiency is less sensitive to changes in power demand than the efficiency of the fuel cell.



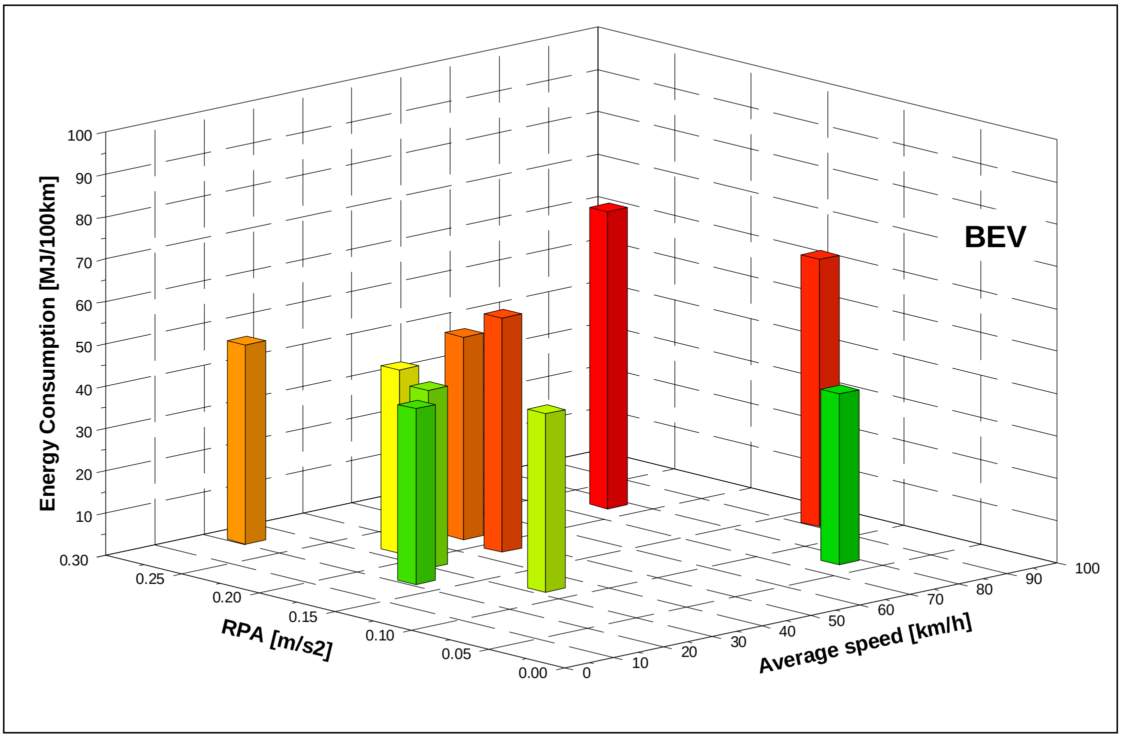


Figure 21: Energy consumption for BEV versus RPA and average speed

In Section 2.5 and Appendix A, it was already stated that driving cycles can be characterised by several parameters. Two important parameters are the average speed and RPA, which were already used to create Figure 12. For the LD BEV, the energy consumption is shown as function of the driving cycles' RPA and average speed. More demanding cycles (higher average speed and/or RPA) consume more energy than cycles with low average speed or RPA.

To give a more detailed explanation for the energy consumption of the drivelines relative to each other is irrelevant at this point. The occurring differences can be the result of many distinctions in the models, such as dimensioning and efficiencies of components, as well as the control strategy which has a profound influence on the vehicle behaviour. Only the *behaviour* of drivelines relative to each other is of interest, e.g. the awareness that small changes in demanded energy at the wheels may have different effects on energy consumption.

Main conclusion from these simulation is that different types of driving cycle also differently effect the energy consumption of alternatively powered vehicles. It therefore is necessary that a cycle is used which is most representative for the actual usage.

LD Simulation 2

- *Model(s):* PHEVfw, PHEVbat, SHEVfw, SHEVbat
- *Simulation aspect:* Energy consumption
- *Parameter variation:* Driving cycle

The energy consumption for these four hybrid vehicles is calculated from all simulation results by using the regression method to correct ΔSOC. Again it is stressed that the mutual vehicle ranking is not the essence of this exercise. What is of importance are the general differences in driveline behaviour and the influence of those differences on the energy consumption (Figure 22) and emissions (not in the simulations).

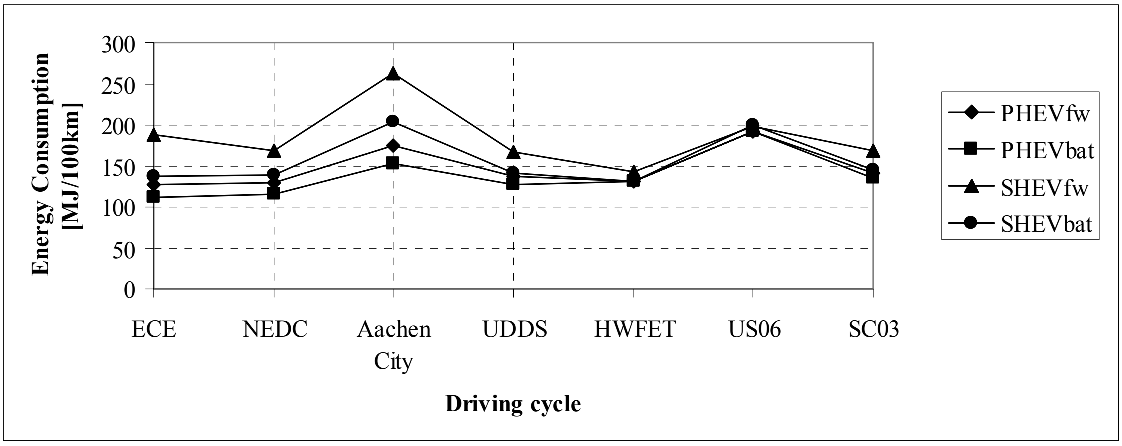


Figure 22: Energy consumption for four LD hybrid vehicles over 7 different driving cycles

The conclusions that were drawn on the basis of the results for 'LD Simulation 1' are generally valid here too. Quite similar behaviour is found for the drivelines. The size of changes in energy consumption due to different driving cycle characteristics depends on the driveline. The series hybrid with flywheel, for instance, shows larger sensitivity for changes than the other powertrains.

Anyhow, the fact that the used cycle has a major influence on the energy consumption, and therefore also on the emissions, emphasises the need for a driving cycle (or several driving cycles) which represent the actual use of a vehicle in real-life.

5 Vehicle measurements

In the MATADOR project measurements on several vehicles have been performed. Unfortunately, only a limited number of (hybrid) electric vehicles is available. This chapter discusses the results of the tests of vehicles over several driving cycles. Where possible the test results are compared to the simulation results to show their correlation.

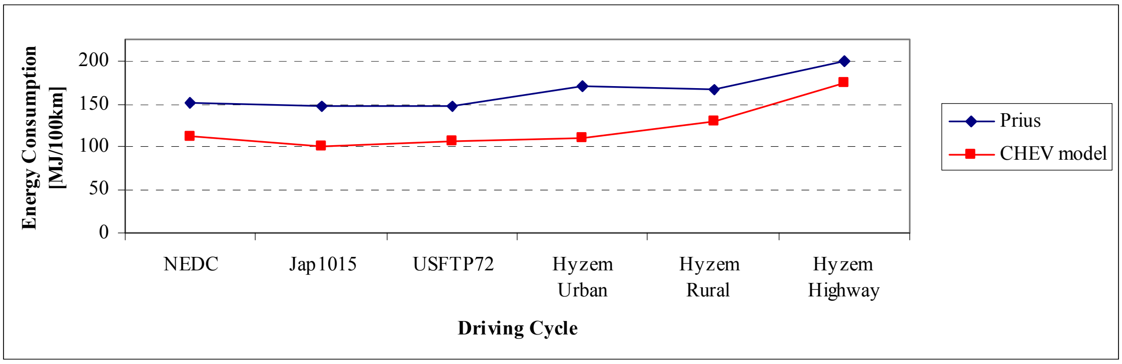
5.1 Toyota Prius

In the Subtask 2.4 report, measurements on a Toyota Prius (Figure 23) combined hybrid electric vehicle (hot cycle average results are listed in Table 2) were used to investigate ΔSOC correction methods. The same measurements are now used to discuss the influence of different driving cycles on an existing hybrid electric vehicle. In Figure 24 the emissions and energy consumption of the tested Toyota Prius (Japanese version) are shown for several driving cycles. The HC emissions have not been plotted since the measurement resolution was not high enough to give distinct information (no differences were found). More information on the vehicle and the tests can be found in Appendix D.

Figure 23: Toyota Prius on the rollerbench at TNO

Table 2: Emission and fuel consumption of a Toyota Prius over several driving cycles

Average hot cycles	HC g/km	CO g/km	CO_2 g/km	NO_x g/km	FC l/100km
NEDC	0.01	0.034	112.7	0.043	4.71
Japanese 10-15	0.01	0.043	109.7	0.030	4.58
USFTP72	0.01	0.057	109.7	0.050	4.58
Hyzem Urban	0.01	0.072	128.5	0.123	5.37
Hyzem Rural	0.01	0.131	123.4	0.135	5.16
Hyzem Highway	0.01	0.161	147.7	0.200	6.17



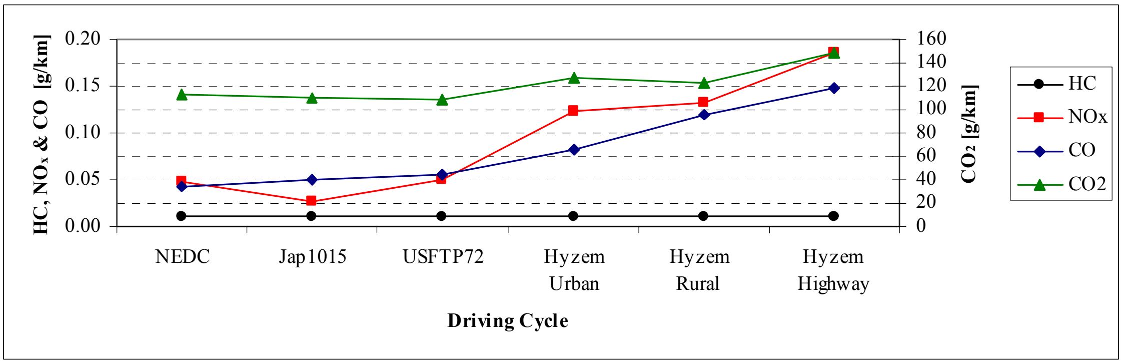


Figure 24: Energy consumption and emissions of a Toyota Prius on different driving cycles

The general trend in energy (fuel) consumption is the same as was already found in the simulations. With increasing energy requirement at the wheels, the overall energy consumption of the vehicle also rises. Both the vehicle and the combined HEV model show quite similar results (keep in mind that only the patterns can be compared due to differences between the vehicle and the model, e.g. engine map, control strategy, simplifications, etcetera). The strong correlation between energy consumption and CO_2 emission here again is clearly visible due to the low influence of the other emissions components in the carbon balance method.
The influence of a more demanding cycle can also be distinguished in the other emission parameters. Here too, higher amounts are found with increasing energy requirement. To what extent a change appears, however, is dependent on the specific component. The CO emissions, for instance, show a larger increase than the NO_x, when looking at the Hyzem Urban and Rural driving cycles. This, however, is the other way around, when looking at the USFTP72 and Hyzem Urban cycle.

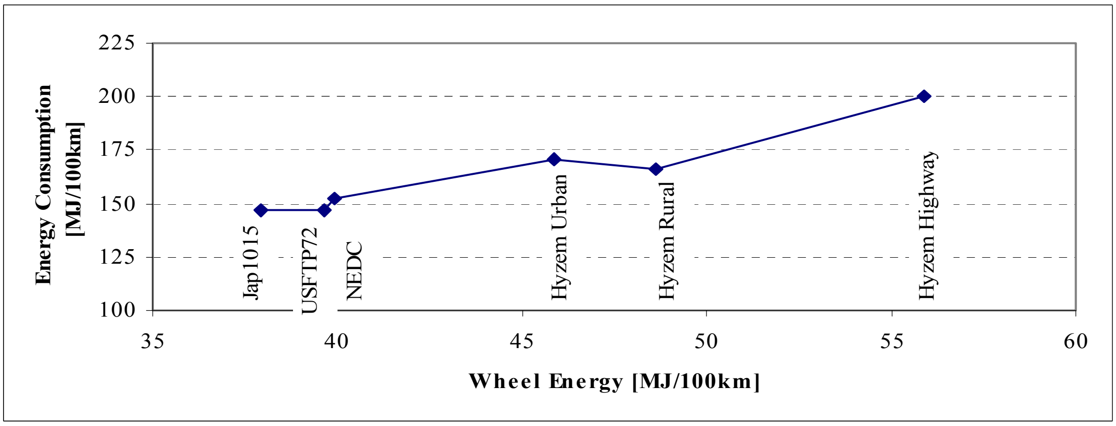


Figure 25: Energy consumption versus Wheel Energy for a Toyota Prius on six cycles

Plotting of the energy consumption versus the required wheel energy results in Figure 25. Again it is apparent that higher energy requirements in general result in higher energy consumption. The simulations already showed that a linear relation between wheel energy end energy consumption is not necessarily present. The results of the tested Toyota Prius also show that the energy consumption is dependent on the specific cycle. Each cycle calls for its own operating conditions, causing the entire system to run in high efficiency operating points or in less efficient points. This is therefore highly dependent on the tested driveline and its components. A differently dimensioned driveline might have shown ever increasing energy consumption with higher wheel energy requirement or more fluctuating behaviour. The general trend (increase with higher demands), however, stays valid.

Another way of representing the demands of the driving cycle, is using the RPA and average speed. The results are shown in Figure 26. With higher average speed or higher RPA (increasing demand of the cycle), the energy consumption is higher.

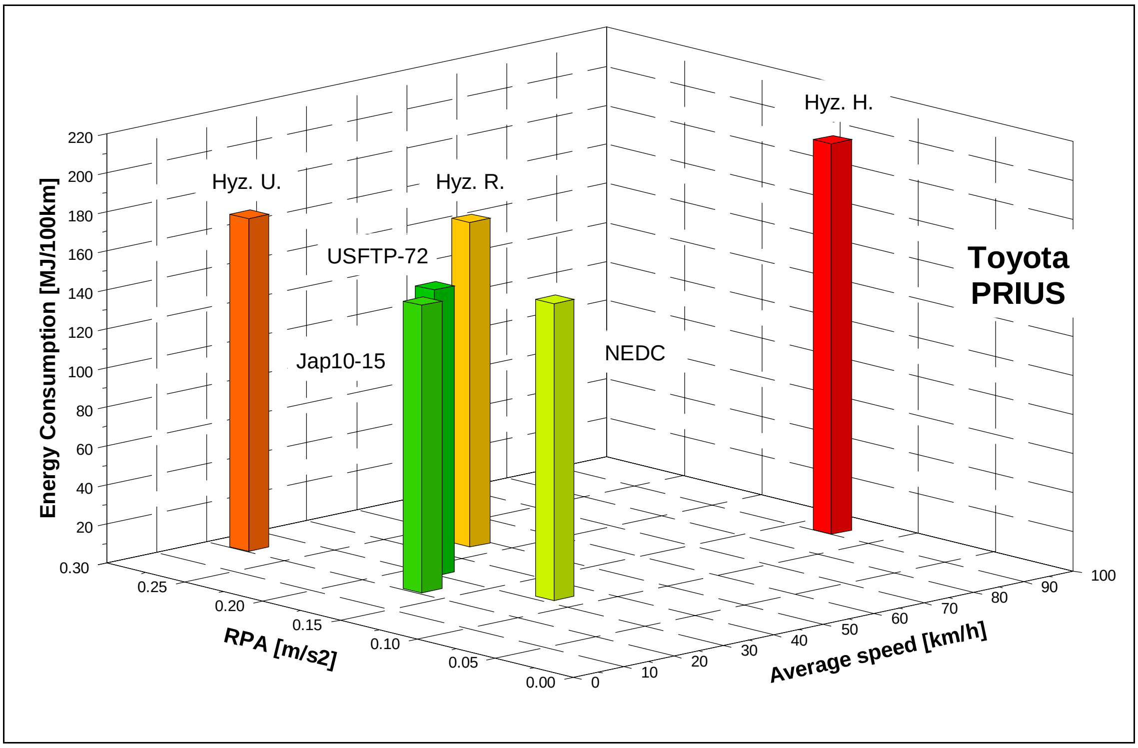


Figure 26: Toyota Prius' energy consumption vs. RPA and average speed for 6 different driving cycles

5.2 Renault Express Electrique

The Renault Express Electrique (Figure 27) is equipped with a battery electric driveline. The vehicle was driven over 6 different driving cycles, three legislative cycles and three real-life cycles. For each cycle the energy consumption was determined. The tests were performed according to the European standard procedure EN1986-1 [5]. More information on the vehicle and the measurements can be found in Appendix E.

Figure 27: Renault Express Electrique on the IAE dynamometer

Table 3 lists and Figure 28 shows the energy consumption of the Renault Express Electrique over six different driving cycles. The energy consumption has been determined at two levels; at the battery (in/out) and at the grid (charger). The difference between both levels is caused by the charger efficiency and the battery losses due to the internal resistance (more demanding cycles result in higher internal losses). The actual energy consumption of the vehicle is measured at the grid, since charging to its initial State-of-Charge is the only possibility to account for the ΔSOC over the cycle.

Table 3: Energy consumption at grid and battery level

	Energy Consumption [MJ/100km]	
	battery	**grid**
NEDC	57.6	126
Jap1015	46.8	90
USFTP75	57.6	108
Hyzem Urban	57.6	118.8
Hyzem Rural	68.4	126
Hyzem Highway	82.8	158.4

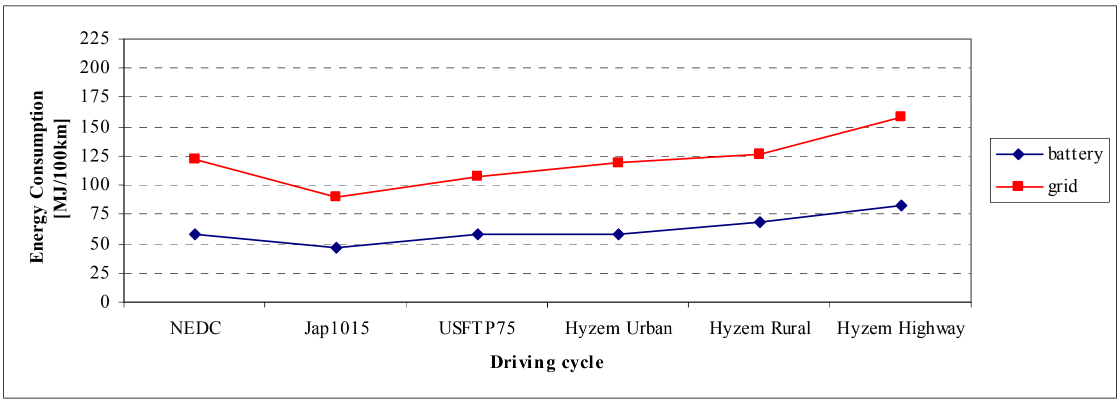


Figure 28: Energy consumption of a Renault Express Electrique over 6 different cycles

Comparison of the Express' and Prius' results shows that the Express in absolute figures is more energy efficient than the Prius (Figure 24). The vehicle mass, which has a large influence on the energy consumption, is quite similar for both vehicles. On the basis of mass, large differences in energy consumption were not to be expected. It has to be kept in mind that the Express' energy consumption is derived from the used electricity from the grid, whereas the Prius' energy consumption is calculated from the fuel consumption. As is explained in the Subtask 2.6 report "*Comparing electricity and fuel consumption*", the energy carriers electricity and fuel cannot simply be balanced. For a more honest comparison, the power plant efficiency for instance should also be included. As a result the ranking of (these) electric and hybrid vehicles can change.
What is more interesting, and not entirely unexpected, is that both vehicles show quite similar response to the driving cycle characteristics, yet not to the same extent. More demanding cycles, in both cases, request more energy. This can also be seen in Figure 29, in which the energy consumption of the Express is plotted as function of RPA and average speed.

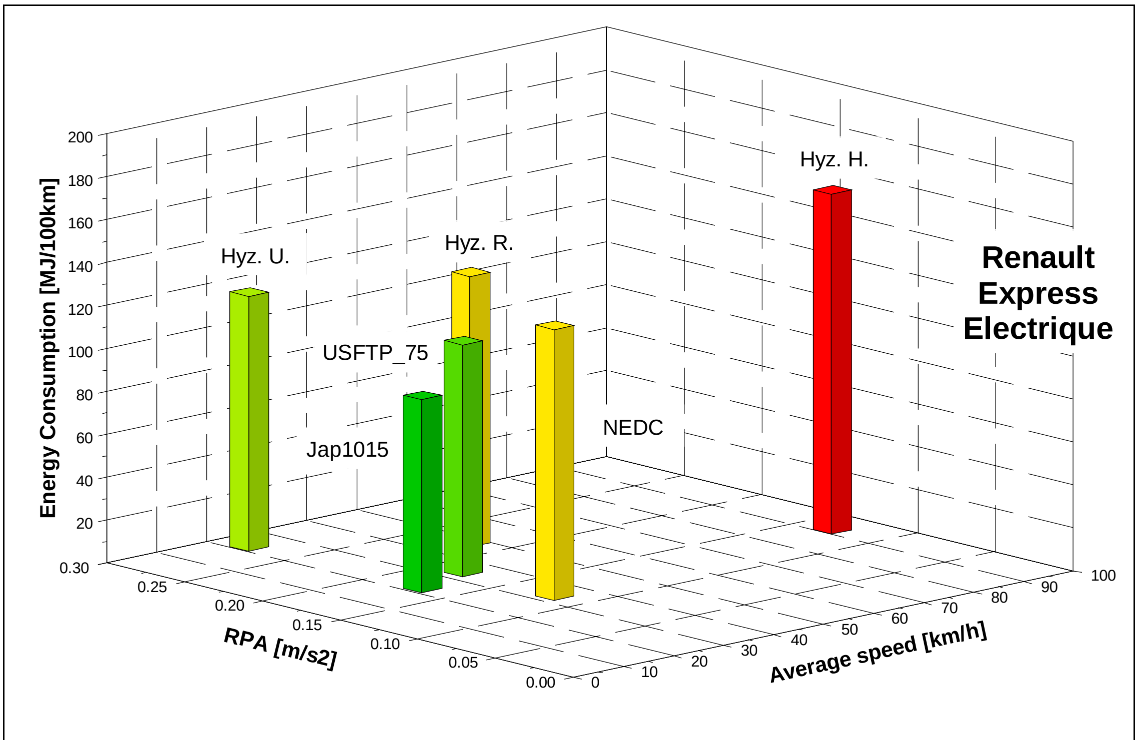


Figure 29: Renault Express Electrique's energy consumption vs. RPA and average speed for 6 different driving cycles

5.3 ALTROBUS

The ALTROBUS (Figure 30) is equipped with a series hybrid electric driveline. The tested vehicle was especially built for experimental purposes. The APU, consisting of a diesel engine and a Permanent Magnet generator, can only operate in one operating point. More information on the vehicle can be found in Appendix F.

Figure 30: ALTROBUS on the ENEA dynamic rollerbench

The ALTROBUS was tested by ENEA (Italy). The vehicle is evaluated over six different driving cycles, which are related to those used for the Toyota Prius and Renault Express Electrique. Due to the maximum speed limitation, only urban parts (speeds up to approximately 50 km/h) were driven. As a result, the ALTROBUS results cannot be compared to those of the other vehicles and only a qualitative consideration is made.

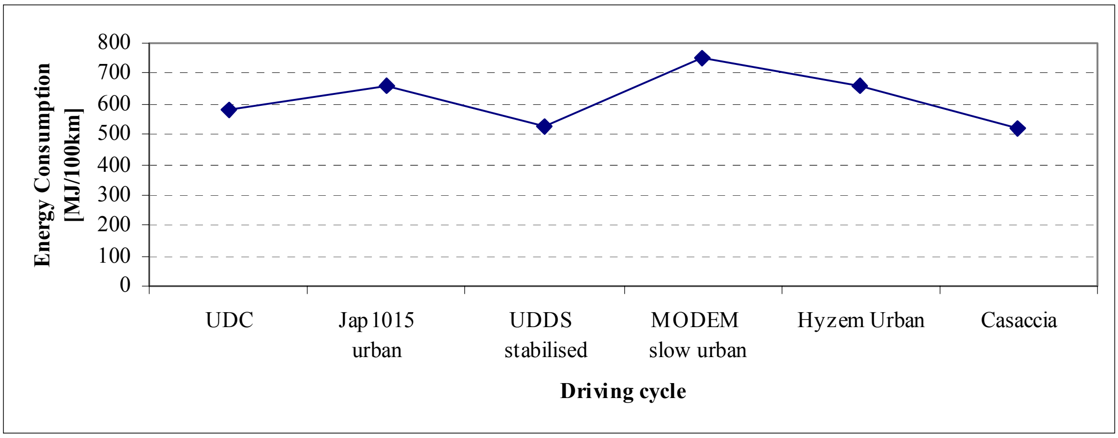


Figure 31: Energy Consumption of ALTROBUS over several urban cycles

Figure 31 shows the energy consumption over the different cycles. These values have been obtained by applying the linear regression method to the measurement results in order to correct for ΔSOC over the cycle. Not unexpected, different values are found for each cycle. The test results clearly show that the applied driving cycle is of major importance to the environmental performance of a vehicle. The energy consumption on the MODEM cycle is approximately 50% higher than that on the UDDS cycle. These differences show that vehicles cannot be compared without a representative test.

6 Conclusion and Recommendations

An important focus of the research in the MATADOR Task 2 project has been driving cycles. The characteristics of a driving cycle (average power, dynamics, etc.) strongly influence the energy use and emissions and also influence the results of comparisons between vehicles with different propulsion systems. In this report, the influence of driving cycle characteristics on (electric and hybrid) driveline behaviour and environmental performances is evaluated by means of computer simulation and vehicle measurements.

Existing driving cycles

At this moment, a large number of different driving cycles is available for LD vehicles. Several of these are used for legislative testing, while others have been derived from recorded driving patterns and are used for R&D purposes.

The three basic legislations covering the testing of light-duty road vehicles use the following driving cycles:

Europe (West and East, as well as some countries outside Europe)

- New European Driving Cycle (NEDC)

United States (and Canada, several South American and many Asian countries)

- City Cycle (USFTP-75)
- Highway Cycle (HWFET)
- SC03 Air Conditioning Cycle (from January 2000)
- US06 High Speed/High Load Cycle (from January 2000)

Japan

- 11 Mode Cold Cycle
- 10-15 Mode Hot Cycle

Besides these cycles, many institutes, organisations, and universities develop and apply driving cycles from recorded driving patterns that are to represent real-life driving conditions. Examples of these cycles are:

- MODEM
- HYZEM Urban, Rural, and Highway
- Aachen City Cycle
- Casaccia Cycle

The first two cycles are the result of an extensive research on European driving behaviour, conducted by the French research institute INRETS.

All of these driving cycles have different characteristics. In Appendix A of Subtask 2.8, background information and methodology for the development and characterisation of driving cycles is presented. Two of the parameters that can be used to characterise the demands of a driving cycle are the average speed and the Relative-Positive-Acceleration (RPA – m/s^2), which is an indication for the dynamics of a cycle. Research on HD vehicles shows that these parameters have strong correlation with the energy consumption of the vehicles [2]. With increase of these values the wheel energy demands will also be higher. By putting these parameters in one graph, the mutual relation between cycles can be indicated (Figure 32).

Differences between cycles are clearly visible here and most remarkable is that the older legislative cycles (black markers) are less demanding than the more recently developed speed profiles of the MODEM and HYZEM cycles. This indicates that the (modal) standard cycles, especially in Europe and Japan, bear relatively little resemblance to the conditions of actual vehicle use.

This issue of representativity is also under discussion for testing of conventional ICE-vehicles, as results from standard tests are not only used for technical evaluation and homologation procedures but also for e.g. the calculation of energy consumption and emission factors used in policy studies or for policy measures stimulating clean and efficient vehicles. For vehicles with electric and hybrid power trains the problem is even more pressing as vehicles can be designed and optimised for very specific purposes and, therefore, may perform completely different on different driving cycles.

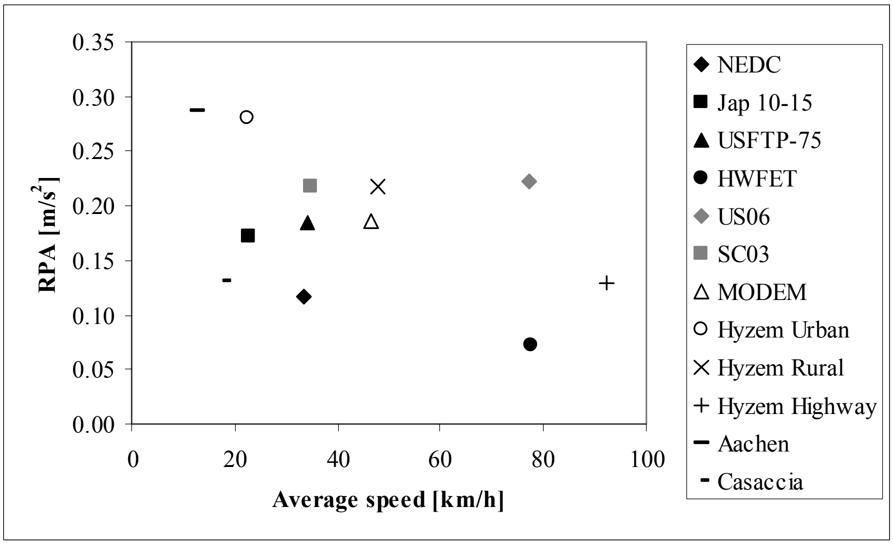


Figure 32: RPA versus Average speed for several driving cycles

Influence of the driving cycle on driveline behaviour and energy consumption

Light-Duty vehicle technologies are compared and evaluated on the basis of the measurement results over driving cycles. It is known that the driving cycle characteristics influence the environmental performance (energy consumption and emissions) of a vehicle. In the past, vehicle and driveline technologies were quite similar, so that the effect was the same for all vehicles. This will change with the introduction of alternatively powered vehicles. In order to make a consistent comparison of technologies, it is necessary that a reliable and representative basis for comparison is available. The research of this subtask concentrates on studying this aspect of driving cycles by means of computer simulation and vehicle measurements.

SOC behaviour

In simulations it is found that the general driveline behaviour shows similarities in the response to different driving cycles. Most important parameter here is the State-of-Charge of a storage system in a hybrid vehicle which will (eventually) show to have periodic behaviour. As an example the result of simulations of a Series Hybrid Electric vehicle are presented in Figure 33. In practise, this SOC behaviour might not be found due to the fact that a human driver is not capable of driving several driving cycles in exactly the same way. The stimulus posed upon the driveline system then is not as nicely periodic as in the simulations, and the system cannot adjust and settle for periodic behaviour. Furthermore, the real-life control might significantly influence the system's response, since the powertrains are highly complex and encompass many more system limits than the computer models (for example the influence of temperature on engine operation).

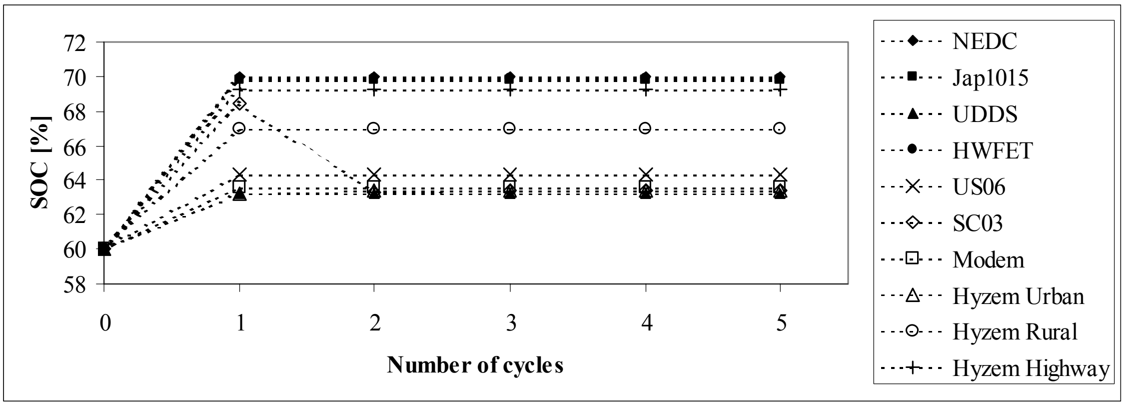


Figure 33: Influence of driving cycle; initial and final SOC for LD SHEV over 5 consecutive cycles

Energy consumption

Once the effect of ΔSOC (Subtask 2.4) is accounted for, the actual energy consumption of a vehicle is determined and a comparison of different drivelines over different driving cycles can be made.

In one of the simulations, five vehicle models were evaluated over the ten driving cycles listed in Figure 33. The energy consumption for these five models is plotted in Figure 34. The influence of different driving cycles is plainly visible. Each cycle results in a different value for the energy consumption and each driveline responds according to its own specific characteristics.

Important note for all results obtained from the simulations is that the figures are not meant to rank different driveline systems mutually, yet only to illustrate the differences between cycles. None of the models has been validated to the extent that energy consumption can be considered as a meaningful prediction of the actual consumption of a real vehicle. The models do, however, contain all the essential physics so that the response to changing test conditions is adequately simulated. Also due to the different energy sources (electricity, petrol, hydrogen), the figures do not provide an honest and consistent basis for comparison.

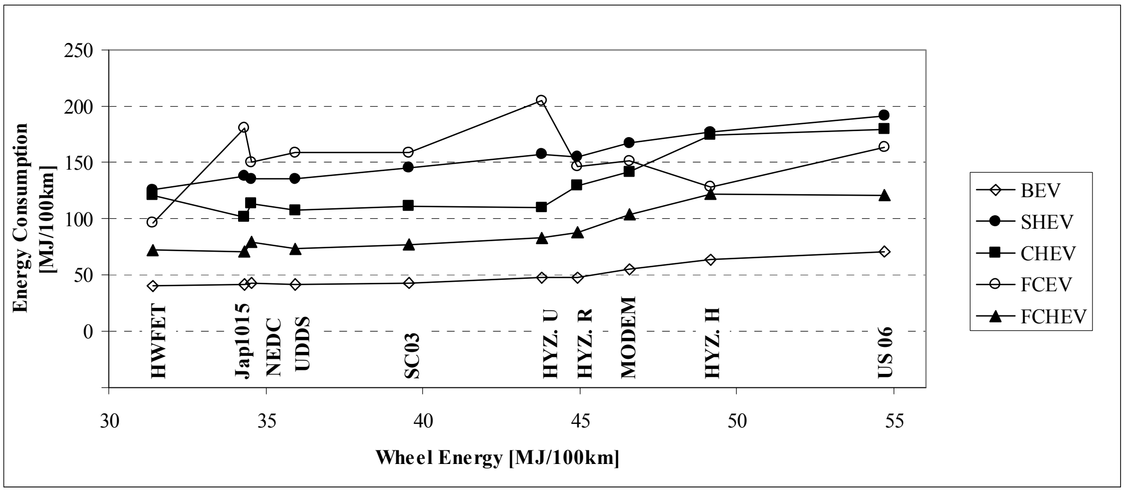


Figure 34: Energy consumption for the LD vehicle models over different driving cycles (ranked for wheel energy demand)

Figure 34 provides information on the relation between the energy demand at the wheels on a certain driving cycle and the energy consumption of those vehicles. The required energy at the wheels, however, depends on several vehicle parameters (amongst others mass, air resistance, etc.) and cannot be measured in practise. The parameters 'RPA' and 'Average speed' are representative for the cycle demands. In Figure 35, the energy consumption of the BEV model and that of a Toyota Prius are plotted for several cycles as function of these two parameters (mind the different Z-scales). These figures are just examples of all the results. In the Appendices, similar figures for other simulations and measurements can be found.

Figure 35 clearly shows that increase of RPA and/or Average speed results in a higher energy consumption. Both in the simulations and the measurements, only one trend is found and this leads to the following conclusions:

1. More demanding cycles generally require more energy. It is possible, though, that with increasing demands at the wheels the overall driveline efficiency increases to such an extent that the energy consumption decreases (the relation between energy consumption and wheel energy then would be parabolic).
2. The influence of different driving cycle characteristics is different for different drivelines.
3. A representative test value (for honest ranking) consequently can only be found when a representative cycle is used.

The introduction of dedicated purpose designed Light-Duty vehicles seems to require that the test enables to account for this specific use. Just like in the current European procedure, it might be necessary to define several cycles (e.g. urban and extra-urban, or urban, rural, and highway patterns) in order to obtain results that represent the actual vehicle use.

The above considerations lead to one main overall conclusion:
In order to enable a consistent comparison, it is essential (maybe even crucial) to use a driving cycle that is representative for the real-life operating conditions of a vehicle. Representativity of the driving cycle implies that the time-speed profile not only has representative average dynamics. It also requires that the cycle has a representative mix of road types (urban, rural, highway) and that the cycle has representative length. This assures a representative weighting of e.g. the steep acceleration and deceleration associated with the highway part of the cycle, and it may also help to solve problems that are more specific to vehicles with advanced propulsion systems.

Recommendation

In order to get more insight into all related aspects in testing (advanced) vehicles, it is highly recommended that more measurements are conducted on vehicles with different hybrid or other alternative powertrains. Especially the influence of driving cycle characteristics on the exhaust emissions still has to be determined. Due to the very limited availability of hybrid vehicles, it has not yet been possible to investigate this. It is expected that the differences between drivelines will show even more clearly in the emission results than that they already do in the energy consumption figures.

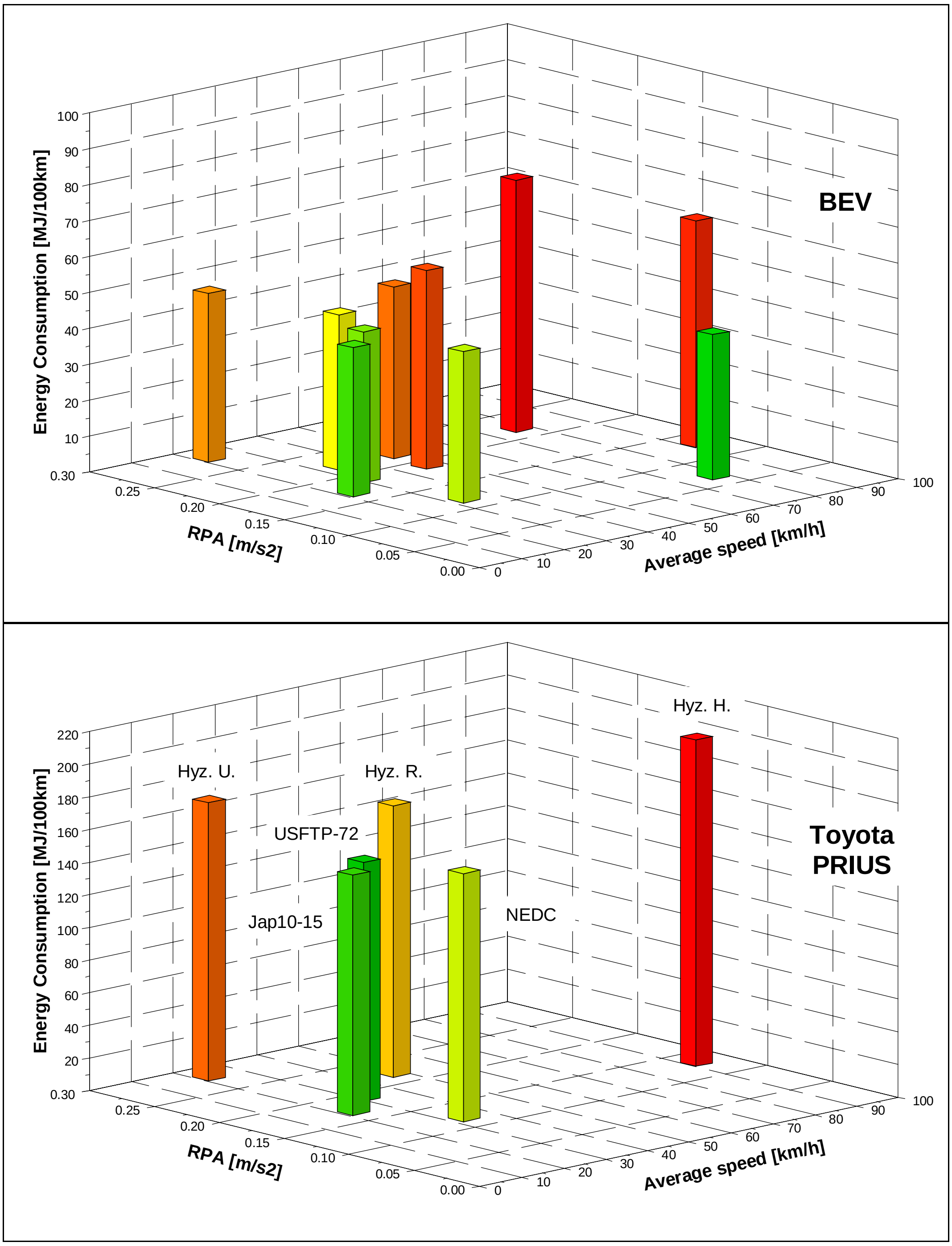


Figure 35: Energy consumption for BEV and Toyota Prius vs. RPA and Average speed

References

[1] Joumard R., A.J. Hickman, J. Nemerlin and D. Hassel, "Modelling of emissions and consumption in urban areas", Final report. Deliverable 12 of the DRIVE project - modem / Modelling of emissions and consumption in urban areas, LEN 9213 report, INRETS, Bron, France, 54p, 1992.

[2] Weijer, C.J.T. van de, "Heavy-Duty Emission Factors - Development of Representative Driving Cycles and Prediction of Emissions in Real-Life", PhD-thesis, Graz University of Technology, October 1997.

[3] Weijer, C.J.T. van de, Graaf, R. van der (1993) "Urban Bus Driving Cycle", Proceedings 4th International EAEC Conference, 16-18 June, 1993, Strasbourg, page 513-528.

[4] André, M. "European Development of Hybrid Technology approaching efficient Zero Emission Mobility (HYZEM), Driving patterns analysis and driving cycles", LEN 9709 report, INRETS, Bron, France, 62p, 1997.

[5] EN1986-1: Electrically propelled road vehicles – Measurement of energy performances; Part 1: Pure electric vehicles, 1997

Appendix A Theoretical background on driving cycles

Any comparison of different vehicles with regard to their real-life performance has to be based on a certain load pattern. As the primary purpose of most vehicles is driving, vehicle speed can in practice be considered as the principal factor in the determination of the vehicle and engine load. Therefore, standardised driving cycles are developed. This chapter provides the theoretical background for the assessment and the development of driving cycles. A driving cycle is defined as a time-speed sequence designated for a certain type of vehicle and designed to represent a driving pattern in a particular environment. Because in practice no two vehicles are subjected to the same driving pattern, it is inherently impossible to make a waterproof standardised driving cycle for all vehicles. For different purposes, however, it is necessary to have some form of a standardised, sufficiently representative driving cycle. These purposes are listed in paragraph A1, which also shows that the criteria for a certain driving cycle highly depend on the purpose. In order to make cycle-analysis possible or to develop a representative driving cycle, one should know which influences make a certain cycle look as it does (paragraph A2), and which parameters can be used to characterise a driving cycle (paragraph A3).
More information on this subject can be found in [2].

A1 Purposes and criteria

Because the criteria for a certain driving cycle differ much depending on the purpose, the first question when choosing or developing a cycle is why it is needed and what it is going to be used for. The most important purposes for the use of driving cycles are:

1. *Approval test*
   Government agencies set limits on health-endangering and environmentally harmful elements in exhaust gases. For this purpose it is necessary to express these limits, based upon the emissions produced on a certain cycle.
2. *In-use compliance*
   Interest in the effect of engine life on vehicle emissions has led to a need to test vehicles over their life-time. Several in-use compliance test programs for vehicles were started, amongst others in the Netherlands, in Germany, in Sweden and in the USA.
3. *Troubleshooting faulty or maladjusted vehicles*
   In practice some simplified cycles are used for engine check-ups. These cycles usually consist of some stationary load points and a free acceleration test in order to test the most important engine functions. In practice these tests are carried out as an engine load cycle rather than a speed pattern.
4. *Designing vehicles and components for a certain application*
   For the development of a vehicle, all components must be designed in such a way that the vehicle performs well in all situations in future use. Average representative cycles are needed to calculate for instance the required fuel tank capacity in order to attain a specified range or auxiliary power unit demand for hybrid vehicles. For this purpose besides average cycles, also "worst case" cycles are of importance, representing the most severe load that the vehicle could be submitted to in practice.
5. *Technology assessments*
   The effects of the application of different fuels and technologies can differ much from one cycle to another (Chapter 0). For this purpose a representative cycle is needed that leads to an honest ranking of the different technologies for specific applications. With the growing use of simulation models for the comparison of different technologies the need for realistic driving cycles increases. In practice it can be seen that despite the accurately simulated components, the driving cycle is often disregarded.

6. *Producing absolute emission factors*
   In a growing number of cases the emission and fuel consumption results of a certain cycle test are needed in absolute units, e.g. for assessing overall environmental impacts and for monitoring the effects of environmental policy. For this purpose emission factors are needed that are based upon a representative driving cycle.

Depending on the purpose, standardised legislative driving cycles should more or less fulfil the following seven criteria which can be roughly divided into two categories.

I. Criteria of representativity:

1. The basic characteristics, composition of modes, and gear usage should be consistent with the average corresponding values gathered during in-use vehicle operation.
2. The cycle should match emissions and fuel consumption in relative terms, which leads to an honest ranking of different technologies.
3. The cycle should match the actual observed driving patterns in terms of mass emissions and fuel consumption in absolute terms.
4. The possibility for optimising the emissions and/or fuel consumption for a certain cycle ("cycle bypassing") should be prevented.

II. Criteria of reproducibility and measurability

5. The cycle should be as simple as possible, easy to perform and reproducible. Costs for equipment and for testing should not be too high.
6. All (or most) tested vehicles should be able to attain designated cycle speeds and acceleration rates (performance achievable by the vehicle).
7. The cycle performance must be achievable by the test equipment (limited braking rates on a roller bench test, achievable dynamics, et cetera).

The relation between the purpose of the cycle and the criteria is clarified in Table 4.

Table 4: Criteria for driving cycles in relation to their purpose

Criteria	Purposes	Approval tests	In-use compliance	Trouble shooting	Designing vehicles and components	Comparison of fuels and technologies	Project inventory & emission factors
I	1. Similar basic characteristics	+	+	+	+++	+	+
	2. Match f/c + e. in rel. terms (Ranking)	+++	++	++	++	+++	+++
	3. Match f/c + emissions in abs. terms	++	++	+	++	++	+++
	4. Prevention of cycle beating	+++	+++	+	++	++	+++
II	5. Simplicity and reproducibility	++	+++	+++	0	++ 0*	+
	6. Achievable performance (vehicle)	++	++	++	0	++ +*	+
	7. Achievable performance (equipment)	++	++	++	0	++ 0*	+

0: no interest
+++: high interest
*: in case of computer simulations

In practice, it appears not always possible nor necessary to find a driving cycle that meets the criteria of representativity as well as the criteria of measurability and reproducibility. In the early days of the passenger car emission legislation, the emphasis was laid on the criteria of measurability in combination with the CO-emission problem at that time, which resulted in less emphasis on representativity.

With the growing interest in the environmental impact of vehicle use, representativity has gained interest. The most important aspect for the need of representative driving cycles is the ranking of different vehicles or technologies. Even more than before, ranking that ensures from approval tests should provide a realistic picture of ranking in real-life. This gives legislation authorities the opportunity to better influence environmental pollution caused by vehicles. Although an honest ranking of different vehicles and technologies generates a good relative comparison, it does not imply that the data can be used as an input for emission factor models. For this purpose, not only the relative, but also the absolute level of the emissions should relate closely to real-life.

History shows that the results from approval tests will always be used to develop emission factors. This means that during the development of a driving cycle for approval tests, one should take the criteria for representativity into account, although the direct need for representativity is only modest. Moreover, if an approval driving cycle can really be regarded, in absolute sense, to be representative of real-life, the honest ranking of different engines and technologies, which ís of great importance for approval tests, can also be guaranteed.

A2 Influences on driving patterns

For the analysis of driving cycles and the development of representative standardised cycles it is essential to know why driving patterns look the way they do. If two vehicles were to drive from A to B, the patterns would surely look different. The shape and character of a certain cycle is affected by several influences that can be divided into three categories:

- Driver forced: e.g. the driver does not want to go any faster or has an aggressive driving style.
- Vehicle forced: e.g. the vehicle cannot drive any faster, because of its limited power.
- Traffic and road forced: e.g. the vehicle cannot drive any faster due to other traffic or the road configuration.

In the future technologies such as intelligent cruise-control, co-pilot systems and external vehicle control may introduce a fourth category of vehicle influences, the “environment” forced patterns. The three categories above will be highlighted in the following paragraphs.

A2.1 Driver forced patterns

Most likely the biggest influence of all, the behaviour of the driver himself, has a great effect on what the driving pattern looks like. In light-duty vehicles, the maximum power of the vehicle is hardly ever used, which means that the driver influences the amount of power actually used. However, unlike light-duty vehicles, accelerations of heavy-duty vehicles are rarely driver forced and are characterised by full throttle engine load. This is mainly due to the low power-to-mass ratio of trucks when compared to passenger cars. The reason for this can be found in the higher priority for low fuel consumption for heavy-duty vehicles, their limited top speed and relative low power that is needed to attain their maximum speed. But above all, passenger cars are practically always over-powered for marketing reasons. Nonetheless, there appears to be a very logical relation between the average driving behaviour of vehicles with high as well as low power-to-mass ratios. FiGE in Germany studied the behaviour of a large number of both light-and heavy-duty vehicles (passenger cars and trucks) in real-life [3]. In these data, the driver characteristic is very well reflected. From these data some interesting analyses can be made (Figure 32). The actual power used can be expressed by the amount of power that is available at the actual engine speed up to which the driver pulls through when accelerating (= available power before shift) and to the power that is available at the engine speed at which the engine runs just after shifting (= available power after shift). When these two different available powers are plotted against the rated (maximum) power a correlation is visible that is applicable to light- as well as to heavy-duty vehicles. In order to be able to compare different vehicle categories, the power is presented relative to the mass of the vehicle.

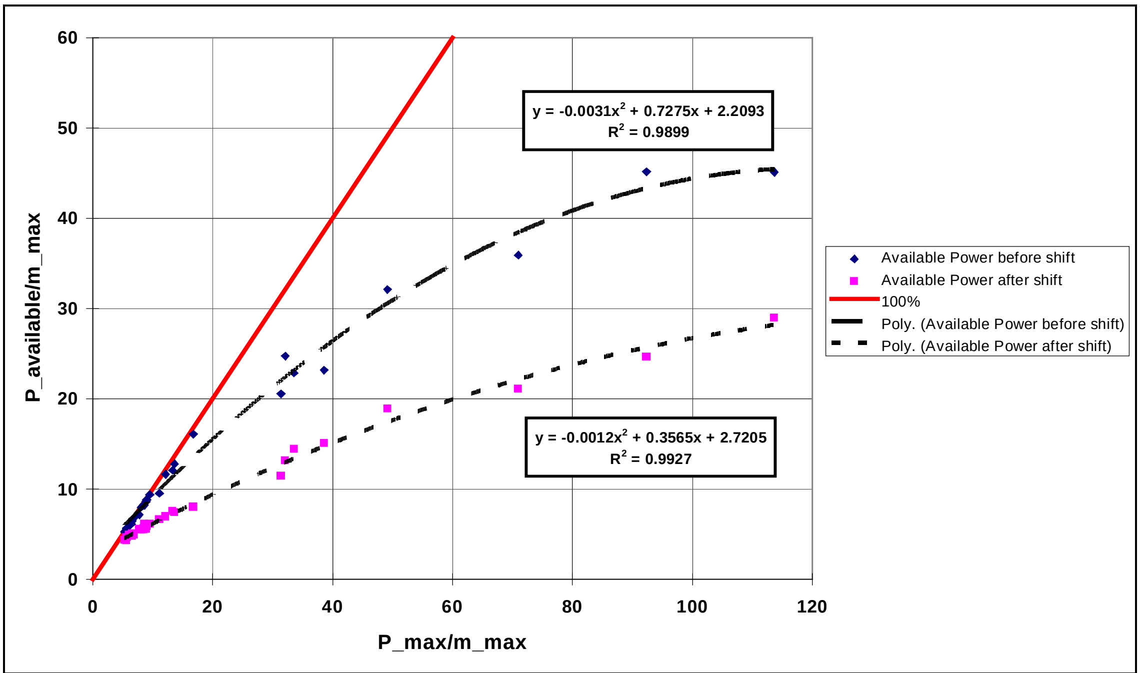


Figure 32: Correlation between the available power at engine speeds before and after a typical shifting phase during an acceleration phase and the maximum power (both related to the vehicle mass); heavy and light duty vehicles, including passenger cars; Assessed from [3].

The figure above shows that a very important aspect of the driver characteristic (the shifting point and as a consequence, the used power) can be predicted by a vehicle parameter (the available power). If a vehicle has more power-per-mass available (the right side of the figure), it will in practice use more power, but less if presented relative to the maximum power. And it appears that for heavy-duty vehicles (< ±20 kW/ton) the maximum power that is required in practice is always very close to the maximum power.

A2.2 Vehicle forced patterns

The analysis above showed that accelerations of particularly heavy duty vehicles can be considered to be mostly vehicle forced patterns. The acceleration of light-duty vehicles is in principle mainly driver forced, but the impression exists (Figure 32) that the driver reacts mainly to the vehicle characteristics. So effectively one could say that it is still vehicle forced. This needs further investigation, however.

In this respect the question is which vehicle parameters influence these patterns. For this purpose an acceleration sequence is analysed in an earlier study at TNO [2]. The result of this analysis implied that the power-to-mass ratio of the vehicle is by far the most influencing vehicle parameter that influences the shape of vehicle forced patterns. Two vehicles with similar [kW/ton] ratio will show similar vehicle forced driving patterns, nearly independent of the absolute amount of power.

A2.3 Traffic and road forced patterns

If the driver wants to drive faster and the vehicle can go faster, the traffic or road structure will of course not always allow it. This can be caused by other traffic in front of the vehicle, cross roads, traffic lights, curves, et cetera. These patterns are referred to as traffic forced patterns and occur, depending on many factors:

Driving route
The road category (urban/rural/highway) shows the most influence on the shape and character of the driving patterns and is therefore to be considered as the biggest traffic and road forced influence. Besides this, traffic on a certain route can change very much depending on things like the character of the city or region, the geographical area (compare for instance an Italian city to a Swedish city), and on the character of the road.

Environment
Weather conditions directly influence traffic intensity. The weather can also influence the driver (he is for example more careful during rain and snow or "easy going" on hot days), which will reflect on the driver forced patterns.

Driving moment
Traffic intensity changes heavily in time. This is true for the time of the day that shows variance from rush-hour till night, but also for the day of the week. Finally the time of year influences the traffic intensity as for instance holiday periods show less inner-city traffic or traffic peaks on certain highways.

It has to be remarked that in many cases there is a relation between traffic and road forced patterns and vehicle and driver forced patterns. If for instance a curve limits the speed, the actual speed will still differ from driver to driver and from vehicle to vehicle.

A3 Characterisation of driving cycles

After analysing the relevant influences, the question remains how to characterise a certain driving cycle. General frameworks are looked for, which are independent of the exact purpose of the characterisation. From relevant literature [2] and from experience at TNO, Table 5 is established. The cycle characteristics can be divided in two groups:

- Cycle descriptions, expressed as a diagram, table, matrix et cetera.
- Cycle parameters, expressed by a certain value.

Table 5: Cycle characteristics

Cycle descriptions	**Unit**	**Definition**
1. Speed-Acceleration-Gradient matrix (VAG-matrix)	[m/s], [m/s^2], [%]	
2. Speed-Acceleration matrix (VA-matrix)	[m/s] [m/s^2]	
3. Speed histogram	[m/s]	
Cycle parameters		
4. Total cycle distance x	[m]	
5. Total cycle time	[s]	
6. Total operational cycle time T	[s]	Time that the engine is switched on
7. Average duration of a stop (+ distribution)	[s]	Average time of a stop, excluding the time that the engine is switched off
8. Average duration of a driving sequence (+ distribution)	[s]	Average time of a driving sequence (time that v>0, between two stops)
9. Average total cycle speed	[m/s]	Total travel distance, divided by total time
10. Average (operational) speed	[m/s]	Total travel distance, divided by the operational cycle time
11. Average running speed	[m/s]	Total travel distance, divided by the time speed > 0
12. Standard deviation of speed	[m/s]	STDEV(v)
13. Maximum cycle speed	[m/s]	
14. Relative Cubic Speed RCS	[m^2/s^2]	$RCS = \frac{\frac{1}{T}\int_0^T (v_i)^3 \, dt}{\bar{v}} = \frac{\int_0^T (v_i)^3 \, dt}{x}$
15. Mean cycle acceleration rate	[m/s^2]	Average acceleration
16. Mean cycle deceleration rate	[m/s^2]	Average deceleration
17. Root Mean Square of acceleration RMSACC	[m/s^2]	Measure of speed noise. $RMSACC = \sqrt{\frac{1}{T}\int_0^T (a^2)\, dt}$
18. Positive Kinetic Energy PKE	[m/s^2]	Acceleration energy required in a certain driving pattern, $PKE = \frac{(v_f^{\,2} - v_s^{\,2}), \frac{dv}{dt} > 0}{x}$
19. Relative Positive Acceleration RPA	[m/s^2]	$RPA = \frac{\frac{1}{T}\int_0^T (v_i * a_i^+)\, dt}{\bar{v}} = \frac{\int_0^T (v_i * a_i^+)\, dt}{x}$
20. Standard deviation of acceleration	[m/s^2]	STDEV(a)
21. Relative standard deviation of accel. power	[m/s^2]	Standard deviation of v*a, divided by average speed
22. Maximum acceleration	[m/s^2]	
23. Maximum deceleration	[m/s^2]	
24. Standard deviation of acceleration power	[m^2/s^3]	Standard deviation of v*a (STDEV(v*a))
25. Mean acceleration power	[m^2/s^3]	Average value of v*a if a>0
26. Mean deceleration power	[m^2/s^3]	Average value of v*a if a<0
27. Percentage of cycle time idling	[%]	
28. Percentage of cycle time cruising	[%]	
29. Percentage of cycle time accelerating	[%]	
30. Percentage of cycle time decelerating	[%]	
31. Percentage of stopping time	[%]	
32. Stops per distance	[-/km]	
33. Gradient factor	[%, rad]	Standard deviation of gradient
34. Maximum gradient	[%, rad]	(Possibly at different constant speeds)
35. Relative Positive Gradient RPG	[rad]	$RPG = \frac{\frac{1}{T}\int_0^T \left(v_i * \theta_i^{+}\right) dt}{\bar{v}} = \frac{\int_0^T \left(v_i * \theta_i^{+}\right) dt}{x}$

In principle, it would be better to work with the three dimensional speed-acceleration-gradient matrix (VAG-matrix), than to use any of the other cycle characteristics or parameters, simply because of the fact that these others can all be derived from a VAG-matrix. The matrix entries are obtained by distributing the speed, acceleration and gradient fields into equal increments, calculating the probability for each matrix element (“cell”). If a high enough resolution is applied, this provides a sound basis for comparison between cycles and the prediction of energy use and/or emissions of a certain vehicle. A clear disadvantage of including the gradient in the matrix is that because of the need of having a large number of cells in the matrix, and consequently the risk of a low number of entries per cell, the division of the three axes (the cells) cannot be too small, with a resulting decline in accuracy. A second disadvantage is that, in practice, it appears difficult and expensive to accurately monitor the gradient. Finally, gradients usually do not occur in standardised driving cycles, because of the difficulty of incorporating the gradient in rollerbench tests or, to a lesser extent, in simulations.

For these reasons it is usually decided to leave the measurement of gradient out, or to introduce the influence of the gradient afterwards, based upon mathematical relations. If recording the gradient is left out, the road measurements which possibly do include gradient influence, have to be analysed with this in mind. The speed-acceleration matrix (VA-matrix) is therefore the more practical and in many cases the better solution. It covers all vehicle motion energy parameters for a vehicle on a flat road. In general a division in segments in the order of 2 m/s and 0.2 m/s^2 leads to a matrix that makes all necessary analyses possible. The VA-matrix provides the basis for the statistical method for producing standardised representative driving cycles, as presented in Chapter A4, and will be further clarified there.

Although the comparison between two cycles using the VAG- or VA-matrix would be very accurate, the creation of complete matrices for different cycles is complicated and not always possible. Therefore, a limited number of essential driving cycle parameters (see Table 5) is looked for to be able to quickly compare and assess different cycles or make a prediction of different vehicle performances, for instance fuel consumption or emission production.

It depends on the purpose of the research which cycle parameter expresses the identity of a certain cycle best. If, for instance, a cycle is used to describe worst case situations for the development of a certain vehicle, parameters as maximum speed and maximum acceleration and deceleration are of specific interest. If the cycle characterisation is applied to emission and fuel consumption research, one can assess the representativity of a certain cycle parameter best by calculating the correlation with the emission factors and fuel consumption.

A4 The development of representative driving cycles

As explained in Chapter A3, in a growing number of cases a driving cycle is needed that is representative for actual vehicle use. In this paragraph, a general theory is described to develop representative driving cycles for any type of vehicle. A representative driving cycle is defined as a speed-time sequence of limited length, in which as many essential cycle characteristics as possible comply with the driving pattern of the intended vehicle in mind. This means that on the one hand all influences as mentioned in paragraph A2 (driver, vehicle and traffic) must occur in the cycle in a representative way. On the other hand, for reasons of measurability, this should not lead to a cycle that is too long. In general the lengths of driving cycles are in the order of magnitude of 5 to 60 minutes. The method for the development of representative driving cycles that is described here, is composed of two phases that deal with these two main items. The first phase involves the collection of data, which are selected and combined in such a way as to produce a big representative driving cycle, referred to as the “reference cycle”. This phase is further clarified in paragraph A4.1. In the second phase a cycle of the desired length is statistically derived from this reference cycle, to form the representative driving cycle, hence

referred to as "desired cycle". In this phase, described in paragraph A4.2, the purpose is to develop a short cycle that shows cycle characteristics (as listed in Table 5) that are as close as possible to those of the reference cycle.
More information on this subject can be found in [2].

A4.1 The development of a reference cycle

As mentioned, the first phase consists of the development of a representative cycle, without taking the length of the desired cycle into account. Representative in this respect means that all influences as described in paragraph A2 have to be included similar to real-life. These influences are summarised as:

- Driver influences
- Vehicle influences
- Traffic influences:
  - A. Driving route
  - B. Environment
  - C. Time of driving (time of the day, day of the week, time of the year)

To find out to what extent and in what relation these influences affect the driving patterns is largely defined by statistics. Eventually, all statistics that are not known have to result from the measurements. The translation of statistics for the processing of the influences mentioned can be achieved in two ways:

- *Measuring representativity*
  In this case, the measurements are organised in such a way that the resulting measured data can be considered as representative. This result has to be accomplished during the data acquisition phase (paragraph A4.1.1).
- *Creating representativity*
  In this case, the data are processed in such a way that the created result is representative. The only demand for the data collection is that all situations and all influences that could occur in a cycle of the desired length are measured, however, not necessarily in a representative proportion. This result is obtained during the processing of the data to a reference cycle (paragraph A4.1.2).

It depends highly on, amongst others, the purpose of the cycle development and on the scale (and budget) of the measurements, to what extent the influences are processed by either *measuring representativity* or *creating representativity*. Finally, it should be mentioned that a third option for the development of a representative reference cycle is formed by the manipulation at the end (manually influence the patterns), which could for instance be necessary if not enough data have been measured to form a representative basis.

A4.1.1 Data acquisition

As stated above, all influences that have to be embodied through *measuring representativity*, will have to be considered before the organisation of the measurements. For the method described it is necessary that all situations and all influences that could occur in a cycle of the desired length are measured. The advantage of the method described, however, is that in principle it is not yet a must to include all of these influences in a representative way. The representativity, as stated above, can also be created. This is partly done by weighting the measured data in the second phase.

The most important parameter to be measured is of course speed, which, as it is found in practice, must be recorded with a frequency of at least 2 Hz. Acceleration can be derived from the speed, if the resolution of the speed measurement is high enough. Hence, depending on the purpose of the cycle development, parameters as road gradient, engine torque, engine speed, traffic conditions, temperatures, vehicle load rate, fuel consumption, et cetera can be measured and recorded.

Three main methods for the data acquisition can be distinguished:
- Instrumented representative vehicles, driven by a trained test driver who is aware of the purpose of the measurements and will make sure to take all influences into account in a way as representative as possible.
- Instrumented representative vehicles that are put into normal service and will be driven by a large number of every day drivers of the specific type of vehicle.
- A specially equipped vehicle that closely follows the intended vehicle.

A4.1.2 Processing the data into the reference cycle

To create the reference cycle, the measured data are combined in such a way that the sum can be defined as representative of the intended vehicle use. In this phase all influences that have to be taken into account through the process of "*creating representativity*" have to be considered. In this process the different measurements are split up into sections, that can be weighted separately, based on user-statistics. Suppose, for instance, that a specific highway cycle is looked for that according to the statistics has to represent 7/8 normal driving and 1/8 congested driving patterns. If the measurements show an equal share of free driving and congested patterns, one has to split these sections and give a weighting factor of 7 to the free driving section.

The result from the weighted summation is a cycle that may be very much bigger than the total amount of measurements, due to the use of weighting factors. Examples of the application of the method show reference cycles from several hours up to more than 10,000 hours. But most important is that the representativity of these reference cycles is guaranteed, which in this phase is the only thing that matters. If the reference cycle is ready, a list can be set up of all cycle characteristics, as mentioned in Table 5. In the next paragraph a method is explained to create a cycle of the desired length, with its characteristics showing as much similarity as possible to those of the reference cycle.

A4.2 Creation of the desired cycle

If all influences are taken into account in a representative way, the reference cycle on its own would fulfil all representativity criteria that are required for driving cycles (Table 4). However, in practice such a cycle would of course prove itself useless for bench testing or real time simulation models, because of the long period that generally characterises reference cycles (several hours up to more than 10,000 hours). In general the desired length of driving cycles is below 60 minutes. This can be dictated by the purposes, general limitations of the test equipment or by the allowed cost of the measurements that have to be performed using the cycle. In some cases the daily use of the vehicle may lead to a specific preferred cycle duration. Urban buses, for instance, tend to stop on a regular basis in order to run on schedule again. These stops are henceforth called "buffer stops". In such a case it is best to choose the cycle duration that equals the average time between two of these buffer stops.

Knowing all characteristics of the reference cycle, the purpose now is to construct a cycle that resembles these characteristics as closely as possible. For this a statistical approach is presented which consists of the following four steps:
- Analysis of the reference cycle
- Creation of sample cycles
- Statistical comparison and selection of a cycle
- Completion of the cycle

In the next paragraphs, these steps will be further explained.

A4.2.1 Analysing the reference cycle

The cycle characteristics (Table 5) of the reference cycle can all be calculated. This already gives a good idea of what the cycle should look like. The most important values with regard to this method are the lengths of driving sequences and stops. A driving sequence (henceforth called "sequence") is defined as a speed pattern between two stops. A stop is defined as a certain time with consistent zero speed. As the end of the cycle can also be considered a stop, the number of stops equals the number of sequences. The length of this last/first stop might be of importance if (a part of) the cycle is repeated, with regard to cooling down characteristics of the engine and other components. Figure 33 gives an example of a short cycle, consisting of 3 stops and 3 sequences.

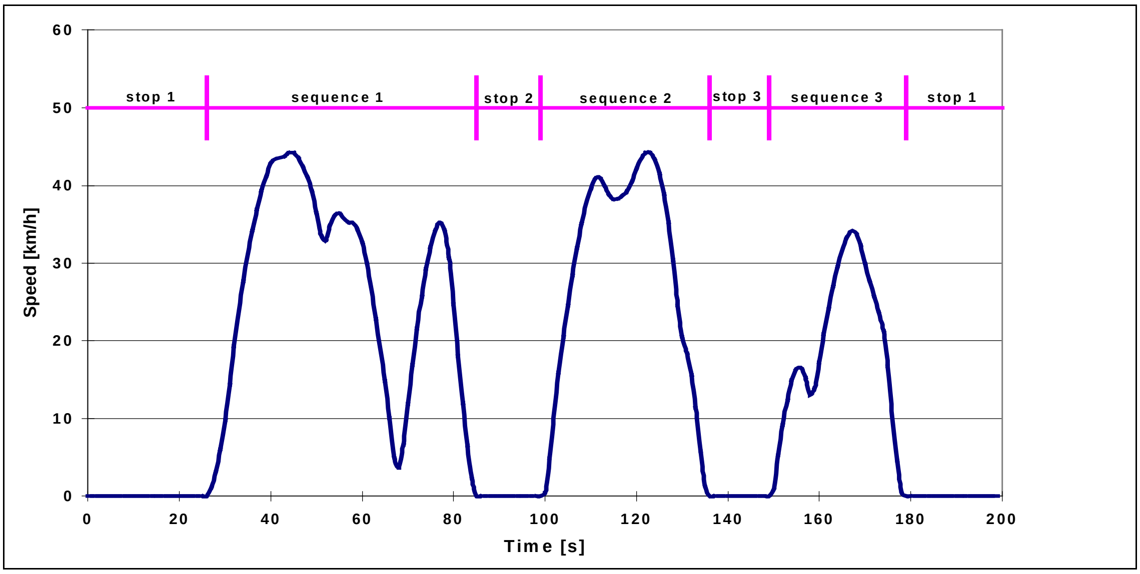


Figure 33: Short cycle, consisting of 3 stops and 3 sequences

The analysis of the cycle starts with the separation of driving sequences and stops. After the calculation of the average duration of a stop and the average duration of a sequence, the number of desired sequences and stops can be calculated from the desired cycle time.

The length of the sequences as well as of the stops have to display a distribution similar to those of the reference cycle. Because the reference cycle in general will show a large number of sequences and stops, the distribution will show a wave pattern that cannot be replicated with the distribution of the limited number of stops and sequences in the desired cycle. Therefore a "longitudinal shaped" wave has to fit the "transversal wave" of the reference cycle. With the least square method a best fit can be found. Figure 34 shows, as an example, the distribution of sequence length as it was used for the creation of an urban bus cycle, of which the reference cycle had 10,818 sequences.

If the distribution of the sequences is known, a cycle has to be created that is composed of the different sequences of the length determined. In order to find the right sequences, a large set of sequences of the different indicated lengths have to be put together. These sequences can be selected from the measurement data, but may very well come from earlier measurements or may even purposely be recorded afterwards. The sequences of similar length in one set have to show a variation as wide as possible in order to make as many different cycles as possible. The stops will be added to the cycle in a later phase.

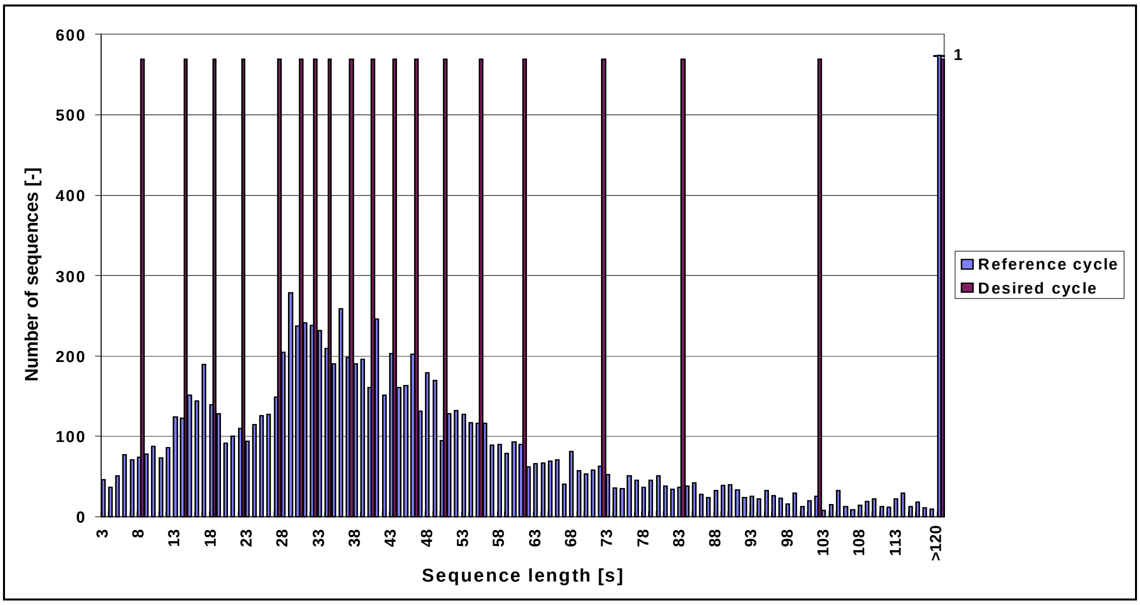


Figure 34: Example of distribution of sequence length for both the reference cycle and the desired cycle (urban bus)

A4.2.2 Creation of sample cycles

If a set is developed for each calculated sequence length, all containing several (10) sequences of the specific length, it is possible to make a large number of cycles of the desired length. For this, one sample is taken from each of the sequence sets to be combined to a cycle. For example 19 sets with each 10 sequences lead to 10^{19} possible cycles. From these combinations of sequences, the one that is most comparable to the reference cycle has to be selected. As the speed-acceleration matrix (VA-matrix) was found to be to be the best characterisation of a cycle (see paragraph A3) the comparison will be based upon this matrix. The VA-matrix of the reference cycle can be set up as soon as the reference cycle has been developed. The matrix entries are obtained by dividing the speed and acceleration values into equal divisions. The cumulated result has to be divided by the total cycle time. This will return the percentage of time that a certain combination of speed and acceleration occurs. Figure 35 displays the result for an urban bus driving cycle.

If the VA-matrix for the desired driving cycle displays a pattern similar to that of the reference cycle, all other important cycle characteristics will be representative for the reference cycle, and consequently also for real-life.

		Speed [m/s]												
	% of time		0	2	4	6	8	10	12	14	16	18	20	22
Acceleration [m/s²]		0	2	4	6	8	10	12	14	16	18	20	22	24
	2													
2	1.8			0.01										
1.8	1.6		0.06	0.23	0.01									
1.6	1.4		0.18	0.48	0.21	0.02								
1.4	1.2		0.27	0.34	0.52	0.25	0.02							
1.2	1		0.38	0.33	0.66	0.89	0.30	0.05						
1	0.8		0.46	0.31	0.57	0.86	1.24	0.48	0.05					
0.8	0.6	0.01	0.48	0.29	0.50	0.64	0.92	1.07	0.55	0.09	0.02			
0.6	0.4	0.07	0.46	0.25	0.44	0.52	0.62	0.78	0.83	0.40	0.12	0.03		
0.4	0.2	0.28	0.57	0.32	0.52	0.56	0.69	0.89	0.97	0.49	0.15	0.04	0.01	
0.2	0	0.90	0.47	0.29	0.49	0.52	0.66	1.03	1.21	0.63	0.18	0.04	0.01	
	0	41.05	0.14	0.12	0.16	0.19	0.24	0.42	0.50	0.29	0.08	0.01		
0	-0.2	0.83	0.33	0.33	0.50	0.57	0.64	0.99	1.11	0.66	0.18	0.04	0.01	
-0.2	-0.4	0.32	0.50	0.29	0.53	0.69	0.73	0.99	0.91	0.45	0.13	0.03	0.01	
-0.4	-0.6	0.09	0.48	0.22	0.30	0.37	0.39	0.40	0.35	0.13	0.04	0.01		
-0.6	-0.8	0.02	0.51	0.25	0.33	0.37	0.36	0.36	0.28	0.10	0.03	0.01		
-0.8	-1		0.44	0.27	0.37	0.44	0.44	0.29	0.17	0.06	0.02			
-1	-1.2		0.34	0.28	0.32	0.34	0.28	0.19	0.10	0.03	0.01			
-1.2	-1.4		0.24	0.25	0.24	0.25	0.21	0.13	0.06	0.02				
-1.4	-1.6		0.18	0.28	0.25	0.25	0.21	0.13	0.05	0.01				
-1.6	-1.8		0.09	0.25	0.21	0.19	0.16	0.08	0.03	0.01				
-1.8	-2		0.03	0.16	0.15	0.13	0.10	0.04	0.01					
-2	-2.2			0.07	0.08	0.07	0.05	0.02	0.01					
-2.2	-2.4			0.03	0.05	0.04	0.02	0.01						
-2.4	-2.6			0.01	0.02	0.02	0.01							
-2.6	-2.8				0.01	0.01								
-2.8	-3													

Figure 35: Example of a VA-matrix (Urban Bus Driving Cycle); percentage of time

A4.2.3 Statistical comparison and selection of a cycle

The selection of the best cycle shall be based upon statistical comparison between the VA-matrix of the reference cycle and all sampled cycles. The best known classic test to find out how well data follow a distributional hypothesis is the exactness-of-fit test based on the chi-squared statistic [2]. The chi-squared technique tests observed frequency with the expected frequency of each of these VA-cells. The better these frequencies match, the lower the chi-squared value will be, and the better the representativity. To what extent the observed frequency represents the expected frequency depends on the chi-squared value, in combination with the numbers of degrees of freedom (ν). The number of degrees of freedom is defined by the number of different parameters that are tested (in this case the number of VA-cells). The representativity can be deducted from available tables.

There are two important conditions for the use of the chi-squared method. The first demand is that the events occur independent of each other. Indeed all combinations of speed and acceleration can occur independent of each other, although only if the sample is really taken at random. In case a driving cycle is sampled, there is nevertheless a certain matter of dependency between the degrees of freedom. If at one point in the cycle the speed and acceleration is known, the next second will show a rather predictable speed. This does nevertheless not mean that the method cannot be used, as the cycle with the lowest chi-squared will still be the best fitting cycle. The translation from the chi-squared value to an absolute expression of exactness-of-fit, however, turns out to be much too optimistic.

A second demand for the use of the chi-squared test is that the number of expected frequencies cannot be too small, because it would otherwise become too big an influence on the total chi-squared due to the low denominator in the chi-squared equation. Statistics prescribe a minimum value for the number of expected frequencies of 5. This leads to the necessity of grouping several VA-fields. By choosing fields with approximately the same power requirement, the loss in accuracy can be kept very small. The number of cells that is obtained in this way constitutes the number of degrees of freedom. The chi-squared technique tests observed frequency with the expected frequency of each of these combined VA-cells.

The selection of the definitive cycle is carried out as follows: A sample cycle is created, out of sequences from each of the particular sequence sets. The VA-matrix of the sample cycle is calculated and divided into subgroups in order to obtain at least 5 expected frequencies per group. The contents of the different groups are compared, using the chi-squared test. In this way the combination of sequences that shows the lowest chi-squared will be selected to form the basis of the desired cycle.

Due to the large number of possible cycles (10^{19} in the case above) a computer tool is necessary for use in the calculations above. But even with this help, the large number of cycles would lead to an unacceptable calculation time. This can be solved by first taking only a limited number of sequences (e.g. 3 or 4 instead of 10), which lowers the number of possible combinations. To the best selection of measurements 2 or 3 new sequences can then be added for each of the different sequence lengths, after which the selection can be repeated until all 10 samples have been considered.

A4.2.4 Completion of the cycle

Once the best combination has been established, the cycle can be finished by arranging the sequences as well as the stops in the right order. In this process, one has to consider the behaviour of the specific vehicle in real-life. In the case of the urban bus driving cycle it was realised that buses normally run from one suburban area to another via the town centre. The distribution of the stops reflects this common rule. In general the longest stop will be placed at the end (= the beginning) of the cycle. Doing so, an engine-off prescription could also be specified, for instance in the case of buffer stops.

The method as described in this chapter is found to be very accurate. If a cycle is selected from a sufficient number of sequence-samples, using the chi-squared comparison of the VA-matrices, all other cycle characteristics (average speed, stops per distance, acceleration parameters, et cetera) turn out to correspond within 1% accuracy.

Appendix B Main parameters simulation models

	Heavy Duty		Light Duty								
	PHEV	**SHEV**	**BEV**	**PHEVfw**	**PHEVbat**	**SHEVfw**	**SHEVbatfol**	**SHEVbatsoc**	**CHEV**	**FCEV**	**FCHEV**
IC engine	Otto	Otto	–	diesel	diesel	diesel	diesel	Otto	Otto	–	–
P [kW]	130	130		60	60	55	55	65	49	–	–
APU op 1		27						13.5			
APU op 2		69						38			
Fuel Cell	–	–	–	–	–	–	–	–	–	H_2	H_2
P [kW]										90	36.5
APU op 1											10.95
APU op 2											36.5
Generator	–	PM	–	–	–	PM	PM	PM	PM		
P [kW]		75				31	31	75	22.5		
base speed [rpm]		3500				2400	2400	4000	4000		
Electric Motor	PM	PM	PM	PM	PM	PM	PM	PM	PM	PM	PM
P [kW]	120	247.5	(2x)	20	20	65	65	(2x) 37.5	30	(2x)	(2x) 37.5
base speed [rpm]	500	2500	3000	480	480	480	480	3000	940	3000	3000
Battery	NiCd	NiCd	NiCd		NiMH		NiMH	NiCd	NiCd	–	NiCd
Capacity [Ah]	50	50	65					6.5	6.5		6.5
Cell Voltage [V]	1.2	1.2	1.2					1.2	1.2		1.2
Rinternal [mΩ]	0.72	0. 72	0.72					0.72	0.72		0.72
Number of cells	500	500	240					240	240		240
P [kW]					22		72				
E [kWh]					3.6		11.5				
Flywheel											
P [kW]				22		72					
E [kWh]				0.733		0.27					
Vehicle											
Mass [kg]	15000	15000	1350	1328	1387	1477	1669	1350	1350	1350	1350
C_w	0.6	0.6	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
A [m^2]	7	7	2	2	2	2	2	2	2	2	2

PHEV – HD Parallel HEV; SHEV – HD Series HEV with simple APU control (3 algorithms); BEV – LD Battery Electric Vehicle; PHEVfw – LD Parallel HEV with electromechanical flywheel storage; PHEVbat – LD Parallel HEV with battery storage; SHEVfw – LD Series HEV with flywheel storage; SHEVbatfol – LD Series HEV with load follower CS and battery; SHEVbatsoc – LD Series HEV with battery and simple APU control 2; CHEV – LD Combined HEV; FCEV – LD Fuel Cell Electric Vehicle; FCHEV – LD Fuel Cell HEV with battery and simple APU control 2

Appendix C Simulation results

In the main text, examples are given for several simulations. In this appendix the other results that are mentioned in the main text, are showed and listed. This concerns the results of more drivelines, other conditions, etcetera. Whenever a reference to this appendix is given in the main text, the figure, table and/or page numbers are used for reference here.

Figure 16, page 21

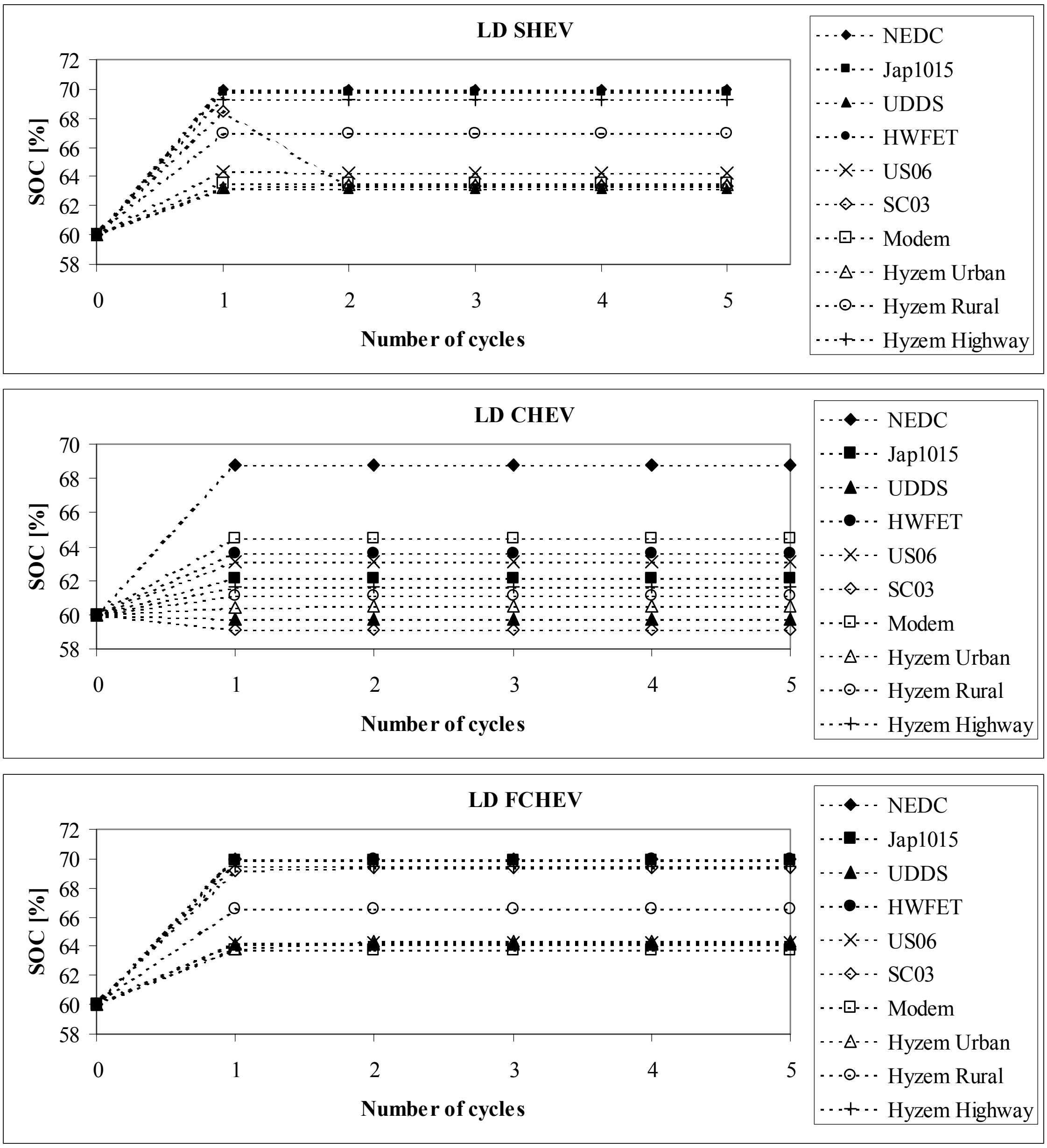


Figure 36: Influence of driving cycle; initial and final SOC for LD vehicles over 5 consecutive cycles

Figure 17, page 22

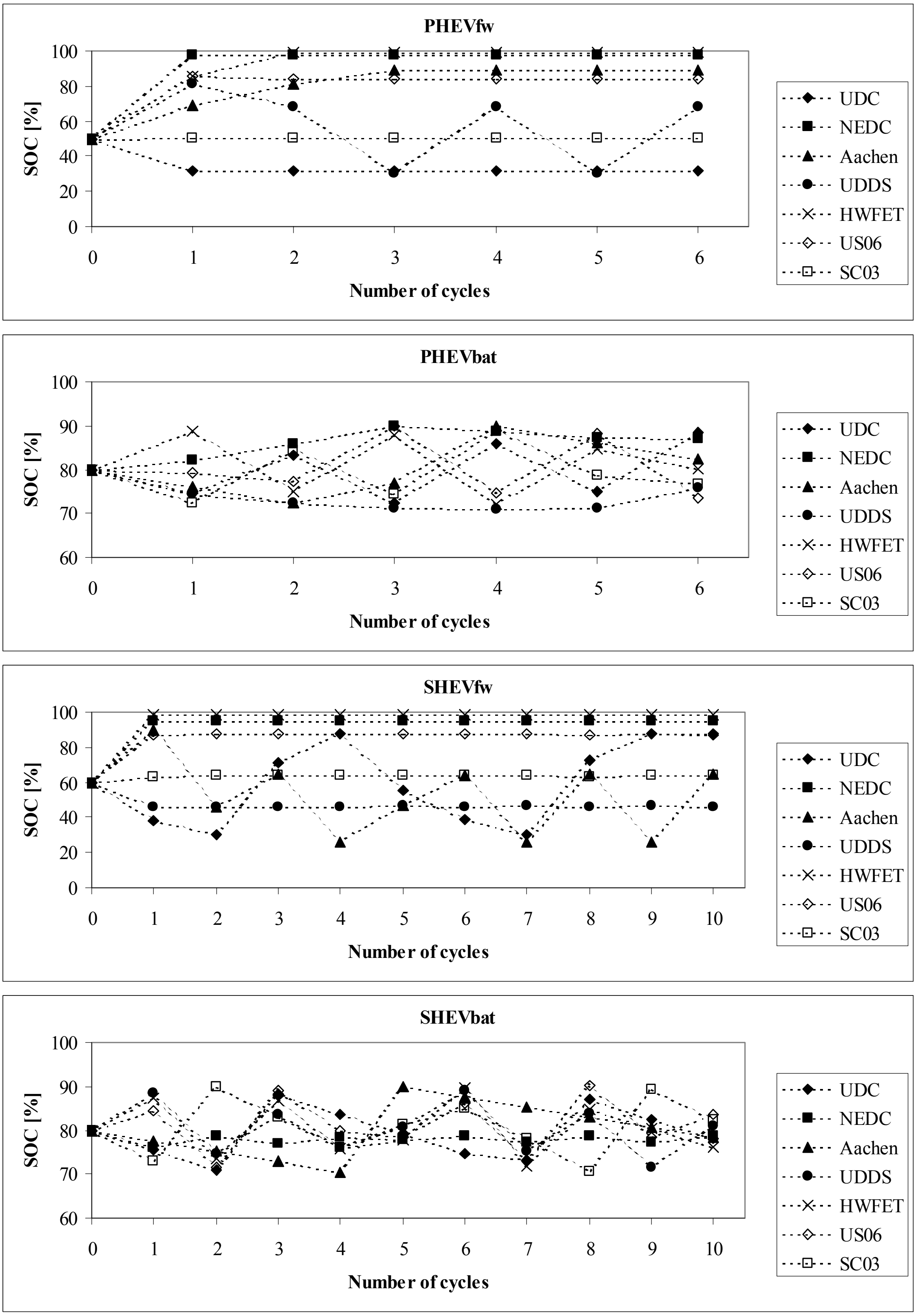
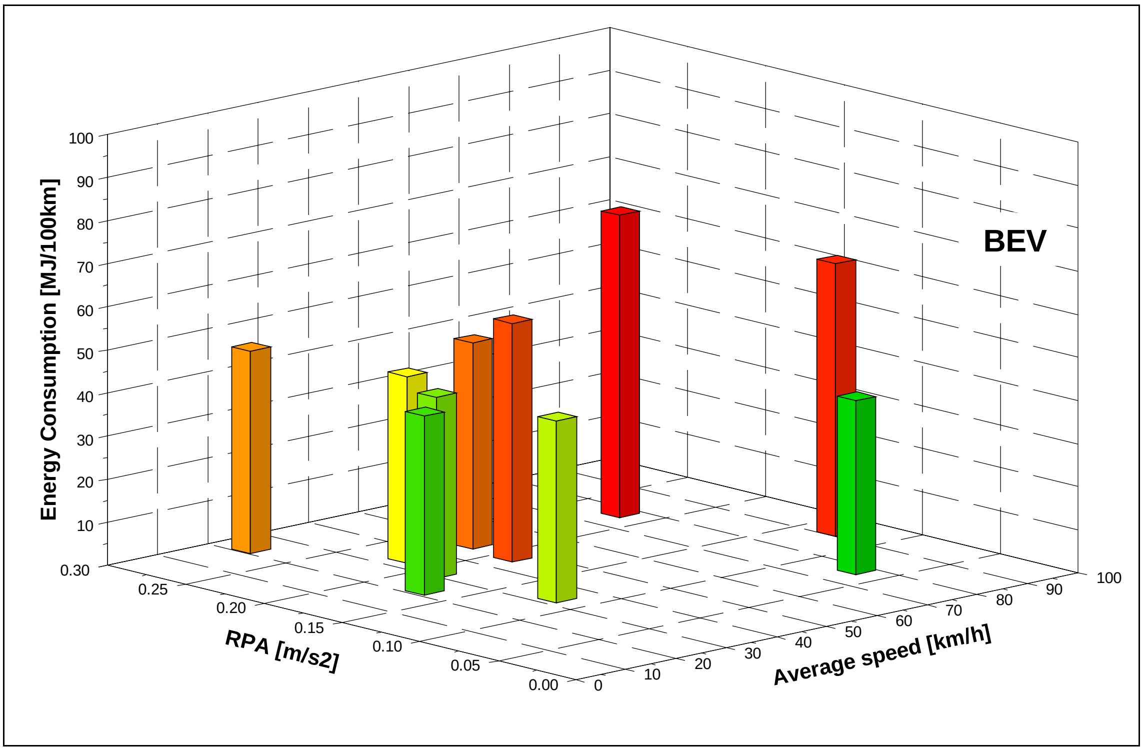
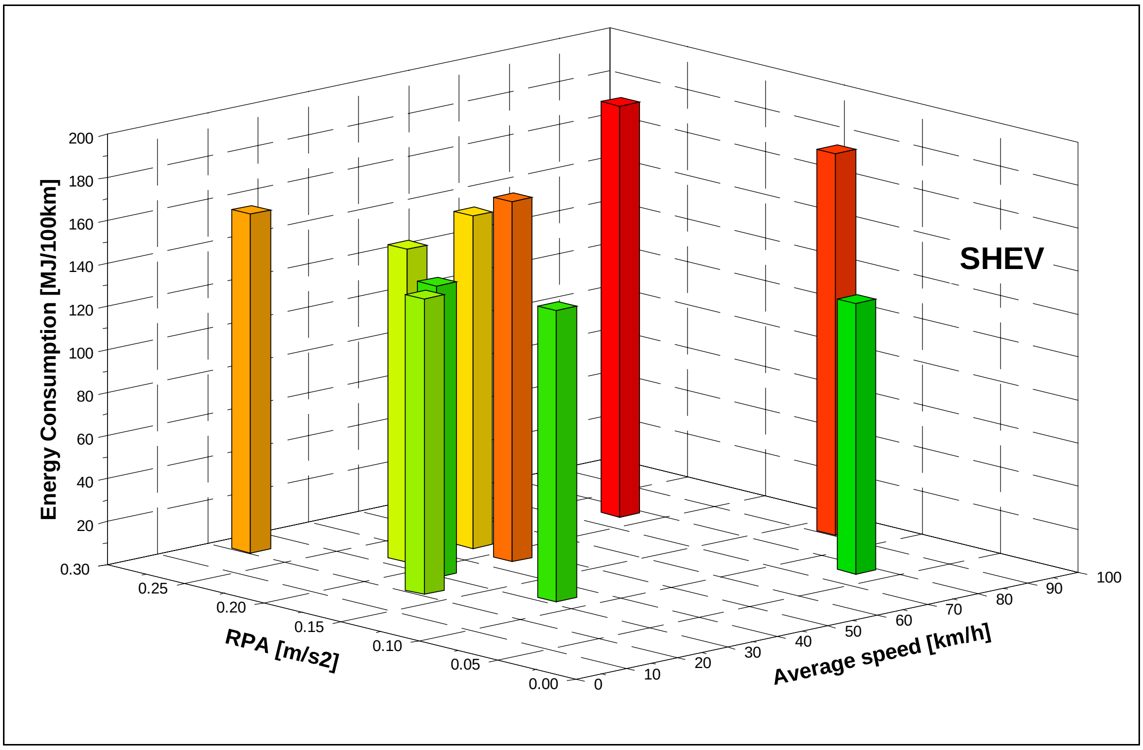
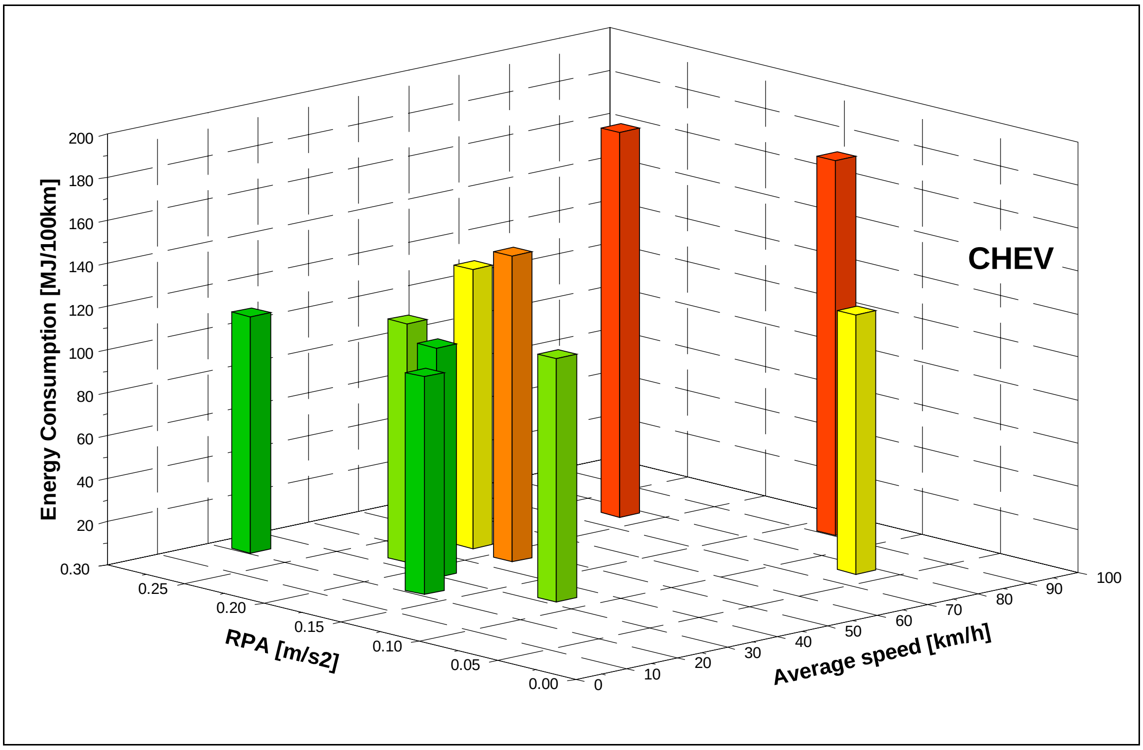


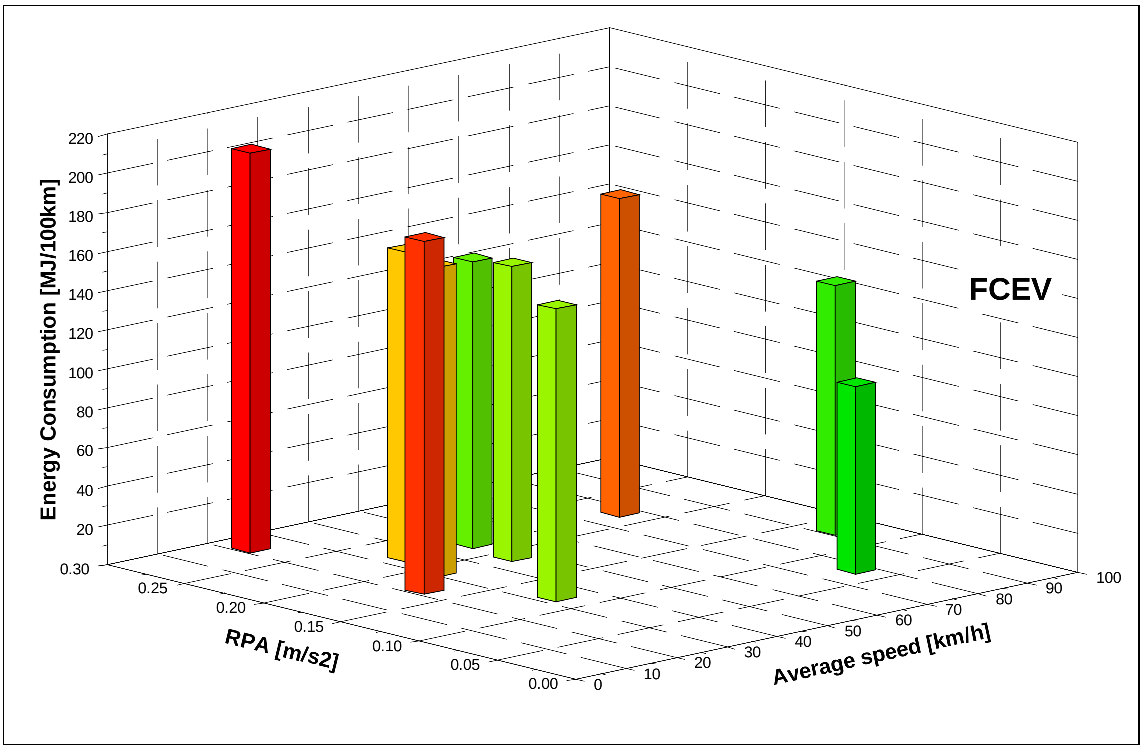
Figure 37: Influence of driving cycle; initial and final SOC for PHEV and SHEV with battery or flywheel

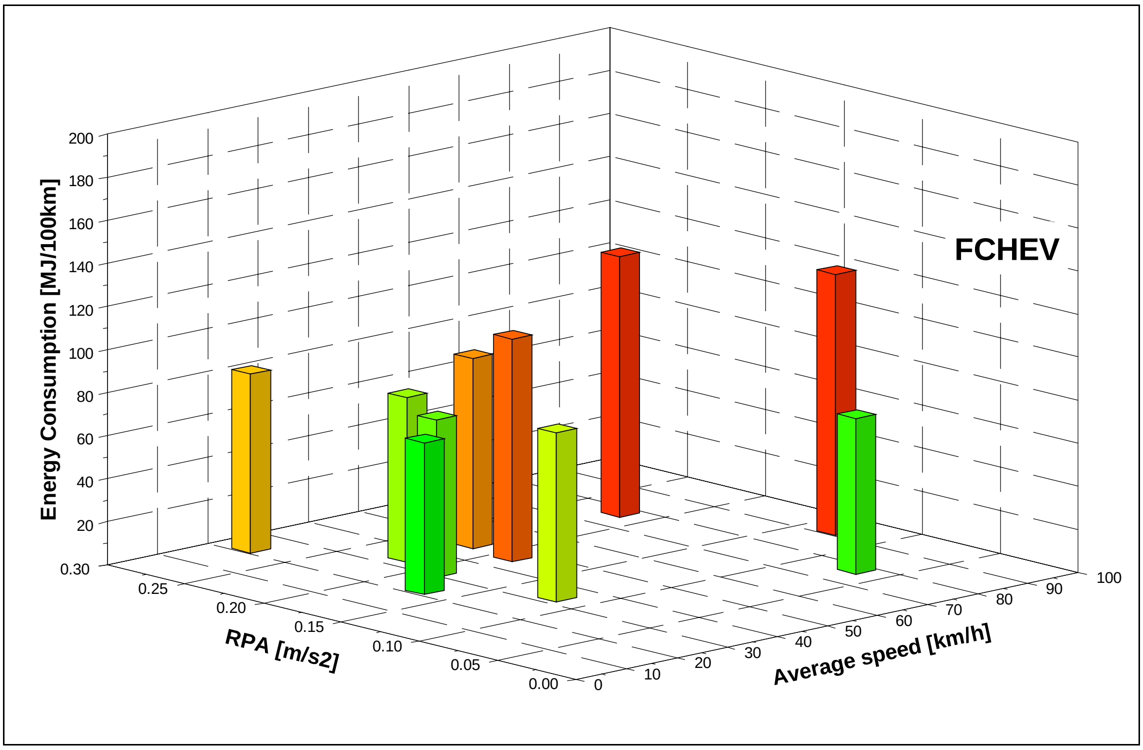
Figure 21, Page 25






CHEV
Energy Consumption [MJ/100km]
RPA [m/s2]
Average speed [km/h]


FCEV
Energy Consumption [MJ/100km]
RPA [m/s2]
Average speed [km/h]


FCHEV
Energy Consumption [MJ/100km]
200
180
160
140
120
100
80
60
40
20
0.30
0.25
0.20
0.15
0.10
0.05
0.00
RPA [m/s2]
0
10
20
30
40
50
60
70
80
90
100
Average speed [km/h]

Appendix D Toyota Prius

In the framework of the MATADOR project, a Toyota Prius was thoroughly tested by TNO Automotive (Delft, the Netherlands). Part of the measurements was the evaluation of the vehicle over six different driving cycles.

D1 The vehicle

The Toyota Prius (Figure 38) is the first series produced hybrid electric vehicle in the world. It was put to the market in Japan at the end of 1997 and will most likely become available onto the US and European market in the summer of the year 2000.
The Toyota Prius is equipped with the THS drive system. THS stands for Toyota Hybrid System. The THS system is a so-called combined hybrid configuration. **Error! Reference source not found.** shows the powertrain lay-out of the Toyota Prius. The technical specifications for the Toyota Prius are listed in Table 6.

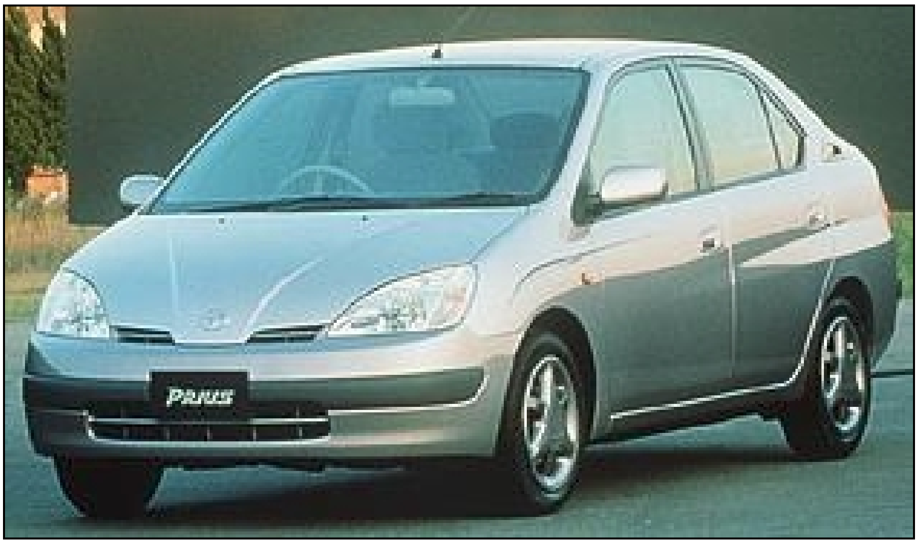


Figure 38: Toyota Prius Hybrid Electric Vehicle

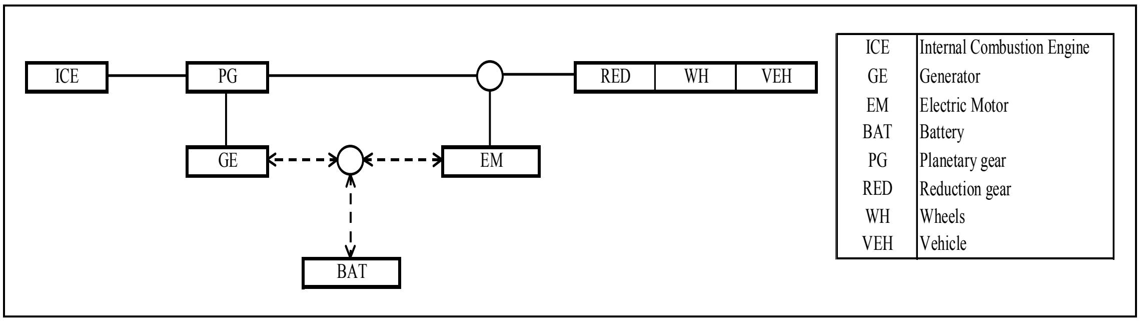


Figure 39: Toyota Hybrid System component configuration

Table 6: Toyota Prius technical specifications

Internal combustion engine		**Reduction gear**	
Type	Otto	gear ratio [-]	3.927
Max power [kW]	43	**Wheels**	
Max speed [rpm]	4000	$R_{dynamic}$ [m]	0.295
Max torque [Nm]	102	Number of wheels (front/rear)	2 / 2
Electric motor		**Vehicle**	
Type	Permanent magnet	Mass [kg]	1240 / 1515[1]
Power (nom/max) [kW]	max 30	C_w [-]	0.3
Base speed [rpm]	940	A [m^2]	-
Generator		**Battery**	
Type	Permanent magnet	Type	NiMH
Power (nom/max) [kW]	-	Capacity [Ah]	6.5
Base speed [rpm]	-	Cell voltage [V]	1.2
Planetary gear		Number of cells [-]	240
gear ratio [-]	-	Internal resistance [mΩ]	-

D2 Measurement procedure

The vehicle has been tested over several different driving cycles. The test cycle was driven in sequences of five with a ten minute rest in between (ignition turned off), see Figure 40. A preconditioning cycle followed by 16 hours of conditioned soak was performed the day before the sequential test.

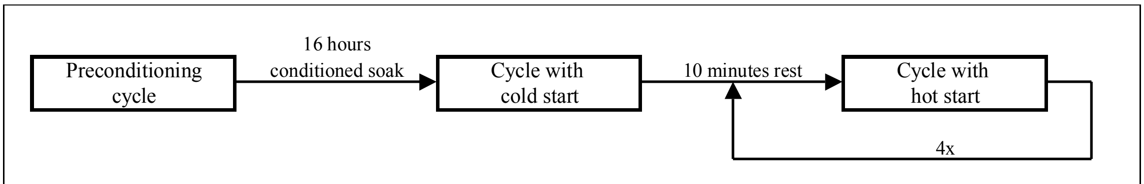


Figure 40: Test sequence used for measurements on a Toyota Prius

Before each cycle the Prius had to be brought into 'Service Mode' in order to be able to test the vehicle on a 2WD rollerbench. On the road the vehicle is driven in 'Normal Mode'. It is assumed that the 'Service Mode' does not affect the drivetrain management, and thus that the results are representative for the vehicle performances on the road.
The measurements have been performed under standard test conditions. For all consecutive cycles the bag emissions (HC, CO, CO_2, and NO_x) were sampled per cycle, and sometimes separate bags were used to divide characteristic phases (e.g. the NEDC was split into the UDC and EUDC). The emission factors are calculated for each phase and for the complete cycle using the actually driven distance on the chassis dynamometer. The fuel consumption (FC [l/100km]), in turn, is calculated from the bag emissions using the carbon balance method (Equation 1). The concentrations of HC, CO, and CO_2 are in g/km and the fuel's density (ρ) is in kg/l.

1 Curb weight respectively maximum weight.

$$FC = \frac{0.1154}{\rho_{fuel}} \cdot (0.866 \times HC + 0.429 \times CO + 0.273 \times CO_2) \qquad \textit{Equation 1}$$

During the tests the current into and out of the NiMH power battery is measured. From this signal the change of capacity in Ampèrehours (Ah) is calculated by integrating the current. The ΔSOC value is obtained by relating the ΔQ (in Ah) to the maximum battery capacity (6.5 Ah).

D3 Measured and calculated parameters

The following measuring signals were recorded:

Low frequency:

- Speed of the rollerbench, v(t) at 1Hz
- Speed of the ICE, $n_{ICE}(t)$ at 1 Hz
- NiMH battery
  - current (DC), $I_{BATT}(t)$ at 1Hz
  - voltage (DC), $U_{BATT}(t)$ at 1Hz

High frequency:

- Electric motor
  - Phase current (AC), $I_{MOT}(t)$ at 7500Hz
  - Phase voltage (AC), $U_{MOT}(t)$ at 7500Hz
- Generator
  - Phase current (AC), $I_{GEN}(t)$ at 7500Hz
  - Phase voltage (AC), $U_{GEN}(t)$ at 7500Hz

The following signals were calculated:

- Battery power (Equation 2)
- Electric motor power (Equation 3)
- Generator power (Equation 4)
- ΔSOC (Equation 5)

$$P_{BATT}(t) = U_{BATT}(t) \cdot I_{BATT}(t) \qquad \textit{Equation 2}$$

$$P_{MOT}(t) = 3 \cdot U_{MOT}(t) \cdot I_{MOT}(t) \qquad \textit{Equation 3}$$

$$P_{GEN}(t) = 3 \cdot U_{GEN}(t) \cdot I_{GEN}(t) \qquad \textit{Equation 4}$$

$$\Delta SOC = \int_{t=\text{cycle start}}^{t=\text{cycle end}} I_{BATT}(t) \cdot dt \qquad \textit{Equation 5}$$

For all the cycles except the preconditioning cycle the bag emissions of HC, CO, CO_2 and NO_X were measured over the different characteristic phases in each cycle. For example, the NEDC was split up into two phases, the UDC (bag 1) and the EUDC (bag 2). The emission factors are calculated for each cycle phase and for the complete cycle using the driven distance on the rollerbench.

$$\text{emission factor [g/km]} = \frac{\text{bag emission [g/cycle]}}{\text{cycle distance}} \qquad \textit{Equation 6}$$

With:

$$\text{cycle distance} = \int_{t=\text{cycle start}}^{t=\text{cycle end}} v(t) \cdot dt \qquad \textit{Equation 7}$$

D4 Results

The vehicle was driven over 6 different driving cycles:

1. New European Driving Cycle (NEDC)
2. Japanese 10-15 Mode Hot Cycle (Jap1015)
3. US City Cycle (USFTP75)
4. Hyzem Urban
5. Hyzem Rural
6. Hyzem Highway

The results of the calculations for each driving cycle are presented in Table 7.

Table 7: Measurement results for a Toyota Prius

	dQ [Ah/100km]	**HC** [g/km]	**CO** [g/km]	**CO2** [g/km]	**NOx** [g/km]	**FC** [l/100km]
NEDC (UDC+EUDC) (cold)	-	0.02	0.13	132.6	0.05	5.54
NEDC (UDC+EUDC) (hot)	-0.098	0.01	0.03	112.8	0.04	4.71
	0.372	0.01	0.03	112.9	0.05	4.71
	0.462	0.01	0.06	113.4	0.05	4.74
	0.243	0.01	0.05	112.6	0.05	4.71
Japanese 10-15 (cold)	-0.289	0.18	0.70	169.3	0.08	7.13
Japanese 10-15 (hot)	-1.070	0.01	0.09	108.0	0.02	4.51
	-0.175	0.01	0.05	108.7	0.02	4.54
	0.570	0.01	0.03	110.9	0.04	4.63
	-0.061	0.01	0.03	109.9	0.03	4.59
USFTP75 (cold)	0.323	0.04	0.29	126.8	0.04	5.32
USFTP72 (hot)	-1.879	0.01	0.05	104.8	0.05	4.38
	0.275	0.01	0.07	110.1	0.04	4.60
	-0.146	0.01	0.05	109.2	0.05	4.56
	0.269	0.01	0.05	110.9	0.06	4.63
Hyzem Urban (cold)	1.358	0.15	0.98	175.7	0.05	7.42
Hyzem Urban (hot)	-5.445	0.01	0.12	119.2	0.12	4.98
	0.036	0.01	0.12	130.3	0.12	5.45
	0.540	0.01	0.05	129.4	0.11	5.40
	0.306	0.01	0.04	127.4	0.14	5.32
Hyzem Rural (cold)	0.864	0.10	0.72	140.9	0.11	5.94
Hyzem Rural (hot)	-0.371	0.01	0.15	123.6	0.14	5.17
	0.394	0.01	0.08	123.4	0.16	5.15
	0.409	0.01	0.11	123.5	0.12	5.16
	0.409	0.01	0.14	122.6	0.11	5.13
Hyzem Highway (cold)	0.527	0.03	0.22	156.1	0.22	6.53
Hyzem Highway (hot)	0.159	0.01	0.12	147.4	0.19	6.15
	0.096	0.01	0.12	148.0	0.18	6.18
	0.063	0.01	0.20	148.7	0.20	6.22
	0.308	0.01	0.15	149.4	0.17	6.24

Appendix E Renault Express Electrique

The measurements on the Renault Express Electrique, according to the European standard procedure EN1986-1, were performed by the Institute for Automotive Engineering (Arnhem, the Netherlands).

E1 The vehicle

The Renault Express Electrique is a battery electric vehicle, based on the conventionally ICE powered version. The vehicle is based on the conventionally powered Renault Express. In Table 8 data on the electric Express is listed.

Figure 41: Renault Express Electrique on the IAE dynamometer

Table 8: Specifications for the Renault Express Electrique

Vehicle		**Controller**	
Gross Vehicle Weight	1235 kg	Manufacturer	ABB
Curb Weight	1337 kg	Controller	High freq.chopper
Pay load (incl. driver)	395 kg	Regenerative capability	1.0 m/s^2 (braking)
Maximum speed	95 km/h	**Battery**	
Range	40 – 70 km	Manufacturer	–
Driveline		Type	Pb-gel
Manufacturer	ABB / GN 21	Voltage	120 V
Type	DS – VB	Capacity	140 Ah
Driven axle	front	Weight	325 kg
Nominal power	22 kW @ 2000 rpm	**Charger (from the grid)**	
Maximum torque	125 Nm	Manufacturer	–
Maximum speed	7000 rpm	Supply voltage	220 V
		Max. charging current	22 A (typical)

E2 Measurement procedure

The European standard procedure EN1986-1 is performed in a period of 24 hours and is described here in short:

1. The vehicle is charged according to the normal, by the manufacturer prescribed procedure;
2. At time t_0, the procedure is started by unplugging the vehicle from the mains (grid);
3. The vehicle has to be moved to and from the dynamometer (when necessary) without using the vehicle's own power source;
4. Within 4 hours from t_0, the test has to be continued on the dynamometer;
5. The vehicle must be reconnected to the mains within 30 minutes after the test on the dynamometer has been ended;
6. The vehicle has to be disconnected at 24 hours from t_0, until then the absorbed energy from the mains has to be recorded.

E3 Measured and calculated parameters

In order to find the desired results, several parameters were measured during the test, while others were derived from measured ones. The measured parameters are:

- Traction battery
    1. Current (I in A)
    2. Voltage (U in V)
- Dynamometer speed
- Vehicle speed
- Energy from the grid (E_G, recorded manually)

The following parameters were calculated from the measured data:

- Energy from the charger into the batteries (Equation 8): $E_{B,C}$ [kWh]
- Capacity from the grid into the batteries (Equation 9): $E_{I,C}$ [Ah]
- Energy from the batteries during driving (Equation 8): $E_{B,DC}$ [kWh]
- Capacity from the batteries during driving (Equation 9): $E_{I,DC}$ [Ah]
- Covered distance during driving (Equation 10): S_{DC} [km]
- Average (arithmetic mean value) battery voltage during driving: U_A [V]
- Energy consumption, relative to grid (Equation 11): EC_G [kWh/km]
- EC_G-ratio, related to the EC_G of the NEDC (Equation 12): R_E [-]
- Charging efficiency (Equation 13): η [-]
- Energy consumption, relative to battery (Equation 14): EC_B [kWh/km]

- Energy consumption, relative to the grid (Equation 15): $EC_{B,I}$ [Ah/10km]
- Failure time: F [%]

These parameters are calculated with the following equations:
i = C for Charging *or* DC for Driving the Cycle

$$E_{B,i} = \int_{t=t_1}^{t=t_2} U(t) \cdot I(t) \cdot dt$$ *Equation 8*

$$E_{I,i} = \int_{t=t_1}^{t=t_2} I(t) \cdot dt$$ *Equation 9*

$$S_{DC} = \int_{t=t_1}^{t=t_2} v(t) \cdot dt$$ *Equation 10*

$$EC_G = \frac{E_G}{S_{DC}}$$ *Equation 11*

$$R_E = \frac{EC_{G,\,Cycle}}{EC_{G,\,NEDC}}$$ *Equation 12*

$$\eta = \frac{E_{B,C}}{E_G}$$ *Equation 13*

$$EC_B = \frac{E_{B,C}}{S_{DC}}$$ *Equation 14*

$$EC_{B,I} = \frac{E_{I,C}}{S_{DC}} \cdot 10$$ *Equation 15*

E4 Results

The vehicle was driven over 6 different driving cycles:
1. New European Driving Cycle (NEDC)
2. Japanese 10-15 Mode Hot Cycle (Jap1015)
3. US City Cycle (USFTP75)
4. Hyzem Urban
5. Hyzem Rural
6. Hyzem Highway

The results of the calculations for each driving cycle are presented in Table 9.

Table 9: Results of the measurements on a Renault Express Electrique over 6 different driving cycles

Cycle		NEDC	Jap1015	USFTP75	Hyzem Urban	Hyzem Rural	Hyzem Highway
E_G	[kWh]	3.63	1.05	5.22	1.12	3.85	16.10
$E_{B,C}$	[kWh]	2.67	0.80	4.01	0.82	3.03	12.21
$E_{I,C}$	[Ah]	21.08	6.23	31.91	6.39	23.90	96.56
$E_{B,DC}$	[kWh]	1.72	0.55	2.76	0.53	2.04	8.28
S_{DC}	[km]	10.58	4.18	17.61	3.39	10.92	36.63
E_I	[Ah]	16.20	4.90	26.22	4.89	19.60	83.41
U_A	[V]	114.3	119.1	113.4	119.0	112.5	102.1
EC_G	[kWh/km]	0.35	0.25	0.30	0.33	0.35	0.44
R_E	[-]	1	0.73	0.86	0.96	1.03	1.28
η	[-]	0.74	0.77	0.77	0.74	0.79	0.76
EC_B	[kWh/km]	0.16	0.13	0.16	0.16	0.19	0.23
$EC_{B,I}$	[Ah/10km]	15.32	11.72	14.89	14.40	17.94	22.8
F	[%]	7.7	0	3.3	0	15.4	69.3

Appendix F ALTROBUS

In the framework of the MATADOR project, a series hybrid bus was tested by ENEA, Italy.

F1 The vehicle

The ALTROBUS is developed by the ALTRA society in co-operation with the Ansaldo Ricerche and Fiat-IVECO companies. Two versions of the ALTROBUS were built. The first is 12 meters long, has a weight of approximately 12.8 tons, and can carry about 85 passengers. The other one measures 6 meters, weighs 4.2 tons, and can carry 21 people.

The ALTROBUS is equipped with a series hybrid power train. An electric motor drives the rear wheels. Electric power is provided by a lead-acid battery and a generator set, consisting of an IDI diesel engine and a synchronous PM machine. The control for the generating system is not automated. The driver decides when the engine should be started or shut down.
The vehicle has a range of 150-200 km in thermal mode (engine on) and 20 km in the all electric mode.

A special version of the 6m vehicle was specially designed by ALTRA for ENEA. The drive system is installed on a standard truck chassis in order to give more freedom for experimental purposes. This test vehicle, for instance, has been equipped with an automated control for the APU, of which the control algorithm can be altered. Figure 42 shows the vehicle on the rollerbench at ENEA. The specifications for the ENEA version of the ALTROBUS are listed in Table 10.

Figure 42: ALTROBUS on the ENEA dynamic rollerbench

Table 10: ALTROBUS technical specifications (ENEA version)

Internal combustion engine		**Electric Motor**	
Type (fuel)	IDI diesel	Type	Separately excited DC motor
Displacement (cc)	1204		
Max. power [kW]	24 @ 3600 rpm	Rated power [kW]	22 (1500-4500 rpm)
Rated speed [rpm]	2200 rpm	Rated voltage [V]	192 (Armature)
Regulation	mechanical		85 (Field)
Generator		Max. speed [rpm]	4800 rpm
Type	Synchronous PM	Max. torque [Nm]	172 @ 1200 rpm
Rated power [kW]	10 @ 2200 rpm	Features:	
Rated voltage [V]	220	• DC-DC electronic power converter	
Battery		• Current controlled mode	
Type	Lead acid	• Separate Control of Armature and Field current	
Capacity (C_5) [Ah]	100	• Regenerative braking	
Number of cells	96		
Electronic battery charger		**Vehicle**	
Rated power [kW]	10	LxBxH [m]	6.0 x 2.1 x 2.8
Rated voltage [V]	192	Weight [kg]	3500
Mechanical transmission		Max. speed [km/h]	55
Type	Fixed reduction gear	Regenerative braking [kW]	15 and 30
Gear ratio	2.26		

F2 Measurement procedure and measured parameters

The test is started with 80% State-of-Charge. ΔSOC is kept between ±5% (75 to 85%).
The available battery capacity is 70Ah at the C_5 discharge rate, instead of 100Ah (manufacturer specification).
The room temperature varies between 10 and 15 °C.

During each test, a set of parameters has been measured and recorded:

1. Vehicle speed
2. Battery current
3. Electric motor current
4. Battery voltage
5. Fuel consumption
6. State-of-Charge
7. Travelled distance
8. Energy for recharging the battery from the mains
9. Test time

Sign convention for several signals:

Generator current:	positive when engine is active
Battery current:	positive during discharge, negative when being charged
Electric motor:	positive when driving, negative during regenerative braking

F3 Results

The ALTROBUS was driven over 6 different cycles. Due to the limitations (maximum speed) only urban parts of the cycles were driven. The following cycles were used:

7x Urban Driving Cycle (UDC, Urban part of NEDC)
10x Japanese 10-15 (only urban part = first 440 seconds)
3x Hyzem Urban
11x MODEM (only slow urban part)
5x UDDS (only stabilised part)
8x Casaccia cycle (Figure 43)

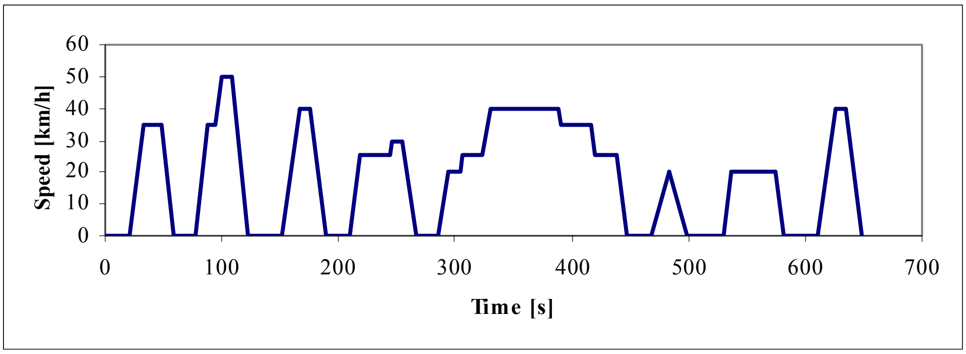
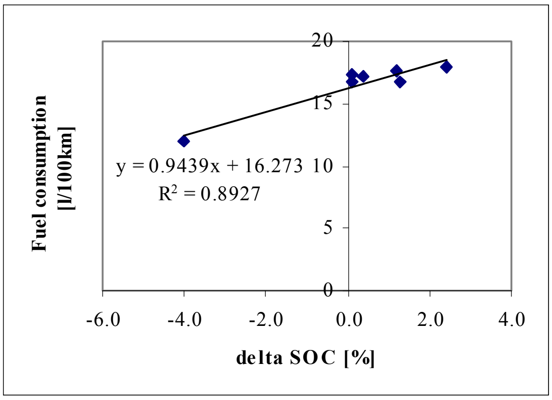
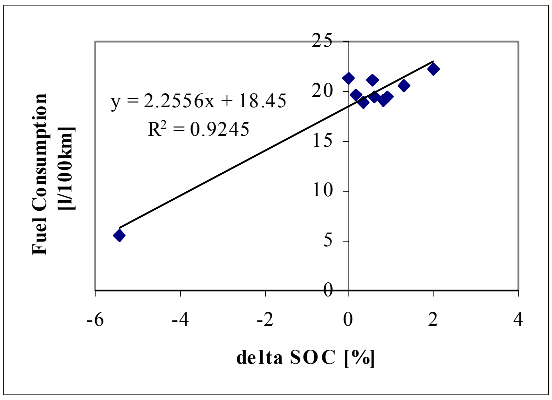


Figure 43: Speed trace of the ' Casaccia driving cycle'

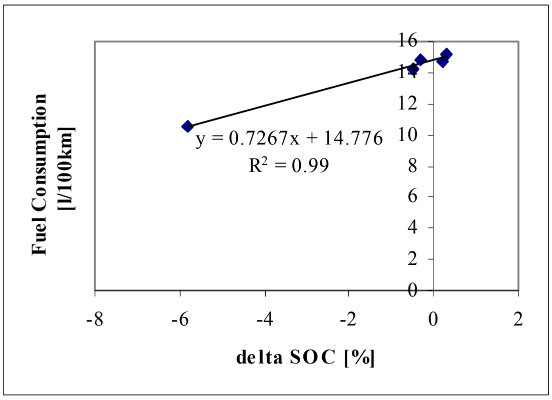
Not all cycles are driven without difficulties. Especially with higher speeds, the vehicle sometimes was not able to reach the desired speed. On the Hyzem Urban cycle the vehicle turned out to be charge depleting and the test was stopped after three cycles since the battery voltage had become to low. The energy consumption of the ALTROBUS is determined by means of linear regression of ΔSOC and fuel consumption. The regression plots are presented in Figure 44.



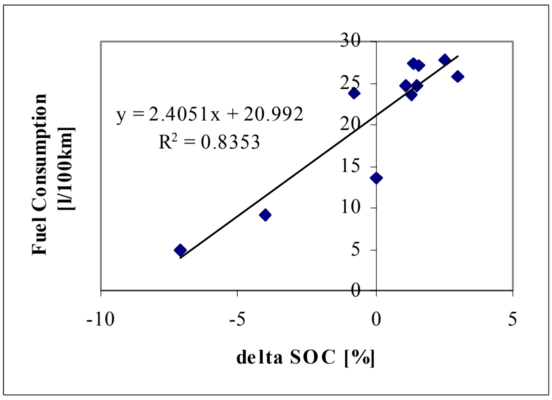
UDC



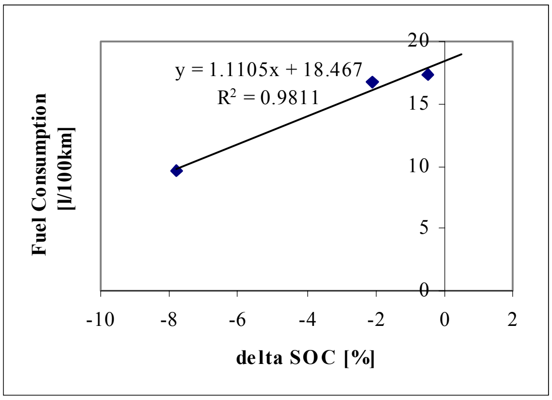
Japanese 10-15



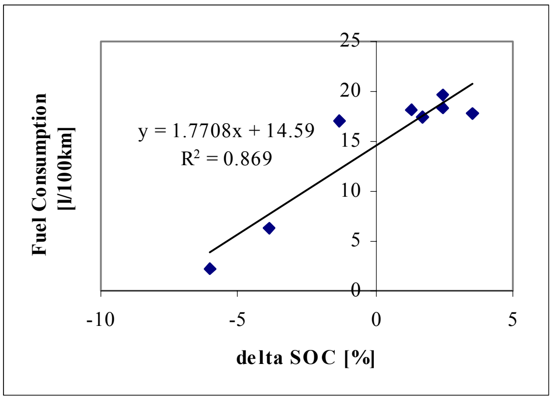
UDDS



MODEM slow urban



Hyzem Urban



Casaccia

Figure 44: Regression lines for the ALTROBUS over six different driving cycles

MANAGEMENT TOOL for the ASSESSMENT of DRIVELINE TECHNOLOGIES and RESEARCH

MATADOR

Contract JOE3-CT97-0081

Task 2:

Testing methods for vehicles with conventional and alternative drivelines

Subtask 2.9

Test methods and driving cycles for HD vehicles

TNO Automotive

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by
Iddo J. Riemersma (TNO Automotive)

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Nomenclature

Abbreviations

ACEA	Association des Constructeur Européens d'Automobiles
APU	Auxiliary Power Unit
BEV	Battery Electric Vehicle
CS	Control Strategy
ELR	European Load Response test
ESC	Engine Stationary Cycle
ETC	European Transient Cycle
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
FCHEV	Fuel Cell Hybrid Electric Vehicle
FiGE	Forschungsinstitut für Gerausche und Erschütterung
GRPE	Group of Reporters on Pollution and Energy
GVW	Gross Vehicle Weight
HD	Heavy-Duty (generally vehicles > 3.5 tons)
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
ICEV	(Conventional) Internal Combustion Engine Vehicle
ISO	International Standards Organisation
LD	Light-Duty (generally vehicles < 3.5 tons)
MATADOR	Management Tool for the Assessment of Driveline TechnOlogies and Research
OICA	Organisation Internationale des Constructeurs d'Automobiles
TNO	(Netherlands) Organisation for Applied Scientific Research
UN-ECE	United Nations Economic Commission for Europe

Symbols

CO	Carbon mono-oxide emission	[g/km] [g/kWh]
CO2	Carbon dioxide emission	[g/km] [g/kWh]
HC	Hydro carbonate emission	[g/km] [g/kWh]
NOx	Nitrogen oxide emission	[g/km] [g/kWh]
BSFC	Brake Specific Fuel Consumption	[g/kWh]

Contents

1 Introduction

In the context of Task 2 of the MATADOR-project (Management Tool for the Assessment of Driveline Technologies and Research, EU-contract JOE3-CT97-0081), research is carried out in support of the development of test procedures for electrically propelled road vehicles and vehicles with other alternative drivelines. The definition of testing procedures for determining energy consumption and emissions of vehicles with different drivelines requires the evaluation of technical aspects, specific of each vehicle technology. Furthermore, the development of testing procedures that allow for a comparative technical benchmarking of different vehicle powertrains is an even more complicated task, because the performance of each technology could be significantly different (alternative fuels, hybridisation, combined energy sources), asking for various measuring needs. Key issues have been addressed and are evaluated in terms of their impact on testing methods.

Conventional Heavy Duty (HD) vehicles do not only differ from Light Duty vehicles by weight and power, as will become apparent in this report. From a testing point of view the main difference is the fact that for legislation purposes not the *vehicle* is tested over a driving cycle (as is the case for LD vehicles), but that the *engine* is tested in an engine test. For the definition of test procedures for HD BEVs, HEVs, and FCEVs this introduces a number of problems, that will be addressed.

This report starts with a description of the currently testing methods in use for HD vehicles, and an overview of the issues that arise when applying these to (hybrid) electric or other alternative powertrains. In order to reckon with the identified problems, several boundary conditions are set for future test cycles, illustrated by the results of simulations and vehicle tests. The report is completed with conclusions and recommendations on the subject.

2 Test cycles for conventional HD road vehicles

An important element of the legislative test method to measure exhaust gas emissions and fuel consumption of conventional road vehicles is the test cycle. In this respect, a distinction has to be made between light duty and heavy duty vehicles:

- In the case of LD vehicles (passenger cars and light commercial vehicles) testing is done with the complete vehicle on a chassis dynamometer that allows the simulation of a trip made with the vehicle. The test cycle in this case is a driving cycle, defined as a time-speed sequence.
- In the case of HD vehicles (in principle vehicles above 3500 kg GVW), it was decided to certify engines rather than vehicles. Consequently, the test cycle is set up for an engine on an engine testbed. The test cycle in this case is defined as an engine cycle. Testing is done 'steady state' or 'transient'. The steady state cycle consists of the measurement of a series of fixed points in the engine's speed-torque map. The transient engine cycle consists of the simulation of a vehicle-based driving cycle on an engine testbed.

In the case of HD vehicles the variety of vehicles is large, with much smaller series for each configuration. Moreover, the original manufacturer often only produces a self-propelled chassis, or a chassis with cabin, on which a specialised firm builds a special body. In such cases it is impossible for the manufacturer to certify the final product, whereas the body builder cannot be held responsible for the emissions and only partially for the fuel consumption. Furthermore, the measurement of a HD vehicle on a chassis dynamometer is difficult, expensive and often even downright impossible.
Another important aspect is the use of the vehicle, which may be quite different. A long distance truck for instance will be operated quite differently from a city bus or a distribution truck. Different driving patterns result in different load patterns for the engine.

For the above mentioned reasons it was decided to certify engines rather than vehicles. Emission limits are not written in absolute terms as for LD vehicles (g/km), but related to power delivered by the engine (g/kWh).

There are three basic legislations covering the testing of road vehicles, all using different test cycles:

- The US legislation (sometimes to be divided into the Californian and the US Federal legislation). This legislation is also adopted by Canada, several South American countries and many Asian countries.
- The Japanese legislation. This is mostly limited to Japan itself.
- The European legislation. This is adopted by both West and East Europe and some countries outside Europe.

Besides the legislated test cycles, different real-world 'actual' test cycles are developed in order to represent the actual use of vehicles.

As there is no legislation that prescribes a *vehicle* test, dedicated vehicle driving cycles for HD vehicles are rare. One example is the so-called Dutch Urban Bus Cycle [1][3]. Another reason for the absence of these cycles is the fact that there are limited facilities available for testing HD vehicles; within the whole of Europe there are only 3 HD dynamic rollerbenches.

The next paragraph gives an overview of the currently used test cycles for HD vehicles.

2.1 Engine cycles for Heavy Duty vehicles

Most testing on heavy duty engines is currently done 'steady state'. The test cycle consists of measuring a series of fixed points in the engine's speed-torque map. The emission results of these points (in g/h) are then multiplied with a weighting factor and summed. Similarly, a weighted sum of the power in these points is determined. Dividing the weighted emissions by the weighted power produces the end result in g/kWh. The predefined points are measured with a warm (stabilised) engine. This is the current procedure in Europe (Figure 1) and Japan (Figure 2). The European version is known as the ECE R49 13-mode test, after the number of measuring points. The actual measuring points however differ for both legislations. Also, the original US procedure followed this pattern, using more or less the same operating points as later adopted for the European legislation, but with different weighting factors. For non-road engines ISO has developed a procedure that is based on the 13-mode test but with different weighting factors for the points, according to the intended use of the engine. In some exceptional cases even the actual measuring points may be different. This procedure has found its way into the EU legislation for agricultural tractors and non-road-going mobile machinery.

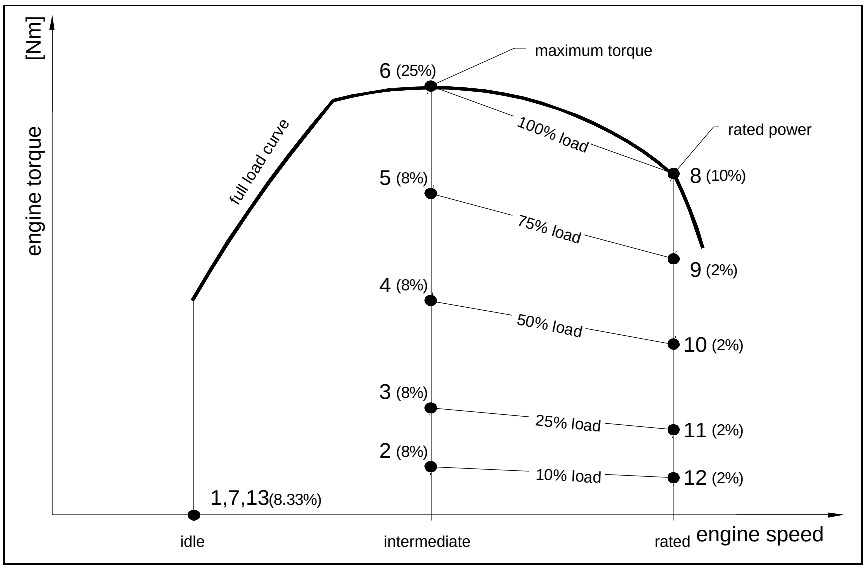

Figure 1: ECE R49 European 13-mode test

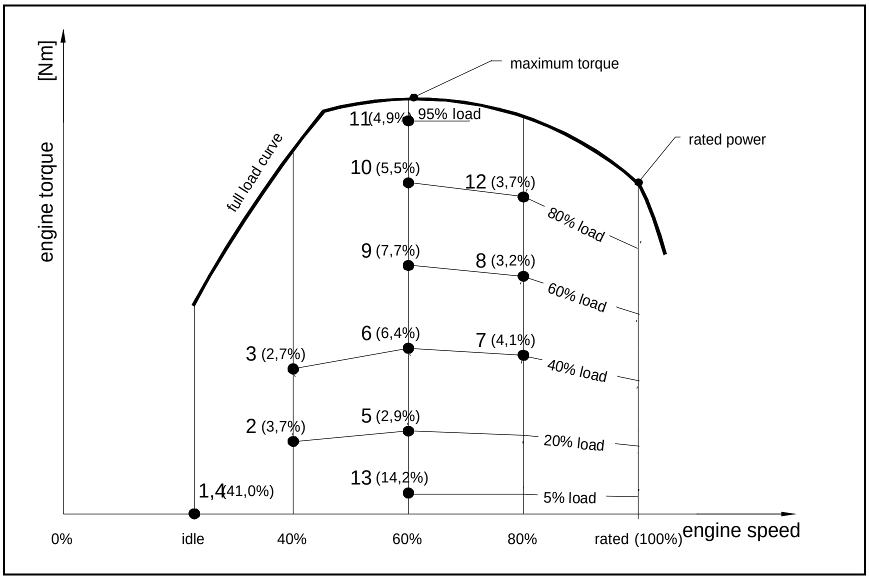

Figure 2: Japanese 13-mode test

The current US procedure uses a transient engine cycle (Figure 3). This test actually consists of the simulation of a vehicle-based driving cycle on an engine testbed. This requires the possibility to simulate vehicle inertia effects on the engine testbed, which makes this an expensive piece of equipment. The exhaust sampling system required, is equivalent to that for the current LD procedure, due to the larger cylinder capacity. The usually large flow through HD engines requires sizeable, and therefore expensive, dilution equipment. The use of equipment needed for a transient engine test is therefore, at this moment, limited to major manufacturers and advanced research institutes. Results are still expressed in g/kWh. The cycle is representative for urban operation only (including, however, urban freeway use). The cycle starts with a cold engine, in order to include cold start emissions.

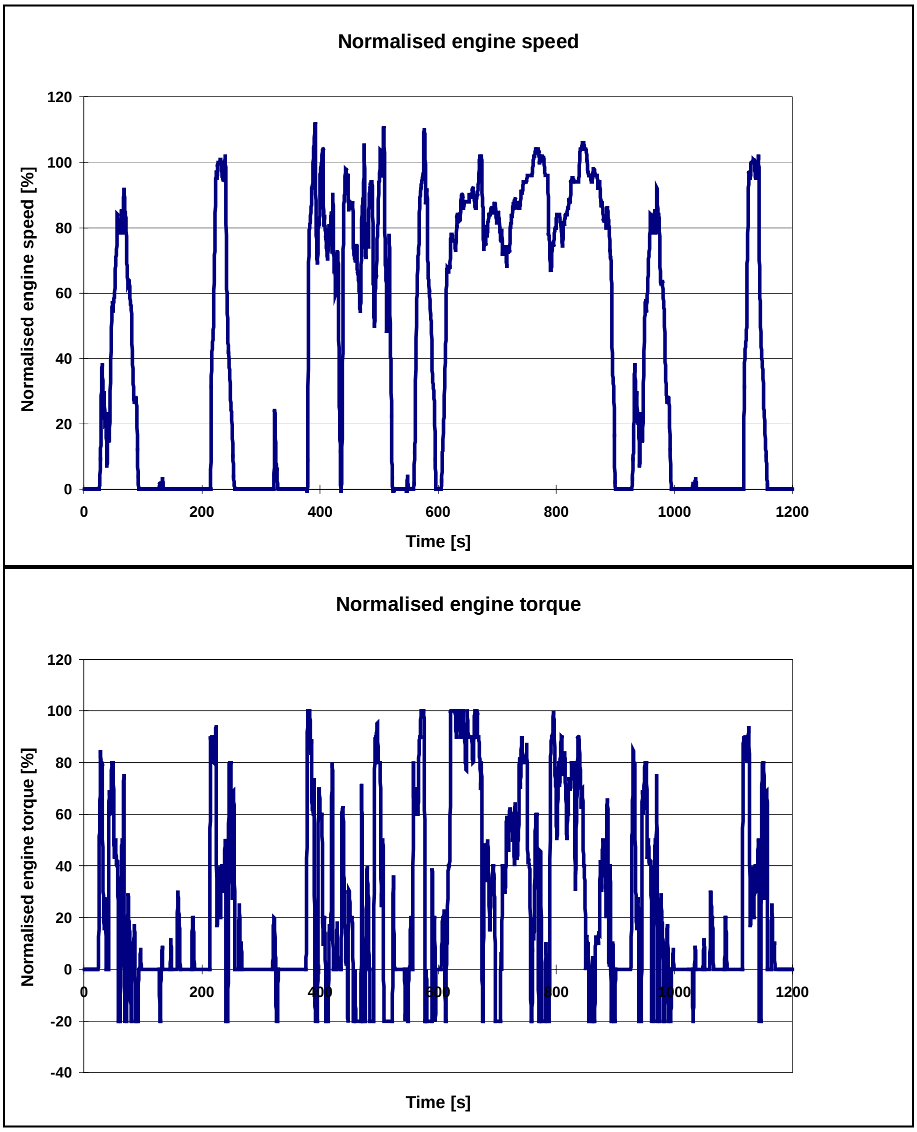

Figure 3: *US transient Engine Cycle*

By October 2000, the EURO 3 European legislation will replace EURO 2 for newly introduced engine types, and one year later for all new engines. It still contains a steady state procedure, but also a transient engine test, dependent on the used engine technology. They are described in detail below.

- The steady state procedure (European Stationary Cycle, ESC, Figure 4) will be mandatory for all HD engines. The ESC is a strong modernisation of the current test procedure, much better matched to the actual use of modern road-going engines. It is developed by the Organisation Internationale des Constructeurs d'Automobiles (OICA) and the Association des Constructeurs Européens d'Automobiles (ACEA). Like the present European R49 13-mode test, the newly developed ESC is a stationary 13-mode test cycle. However, there are some differences between the two cycles. The engine speeds at the measuring points have changed. All measurements take place in a pre-defined range, which is used most in European traffic. For this, three engine speed lines (A, B, C) have been defined depending on the maximum engine torque curve (Figure 4). The weighting factors have been modified as well. The location of the load points as well as the weighting factors have been derived from a large number of measurements that were performed on heavy-duty vehicles by the "Forschungsinstitut für Geräusche und Erschütterung" (FiGE) [2]. Additionally, the NO_x emission is to be measured at three test points within the operating area. The points are to be selected randomly by the technician performing the test. The NO_x emission measured has to correspond to a certain limit with respect to the values calculated from the modes of the test cycle enveloping the selected test points. This NO_x measurement procedure ensures the effectiveness of the emission control of the engine within the typical engine operation range and prevents cycle bypassing to a certain extent. For the assessment of smoke emissions during transient engine load, the ESC is extended with the European Load Response Test (ELR), which also has been developed by OICA/ACEA. In this test the load is increased from 10% to 100% at constant speed measured at three different engine speeds (A, B, C in Figure 4). Additionally, a fourth load-step at a speed between point A and C must be chosen. The value found has to be comparable to the values determined in the previous load-steps.
- Transient behaviour can have a substantial influence on the production of emissions. For conventional diesel engines the transient effects appear to be well within rather narrow limits. This could, however, be very different for certain near-future technologies that may show very big effects during transient engine load. Therefore, the European Transient Cycle (ETC, Figure 5) will be mandatory for Otto engines, and Diesel engines with exhaust gas aftertreatment systems or exhaust gas recirculation. The ETC was developed by FiGE, by order of the Umweltbundesamt (UBA Berlin). From the already mentioned heavy duty cycle database [2], the "FiGE transient cycle" was derived, which was later renamed to ETC. The cycle is a simulation of urban, rural and highway traffic, each with a 33% time-share. This distribution, however, is not supported by statistics. The cycle is represented by normalised torque and speed as is shown in the case of the US Transient Cycle (Figure 3). For improved interpretation of the cycle, it is often presented as a time-speed pattern, as is shown in Figure 5.

In October 2005 the Euro 4 legislation will become effective for newly introduced engines, and one year later for all engines. Compared to Euro3 this incorporates stricter emission regulations, and an obligation of the ETC test on all engines. For the year 2008 and beyond, one strives for world harmonisation. One step in that direction is the development of an appropriate world wide engine test cycle, that is representative for engine load in real-life. Currently, TNO and TÜV Automotive are working on a proposal for a world-cycle, based on a very large database of world-wide in-use driving data, together with detailed statistics. They perform this assignment by request of the GRPE (Group of Reporters on Pollution and Energy) of the United Nations Economic Commission for Europe (UN-ECE), and are financially supported by the Dutch Ministry of Environment and the German Federal Environmental Agency. The UN-ECE is responsible for the proposals for the definition of engine test procedures, as well as for the setting of emission regulations (Table 1).

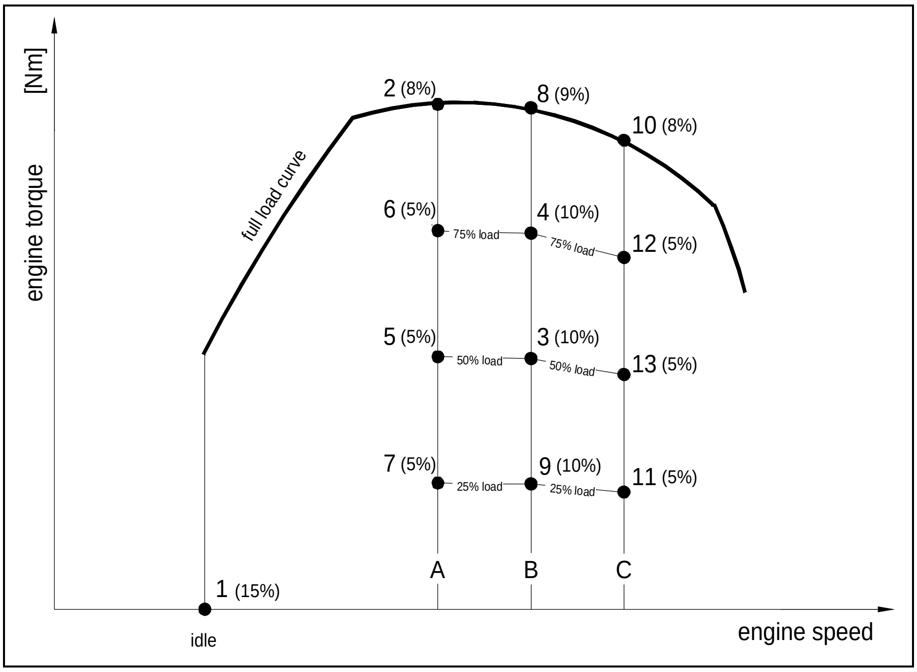

Figure 4a: Load points with weighting factors for the ESC stationary test

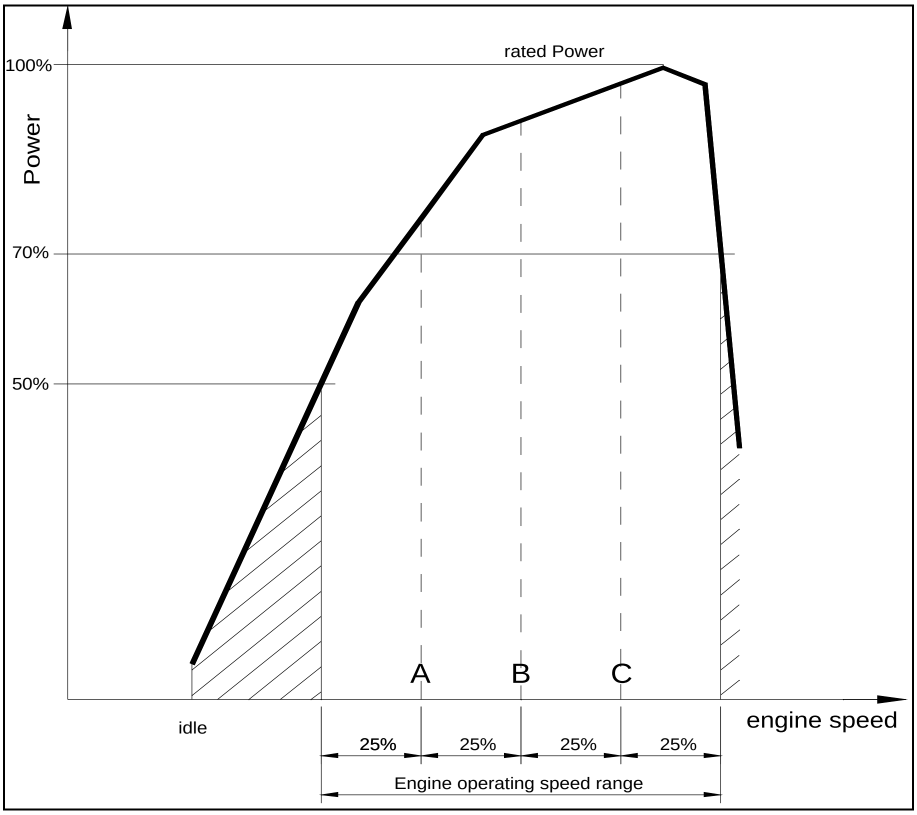

Figure 4b: Determination of the engine speeds for the ESC stationary test

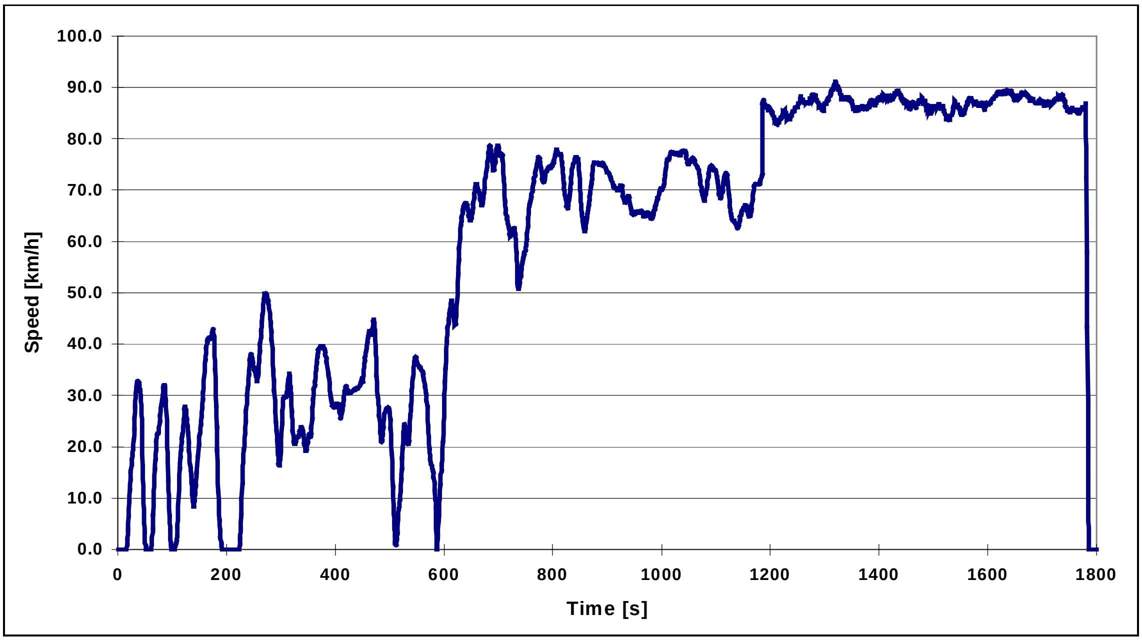

Figure 5: European Transient Cycle (ETC), here visualised by a time-speed pattern

Table 1: GRPE decisions on approval test cycles

Technology		**Engine Test Cycle**
Euro2 1996		ECE R49 13-mode test (since 1982)
Euro3 10-2000 10-2001	New HD engines All HD engines	ESC + ELR
	Modern Diesel (exhaust after-treatment systems)	ESC + ELR + ETC
	Otto (LPG/CNG)	ETC
Euro 4 10-2005 10-2006	New HD engines All HD engines	ESC + ELR + ETC
World 1 ± 2008		World Harmonised Transient Cycle (expected)

Fuel consumption of HD engines is not officially regulated, but can be determined in the same way as the emissions in g/kWh.

For determining emission and fuel consumption factors on the vehicle level, the results of the approval testing have to be fed into calculation models that link the engine to a specific vehicle and a specific driving pattern in order to obtain emissions and fuel consumption in g/km [1].

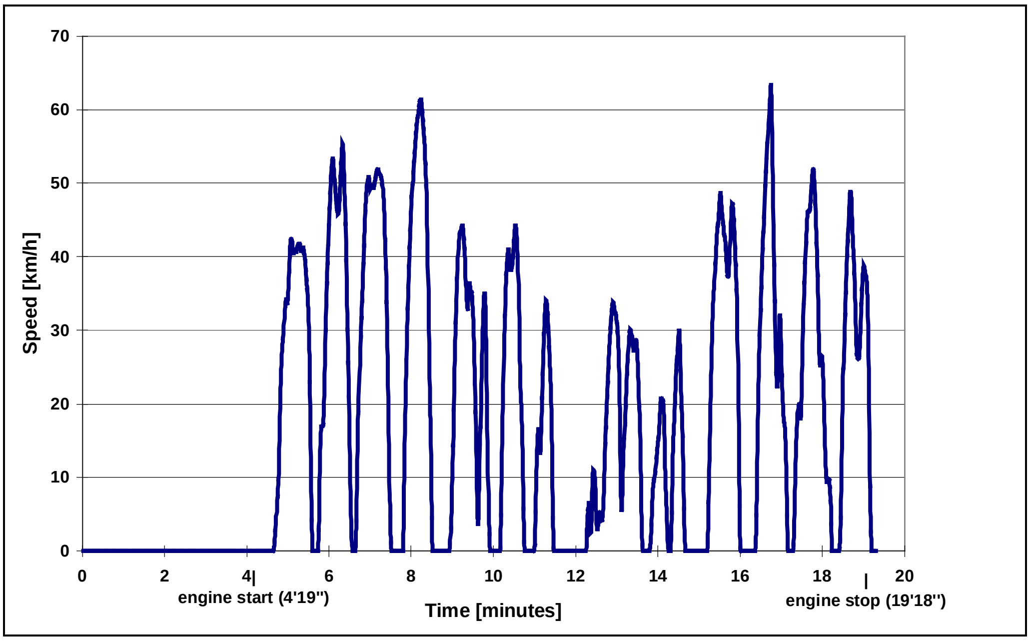

Figure 6: Speed trace of the 'Dutch Urban Bus Driving Cycle'

Besides the legislated *engine* cycles, also different real-life 'actual' *driving* cycles have been developed in order to represent the actual use of heavy duty vehicles, and to create the possibility to test heavy duty vehicles on a rollerbench. This is a transient test and requires the possibility to simulate vehicle inertia effects on the rollerbench. Compared to the earlier mentioned transient engine testbed, this is an even more expensive piece of equipment, as the inertia effects are simulated on the entire vehicle. The requirements for the exhaust sampling system are the same as for the transient engine testbed. At this moment there are only three institutes in Europe with a transient rollerbench for HD vehicles. The test is in this case, as for LD vehicles, vehicle based, and the results are expressed in g/km.
An example of a driving cycle for a specific group of HD vehicles is the Dutch Urban Bus Driving Cycle, developed by TNO to represent the average use of urban buses in the Netherlands (Figure 6) [1][3].

3 Problem definition for applying current test procedures

This chapter illustrates the problems that can occur when current HD test procedures for conventional vehicles are applied to non-conventional HD driveline types (e.g. BEV, HEV and FCEV). First the background of these procedures is clarified, followed by the identification of possible problems. On the basis of the identified issues for the engine test procedures, the boundary conditions for vehicle-based driving cycle properties are outlined.

3.1 Background

Until now, Heavy Duty vehicles are not tested as a whole. As explained in the previous chapter, only the engine is regulated by approval tests, because HD vehicles appear in many combinations of engine, chassis, body-work, and loading facilities. At this moment and in the near future, hybrid propulsion technology will also enter this category of vehicles. In an ICE-based hybrid vehicle, the engine is used differently compared to a conventional vehicle. The engine is e.g. used in only one operating point or in a limited operating range, and may be switched off while the vehicle is driving electrically. This means that the results of a conventional engine test are not representative for the environmental performance of the hybrid vehicle. Regulations could hardly cope with all of the possible operating conditions this would bring. Other merits of hybrid propulsion technology, such as the possibility of regeneration of braking energy, are also not taken into account by an engine test. Consequently, an engine test cycle will no longer suffice for approval testing. It should be replaced by a driveline-based test, or even better a vehicle-based test, that is representative for all of the driveline behaviour during real-life driving conditions.

3.2 Identification of problems

Hybrid propulsion systems appear in many different configurations, with a variety of applied components, and numerous control strategies. Important issues that are not properly dealt with by applying current test procedures will be illustrated here for the case of a series hybrid driveline, but they also apply to other types of powertrain configurations.

<u>Regenerative braking</u>
One of the major advantages of a (series) hybrid electric propulsion system is its ability to regenerate braking energy. This property is not taken into account when only the engine is tested, as this energy comes from the wheels, and is restored in the battery. From this point of view, an honest comparison between conventional and hybrid propulsion systems can only be guaranteed by testing the driveline as a whole (or even the complete vehicle) for real-life conditions. A driving cycle based on real-life driving patterns could very well suit this purpose.

<u>Engine load points</u>
The primary engine of a series hybrid propulsion system is usually operated in one (or a few) point(s) of its engine map, where fuel efficiency and emissions are most favourable (the so-called 'sweet-spot'). The delivered power is controlled by switching the engine on and off. Engines of conventional propulsion systems are operated in all parts of the engine map, because they need to deliver the exact amount of power requested by the driver, together with a certain engine speed dictated by vehicle speed and selected gear.
For this case, an engine test may appear to be applicable. Of course, it would need to be tuned to the operating points of the engine, instead of prescribing a number of operating points within the engine map. But then a problem arises in weighing the test results. In the current 13-mode test,

both the operating points and the weighting factors are defined. Once the operating point(s) of the engine are defined by the manufacturer of the vehicle, there is no unambiguous way to determine appropriate weighing of these in order to obtain a comparative result. By using a vehicle based driving cycle, the weighing is implicitly guaranteed, as long as the cycle is representative for real-life driving patterns.

Cold start emissions
HD engines are currently tested while the temperature is in normal operating condition. For current HD applications this is acceptable, as these are used for long periods and therefore will be hot for most of the time. Besides, current technology engines are not equipped with catalysts or other exhaust aftertreatment systems that need to reach high operating temperatures to work properly. For hybrid propulsion systems this situation may change. The engine can be shut down during driving for short or longer periods, causing the engine and its exhaust aftertreatment systems to cool down. When the engine is started again, some time is needed to reach normal operating temperature, during which the emissions may be significantly higher. Again, this is only reproducible by testing the vehicle on a driving cycle that represents real-life conditions.

Power boosting
The combustion engine of a parallel hybrid driveline will operate just like in a conventional driveline, when used in the normal drive-mode. Some of the parallel hybrid drivelines however have a possibility of power boosting, which means that the electric motor assists the combustion engine during accelerations for reasons of emission reduction. If only the combustion engine is tested, this effect will not show in the test result. This property can only be correctly dealt with by using a driveline-based or vehicle based test cycle.

Finally, there is one other aspect that needs to be highlighted here. Conventional HD engines are currently tested in a static 13-mode test, though in real-life they undergo dynamic load changes. The extra produced emissions due to this transient behaviour are not negligible, especially for advanced engine technologies that have low static emissions. Engines in (series) hybrid propulsion systems however, show a far more static operation, with less transient emissions. A static test will therefore not allow for a comparative test result between conventional and hybrid propulsion systems.

The identified problems that arise when current test procedures are applied on non-conventional HD drivelines, clearly indicate that:

- current engine based test procedures are not suitable for non-conventional HD drivelines (BEV, HEV, FCEV);
- only testing the engine will not suffice. The driveline as a whole (or even better, the vehicle as a whole) needs to be tested on a driving cycle;
- in order to obtain an honest test result, the test needs to represent real-life conditions; a static test is not preferable.

3.3 Requirements for future test procedures

It has been found that current test procedures are not suitable for non-conventional HD drivelines, and that (representative) driving cycles form a far better basis for the mutual comparison of environmental performance for drivelines. Based on these conclusions, the most important requirements for future test procedures can be outlined.
First, the type of driving cycle is investigated. What is regarded as 'representative', can be quite different for categories of HD vehicles. LD vehicles are all more or less driven in the same way, so they can also be tested on the same cycle. In case of HD vehicles, there is a large variety in driving conditions, depending on the intended use of the vehicle (long distance transport,

distribution, city passenger transport). Different driving conditions will have different effects on the load pattern of the engine. This calls for dedicated cycles for each type of vehicle operation, as it would not be rational to certify an engine for e.g. a long distance truck on a bus cycle, due to the different operating conditions.

The importance of a driving cycle being representative has been stressed several times. This does not only mean that it is based on a real-life driving pattern, but moreover a cycle with characteristics that match the 'average use' of the observed vehicle category. This can be illustrated by looking at the possibility of regenerative braking in hybrid vehicles. The amount of energy that is regenerated depends heavily on the dynamics of a driving cycle. If for instance large periods with (almost) constant speed occur in a cycle, this amount will be small. For a test cycle that has lower dynamics than real-life driving patterns, the advantage to regenerate braking energy is insufficiently emphasised. However, if a driving cycle shows (too) high dynamic vehicle behaviour, the hybrid propulsion system may be depicted too positively in comparison to a conventionally driven vehicle. This is only one aspect that calls for representativity; similar considerations can be made for the other identified problems of paragraph 3.2.
The development of representative driving is a complex process. The key issue is to create a test cycle with the same relevant characteristics as that of a large database with driving patterns that together represent the average use. This process is described in detail in Appendix A of Subtask Report 2.8 '*Driving cycles for LD vehicles*', and can also be found in [1].

As a result of the fact that in current test procedures only the engine is regarded, there are only few (dedicated) driving cycles available, and therefore also the number of HD vehicle dynamic rollerbenches is limited; at this moment there are only three known facilities within the whole of Europe. So, in order to be able to perform these driving cycle tests, large investments are required if future legislation were to be based on vehicle driving cycles. Apart from this, the testing on a rollerbench also induces a problem. Regenerative braking is applied only on the driven wheels. As the full mass of the vehicles is simulated on these wheels, the regenerated energy is overestimated. This problem is illustrated in Subtask 2.12, '*Regenerative braking on 2WD dynamometers*'.

Alternatively, it may be possible to define more pragmatic testing methods that do not demand a large investment, but still give representative results. One possibility is to drive a cycle on a test track, and to monitor the power output of the ICE (or APU). Later on, the ICE can be tested on an engine testbed, by applying the same load pattern. Hybrid HD vehicles have not yet been tested extensively, so there is relatively little experience in this area
In case the vehicle has an APU, the load can also be applied electrically. At TNO there is a facility called a Digatron system, that can simulate a generator, battery or electric motor. This device is very well suited to simulate this electrical load. The advantage of this method is that there is no need to take the engine out of the vehicle.
If a hybrid electric HD vehicle is tested, the battery current and voltage also need to be monitored, during the driving of the cycle on the test track, in order to allow for a ΔSOC correction. In Subtask 2.4 '*ΔSOC correction methods for HEVs*' this subject is described in detail.

3.4 Simulations and vehicle tests

In Subtask 2.8 '*Representative driving cycles for LD vehicles*', the influence of cycle parameters on fuel consumption is described in detail for LD vehicles, with a number of accompanying simulations. There is no reason to assume that HD vehicles would respond differently, so the findings of this subtask apply here as well. For this subtask, no other simulations of interest to this subject could be identified (the lack of HD driving cycles also contributes to this). The considerations of the previous paragraphs may very well speak for themselves, though further illustration would have been preferable.

One hybrid bus was tested over the Dutch Urban Bus Cycle, in the course of a related project '*Pragmatic Measuring Procedures Hybrid Electric Vehicles*' that TNO performed. In the tests, the fuel consumption was measured, the braking strategy was determined, and the regenerated energy was observed. As the measurement program only consisted of one vehicle type and one driving cycle, the test results are not extensive enough to support or reject the findings of this subtask.

4 Conclusions and Recommendations

In this subtask report, problems have been identified that arise when current HD test procedures are applied to non-conventional HD drivelines (e.g. BEV, HEV, and FCEV), and requirements for future test procedures have been outlined. As a result of this analysis, there are four options for test procedures that can be distinguished. In order to provide clear interpretation of the argumentation, it is first necessary to clarify the following terminology:

- *Driving condition*: The driving behaviour of HD vehicles, as it is found in real life on the road.
- *Driving pattern*: A recorded speed-time pattern of (real life) driving conditions. The size of this pattern may vary from a few hours to months of data.
- *Representative driving cycle*: A test cycle of limited length (e.g. 30 minutes) that is derived from the driving pattern via a statistical method, which is representative for all of the recorded data in the driving pattern, and thus for the average real-life use.

More information on this subject can be found in Appendix A of Subtask Report 2.8 '*Driving cycles for LD vehicles*', and can also be found in [1].

Now the identified options are discussed:

1. <u>Current 13-mode test procedure without modification</u>
   This procedure is not considered useful, as only the engine is tested, thereby neglecting the driveline behaviour. Specific characteristics of non-conventional HD drivelines (e.g. regenerative braking possibility, engine switching on/off) that have a profound influence on the environmental performances are not accounted for. Furthermore, the engine may be operated in only one or more operating point(s) that do not, or most likely, will not necessarily coincide with those of the 13-mode test.
   At this moment the procedure is not suitable even for conventional engines, as the engines undergo a static test, while transient emissions produced during real-life conditions are becoming more significant.

2. <u>Similar static test procedure as the 13-mode test, but with adaptation of operating points</u>
   This procedure would test the engine only in the actually used operating points. It may seem a very practical way to solve the problem of the rigid operating points prescribed by the 13-mode test. However, this procedure poses a new difficulty, as there is no straightforward method to weigh the test results of each operating point. Because this is still an engine-based test, the remark of option 1 concerning non-conventional driveline characteristics also applies for this procedure.

3. <u>Driving cycle on a transient rollerbench</u>
   In this procedure, the entire vehicle is tested over a driving cycle (speed-time pattern) on a rollerbench. Therefore, the driveline behaviour is implicitly accounted for. As long as the driving cycle is representative for the real-life driving pattern of the observed type of vehicle and its use, a good test result is obtained.
   From a fundamental point of view, this procedure would be most preferable. However, the required test facilities (HD transient rollerbench, dilution equipment) are expensive, and at this moment only available at three research institutes within the whole of Europe.

4. <u>Driving cycle on a test track</u>
   A more pragmatic way of testing is formed by measuring the power output of the ICE (or APU) together with battery current and voltage, during a driving cycle on a test track. Later on, the ICE is tested in the same operating points on an engine testbed. In case of an APU,

the load is applied electrically, e.g. by using a Digatron system. The best result is obtained by subjecting the ICE or APU to the same (transient) load pattern, because then the temperature course of the engine (and possible exhaust aftertreatment equipment) is simulated correctly. It is expected however, that even with static tests representative results can be found, especially if the ICE or APU uses only one or a few operating point(s).

Several possible test procedures have been identified and analysed. Together with the findings of the previous chapter, the following conclusions can now be drawn:

- Current test procedures for conventional HD vehicles are not suitable for non-conventional HD drivelines (BEV, HEV, FCEV);
- The testing of only the engine is not sufficient for a proper comparative test result. The driveline as a whole (or even better, the vehicle as a whole) needs to be tested on a driving cycle;
- In order to obtain a meaningful test result, the test would have to be formed by a driving pattern. This would ensure that all relevant aspects (including cold start emissions) would be taken into account in a representative way. As it is impractical to define a test in which a vehicle is subjected to many hours of driving, this driving pattern may be reduced into a representative driving cycle of more appropriate length;
- Each HD vehicle category that has a distinctive type of use needs its own dedicated driving cycle. The test cycle characteristics will have to be representative for the ‘average use’ of the HD vehicle category, therefore driving patterns need to be distinguished by vehicle category;
- The best way to obtain a representative test result for HD vehicles, is to use a driving cycle on a transient rollerbench. However, there are also more pragmatic (and less expensive) ways of testing that can be thought of. Especially driving a cycle on a test track seems a promising solution.

These conclusions lead to the following recommendations for future testing of HD vehicles:

- A strict subdivision of HD vehicle categories according to use patterns is needed;
- For each of the identified categories a dedicated cycle needs to be defined, representative for that vehicle type;
- Investments in HD dynamic rollerbenches are needed to obtain enough testing facilities;
- The aspect of regenerative braking on a rollerbench has to be investigated (see also Subtask 2.12 ‘*Regenerative braking on 2WD dynamometers*’);
- Research for more pragmatic methods for testing HD vehicles in a representative way is necessary.

N.B: There are of course easier testing methods that can be thought of, that require much less effort in terms of cycle development and investments. However, the focus of this subtask is to investigate testing procedures that allow for consistent and comparable results, and give a good representation of real-life fuel consumption and emissions. This can only be guaranteed by using representative driving cycles.

5 References

[1] C.J.T. van de Weijer, “Heavy-Duty Emission Factors - Development of Representative Driving Cycles and Prediction of Emissions in Real-Life”, PhD-thesis, Technical University of Graz, October 1997.

[2] H. Steven, “Improvement of the EU Noise Regulations for Cars and Commercial Vehicles; Results of an Analysis of Driving Behaviour Data”, FiGE GmbH, Interim report UBA research project 105 06 068, July 1996.

[3] Van de Weijer, C.J.T., Van der Graaf, R. (1993), “Urban bus driving cycle”, Proceedings 4th international EAEC conference, 16-18 June, 1993, Strasbourg, page 513-528.

MANAGEMENT TOOL for the ASSESSMENT of DRIVELINE TECHNOLOGIES and RESEARCH

MATADOR

Contract JOE3-CT97-0081

Task 2:

Testing methods for vehicles with conventional and alternative drivelines

Subtask 2.10

Dealing with EVs not meeting the demands of the cycle

HTA Biel-Bienne

20 July, 2000

by
Karl Meier-Engel (HTA Biel)

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Nomenclature

Abbreviations

APU	Auxiliary Power Unit
BEV	Battery Electric Vehicle
EC	Energy Consumption
EM	Electric Motor
EN	European Standard
EV	Electric Vehicle
FT	Failure Time
HTA	Hochschule für Technik und Architektur (Biel)
ICE	Internal Combustion Engine
ISO	International Organisation for Standards
ISO/DIS	Draft International Standard
NEDC	New European Driving Cycle
SAE	Society of Automotive Engineers
SHEV	Series Hybrid Vehicle

I	Electric current	A
P	Power	W
RI^2	Losses produced by the internal resistance of the battery (and the wires)	W
Ri	Internal resistance of the battery	Ω
t_{50}	failure times allowed below 50 km/h (five times per hour, for a duration less than 5 s each)	S
t_{gs}	the time used for all gear shiftings (maximum value of 5 seconds allowed for one gear shifting)	s
t_{out}	the time used for all gear shiftings	s
U_M	Motor voltage	V
Uo	Off-load voltage	V

Contents

1 Introduction

Measurements of energy consumption have demonstrated that not all test vehicles are able to complete the prescribed driving cycle, and this means that failure times are obtained that are attributable to inadequate acceleration values or insufficient maximum speeds. It therefore appeared that a direct comparison between the individual vehicles in terms of energy consumption would be difficult.

Therefore the question arose as to how an error time should be evaluated.

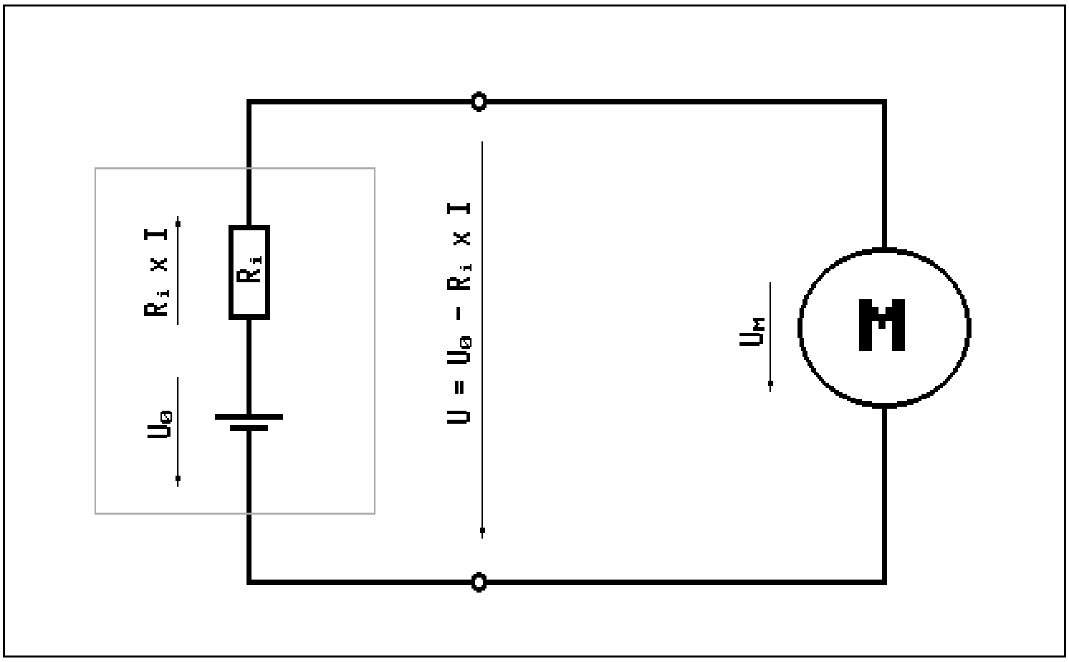


Figure 1: Simplified principle of BEV propulsion system

A look at the simplified principle of the propulsion system of BEVs (Figure 1) shows three important elements:

- The traction battery
- The electric circuit
- The electric motor

The energy consumed from the mains by a BEV depends of the energy consumption on the wheels, the efficiency of the motor, the battery and the electric circuit (the controller is neglected). The maximum electric current for accelerations and at high speed produce losses in the battery and the electric conductor. These losses are described by the formula $P = R * I^2$. If BEVs are used with a high current for a long time these losses will be significant. In the same time the capacity of the battery will decrease.

Example: If the electric resistance of a battery and the electric conductor is about 300 mΩ and the current is 100 A, the losses are $0.3 * 100^2 = 3$ kW.

The influence of this RI^2 phenomena is certainly strong if the accelerator pedal is fully depressed. It is obvious that either the weight of the battery and the maximum electric current are crucial for BEVs.

It is well known that the tractive force is higher for higher speed and acceleration. In the opposite reduction of speed and acceleration should produce a lower force and therefore a lower energy consumption.

HTA Biel-Bienne examined the problem with practical measurements on the test bench in Biel. The "low-cost" method developed for the "Large scale experiment for lightweight electric vehicle in Mendrisio" was used for this purpose.
In addition to the measurement at HTA Biel, TNO Automotive (Delft, The Netherlands) carried out a number of simulations.

The diagram on the following page (Figure 2) shows the tractive force for the commuter electric vehicle IS-Biel. With this study we looked for the minimum engine power for a environmental friendly vehicle with a maximum speed of 100 km/h and the ability to climb up at a gradient of 15%. This characteristic represents a motor power of 10 kW.

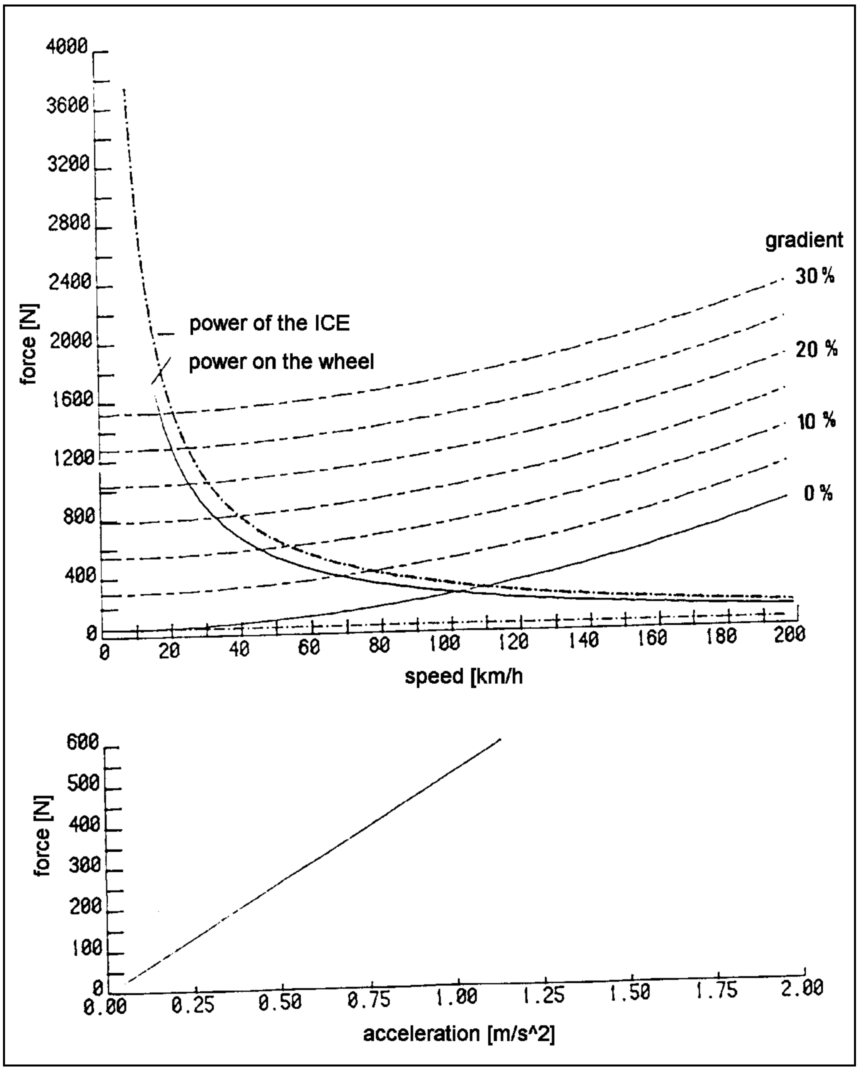


Figure 2: Tractive force diagram for the commuter electric vehicle IS-Biel

Measurement on real EVs can only produce failure times by reducing the maximum power of the electric driveline. The power reduction means a reduction of the maximum current. It is obvious that with this kind of measurement the electric motor is used at a lower efficiency.

2 Literature research

[1] Draft International Standard ISO/DIS 8714 1991-03-06: Reference energy consumption

Findings:
With point "4.4 Presentation of results" the distance travelled in kilometres shall be indicated. If the vehicle on the test bench does not meet the demanded speed this will produce a shorter distance.

Comment:
A "shorter distance" is not a very helpful information for the user.

[2] EN 1986-1: Electrically propelled road vehicles – Measurement of energy performances

Findings:

- Point 5.1 Principle
  The test method described hereafter permits to measure the electric energy consumption at the mains, in Wh/km, after having performed seven times test sequence n° 1 or two times test sequence n°2. The choice shall be noted in the test report.

- Point 4.2 Tolerances
  Tolerances on speed (±2 km/h) and on time (±1 s) are geometrically combined at each point Below 50 km/h, the deviations beyond this tolerances are permitted as follows:
  - at gear changes for less than 5 s, and
  - up to five times per hour at other times, for a duration less than 5 s each.
  - the total time out of tolerances has to be mentioned in the test report.
  - over or equal to 50 km/h, it is accepted to go beyond tolerances provided the accelerator pedal is fully depressed.

Comment:

- Point 5.1 Principle
  This method offers a choice of two different possibilities. Despite this choice the measurements for commuter BEVs with a maximum speed of 80 km/h is difficult.

- Point 4.2 Tolerances

- The information of the total time out of tolerances (failure time) shows clearly that the vehicle is not able to follow the test cycle.
- If the accelerator is fully depressed the electric circuit is working with maximum current. Hence the losses produced in the battery and electric conductor by RI^2 are also on the maximum level.
  If there is a gear shifting needed above 50 km/h there should also be an allowed amount of time out of tolerance.

[3] United Nations Trans/WP.29/484 GE.95-24948 (101)

Draft supplement 1 to the draft regulation.
Uniform provisions concerning the approval of passenger cars equipped with an internal combustion engine with regard to the measurement of carbon dioxid and fuel consumption and

of categories M1 and N1 vehicles equipped with an electric power train with regard to the measurement of electric energy consumption and range.

Findings:

- Point 1.4. Tolerances:
  - Below 50 km/h, the deviations beyond this tolerances are permitted as follows:
    a) at gear changes for less than 5 s, and
    b) up to five times per hour at other times, for a duration less than 5 s each.
  - The total time out of tolerances has to be mentioned in the test report.
  - Over or equal to 50 km/h, it is accepted to go beyond tolerances provided the accelerator pedal is fully depressed.

Comment:

- The information of the total time out of tolerances (failure time) shows clearly that the vehicle is not able to follow the test cycle.
- If the accelerator is fully depressed the electric circuit is working with maximum current. Hence the losses produced in the battery and electric conductor by RI^2 are also on the maximum level.
  If there is a gear shifting needed above 50 km/h there should also be an allowed amount of time out of tolerance.

[4] <u>SAE J1634 ELECTRIC VEHICLE ENERGY CONSUMPTION AND RANGE TEST PROCEDURE</u>

Findings:

- Point 5.3 Speed tolerance:
  For the energy consumption test, speeds lower than those prescribed are acceptable provided the vehicle is operated at maximum available power during such occurrences.

Comment:
If the accelerator is fully depressed the electric circuit is working with maximum current. Hence the losses produced in the battery and electric conductor by RI^2 are also on the maximum level.

3 Definition of failure time

Failure times refers to the amount of time during which the vehicle being tested is unable to perform the prescribed driving cycle due to low acceleration value or insufficient maximum speed.
Speed tolerances of ±2 km/h according to EN1986-1 are accepted. If the speed of the vehicle is lower or higher than this tolerances the test bench will count this time as failure time.
This is the definition used for the measurements by HTA Biel.

Below 50 km/h EN1986-1 allows a deviation beyond the tolerance as follows:

- at gear changes for a duration less than 5 s
- and up to five times per hour, for a duration less than 5 s each

If there is a gear shifting needed above 50 km/h there should also be an allowed amount of time out of tolerances.

It seems obvious that the allowed amount of time out of tolerance should not be included in the failure time.

Hence a possible formula for the determination of the failure could be:

$$FT = t_{out} - t_{gs} - t_{50}$$

FT	=	failure time	[s]
t_{out}	=	total time out of tolerance	[s]
t_{gs}	=	the time used for all gear shiftings (maximum value of 5 seconds allowed for one gear shifting)	[s]
t_{50}	=	failure time allowed below 50 km/h (five times per hour, for a duration less than 5 s each)	[s]

Remark:
This definition has not yet been used for the following measurements. There, only the total time out of tolerances has been used as failure time.

4 Measurements performed by HTA Biel

4.1 Test method

When the HTA Biel developed a method for the measurement of the energy consumption in 1994 only some drafts of standards were available. Because already at this time a pure urban vehicle was absolutely not the goal for the development of electric vehicles we decided to use the new European cycle with the extra urban part. We reduced the maximum speed from 120 to 80 km/h because of the RI^2 phenomena. But also with the reduced speed some EVs were not able to follow the test cycle. Therefore we decided to mention this fact with the amount of time the vehicle was out of the tolerance. We introduced the designation “failure time” (FT) for this characteristic.

For test purpose two electric vehicle were measured with different failure times. The failure times are produced by reducing the maximum power. This can be done with a change of the setup in the controller.

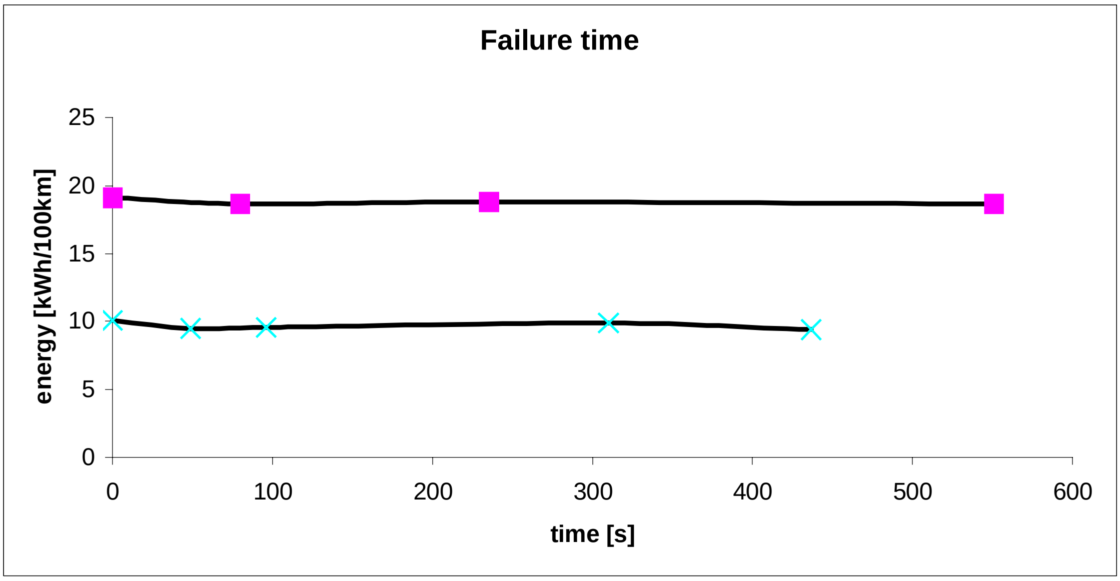


Figure 3: Energy consumption for two EVs; Larel (square markers) and ESORO (cross markers)

The diagram above shows, the measurement results of two vehicles with the Mendrisio test method. Instead of lower energy consumption there is no significant variation to see. Therefore it can be concluded, that in case of failure times, the energy consumption will be higher than expected.

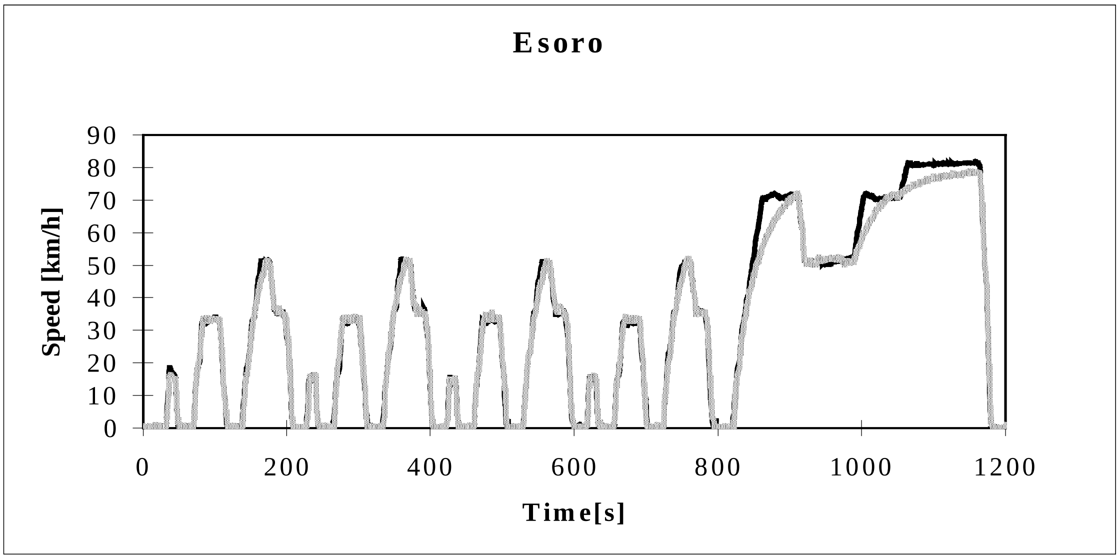


Figure 4: Actual velocity of the ESORO with reduced power (45%)

Figure 4 shows the velocity of the ESORO with reduced power (45%). It is clearly visible, that the acceleration at high speed is too low. Within these times the accelerator is fully depressed. Therefore either the electric current and the losses produced by RI^2 are on the maximum value.

4.2 Findings

If the accelerator pedal is fully depressed because the vehicle cannot meet the speed demanded of the test cycle the energy consumption is higher than it should be in function of the tractive force diagram.
Within the time with the accelerator fully depressed the electric current is at a maximum level. This means the losses produced by RI^2 are also at the maximum.
Hence the overall efficiency is lower and therefore the energy consumption is higher than expected in this mode.

4.3 Conclusions

The fact that a vehicle is producing a failure time on the test bench is obviously an important information. Therefore this value has to be reported according to the standard EN1986-1.

Because of the RI^2 phenomena, EVs will produce great losses at high velocity. Hence this kind of vehicle has a higher efficiency at lower speed. Therefore it is not wise to use a test cycle with a maximum speed over 80 km/h.
EN1986-1 offers already the possibility to execute the measurement with the urban cycle at a maximum speed of 50 km/h. Hence this is already a solution. But for short range use between suburbs and cities the urban cycle is certainly not the best method.

5 Results of the bench tests HTA Biel-Bienne, fleet of Mendrisio, and partner communities

Table 1: Energy consumption of BEVs used in the bench tests

Vehicle	**energy consumption** [kWh/100km]	**failure times** [s]	**energy consumption in Mendrisio** [1] [kWh/100km]			**energy consumption in partner communities** [2] [kWh/100 km]		
			min	max	average	min	max	average
Citroen AX Electrique	17.8	0	22.0	23.9	23.1			18.3
Citroen SAXO Electrique	20.0	0	22.7	28.1	25.6			22.6
Fiat Panda Elettra	23.0	304	42.0	53.3	46.9	34.6	34.6	34.6
Fiat Seicento Elettra	26.3	21						
Honda EV Plus[1)]	22.0	0	?	?	?			
Kewet EL-JET4	16.7	244	19.6	28.8	22.7			
Larel (Vergleichsfahrzeug)	20.0	45	20.5	20.5	20.5			
Ligier Ambra	15.1	0	20.5	24.1	21.1	21.3	21.3	21.3
Ligier Optima Sun II (Eco)	14.9	91	20.1	22.2	20.5			
Ligier Optimax	17.4	0	23.4	23.4	23.4			
Microcar Light	16.5	254	22.8	22.8	22.8			16.2
Mini El L	8.9	802	9.4	19.6	13.4			14.9
Peugeot 106 électric	17.1	0	23.2	30.1	24.5			20.8
Peugeot Partner	31.8	13	33.3	37.9	38.6			
Renault Clio électric	19.4	0	25.9	30.5	29.3			23.3
Renault Express Electrique	24.0	0	36.7	36.7	36.7			
Volta (Projektarbeit)	30.82	239.1	21.9	21.9	21.9	57.7	57.7	57.7
VW Golf Citystromer	20.9	0	25.9	32.4	27.5			

1) 5 cycles instead of 2

6 Correlation between bench and field test

The experience with the “Large scale experiment with lightweight EVs in Mendrisio” shows significant differences between bench and field test results.

What are the reasons for these differences ?

- The test cycle simulates a stretch of road without an incline, and the vehicle is tested in an air-conditioned room at a temperature of between 20° and 30° C. This represents a “best case measurement” that will hard to be reproduced in the daily use.
- A test cycle is only one from thousands of different consumer application.
- The driving behaviour is different from one person to the other.
- The length and difference of altitude of every user distance is different.
- In real use the parameters of every vehicle (temperature, number of passenger, load, road, velocity) are different.

Findings
The correlation between bench-tests and field tests will be hard to find [7]. Bench testing can be performed quickly and yields objective, reproducible information on EV performance in controlled, simulated conditions.
Bench test are:
  - comparable (at least within the same category)
  - affordable (low-cost methods are possible)

Conclusion
Bench tests can be reproduced and are within the same category comparable. Hence it is a useful tool for standards. For the user this “best case measurement” is not very helpful because in real use, it is often impossible to find the same results.
Therefore a combination of results from bench and field tests could provide a better user information.

7 Other possible test methods

7.1 Test cycles with different maximum speed

This method is certainly a possible solution for different categories of vehicles. HTA Biel has already used it for the following categories:

- cars as mentioned in the method for MENDRISIO
- scooters with electric driveline [3]. There only the urban cycle was used on the bench test. This cycle was driven three times.

This categories could be extended with:

- low commercial EVs for communities
- neighbourhood EVs
- electric bikes (HTA Biel uses for this category a road track test [4])

7.2 Test cycle with a constant length of distance

Today most of test-cycles work with the speed as a function of the time. To achieve the same distance for every test there are different possibilities:

- drive for a longer time in the constant speed phases
- continue the test cycle until the desired distance is achieved

The first method means (at least for the test bench in Biel) more costs. The vehicles have been measured to find out at which moment the desired speed cant be achieved. Then the program of the test cycle must be adapted.
The results with the second method are difficult to compare.

Comment
The experience with the energy consumed in practical use showed us, that bench tests are producing values which are difficult to meet. In Mendrisio the energy consumption was 35% higher [5][8]. The partner communities achieved with 12% [6] a much better result. The reasons for these facts are already described in chapter 6. The same behaviour is also well known for ICE vehicles.

8 Computer simulations by TNO

In addition to measurement results obtained by HTA Biel a number of simulations has been executed to determine the influence of failure time on the energy consumption of a vehicle. For these simulations the BEV and series hybrid electric vehicle (SHEV) model as described in the Subtask 2.2 Report on '*Development of simulation models*' have been used.

8.1 Simulation set up

Failure time is defined as the amount of time a vehicle is unable to follow the driving cycle due to low acceleration or top speed. In the simulations, failure time is counted when the speed deviation is more than 1 km/h (it is within a band of 0.2 km/h when sufficient power is available).

In order to get failure time, the nominal (and thus maximum) power of the electric motors is lowered stepwise from 25 to 5.5 kW. Both vehicle models have been simulated over the European Driving Cycle (NEDC) and the Modem driving cycle. The energy consumption is calculated by dividing the net energy use from the battery (BEV) or the fuel (SHEV) by the actually driven distance.

8.2 Simulation results

In Figure 5 and Figure 6 several plots concerning Failure Time (FT) and energy consumption (EC) of the Battery Electric Vehicle (BEV) and Series Hybrid Electric Vehicle respectively are shown for the New European Driving Cycle (NEDC) and Modem driving cycle. Both figures show very similar results.

Cycles
From Figure 5A and Figure 5B as well as Figure 6A and Figure 6B it can clearly be derived that the Modem cycle is more demanding than the NEDC (the energy consumption is also higher, Figure 5C, 5D, 6C, and 6D). Failure time already starts building up below 20 kW, while the electric motor (EM) power can be lowered below 10 kW before failure time is found on the NEDC cycle. At low EM powers, the Modem cycle shows more FT than the NEDC.

Electric Motor Power
Figure 5C and 6C show that the electric motor with 17.5 kW_{nom} has the best overall system efficiency (lowest energy consumption) for the NEDC. The operating points (torque and speed) lie in a more favourable part (the efficiency is the highest around the nominal torque) in the torque-speed map (see Figure 7). With higher as well as lower EM power (often operated at low partial load or at full load respectively) the machine is operated with lower efficiencies.
With decreasing electric motor power the energy consumption rises. In these simulations this occurs for the NEDC when power is below 17.5 kW and for the Modem cycle when power is below 25 kW.

Energy Consumption and Failure Time
Figure 5E, 5F, 6E, and 6F show the energy consumption plotted versus the failure time for each EM power simulated. The data points clearly show that with increasing failure time a rise in energy consumption results.

At high failure times the energy consumption seems to level however (Figure 5F) or even decreases (Figure 6F). For both cycles the highest extra energy consumption is about 15% (with respect to the most optimal simulation).

BEV versus SHEV
Hardly any differences appear between these models. Failure times are the same for both vehicles since both vehicles have the same mass and drive powers. From earlier simulations different energy consumption figures could already be expected. The clearest difference between both vehicles is found in the relation between energy consumption and failure time. Figure 5E and 6E show that for the SHEV model a less smooth line is found. This might be caused by the APU on/off characteristics, which are not evenly distributed over the different simulations. On a more global basis the results nevertheless are the same for both models.

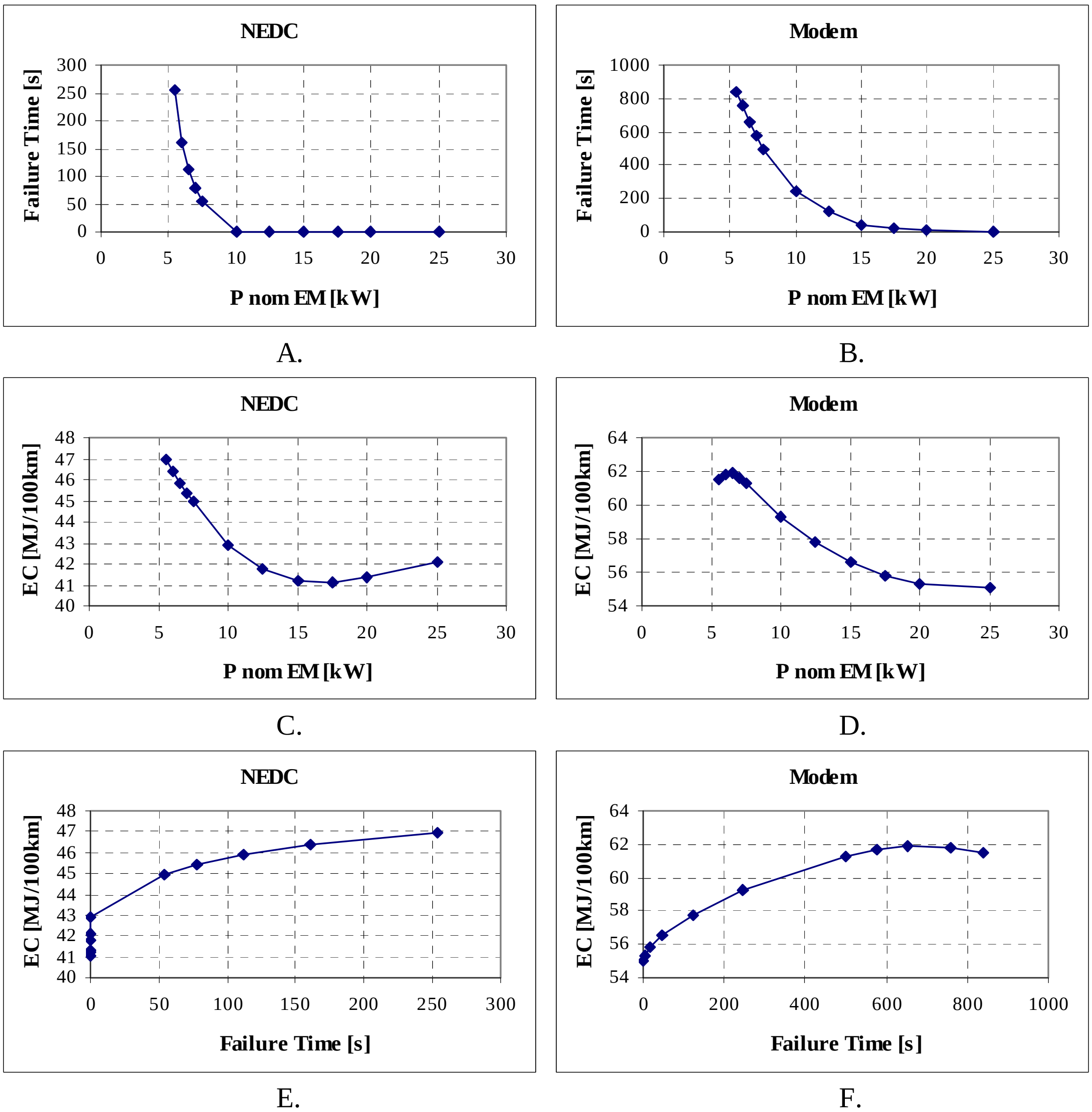
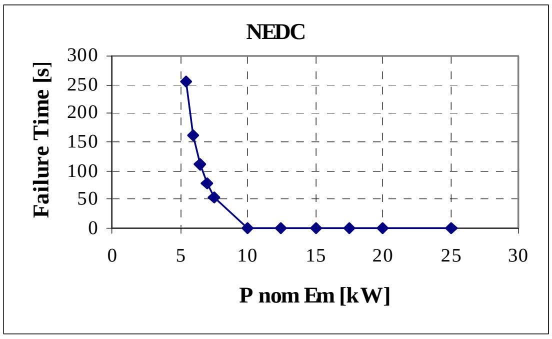
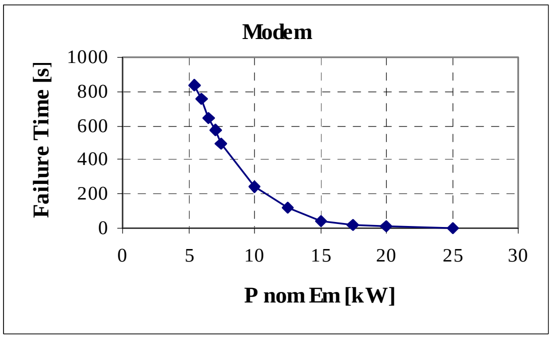


Figure 5: Results Failure Time simulation BEV over NEDC and Modem driving cycles





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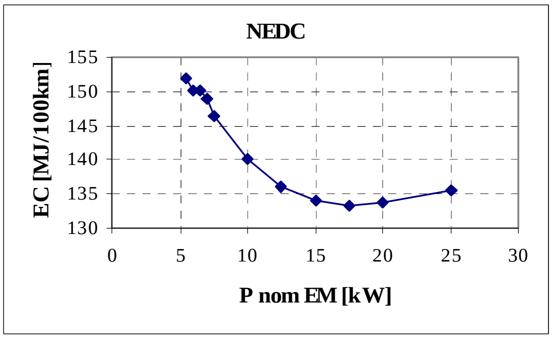

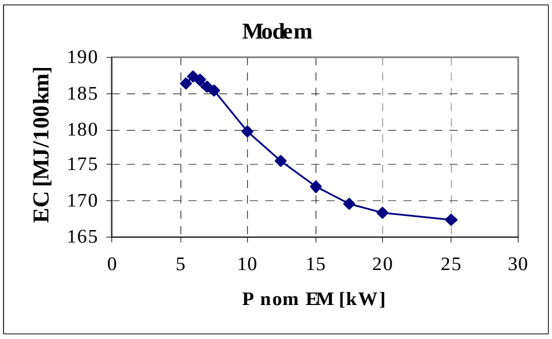

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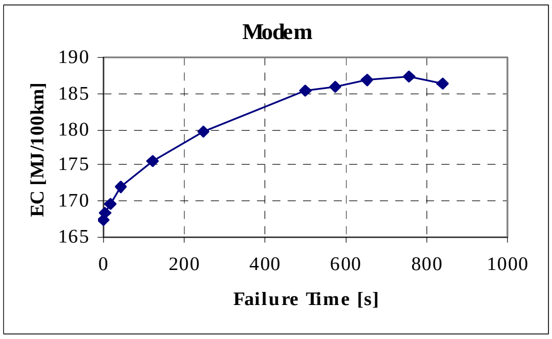
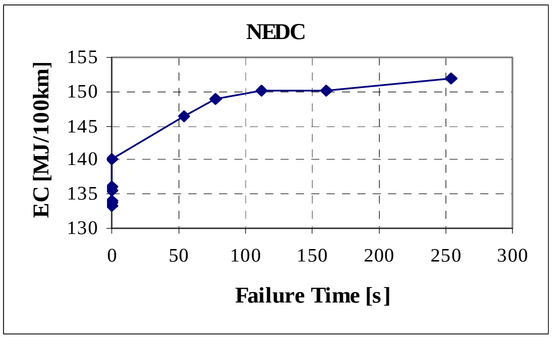




E.　　F.

Figure 6: Results Failure Time simulation SHEV over NEDC and Modem driving cycles

8.3 Differences between the measurements and simulations

The measurements and simulations have not been done exactly the same way. The explanation for the differences can be found in the way that electric motor power was reduced. In the measurement the available power is limited by lowering the maximum allowable current, without influence on machine efficiency. The physical properties of the electrical machine do not change and consequently the electrical powers correspond to those of the original machine. The “efficiency map” in the measurements does not change with limiting the power, which will have an influence on the energy consumption of the vehicle.
In the simulations, the electric motor power is reduced by lowering the maximum mechanical power, which automatically limits the electrical power. In the simulation, therefore, the “physical” characteristics have been changed. Since the efficiency is calculated in the model, it automatically adapts to the new characteristics. The optimum operating points always lie somewhere in the middle of the torque-speed map (Figure 8).
When lowering the maximum power in the measurements, at some point the maximum torque line will cross the highest efficiency zone. When Failure Time occurs, indicating that the maximum power is frequently used, the machine actually might operate at more favourable

conditions, which seems rather unrealistic for full load. It is unlikely that this method is representative for actual vehicles, since it would mean that an electric motor is installed that is operated at partial load at all times, and therefore is overdimensioned.
When power is lowered to such an extent that the allowed maximum power lies below the high efficiency area, the machine can no longer operate at a high efficiency and consequently Energy Consumption and Failure Time will rise.
Since in the simulation the efficiency is scaled down with the maximum torque line, the power/torque map and the efficiency comply to one another.

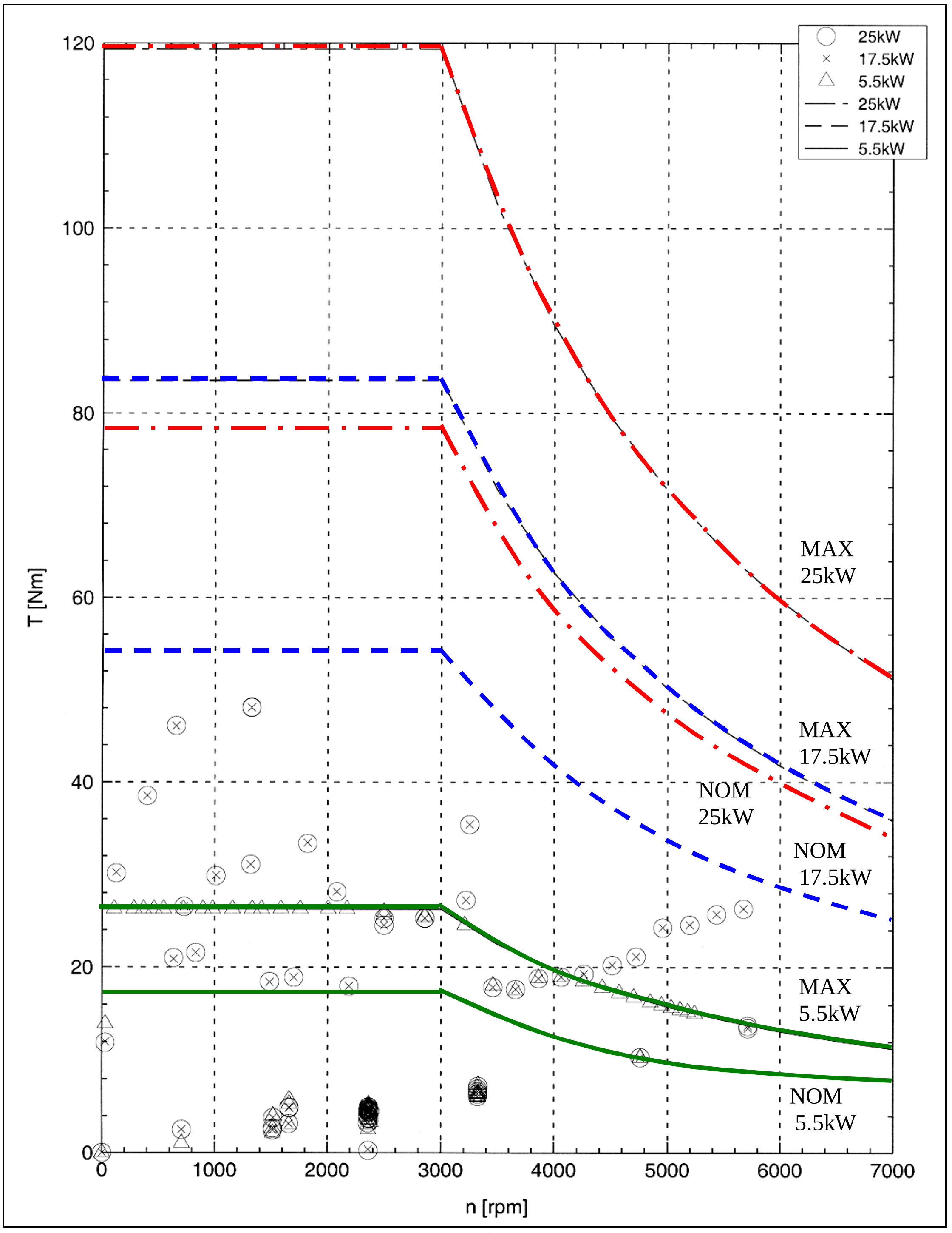
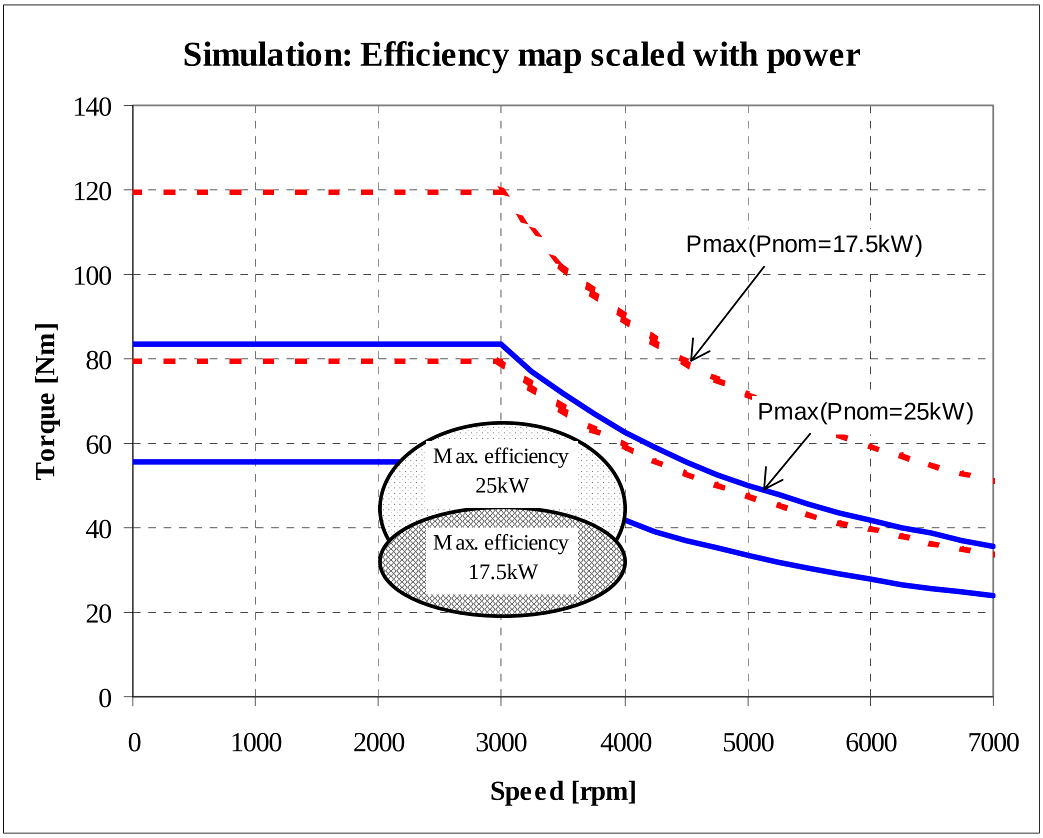


Figure 7: Operating points NEDC for three different electric motor powers



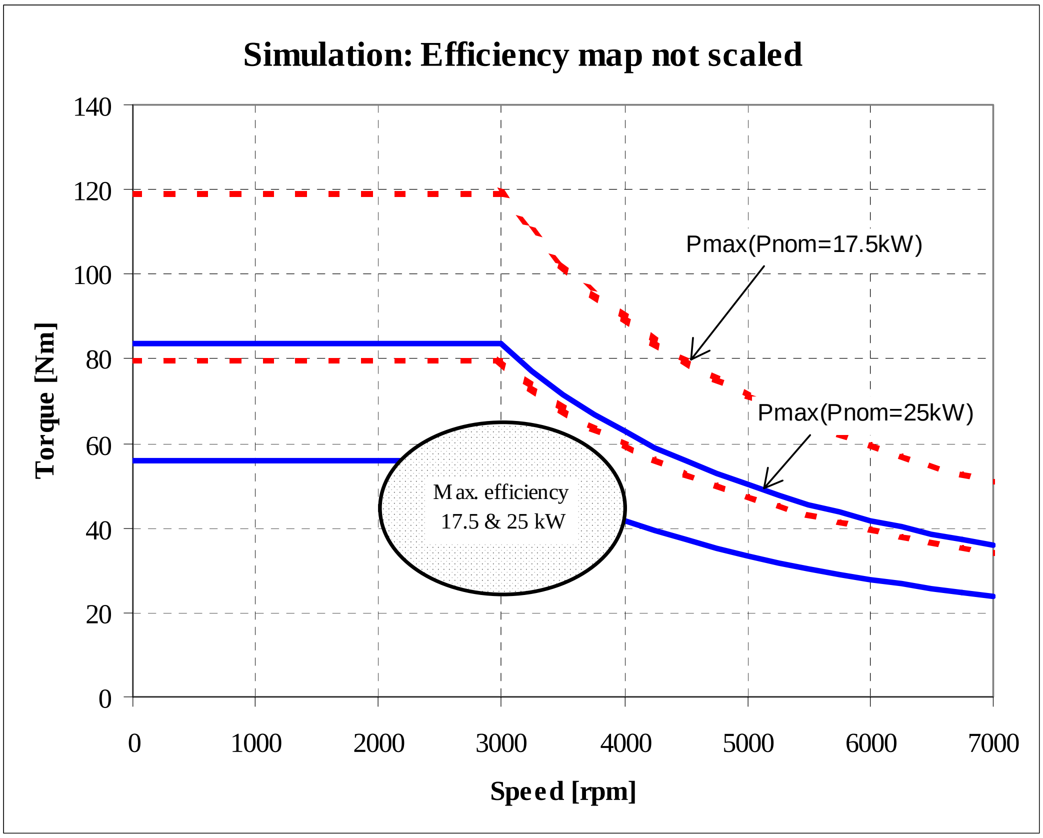


Figure 8: Differences in torque-speed map and efficiency for simulation and measurement

9 Conclusion and Recommendations

Bench tests can be reproduced and are comparable within the same category. For this reason, they provide a useful tool for standards.
Measurements of energy consumption have demonstrated that not all test vehicles are able to complete the prescribed driving cycle, and this means that failure times are obtained that are attributable to inadequate acceleration values or insufficient maximum speeds. It therefore appeared that a direct comparison between the individual vehicles in terms of energy consumption would be difficult.

The maximum electric currents for accelerations and at high speeds produce losses in the battery and the electric conductor. These losses are described by the formula $P = R * I^2$. If BEVs are used with a high current for a long time these losses will be significant. In the same time the capacity of the battery will decrease.
The influence of this RI^2-phenomena is certainly strong if the accelerator pedal is fully depressed. It is obvious that either the weight of the battery and the maximum electric current are crucial for BEVs.

HTA Biel-Bienne examined the problem with practical measurements on the test bench in Biel. The “low-cost” method developed for the “Large scale experiment for lightweight electric vehicles in Mendrisio” was used for this purpose.
In addition to the measurement at HTA Biel, TNO Automotive (Delft, The Netherlands) carried out a number of simulations.

Both the measurements from HTA Biel and the simulations performed by TNO show that energy consumption will rise when a BEV produces some failure time. The simulation results show a highest extra energy consumption of about 15%. Hence the failure time is of significant importance for energy consumption.
The same can be concluded for the SHEV model simulation, since both vehicles have the same mass and drive powers.

Conclusions

The fact that a vehicle produces failure time on the test bench is obviously important information. Therefore this value has to be reported according to the standard EN1986-1.
The amount of failure time allowed during the gear shifting and below 50 km/h, should not be included in the failure time.

Because of the RI^2-phenomena, EVs will always produce great losses at high velocity. Hence this kind of vehicle has a higher efficiency at lower speed. Therefore, it is not wise to use a test cycle with a maximum speed over 80 km/h.
EN1986-1 already offers the possibility to perform the measurement with the urban cycle with a maximum speed of 50 km/h. This is already a possible solution for the measurement of BEVs with a maximum speed below 120 km/h. But for short range use between suburbs and cities the urban cycle is certainly not an optimal solution.

Most of the actual BEVs are not able to drive with a maximum speed of 120 km/h. If the number of BEVs with a maximum speed of about 80 to 90 km/h will increase in the future, an extra-urban cycle for BEVs has to be discussed.

Definition of failure time

Failure times refers to the amount of time during which the vehicle being tested is unable to perform the prescribed driving cycle due to low acceleration or insufficient maximum speed.

In the simulations by TNO, failure time is counted when the speed deviation is more than 1 km/h (it is within a band of 0.2 km/h when sufficient power is available).

According to EN1986-1 speed tolerances of ±2 km/h are accepted. If the speed of the vehicle is lower or higher than this tolerance the test bench will count this time as failure time.
This is the definition used for the measurement by HTA Biel.

Below 50 km/h EN1986-1 allows a deviation beyond the tolerance as follows:
- at gear changes for a duration less than 5 s, and
- up to five times per hour, for a duration less than 5 s each

If there is a gear shifting needed above 50 km/h there should also be an allowed amount of time out of tolerance.

It seems obvious that the allowed amount of time out of tolerance should not be included in the failure time.

A possible formula for the determination of the failure could be:

$$FT = t_{out} - t_{gs} - t_{50}$$

FT	=	failure time	[s]
t_{out}	=	total time out of tolerance	[s]
t_{gs}	=	the time used for all gear shifting (maximum value of 5 seconds allowed for one gear shifting)	[s]
t_{50}	=	failure times allowed below 50 km/h (five times per hour, for a duration less than 5 s each)	[s]

Recommendation

For standards measurements test benches are certainly still a very useful tool. Because the results of such measurements are usually compared with each other, failure times should be recorded.
Information about energy consumption should also include the failure time.

There is a need of a precise definition of failure time. The formula above could be a possible solution. For such a definition it would be helpful, if not only the deviations beyond the tolerances are reported but also the allowed times for gear shifting and the allowed periods of failure below 50 km/h.

References

[1] Meier-Engel Karl: Bench-test for Electric vehicles, Ingenieurschule Biel, Automobile Technology Division, February 1997
[2] Meier-Engel Karl, Reichenbach Christoph: Fehlzeituntersuchung an Elektrofahrzeugen, Ingenieurschule Biel, Abteilung Automobiltechnik, 1995
[3] Meier-Engel Karl, Reichenbach Christoph: Messung von Leicht-Elektromobilen (96/97), Ingenieurschule Biel, Abteilung Automobiltechnik, 1997
[4] Meier-Engel Karl, Reichenbach Christoph: Energieverbrauchsmessung an Elektro-Fahrrädern, September 1997
[5] BFE: Grossversuch mit Leicht-Elektromobilen (LEM) in Mendrisio, 2. Zwischenbericht, August 1998
[6] Muntwyler Urs, Keller Marc: P+D 19480 Messkampagne LEM Partnergemeinden 1997/1998, Dezember 1998
[7] van Spanje Ben: Final report, Programme for collaboration between CEU and National Programmes on electric vehicles, 1997
[8] Moreni Gianni: Results of Mendrisio, Consorzio Abay + Meyer, Polyquest

MANAGEMENT TOOL for the ASSESSMENT of DRIVELINE TECHNOLOGIES and RESEARCH

MATADOR

Contract JOE3-CT97-0081

Task 2:

Testing methods for vehicles with conventional and alternative drivelines

Subtask 2.11

Accuracy and tolerances

Institut für Kraftfahrwesen Aachen

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by
Servé Ploumen (IKA)

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Energy Conservation and Utilisation

Nomenclature

Abbreviations

AC-city	Aachen city driving cycle (developed by IKA)
APU	Auxiliary Power Unit (generally an ICE with generator)
BEV	Battery Electric Vehicle
ECE	Urban driving cycle of the Economic Commission for Europe
HEV	Hybrid Electric Vehicle
HWFET	Highway Fuel Economy Test (standard driving cycle in USA)
HYZEM Highway	HYZEM Highway driving cycle
HYZEM Rural	HYZEM Rural driving cycle
HYZEM Urban	HYZEM Urban driving cycle
Japan 1015	Japanese driving cycle
ICE	Internal Combustion Engine
MATADOR	Management Tool for the Assessment of Driveline TechnOlogies and Research
NEDC	New European Driving Cycle
NiMH	Nickel Metal Hydride battery
SOC	State Of Charge (of the electric energy storage device)
UDDS	Urban Dynamometer Driving Schedule (standard driving cycle in USA)

Contents

1 Introduction

The scope of work which is done for Task 2 of the MATADOR project is divided into subtasks, which each address a certain topic of interest. The knowledge gathered for these subtasks is presented in subtask reports, which include the results of the work done for the specific subtask and the conclusions that consequently can be drawn from the measuring/simulation results.

The MATADOR Task 2 Subtask 2.11 addresses the repeatability problems in determining energy consumption and pollutant emissions of vehicles with alternative drivelines due to fluctuations in driver behaviour as a consequence of the defined accuracies and tolerances. The accuracy problems mostly occur when testing hybrid vehicles, since inaccuracies in this case can lead to a different use of the powertrain.

Driver behaviour in this respect means the characteristic with which the driving cycle is followed. The actuation of accelerator, braking pedals and in case of manual transmissions also the selection of gears can differ from driver to driver. Since there are no exact definitions within HEV-procedures as to how a driver should behave while driving the cycle, differences in measurement results and therefore problems in reproducing these results may occur.

Especially the driver-controlled accelerator movements have an influence on the mostly event-driven control strategies and cause them to switch the operation state of the drive line. Although this only leads to slight differences in actual vehicle speed on the one hand, significant differences in energy consumption and emissions may occur on the other hand even if the tolerances for vehicle speed defined by the standard procedure are respected.

Another aspect within the topic of tolerance is the vehicle conditioning prior to the measurements. The initial temperatures of tyres and power train have a significant influence on energy consumption and emissions. It is important to know how tight tolerances have to be defined in order to yield a accurate reproducability.

In order to investigate the topic thoroughly both, computer simulations and vehicle measurements have been carried out. In chapter 2 the results from the simulation work are presented, in chapter 3 the results from the vehicle measurements.

2 Simulation results

The simulation works for this subtask have been done using simulation models for charge-depleting and charge-sustaining hybrid electric vehicles [1]. Since charge-depleting hybrid vehicles not only depend on fuel energy (as in case of charge-sustaining hybrid vehicles), inaccuracies also may affect electric energy consumption.

The driver influence on energy consumption and emissions is investigated by not only using the speed profile defined by the standard procedures for simulation, but also by simulating the hybrid vehicles over actually measured speed profiles that lie within the defined tolerance band. Since the simulation of pollutant emissions is not always very accurate, the influence of driver behaviour on emissions is only assessed by studying the start/stop-frequency of the internal combustion engine. In typical urban/rural use (application area for hybrid vehicles), especially the HC and CO emissions are highly related to this frequency (caused by mixture-enrichment).

The driver influence gains a second dimension for vehicles with multi-speed transmissions (in this case the parallel hybrid with manual transmission). By altering the gearshift points as a function of motor speed, differences in energy consumption and ICE-start/stop-frequency can be observed.

2.1 Charge-depleting hybrid vehicles

2.1.1 Tolerances in vehicle speed

In order to investigate the above mentioned issues, following simulations have been performed: simulate the hybrid vehicles over the Aachen-city cycle, the NEDC and the UDDS.
The desired vehicle speed which had to be followed by the driver *in simulation* was in these cases not only defined by the standard speed itself, but also by three speed tracks that are directly related to the standard speed:

- a speed profile actually measured from an electric vehicle on the dynamic roller test bench of the ika (defined as measured profile). In this case the standard speed track is followed quite well and the actual velocity shows only slight diversions in vehicle speed due to the control behaviour of the human driver.
- the speed profile defined by the lower tolerance of the standard speed (defined as lower tolerance)
- the speed profile defined by the upper tolerance of the standard speed (defined as upper tolerance)

The tolerances used are defined in the according procedures (2 km/h plus/minus 1 second for the NEDC, 2miles per hour plus/minus 1 second for the UDDS). In case of the Aachen-city cycle, the speed tolerances of the NEDC apply. In order not to falsify the results, the upper speed track has been set to zero in phases were the standard speed is also zero. In Fig. 2.1-1, these speed profiles are displayed for the NEDC as an example.

Because of the high accuracy with which the driver is modelled, the desired speed track is followed very exactly in simulation. Therefore the influence on energy consumption and startup-frequency of the ICE can be studied well.

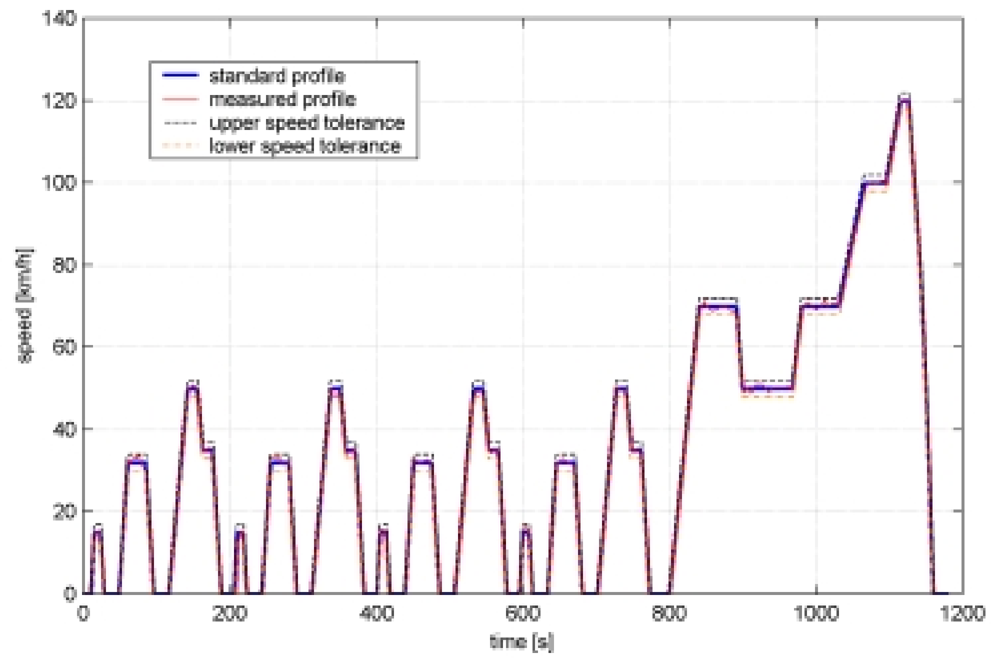

Fig. 2.1-1: Comparison of standard speed, measured profile, upper tolerance and lower tolerance for the New European Driving Cycle

Since the shifting strategy of the parallel hybrid in the vehicle models is defined by speed thresholds of the gearbox input shaft, the shifting behaviour might be quite different to the one in standard situation as a results of different vehicle speeds. To avoid this influence, the shifting strategy has been set equal to the one of the standard speed. This means that the gears have been changed at the same *times* as in standard speed simulation.

As an example of the influence on energy consumption, in Fig. 2.1-2 the energy consumptions of the parallel hybrid in the UDDS cycle are displayed. As can be seen, the distribution of electric and fuel energy can differ remarkably. In case of the lower tolerance, the used electric energy increases while a decrease of fuel consumption is observed. Following the upper tolerance results in the opposite. This behaviour however is not seen in all cases, as Fig. 2.1-3 and other simulation results show.

For the series hybrid the following trends can be observed: The energy demand at the wheel is almost equal to standard situation in case of the measured profile. The energy demand at the wheel for the lower tolerance is lower, the one for the upper tolerance is higher (which is obvious). With a decrease in vehicle speed however, the decreasing motor efficiency results in a higher electric energy consumption, which is seen in the Aachen-city cycle best (since there is no fuel consumption in this cycle, the electric energy consumptions are directly comparable).

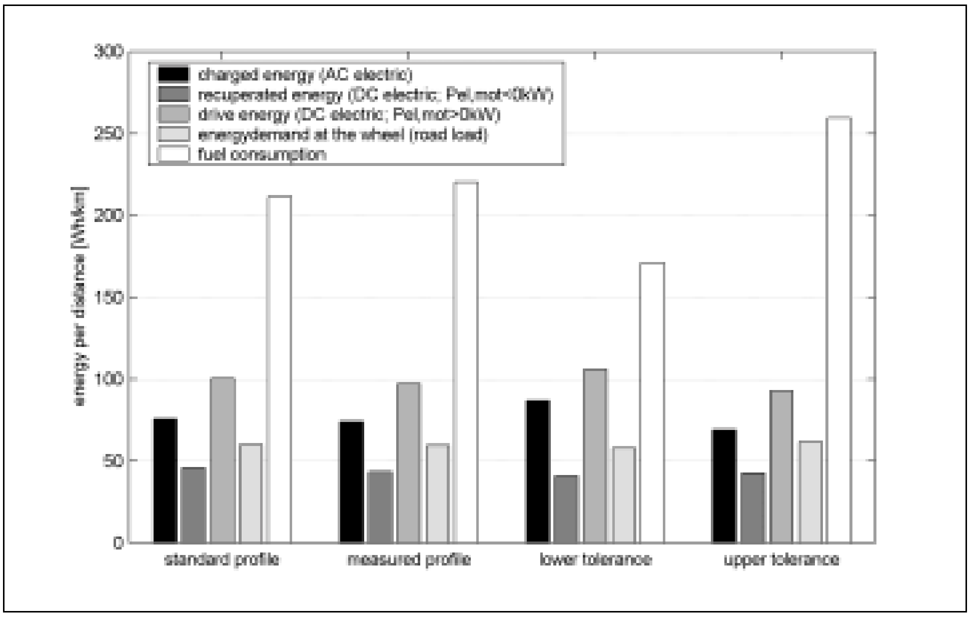

Fig. 2.1-2: Energy consumptions for the charge-depleting parallel hybrid vehicle in dependence of the speed tolerance (Urban Dynamometer Driving Schedule)

Series hybrid				
Echarge [Wh/km]	standard profile	measured profile	lower speed tolerance	upper speed tolerance
AC-city	264.6	253.7	340.5	230.4
NEDC	53.6	52.7	59.7	55.6
UDDS	128.6	126.5	151.9	115.3
Efuel [Wh/km]				
AC-city	0.0	0.0	0.0	0.0
NEDC	314.9	315.1	322.5	308.0
UDDS	147.3	148.7	116.1	158.1
Ewheel [Wh/km]				
AC-city	51.0	50.8	49.9	52.1
NEDC	81.7	81.5	80.5	83.0
UDDS	67.2	67.1	65.3	69.1
Parallel hybrid				
Echarge [Wh/km]	standard profile	measured profile	lower speed tolerance	upper speed tolerance
AC-city	150.5	143.3	163.6	116.7
NEDC	40.1	43.2	43.5	45.5
UDDS	75.8	74.2	86.8	69.3
Efuel [Wh/km]				
AC-city	73.0	80.1	92.0	186.5
NEDC	336.7	330.2	333.8	334.2
UDDS	211.4	220.3	171.1	259.6
Ewheel [Wh/km]				
AC-city	43.4	43.2	42.3	44.5
NEDC	74.2	74.0	73.0	75.5
UDDS	59.7	59.6	57.8	61.6

Fig. 2.1-3: Energy consumptions of the hybrid vehicles in dependence of the speed tolerance

In cycles with higher speeds, as in NEDC and UDDS, the fuel consumption is caused by the direct operation of the APU. In NEDC, the APU is operated at the same times as in standard situation (only in the extra-urban part). In the UDDS however, in the cases of the upper tolerance and the standard track the APU is also operated at few points within the urban part. Without APU-operation in the urban part (UDDS lower tolerance), a lower fuel consumption occurs, since a direct operation of the APU is most efficient at higher speeds.
For the parallel hybrid, the demanded energy at the wheel still shows the same behaviour as the series hybrid, the electric energy and fuel consumption are slightly different though. If compared to the standard situation, the electric energy consumption increases when following the lower tolerance and decreases when following the upper tolerance. The differences in fuel consumption are on the one hand caused by the velocity-dependent threshold for ICE-operation (55 km/h) and on the other hand by the power (not energy!) demand of the cycle. Generally speaking, in the upper tolerance transient cycles (AC-city and UDDS), the power demand more often exceeds the maximum power of the electric motor, which causes the control-strategy to start the engine for a short period of time. Additionally, in the UDDS standard and upper tolerance, the 55 km/h threshold for ICE operation is more often exceeded as for the lower tolerance as a result of the large tolerance (2 mph = 3.2 km/h). This causes a decrease in fuel consumption in the latter case.

Apart from the energy consumptions, also the ICE start/stop frequencies show remarkable differences if deviations in vehicle speed compared to standard speed are observed. In Fig. 2.1-4 the number of ICE-starts within the corresponding cycle are displayed.

Series hybrid				
number of ice-starts	standard profile	measured profile	lower speed tolerance	upper speed tolerance
AC-city	0	0	0	0
NEDC	1	1	1	1
UDDS	3	3	1	4
Parallel hybrid				
number of ice-starts	standard profile	measured profile	lower speed tolerance	upper speed tolerance
AC-city	1	2	2	3
NEDC	1	1	1	1
UDDS	11	11	8	12

Fig. 2.1-4: Number of engine starts of the charge-depleting hybrid vehicles in dependence of the followed speed track

The figures show how sensitive the control strategy reacts on slight differences in vehicle speed. As mentioned before, the most significant differences are seen for the UDDS, whose lower tolerance speed does not exceed the 55 km/h threshold as often as the standard and the upper tolerance speed. The differences are mainly seen for the parallel hybrid, whose ICE operation also is influenced by the reduced power of the electric motor. For the series hybrid, the operation is only caused by the speed-threshold and therefore these figures show no significant differences.

2.1.2 Influence of transmission shifting points

One other aspect of interest within this subtask is the definition of shifting points of the gearbox. For manually shiftable transmissions, the "hybrid" standards prEN 1986-2 and SAE J1711 do not define any shifting points. The testing engineer should rather use the gear with which the desired speed track is followed best.

This applies for the simulated parallel hybrid, since the shifting strategy is based on the transmission input-shaft speed. An upshift is induced whenever this speed exceeds a value of 3200 1/min. The downshift-threshold is defined at 1200 1/min.

In order to investigate the influence of different shifting points, the parallel hybrid vehicle additionally has been simulated for up-shifting thresholds of 2000, 2400, 2800 and 3600 1/min while keeping the downshift threshold at 1200 1/min. As an example, the input-shaft speeds of the transmission are shown for the altered thresholds in Fig. 2.1-5 (ECE cycle).

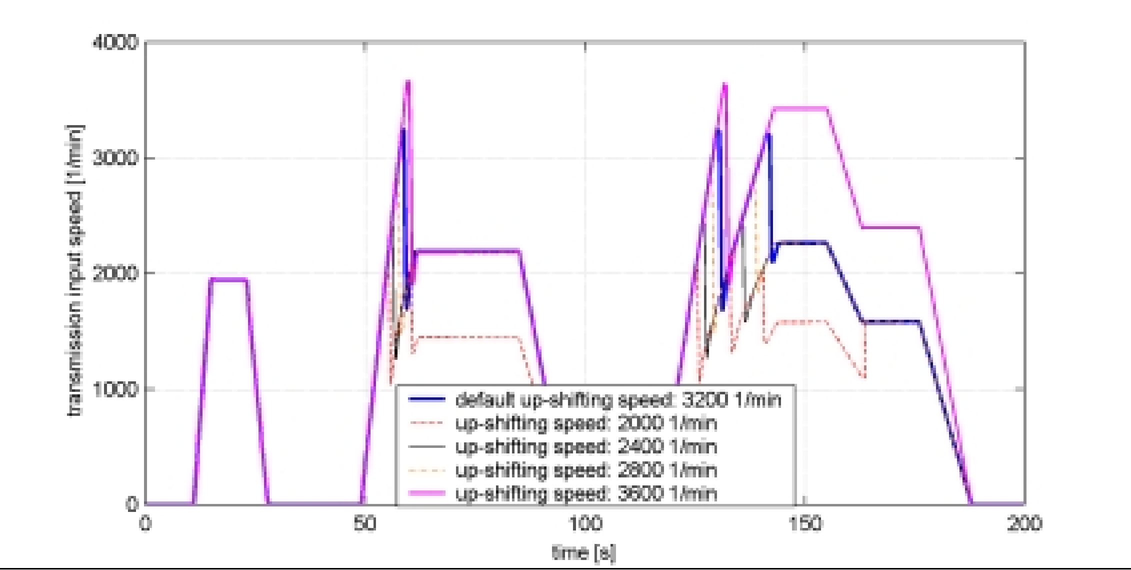

Fig. 2.1-5: Time histories of the gearbox input speed for different up-shift thresholds (ECE cycle)

As can be seen in Fig. 2.1-6, the energy consumptions of the parallel hybrid in the Aachen-city cycle are significantly influenced by the upshift thresholds. In case of a threshold of 2400 1/min, the combustion engine doesn't participate in propulsion energy at all, whereas in the other cases a fuel consumption is observed. Consequently, a difference in fuel consumption of as much as 93 Wh/km (0,92 l/100km) is observed. The differences in recharged energy amounted to 18%.

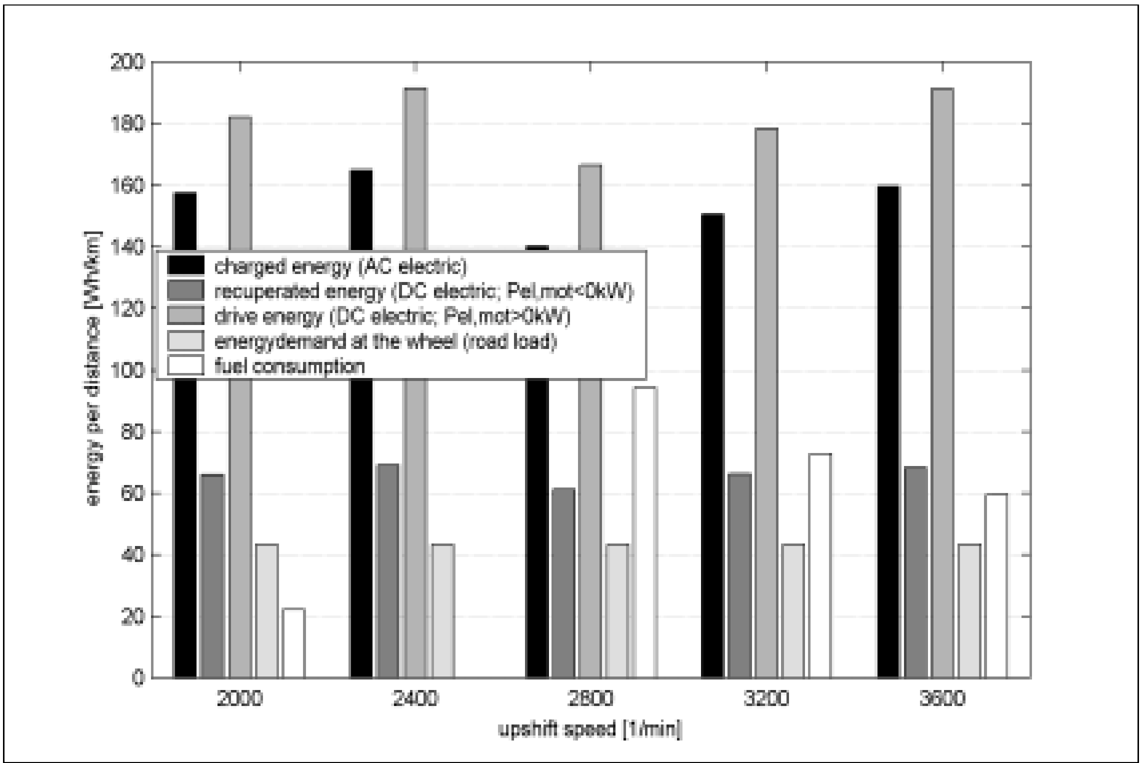

Fig. 2.1-6: Energy consumptions for the charge-depleting parallel hybrid vehicle in dependence of the upshift speed (AC-city cycle)

In Fig. 2.1-7, an overview of the energy consumptions in the different driving cycles is given. One interesting point is seen for the ECE-cycle. When driving with an upshift threshold of 2000 l/min, the ICE is started once in each micro urban cycle, since the electric motor does not provide sufficient power in the range from 0 to 2000 1/min. For higher upshift speeds, the cycle is driven pure electrically. Therefore, the electric energy consumption in these cases is higher.

The general trend in energy consumption is that the fuel consumption increases with higher upshift thresholds. The electric energy consumption however tends to increase with higher upshift thresholds only for some cycles (NEDC, UDDS and japan 10-15). The electric energy consumption in the other cycles show no recognisable trend.

	upshift threshold [1/min]				
Echarge [Wh/km]	2000	2400	2800	3200	3600
AC-city	157.4	164.9	140.1	150.5	159.7
ECE	104.3	122.5	124.0	125.6	131.2
NEDC	31.0	40.7	41.2	40.1	44.3
UDDS	68.6	67.0	72.6	75.8	73.2
HWFET	0.4	0.5	0.5	0.6	0.6
hyzem urban	56.0	58.5	52.1	59.1	41.3
hyzem rural	19.1	14.6	16.3	14.8	15.1
hyzem highway	1.1	1.0	1.1	1.1	1.1
japan 1015	59.4	67.7	75.1	79.9	64.2
Efuel [Wh/km]	2000	2400	2800	3200	3600
AC-city	22.2	0.0	94.2	73.0	59.7
ECE	63.3	0.0	0.0	0.0	0.0
NEDC	282.4	266.9	269.9	336.7	341.9
UDDS	181.9	191.6	195.4	211.4	231.5
HWFET	378.8	381.9	403.3	457.5	476.1
hyzem urban	300.3	338.4	357.7	364.4	463.5
hyzem rural	395.9	416.8	442.8	473.0	537.0
hyzem highway	525.4	528.7	531.1	538.1	564.3
japan 1015	182.6	179.0	179.7	204.9	291.2

Fig. 2.1-7: Energy consumptions of the parallel hybrid in dependence of the upshift speed

Also the start/stop frequency of the internal combustion engine is significantly influenced by the upshift speed threshold (Fig. 2.1-8). As the table shows, the engine is started much more frequently in case of the 2000 1/min threshold as at higher upshift speeds in driving cycles with urban and rural character (due to insufficient power of the electric motor). At higher upshift speeds, the reduced number of ICE startups stays more or less constant for these cycles, since the electric motor has a broader operation range of maximum power. An exception on this is seen for the Japan 10-15 mode. In this cycle, the ICE is in case of the 3600 1/min threshold as frequently started as in case of the 2000 1/min threshold. This is caused by a high power demand after a gearshift from 1st into 2nd gear within the acceleration of the first 10 mode, as Fig. 2.1-9 shows (the japan 10-15 mode is comprised of four 10 modes of 40 km/h maximum and one 15 mode of 70 km/h maximum). The total amount of engine starts within the whole cycle then amounts to five, since in 15 mode also an ICE-start occurs.

For cycles with highway character, the number of startups remains constant, since the startup behaviour then is mainly influenced by the 55 km/h threshold.

number of ice-starts	2000 1/min	2400 1/min	2800 1/min	3200 1/min	3600 1/min
AC-city	1	0	2	1	2
ECE	4	0	0	0	0
NEDC	5	1	1	1	1
UDDS	13	12	10	11	10
HWFET	1	1	1	1	1
hyzem urban	8	9	8	8	8
hyzem rural	14	12	12	12	12
hyzem highway	9	9	9	10	10
japan 1015	5	2	2	1	5

Fig. 2.1-8: Number of engine starts of the charge-depleting parallel hybrid vehicle in dependence of the upshift speed (default: 3200 1/min)

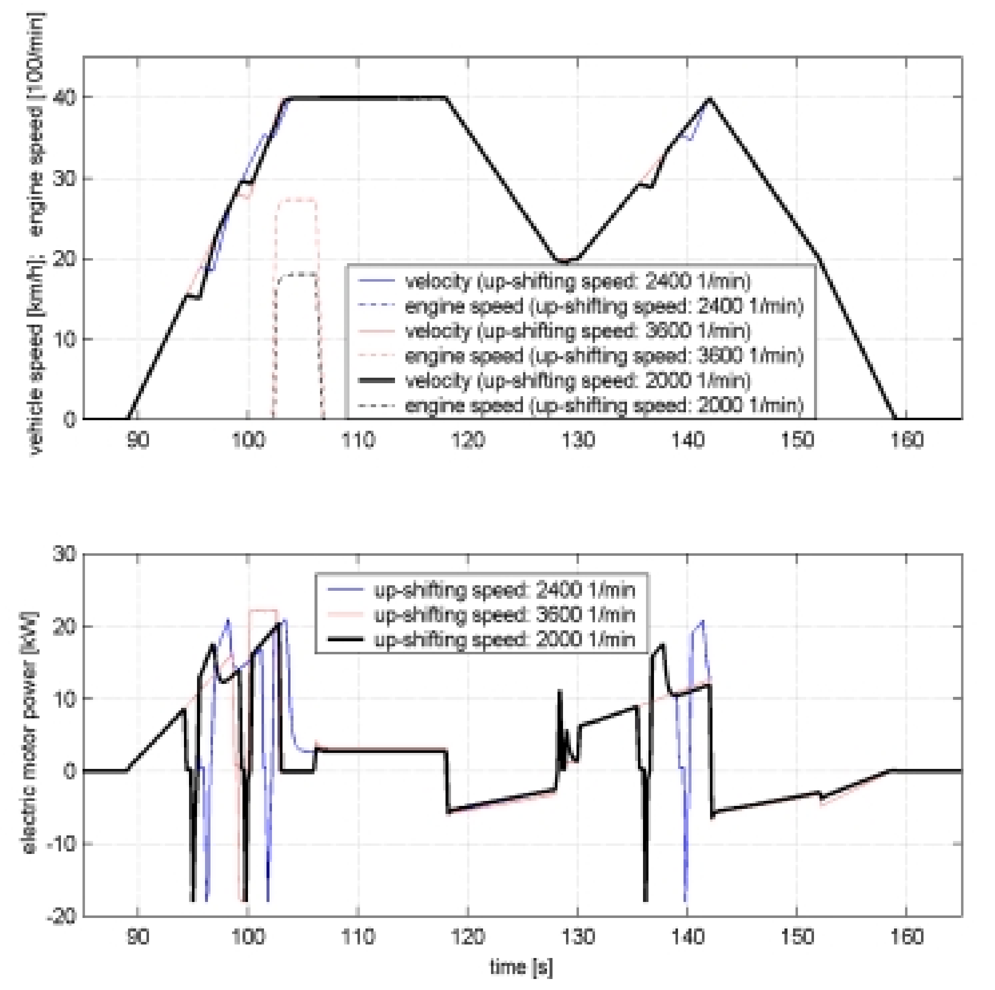

Fig. 2.1-9: ICE-startup behaviour of the parallel hybrid in Japan 10 mode in dependence of the upshift speed

Résumé:

- As for the accuracy and tolerances in vehicle speed the following applies: generally, both electric and fuel consumption change significantly if the speed track differs only slightly from the desired cycle speed. The consumed electric energy increases if the vehicle speed tends to the lower profile, and decreases if the vehicle speed is following the upper profile. The trend in fuel consumption seems to be the opposite. There are however exceptions to this. Also, the number of engine starts per cycle is influenced strongly by the followed speed track. This is on the one hand caused by vehicle-speed thresholds in control strategy and on the other hand by the boost operation of the engine in those cases where the maximum power of the electric motor is insufficient (parallel hybrid only).
- The other significant influence on energy consumption and ICE startup-behaviour is found in the gear shifting strategy of the parallel hybrid. Electric energy and fuel consumption generally increase when the upshift speed thresholds in the shifting strategy are increased. The increase in electric energy consumption is only shown in some driving cycles though. A comparison of the number of ICE starts shows, that only for low upshift thresholds an increase is observed. As soon as the electric motor is able to deliver its maximum power over a broader speed range, the number of ICE-starts remains constant. Again some exceptions are seen in this case, which are mainly caused by a lack of electric motor power at higher vehicle speeds.

2.2 Charge-sustaining hybrid vehicles

The influence of fluctuations in vehicle speed is studied on the charge-sustaining hybrid vehicles as well. In contradiction to the charge-depleting hybrid vehicles, there is no additional energy consumption (electric energy from mains) to be considered. Rather, a difference in the state of charge at the end of the driving cycle may occur, and thereby either complicate the reproducibility of cycles which have to be "SOC-balanced", or falsifying the results gained from ΔSOC-correction methods.

The difference in energy consumption between the standard cycle and the measured velocity profile for the parallel hybrid is given in Fig. 2.2-10. The results were calculated for a cycle with high initial state of charge1.

In the energy consumptions of the flywheel version it shows the balanced state of charge in case of the „standard“ Aachen-city-cycle, whereas the same vehicle at the end of the measured profile has a lower state of charge. Because of the lower demanded energy in this cycle, the charging mode starts a little later, so at the end of the cycle there is recharged less energy. This is the reason the part of the ICE in the total amount of mechanical energy is smaller.

In contradiction to this the difference in fuel and electric energy between both UDDS-cycles is caused by the braking phase from maximum speed at the end of the fastest speed sequence. The slightly stronger deceleration in the standard cycle causes a difference between both states of charge, which lasts to the end of the cycle. So the flywheel is being recharged right before the end of cycle in case of the measured profile, in the standard cycle this is postponed until the cycle has ended.

1 For an explanation of the charge-sustaining control strategies see [1].

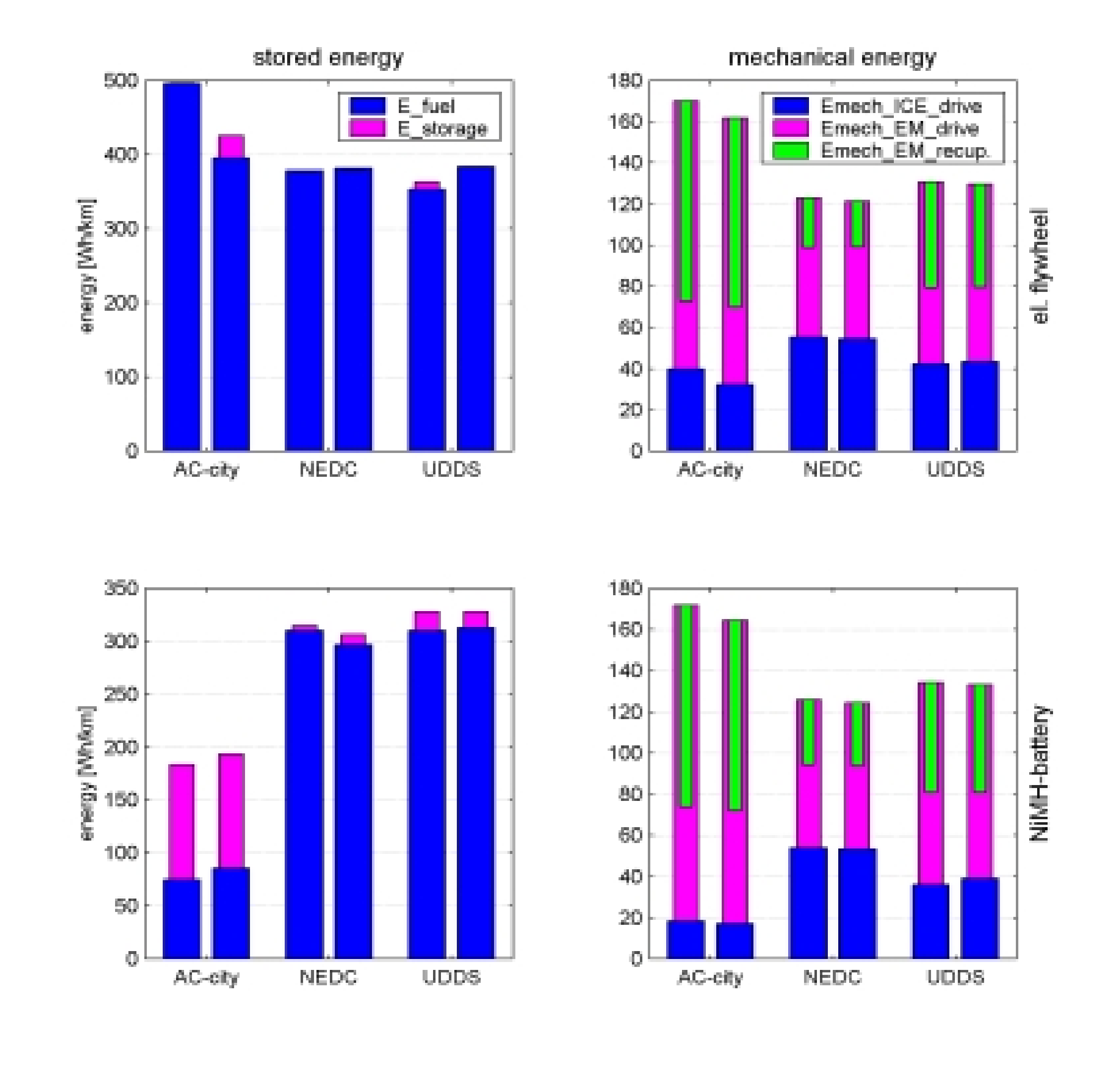

Fig. 2.2-10: Comparison of fuel energy, storage energy and mechanical energy for standard cycle (left bar) and measured velocity profile (right bar) for the parallel hybrid

The energetic differences for the parallel hybrid with battery storage device are comparable with the differences of the flywheel version. Comparing the results of the Aachen-city-cycles shows an obvious difference. Although the energy for driving provided by the combustion engine in the standard cycle is higher than for the measured profile, the fuel consumption in this cycle is lower than the value calculated for the measured profile. The explanation for this is the boost behaviour of the combustion engine. Because of the high energy capacity of the battery the control strategy keeps the drive train in electric mode during the complete cycle and starts the combustion engine just for boost operation. In the standard cycle at the beginning, during the strongest acceleration, this leads to only one ICE start, whereas for the measured profile the ICE takes over the driving function three times for a very short time. So in this case the efficiency of the combustion engine is lower.

For the series hybrid the energy consumptions are given in Fig. 2.2-11. As for the parallel hybrid, also in this representation the results are based on one single cycle with high initial state of charge.

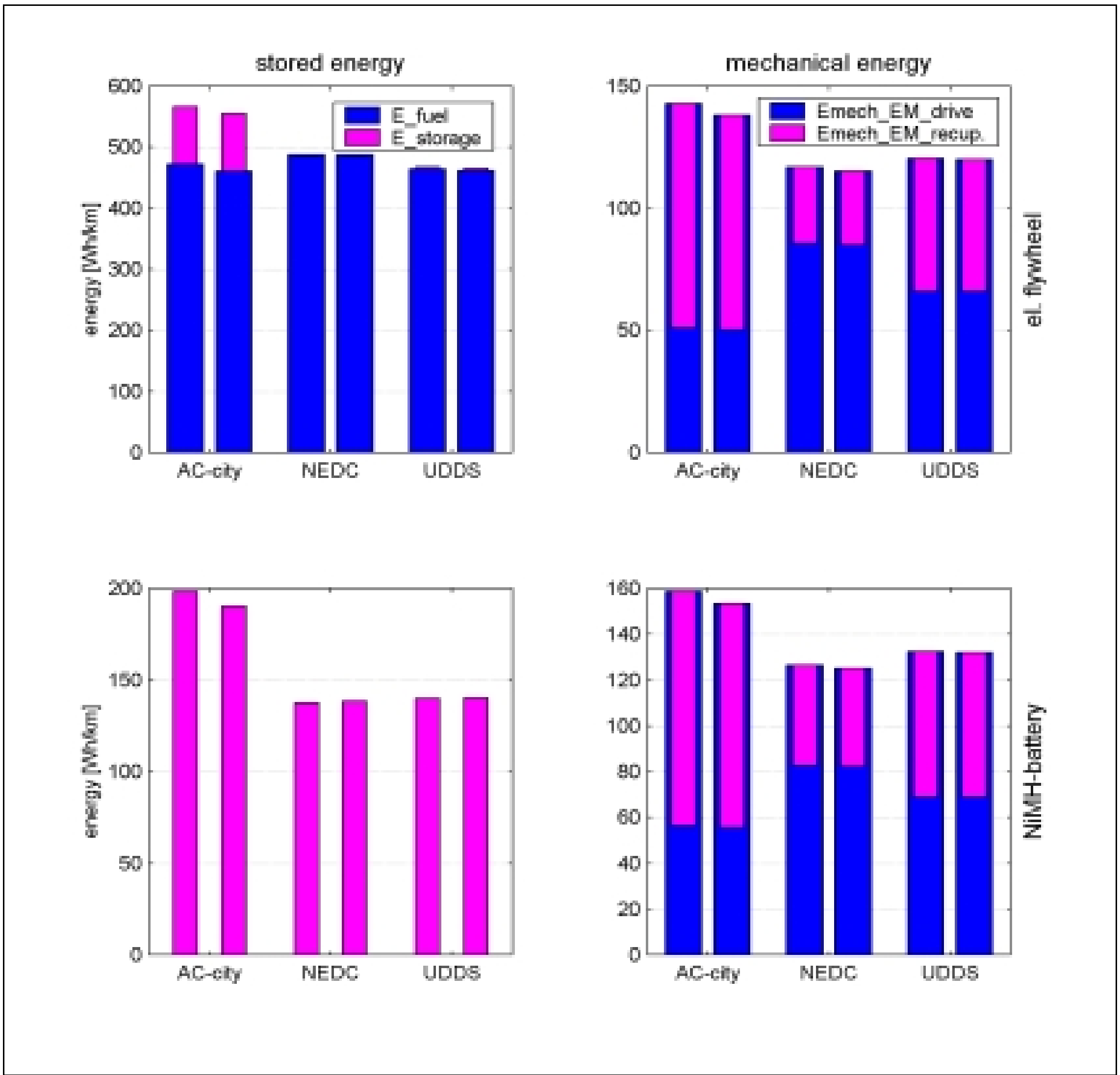

Fig. 2.2-11: Comparison of fuel energy, storage energy and mechanical energy for standard cycle (left bar) and measured velocity profile (right bar) for the series hybrid

Generally, the differences in fuel and electric energy between standard and measured profile are not as high as for the parallel hybrid. The mechanic decoupling of the combustion engine from the drive train in this case causes a phlegmatised influence on the combustion engine operation by the power demand. In case of the series hybrid with battery storage device, the combustion engine is not operated during the first cycle at all.

Some differences appear more clearly in this representation than in the one of the parallel hybrid although. The higher recuperation energy in the standard Aachen-city-cycle because of the stronger decelerations for instance is shown much better.

The effects of the velocity differences on the number of ignitions per cycle of the combustion engine are shown in Fig. 2.2-12. The values are established for six cycles driving with the parallel hybrid and ten cycles driving with the series hybrid.

The higher number of ICE starts of the parallel hybrid in the Aachen-city and NEDC-cycles can be led back mainly to the frequent boost operation in electric mode. Because of the fluctuating velocity courses in the measured profiles, the electric motor is operated at maximum power more often. In the Aachen-city-cycle the number of ICE starts for the battery version exceeds the one for the flywheel version in spite of the much higher energy capacity (the significant weight penalty for the battery version causes higher power demands). Also, both parallel hybrids and the series hybrid with flywheel storage device show a different time course of state of charge in the NEDC-cycle with measured speed profile, which causes an increase in the number of charging operations. Although both phenomena also are shown in the UDDS-cycle, they have no influence on the number of ICE starts per cycle.

number of ice-starts per cycle	AC-city		NEDC		UDDS	
	standard	**actual speed**	**standard**	**actual speed**	**standard**	**actual speed**
phfw	3.7	4.2	9.5	11.5	17.7	17.3
phbat	2.8	4.3	4.8	9.5	14.5	14.2
shfw	1.6	1.6	5.2	6.1	8.0	8.0
shbat	0.2	0.2	0.6	0.6	0.6	0.6
ph=parallel hybrid; sh=series hybrid; fw=el. flywheel; bat=battery						

Fig. 2.2-12: Number of starts of the combustion engine in different cycles

Fig. 2.2-13 representatively shows the effects of different velocity profiles on combustion engine speed, state of charge and actual fuel consumption for the parallel hybrid in the UDDS-cycle. At the end of the cycle there is a difference of 8.6% in fuel consumption, which is quite high. After a longer period of time the difference in fuel consumption in most cycles drops below 1%. In order to meet such tight tolerances it therefore is necessary to drive several cycles to minimise the influences of differing velocities.

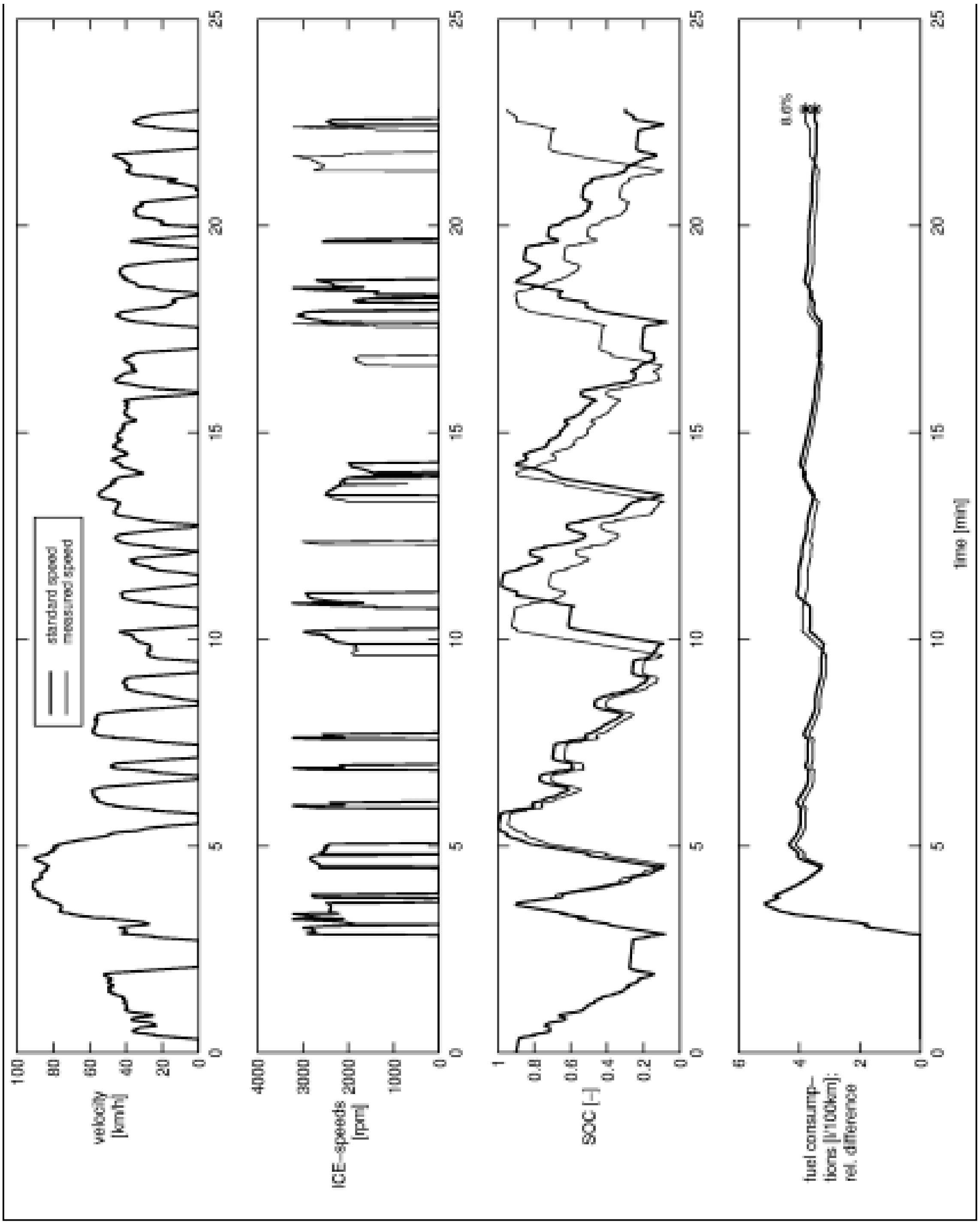

Fig. 2.2-13: Comparison of simulation results for the parallel hybrid in the UDDS-cycle; driven in standard cycle and driven in measured velocity profile

Also the effects of slightly different speed profiles on the fuel consumption as obtained with the method of linear interpolation [2] can be estimated. Fig. 2.2-14 shows fuel consumptions for the standard cycles, as well as for the cycles simulated over measured profiles. It is seen that the errors made by the interpolation method, due to diverting vehicle speeds, are small but noticeable. The table for instance shows a reduced fuel consumption in the measured Aachen-city-cycle. For the series and parallel hybrid with NiMH-battery it is 0.2l/100km, if compared to the real fuel consumption (obtained by the regression method for the standard speed case). The differences of the results obtained by interpolation method on the standard cycle are about 0.1l/100km if compared to the real fuel consumption.

		AC-city		**NEDC**		**UDDS**	
VEH	[l/100km]	**standard**	**actual speed**	**standard**	**actual speed**	**standard**	**actual speed**
phfw	interpolation	4.91	4.80	3.69	3.71	3.82	3.76
	regression	4.89	4.82	3.64	3.70	3.82	3.77
	difference	0.02	-0.02	0.05	0.01	0.00	-0.02
phbat	interpolation	4.18	4.13	3.22	3.25	3.55	3.52
	regression	4.28	4.17	3.25	3.30	3.55	3.54
	difference	-0.10	-0.04	-0.03	-0.05	-0.01	-0.02
shfw	interpolation	7.39	7.27	4.76	4.76	4.65	4.64
	regression	7.37	7.27	4.74	4.78	4.66	4.65
	difference	0.02	0.00	0.02	-0.02	-0.01	-0.01
shbat	interpolation	5.62	5.39	3.91	3.94	3.94	3.95
	regression	5.69	5.46	3.88	3.87	3.94	3.96
	difference	-0.07	-0.07	0.03	0.07	0.00	-0.01

ph=parallel hybrid; sh=series hybrid; fw=el. flywheel; bat=battery

Fig. 2.2-14: Fuel consumption variances because of minor different velocity profiles (measured and standard cycle)

Résumé:

- For the charge-sustaining hybrid vehicles the simulation results showed, that slight fluctuations in vehicle speed especially for the parallel hybrid can cause a different on/off characteristic of the combustion engine. Therefore emission measurements are very likely to yield different results.
- The noticed differences in fuel consumption between results obtained following the standard profile and results obtained following a measured speed profile were small, but significant for each driving cycle. The comparison of the corrected fuel consumptions in the cycles with fluctuations in vehicle speed could prove differences in fuel consumption of up to 0.2 l/100km for the hybrid vehicles with NiMH-battery.

3 Results of experiments

The measurement works for this subtask have been have been carried out at different institutes of the MATADOR-partners. The Audi DUO (parallel hybrid vehicle) has been tested at ika, the Porter Piaggio/Microvett (battery electric vehicle) has been tested at ENEA and the Blue Angel (series hybrid vehicle) has been tested at HTA Biel.

Compared to the simulation works, similar experiments have been carried out, e.g. the influence of driver behaviour and shifting points, which has been investigated on the Audi DUO. But since the experiments are done on actual vehicles, additional information on accuracies and tolerances could be obtained, which mainly include the influence of initial temperatures of the power train.

3.1 Audi DUO hybrid electric vehicle

Since accuracy and tolerance have significant influence on especially *hybrid* vehicles with event-driven control of the drive train (power distribution within the drive train changed because of state-events like predefined SOC-limits or accelerator-positions), the measurements for this subtask of the DUO were performed in hybrid mode. The cycle which has been used is the European Driving cycle (NEDC), which is useful because of his modal character. This allows for a better insight in driveline behaviour compared to more transient cycles as e.g. the UDDS.

The driveline behaviour of the Audi DUO after a cold vehicle startup is shown in Fig. 3.1-1, in which the time histories of vehicle speed and used energies are displayed.

Generally, at the beginning of the driving cycle the combustion engine is started by the control strategy and kept in operation in order to reach a normal operation temperature, meanwhile delivering the propulsion energy (fuel consumption increases in this phase, electric motor energy is almost constant).

After ICE shut-off, the propulsion energy is delivered by the electric motor (fuel consumption stays constant, electric motor energy increases). Usually the electric propulsion starts within the second micro urban cycle and ends at the acceleration phase from 100 km/h up to 120 km/h in the Extra Urban part.

Then, the power delivered by the electric motor reaches its maximum (the driver applies kickdown) and the propulsion task again is taken over by the internal combustion engine. In this phase, the ICE is in such a way controlled, that it does not only deliver the propulsive power, but also additional power for traction battery recharge. This is called load levelling operation of the ICE.

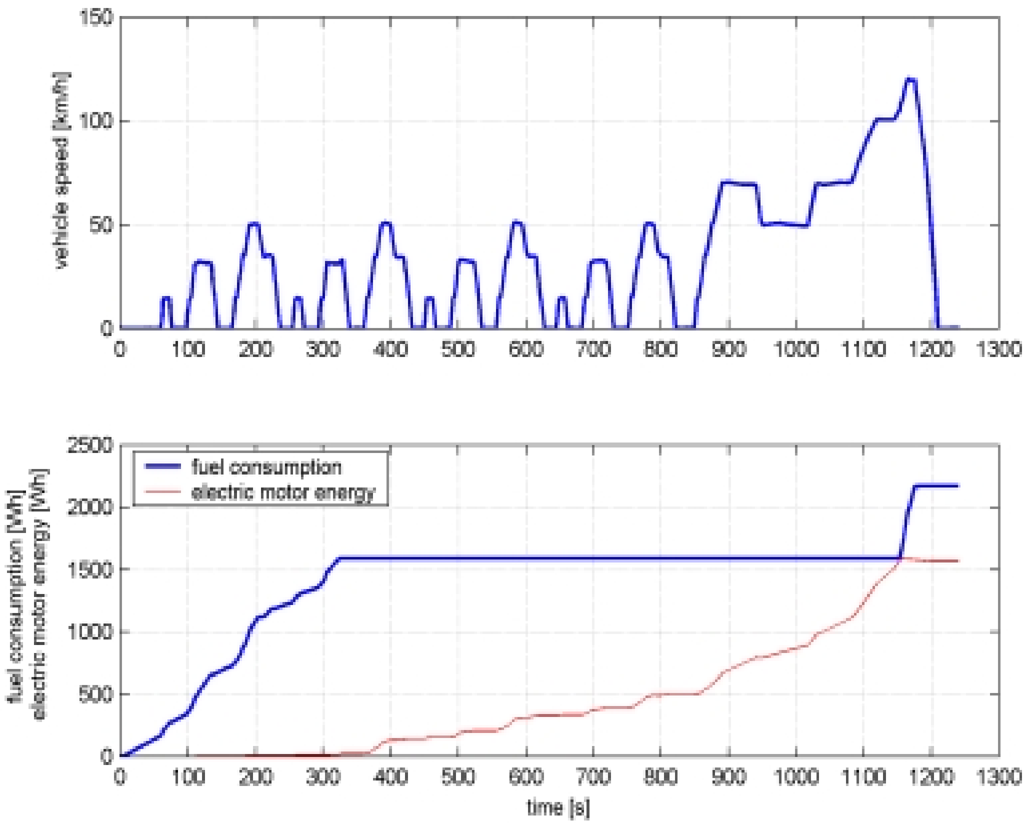

Fig. 3.1-1: Behaviour of the hybrid driveline in terms of energy consumption in NEDC

The conversion of this additional mechanical power is done by the electric motor, which in that case operates in generator mode. This recharge phase is recognised in Fig. 3.1-1 by the negative trend of the DC electric energy from 1150 to 1174 seconds. At braking phases, the fuel supply of the ICE is stopped and after a short period in drag the ICE is declutched and stopped.

3.1.1 Influence of driver behaviour

For the investigation of the repeatability of energy consumption, the Audi DUO has been tested over the NEDC by different drivers in hybrid mode. Since the Audi DUO has a manual transmission, the influence of driver dependent shifting behaviour had to be eliminated. This was realised by using the shifting points of the driving cycle for conventional vehicles with manual transmissions. Note that the European testing procedure for hybrid electric vehicles does not define any shifting points; the test driver should rather use the gears with which the desired vehicle speed is followed best.

The differences between a well balanced and a more nervous driver are shown in Fig. 3.1-2. As can be seen in Fig. 3.1-2, the actual vehicle speed stays within the specified tolerances in both cases, vehicle speed in case of the well balanced driver (driver 1) shows less fluctuations compared to the nervous driver (driver 2) however. Especially the startoff behaviour is much more steady, as can be seen in the plot of traction currents, where an overshoot in traction current is observed for the nervous driver. The driver control at transitions from acceleration/deceleration to constant speed shows also less overshoot-character.

After the electric motor has reached its maximum power (t = 1150 s) and the vehicle as a consequence of that is not able to follow the desired acceleration, the well balanced driver waits a little longer before he applies kickdown, using the complete tolerance band. As a result of that, the duration of ICE operation is reduced by 4 seconds.

The consequences of the differences in driver behaviour in terms of energy consumption are shown in Fig. 3.1-3. Fuel consumption in the first cycle phase as well as electric energy consumption in second cycle phase are smaller for the well balanced driver, the electric energy differences are very small, though. In the third cycle phase, where the combustion engine is started again, the fuel consumption is again increased more strongly in case of the nervous driver, since he applies kickdown 4 seconds earlier as the well balanced driver. Due to the fact that the battery is recharged by additional engine power, the electric motor energy decreases more in this case, compensating for the slightly higher energy consumption during electric propulsion.

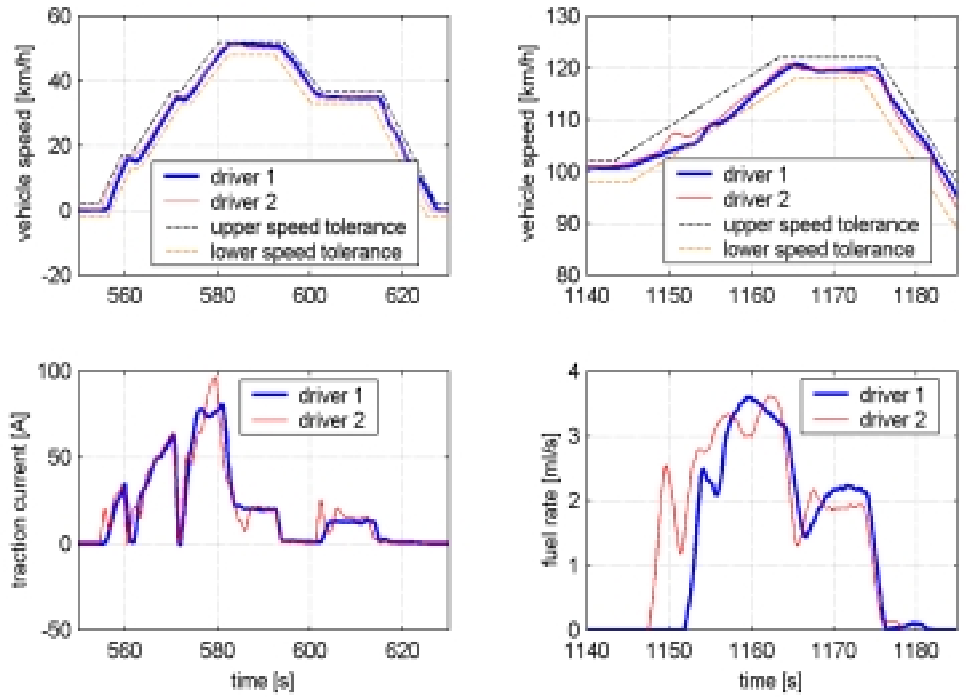

Fig. 3.1-2: Driver influence on traction current and fuel rate

A second driver dependent influence on energy consumption is the use of the kickdown. If the driver from himself does not allow a significant difference between desired and vehicle speed, then he applies kickdown much earlier, as indicated by the plots of driver 3 in Fig. 3.1-4. In contradiction to driver 1, which applies kickdown in the acceleration phase from 100 km/h to 120 km/h, driver 3 already accelerates under full load in the acceleration phase from 70 km/h up to 100 km/h (t = 1094 seconds).

This results in a very different distribution of energy consumption, Fig. 3.1-5. In case of early kickdown, fuel consumption increases from 1.95 l/100 km to 3.08 l/100 km, while energy consumption from mains is reduced from 264 Wh/km to 199 Wh/km, compared to driver 1. The load levelling ICE operation in combination with the significant difference in ICE running time of 56 seconds changes the distribution of energy consumptions (fuel vs. electrical energy) over-proportionally.

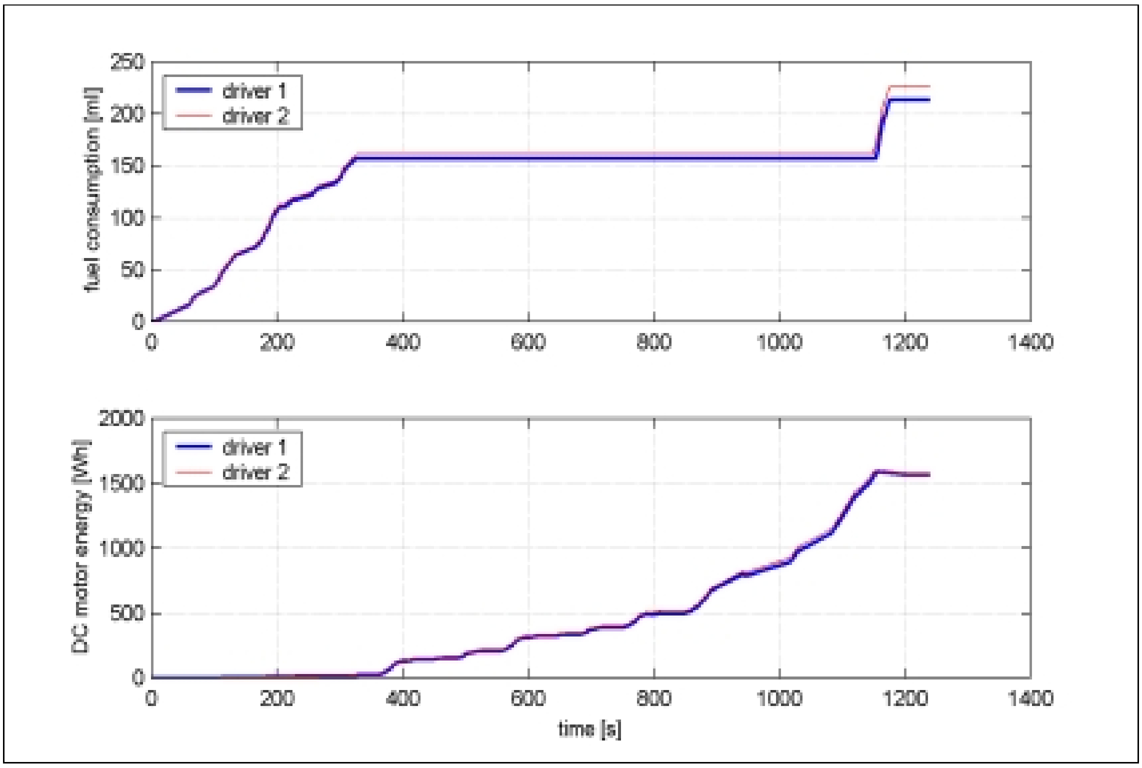

Fig. 3.1-3: Driver influence on fuel consumption and electric motor energy

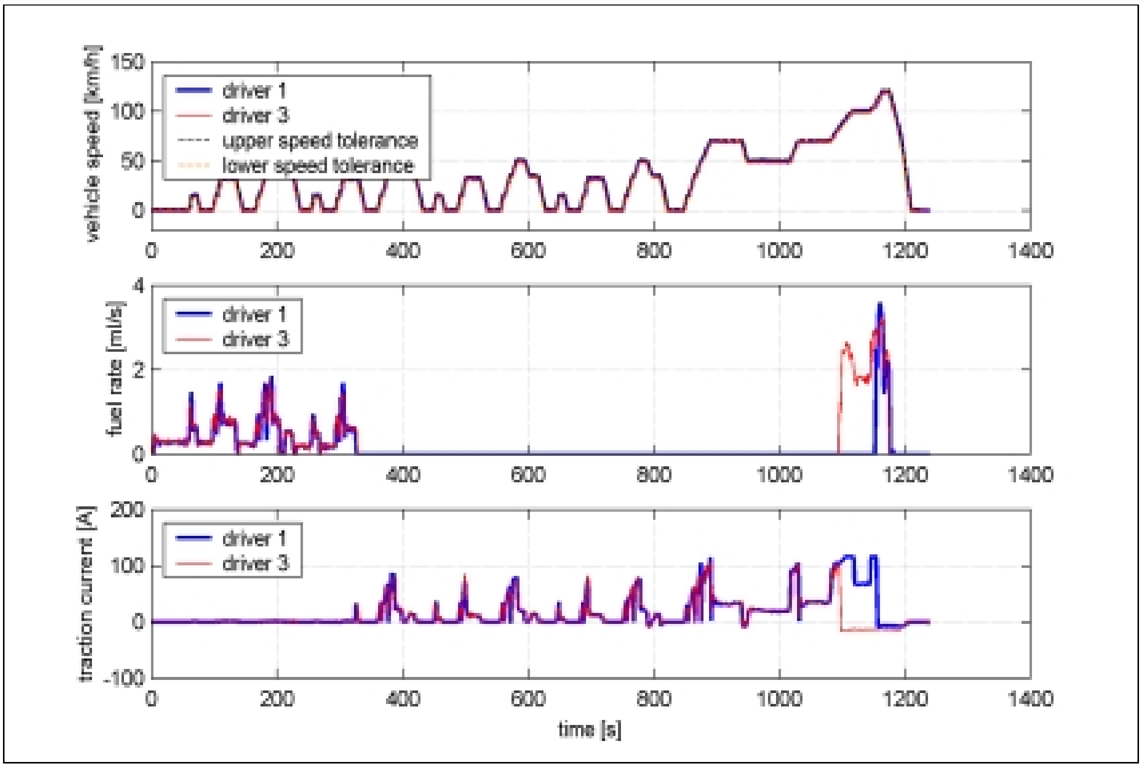

Fig. 3.1-4: Comparison of different kickdown application

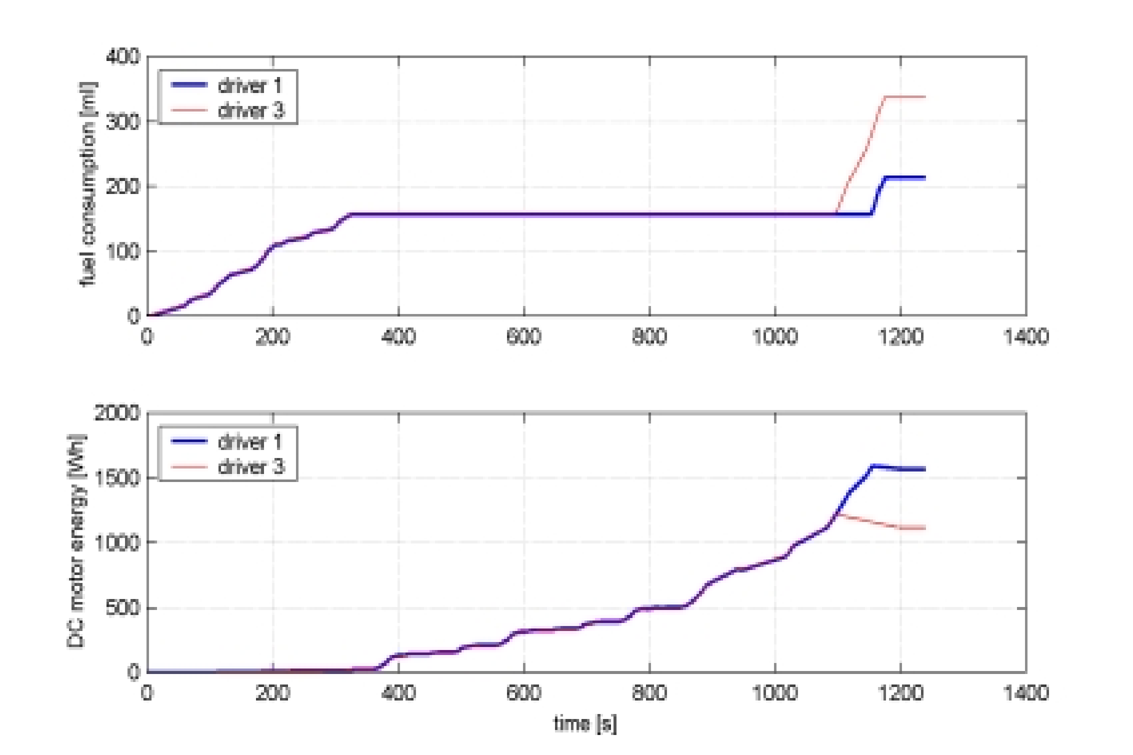

Fig. 3.1-5: Comparison of energy consumptions for different kickdown application

3.1.2 Influence of shifting points

Another driver relevant aspect in the measurement of energy consumption and emissions is the use of the gears in case of vehicles with manual transmissions. Since the Audi DUO is equipped with a manually shiftable transmission, the influence of different shifting points can be investigated. The NEDC was driven by the same driver twice; the first time he shifted into the next gear at 3000 rpm, in the second test the next gear was selected at a transmission input speed of 2000 rpm. The downshift gear selection stayed the same as for conventional vehicles in NEDC.

This resulted in a different warmup phase of the internal combustion engine. Upshifting at lower revolutions resulted in a reduced fuel consumption and therefore in a slower warmup of the internal combustion engine, as can be seen in Fig. 3.1-6 (since a lower fuel consumption is inherent to a lower production of heat). A strong dependence between ICE coolant temperature and duration of the ICE-warmup phase is seen, since warmup always ends at coolant temperatures of about 51 °C. Especially the fuel consumption in the constant speed sequences higher than 15 km/h differs significantly, since the selected gear is always 1 number higher in the case of 2000 rpm upshift speed. The difference in ICE speed is then approximately 800 rpm. As a result of this, the engine warmup is extended until the third velocity sequence in the second micro urban cycle. The additional fuel consumed in this extending time (more than one minute) is higher than the saved fuel for the period in which the engine operates in both cases, as can be seen in Fig. 3.1-7.

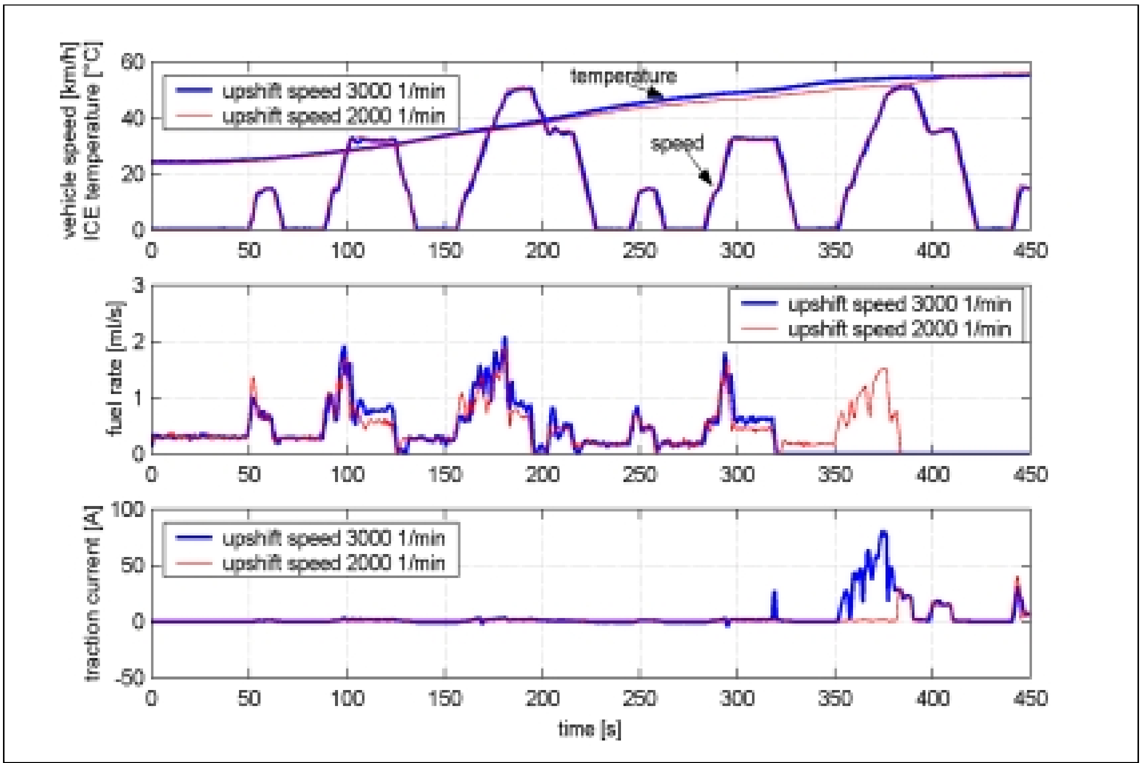

Fig. 3.1-6: Influence of upshift speed on ICE warmup behaviour

The electric energy consumption after engine warmup shows an opposite trend, the energy consumption is increased in case of the 2000 rpm upshift speed. The reason for this is an increase of motor efficiency for higher speeds in combination with lower torques. The reduced energy consumption in electric mode does not fully compensate for the electric energy that is already consumed because of the earlier start of electric operation however.

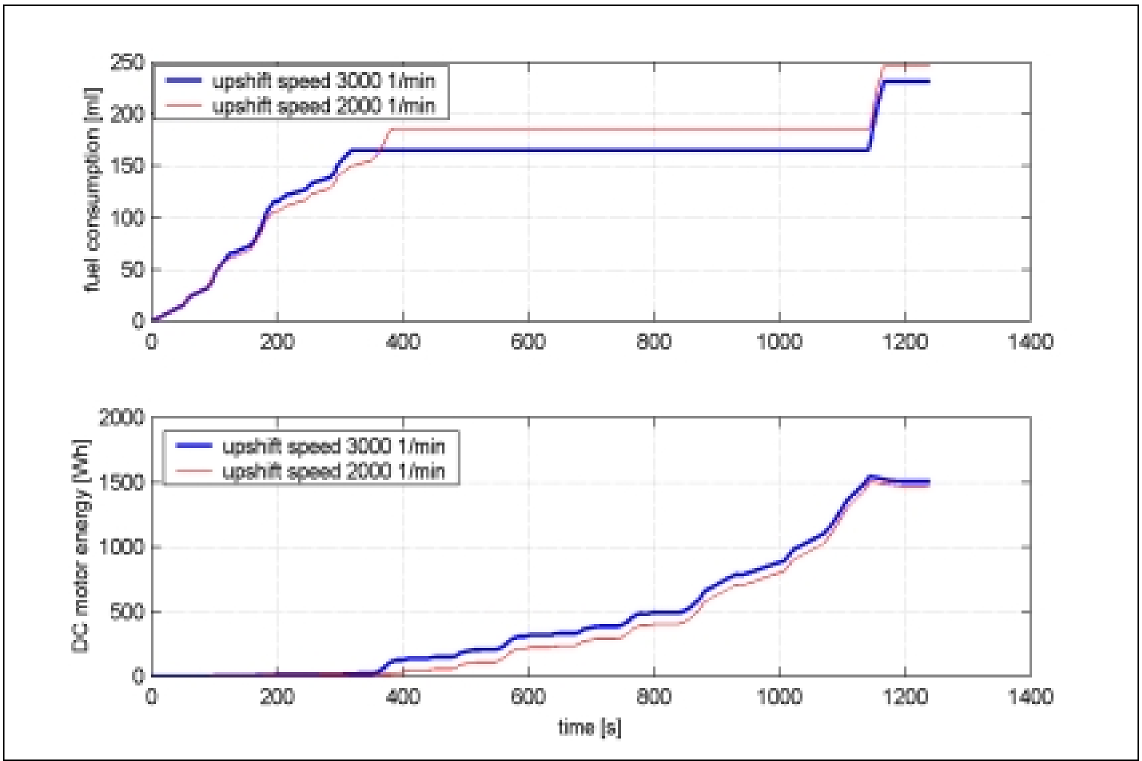

Fig. 3.1-7: Comparison of energy consumptions for different upshift speeds

3.1.3 Influence of initial condition of the internal combustion engine

The previous chapter already showed that the duration of the first ICE running period depends on its coolant temperature. Therefore the (non-driver dependent) influence of the initial drivetrain temperature, especially of the initial ICE temperature, can be investigated. Since the European standard for hybrid electric vehicles prEN 1986-2 refers to the vehicle preconditioning of Directive 70/220/EEC, which defines a soak period of at least 6 hours at a temperature between 20 °C and 30 °C, with the requirement that engine oil- and coolant temperatures must have ambient temperature ±2 °C, two tests with different initial ICE temperatures between 20 and 30 °C were performed in order to investigate the influence of different starting temperatures, one at 25-2°C and one at 25+2°C (see Fig. 3.1-8).
Although both initial temperatures are within the defined tolerance band, the duration of the ICE warmup phase is increased by 43 seconds for the lower starting temperature. The overall fuel consumption is increased by 7 % (from 1.95 l/100km to 2.09 l/100km). A significant difference in electric energy consumption is not observed, the driver influence on energy consumption seems to be bigger.

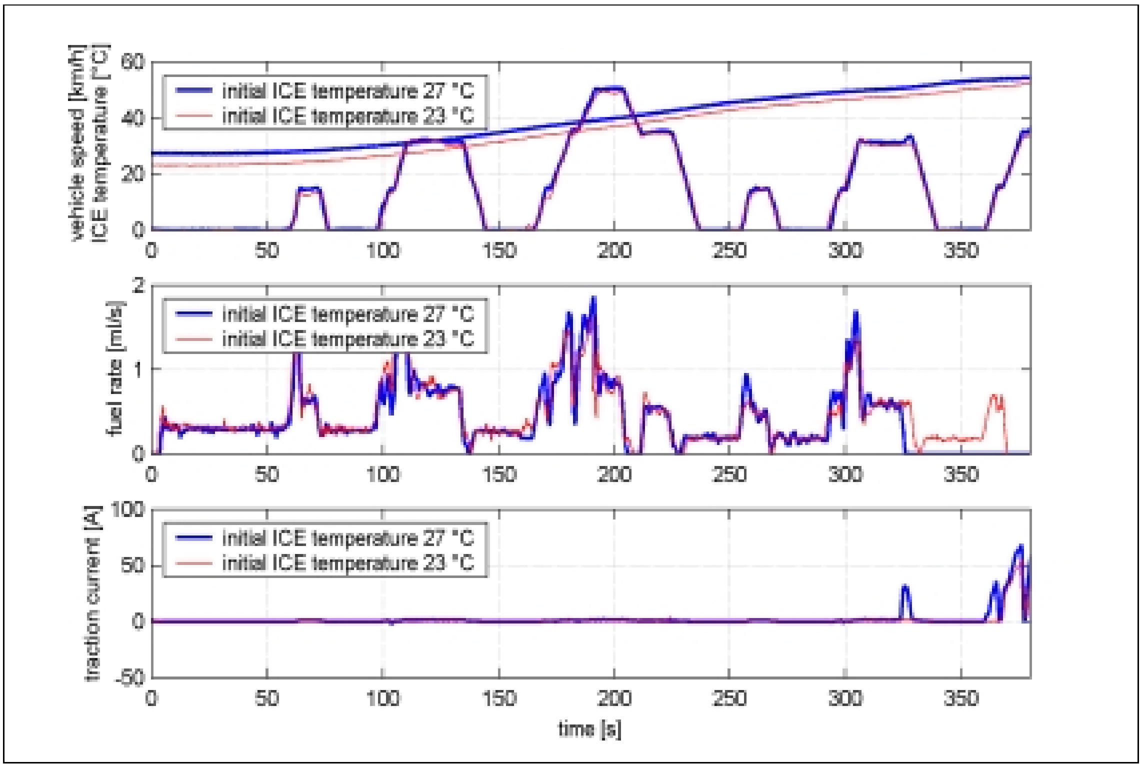

Fig. 3.1-8: *Influence of different starting temperatures on ICE warmup duration*

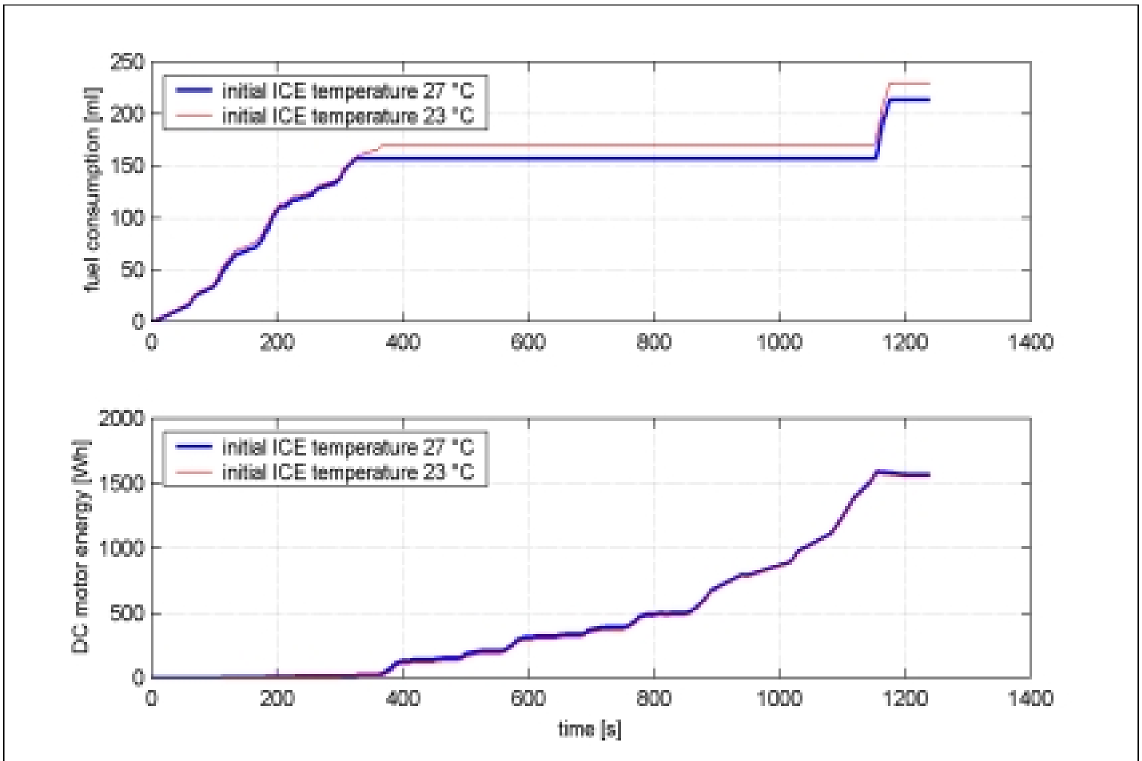

Fig. 3.1-9: *Differences in energy consumption as a result of different initial ICE coolant temperatures*

An overview of the measurement results on the Audi DUO is shown in Fig. 3.1-10. Some fluctuations are also seen for the charging efficiency, which in this case is defined as:

$$\eta_{charge} = \frac{E_{elec.motor} + E_{DC/DC}}{E_{charge,mains}} \qquad \textit{Equation 1}$$

case	Fuel consumption [l/100km]	charging energy from mains [Wh/km]	electric motor energy [Wh/km]	DC/DC-converter energy [Wh/km]	ICE-generator energy [Wh/km]	charging efficiency [%]
well balanced driver	1.95	263.9	144.4	12.0	6.1	59.3
nervous driver	2.05	260.5	142.4	11.7	6.3	59.2
initial ICE temperature 23 °C	2.09	274.1	141.6	11.5	7.0	55.9
initial ICE temperature 27 °C	1.95	263.9	144.4	12.0	6.1	59.3
upshift speed at 3000 1/min	2.10	257.8	136.8	11.3	6.4	57.4
upshift speed at 2000 1/min	2.24	251.6	134.3	10.8	6.9	57.7
kickdown applied at acceleration from 70 to 100 km/h	3.08	198.7	101.7	10.7	7.4	56.6

Fig. 3.1-10: Overview of energy consumptions of the Audi DUO in hybrid mode; NEDC

Résumé:

- A well balanced driver follows the desired speed curve best, the energy flows (fuel and current) are much more steady as for a more nervous driver. The actual velocity stays within the defined tolerance band for both types of driver although. The fuel consumption is considerably higher for a more nervous driver, electric energy consumption is influenced only slightly by different driver behaviour.
- If the driver does not allow significant differences between desired and actual vehicle speed, kickdown is applied much earlier, resulting in a longer engine operation periods (in the case of other cycles/vehicles, kickdown is likely to be applied more often too). This changes the distribution of fuel and electric energy significantly. If the traction battery is recharged during engine operation also, this effect is increased.
- If the gears are selected at different operation points, especially warmup behaviour of the internal combustion engine is influenced, resulting in a significant difference in fuel consumption. The differences in electric energy are only small in this case.
- A second major influence on energy consumption is the initial temperature of the drive train, especially of the internal combustion engine. Even if the initial ICE-temperature is within the specified tolerance (between 20 °C and 30 °C), fuel consumption can differ considerably. The reason for this is the resulting duration of the ICE-warmup. Since the control strategy always ends warmup at the same coolant temperature, warmup duration and as a consequence also fuel consumption is increased in case of lower initial ICE temperatures.

3.2 Comparison of human with automatic driver

Automatic driving systems take over the function of the human driver in testing procedures and consist of actuators for gas-, brake- and clutchpedals, as well as of a gear lever positioning system, which are controlled digitally. Various driving cycles are incorporated in the accompanying software.

In order to investigate the possibilities of using an automatic driving system instead of a human driver, the EN 1986-1 procedure has been carried out on the Porter BEV at the testing facilities of ENEA.

In spite of very similar initial vehicle conditioning, the energy consumption obtained for the ENEA automatic driving system is considerably higher than the energy consumption for the human driver, as Table 1 shows.

Table 1: Energy consumption test results (EN1986-1 seq. 1)

Measured parameters	Test 1	Test 2
Overall travelled distance (7 urban cycles), km	28,136	28,993
Overall Energy consumption, kWh	4,230 [#11]	4,848 [#21]
Average energy consumption (from the battery), Wh/km	138,2 [#12]	161,63 [#22]
Average energy consumption (from the battery), Wh/urban microcycle	141,6	168,2
Recharged energy (from mains after test), kWh	7,230	8,029
Average consumption(from mains), Wh/km	**237,9**	**267,7**
Average consumption (from mains), Wh/urban microcycle	258,2	286,7
Storage system energy efficiency (battery + battery charger), %	58,5	60,3

[#11] Including 265 Wh consumed for vehicle pre-conditioning
[#12] Including 2,250 km travelled during vehicle pre-conditioning.
[#21] Including 138 Wh consumed for vehicle pre-conditioning
[#22] Including 1,000 km travelled during vehicle pre-conditioning.

The increase in energy consumption of the second test is caused by the acceleration characteristics of the automatic driver. The automatic system accelerated with higher rates than the real driver. ENEA thinks that it is possible to minimise the differences in driving behaviour by better regulating the controller of the acceleration actuator of the used automatic driver.

The advantages of a better reproducibility in case of an automatic driver therefore are only of interest for systems which behave representative to a human driver. Automatic driving systems meeting such demands are commercially available, but are quite expensive.

3.3 Blue angel hybrid electric vehicle

A possible way of dealing with differences occurring in energy consumption as a results of driver/conditioning-fluctuations is presented by the Hochschule für Technik und Architektur Biel/Bienne, which have formulated a *low-cost* method of measuring energy consumption and exhaust emissions on hybrid vehicles using the combined gas/electric Blue Angels series.

The measurement procedure is based on the one used in the study called “Measurement of the energy consumption of electric vehicles” [3], in which the test vehicle is taken through three driving cycles of approx. 10 km each on the test bench. Since it is to be assumed that the user of such a vehicle probably lives in an urban area, the first cycle is performed using the electric motor only (as far as possible) and starting with a fully charged battery, while the remaining two cycles are to be covered in hybrid mode.

The cycle which has to be used is the NEDC. The speed is limited to 80 km/h however, such that low powered vehicles also can follow the desired speed track.

After completion of the third cycle, the battery has to be recharged for 8 hours, recording the required amount of energy taken from the mains. The fuel consumption is to be calculated by using the exhaust measurements.

The measurement procedure has to be performed three times, after which the mean values for the consumption of electrical power (mains supply) and thermal energy (gas) are indicated separately.

The measurement results for the Blue Angel HEV are shown in Fig. 3.3-11. As the figure shows, the differences in fuel consumption of the three different tests are remarkably high, they amount to 33%. This is explained by the different operation times of the ICE. The maximum difference in electric energy from mains is about 7%. In order to account for this changing driveline behaviour, the test has to be performed three times. The presented results is determined by averaging the results of the three different tests.

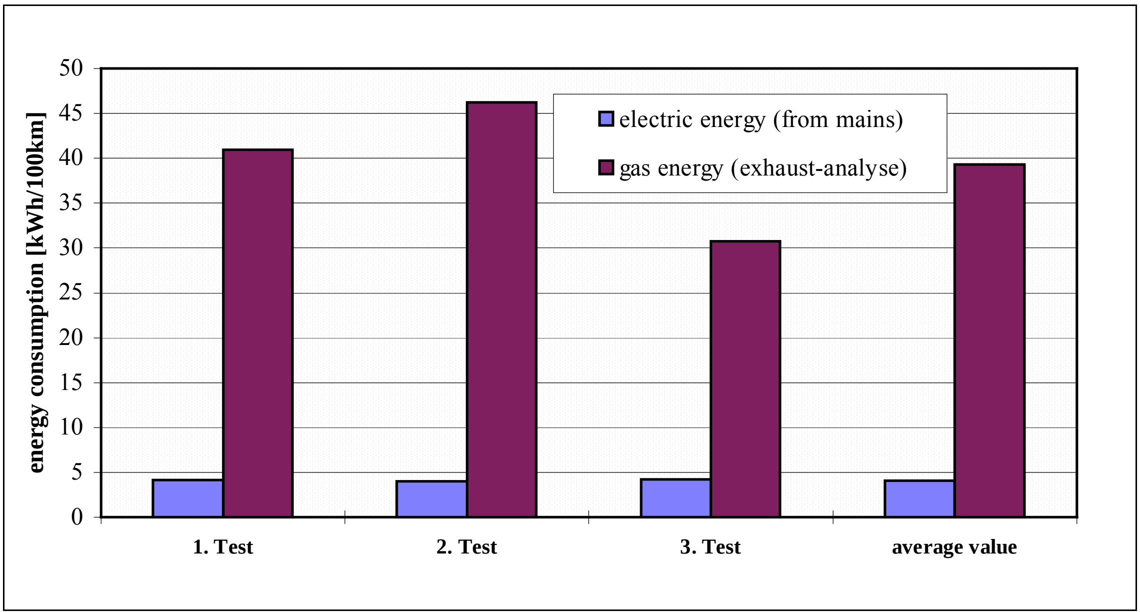

Fig. 3.3-11: Electric and fuel energy consumption of the Blue Angel series hybrid electric vehicle

This procedure can be of help if the accuracy and repeatability demands are not too high. If the averaged measurement values have to be absolute representative for the fuel consumption in NEDC, then the number measurements surely should be increased. The averaging of more than one measurement results could be a useful tool in a testing procedure for HEVs which also defines stringent rules of accuracy.

4 Summary

In this report, the influence of accuracies and tolerances in testing procedures on the test results has been investigated. In order to do so, various computer simulation experiments and vehicle measurements of mainly mid-class passenger cars with (hybrid) electric propulsion system were carried out.

Research focussed on the following topics:

- Accuracy and specified tolerances with which the desired vehicle speed was followed (computer simulations: simulations of standard speed, measured speed profile and tolerance-adjusted standard speed; vehicle measurements: comparison of different human drivers)
- Definition and influence of shifting strategies in case of vehicles with manual transmission (computer simulations and vehicle measurements)
- Tolerances for the powertrain temperature at the beginning of the testing procedure (vehicle measurements only)

It was shown in general, that while staying within the specified speed tolerances, driver behaviour and the consequently followed speed track have a strong influence on energy consumption and on the start/stop characteristics of the internal combustion engine of hybrid electric vehicles. The start/stop frequency of the engine is related to the pollutant emissions. Especially control strategies which have a direct dependency between start/stop management of the combustion engine and the driver pedal positions may react sensitively on the driver behaviour.

For charge-depleting hybrid vehicles, both electric and fuel consumption change significantly if the simulated speed track differs only slightly from the desired cycle speed. The consumed electric energy increases if the vehicle speed is closer to the lower tolerance bound, and decreases if the vehicle speed moves towards the upper speed tolerance. Differences can amount up to 8% (parallel hybrid vehicle, comparison of standard speed with real speed profile). The trend in fuel consumption seems to be the opposite, where differences of 10% are seen. There are however exceptions to this. For these vehicles, also the number of engine starts per cycle is influenced by the followed speed track. This is on the one hand caused by vehicle-speed thresholds in control strategy and on the other hand by the boost operation of the engine in those cases where power demand is high (e.g. because of high battery weight) and maximum power of the electric motor is insufficient (parallel hybrid). In the Aachen-city cycle for instance, this causes the engine to be started twice as often in a real speed profile simulation when compared to a standardised speed profile simulation.

For the simulated charge-sustaining hybrid electric vehicles, the noticed differences in fuel consumption between results obtained following the standard profile and results obtained following a measured speed profile were small, but significant for each driving cycle. The comparison of the SOC-corrected fuel consumptions in the cycles with fluctuations in vehicle speed could prove differences in fuel consumption of up to 0.2 l/100km (4%). The simulation results for these vehicles also showed similar ICE startup behaviour as for the charge-depleting hybrid vehicles.

Measurements on the Audi DUO showed that a well balanced driver follows the desired speed curve best, the energy flows (fuel and current) are much more steady as for a more nervous driver. The actual velocity stays within the defined tolerance band for both types of driver though. The fuel consumption is considerably higher for a more nervous driver, electric energy consumption is influenced only slightly by different driver behaviour.

However, due to a fundamentally different use of the pedals (while still following the desired speed within the specified tolerances), driver influence can increase fuel consumption by up to 58%, while a decrease in electric energy consumption of 25% occurred in this case. This resulted from a different use of kickdown in the extra-urban part of the NEDC. If the driver does not allow significant differences between desired and actual vehicle speed, kickdown is applied much earlier, resulting in longer engine operation periods. This changes the distribution of fuel and electric energy significantly, which is of main importance for charge-depleting hybrid vehicles (as in contrast to charge-sustaining hybrid vehicles, where the different use of engine/motor is to a large extend corrected by the SOC correction method). If the traction battery is recharged during engine operation also, as in case of the Audi DUO, this effect is increased. For other hybrid vehicles, also the use of other driver pedals like brake and clutch may cause the control strategies to be operated differently.

One option to reach measurement results with a higher reproducibility is to perform the driving cycle with an automatic driving system instead of a human driver. Tests with such a system however have shown, that energy consumption strongly depends on the controller settings. So measurement results may very well vary from one system to another.

Also, the choice of shifting points for hybrid electric vehicles with manual transmission has a significant influence on the energy consumption and ICE start/stop characteristics. Simulation results from the charge-depleting parallel hybrid vehicle showed differences in fuel consumption of up to 0.92 l/100km and differences in recharged energy of up to 18%. Electric energy and fuel consumption generally increase when the upshift speed thresholds in the shifting strategy are increased. The increase in electric energy consumption is only shown in some driving cycles though. For this vehicle, the choice of shifting points also influences the number of ICE starts per cycle for boost purposes. In fact, the choice of shifting points may in some cases decide whether the cycle is driven pure electrically or in hybrid mode. A comparison of the number of ICE starts shows, that only for low upshift thresholds an increase is observed. As soon as the electric motor is able to deliver its maximum power over a broader speed range, the number of ICE-starts remains constant. Again some exceptions are seen in this case, which are mainly caused by a lack of electric motor power at higher vehicle speeds.

The choice of shifting points also influences the warmup time of the internal combustion engine after a cold start (Warm-up time in this case means the period at the beginning of the test-cycle in which the ICE is operated permanently in order to reach normal operation temperatures. Such behaviour has been seen on the Audi DUO and on the Toyota Prius). When driving mainly in lower gears, the engine warms up much quicker (20%), generally because of lower engine efficiencies at higher ICE speeds. The decrease in fuel consumption can amount up to 6% (Audi DUO).

Generally, the power train's starting temperature has a much stronger influence on energy consumption for hybrid vehicles than for conventional vehicles. The ambient temperature range from 20 °C to 30 °C at which the vehicle has to be soaked and operated during the test (consequently, this is the starting temperature of ICE, tyres etc.), as well as the specified coolant and oil temperature tolerances of ±2°C from ambient, are found to be to big. For the internal combustion engine, a difference of 4 °C in starting temperature already results in a different warmup time, which is controlled by coolant temperature, and can cause a difference in fuel consumption of about 7% (Audi DUO). The effects of different initial temperatures on SOC correction methods for charge-sustaining hybrid vehicles are still unknown.

Consequently, following recommendations can be made for HEV testing procedures:

- Human drivers should perform the driving cycles as stated in standard procedures. Also, the speed tolerances should be maintained. The manufacturer should provide a list of operation procedures however. On this list, the driver would be informed at what times/operating points which pedals/pedalpositions (e.g. kickdown) should be applied. For conventional vehicles with manual transmission this is already done for the clutch pedal at standstill in the European procedures.
- Also, the shifting points should be defined for hybrid vehicles with manual transmission. The use of the existing points for conventional vehicles seems obvious. Since hybrid vehicles are often designed for many different applications which may influence the normal use of the transmission, manufacturers may provide a list of shifting points themselves, if can be shown that the vehicle is not able to follow the speed track within the specified tolerances when driving by the default shifting points.
- In order to keep the influence of ambient temperature as low as possible, the starting temperature of the internal combustion engine should be defined at 25 °C ± 1°C, measuring the temperature with a thermal sensor at the outside of the engine cylinder head. As an alternative, the temperature tolerances for the conditioning room could be tightened at this value.
- As a means of minimising the influence of remaining inaccuracies on energy consumption and emissions, the driving test should be performed several times (e.g. three times). The results to be displayed would then be determined by calculating the mean values of the separate tests.

Further research on this topic could should include driver-, shifting- and initial temperature influence on pollutant emissions. Also, the topic could be extended to the accuracy of measurement equipment. On a broader scale, also the proposed recommendations for testing procedures could be validated.

References

[1] E. van den Tillaart, S. Ploumen, "Development of Simulation Models", MATADOR Subtask 2.2 report, March 2000

[2] E. van den Tillaart, "ΔSOC Correction Methods for Hybrid Electric Vehicles", MATADOR Subtask 2.4 report, April 2000

[3] K. Meier-Engel et. al., "Inventory of Test Procedures: State of the Art and Problems", MATADOR intermediate report, September 1998

MANAGEMENT TOOL for the ASSESSMENT of DRIVELINE TECHNOLOGIES and RESEARCH

MATADOR

Contract JOE3-CT97-0081

Task 2:

Testing methods for vehicles with conventional and alternative drivelines

Subtask 2.12

Regenerative braking on 2WD dynamometers

Institute for Automotive Engineering

20 July, 2000

by
Lejo R. Buning (IAE)

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Energy Conservation and Utilisation

Nomenclature

Symbols

a_A	Actual deceleration	m/s^2
c_W	air drag coefficient	
EC	Energy Consumption	MJ
E_B	Braking energy	MJ
E_D	Driving energy	MJ
E_M	Mechanical braking energy	MJ
$E_{M,D}$	E_M, on the **dynamometer**	MJ
$E_{M,R}$	E_M, on the **road**	MJ
E_R	Regenerated energy	MJ
f_R	rolling resistance coefficient	-
F_a	acceleration (or deceleration) force	N
F_A	Air resistance	N
F_C	Speed (linear) dependent resistance	N
F_R	Rolling resistance	N
F_T	Total driving forces	N
g	Gravity acceleration (g=9,81308)	m/s^2
I_R, I_b	Current during regeneration	A
m	Vehicle mass	kg
n_{EE}	Rotational speed of an electric engine	1/s
R	Ratio: front versus rear axle braking capabilities	-
v	Vehicle speed	m/s
ρ	Air density	kg/m^3

Abbreviations

2WD	2 Wheel Drive Dynamometer
BS1-Vehicle	Vehicle, with a braking strategy according Figure 2: Braking Strategy: 1
BS2-Vehicle	Vehicle, with a braking strategy according Figure 2: Braking Strategy: 2
EM	Electric motor
ICE	Internal Combustion Engine
PRB	Parallel regenerative braking system
SOC	State of Charge
RB	Roller Bench
SRB	Sequential regenerative braking system

Contents

1 Introduction

Task 2 of the MATADOR project is related to: Testing methods for vehicles with conventional and alternative drive lines. Besides testing on the road, the main part of testing is executed on 2 or 4 wheel drive dynamometers.
A major advantage of vehicles with alternative drivelines is that they have regenerative capabilities during braking periods, thus regaining energy and reducing energy consumption. When testing a vehicle with an alternative drive line on a four-wheel dynamometer, the road load can be optimally simulated. This, however, is a very expensive test facility and most of these tests are executed on two wheel dynamometers. In consequence of this the non-driven wheels are not participating in the braking process and the driven axle must therefore dissipate all braking energy. This can have a significant influence on the range and calculated energy consumption of the dynamometer test.

The braking process during testing is dependent on the desired speed profile during the test and controlled by the braking strategy parameters of the vehicle controller. This process can be influenced, for example, by: vehicle speed (v), regenerating current (I), and momentary deceleration (a).

In this document the problem regardigin regenerative braking will be evaluated and possible solutions are suggested. In chapter 2 the theory is explained, in chapter 3, an example of several vehicle-braking strategies is illustrated. And in chapter 4 the solutions as described in the relevant test procedures are given. In chapter 5 some results from computer simulations are given, for different braking strategies. And in the last chapter (6), some possible solutions to this problem are given.

Note: This document is RESTRICTED to electric motors, no alternative regeneration systems have been evaluated, though the principle remains the same.

Special thanks go to Marcel Rondel of the TNO Automotive, with whom the basic principle of the so-called 2WD-regenerating problem has been discussed.
Significant contribution has been delivered to this evaluation by the TNO staff: Iddo Riemersma, Robin Vermeulen, and Erik van den Tillaart, in the area of testing: Audi Duo and Toyota Prius and simulations.

2 Nature of the problem

When driving a vehicle, the vehicle generates a total resistance force, which depends on the momentary status of the vehicle:

- Acceleration;
- Constant speed or;
- Deceleration.

The driving force depends on the:

1. Rolling resistance $F_R = f_R * m * g$
2. Air resistance $F_A = c_W * A * 0{,}5 * \rho * v^2$
3. Acceleration resistance $F_a = \pm m \frac{dv}{dt}$
   (either positive (acceleration) or negative (deceleration))
4. The linear speed resistance $F_C = c_0 * v$

The total driving force is: $F_T = F_R + F_C + F_A \pm F_a$

In Figure 1 the speed is given during a certain braking period of the Hyzem Highway cycle, for the calculation of the required/regenerated power the following vehicle simulation model is used:

Parameter	Value	
f_R	0.015	-
m	1250	kg
C_W	0.35	-
A	2.75	m²
ρ	1.2	kg/m³
C_0	0	-
G	9.81	m/s²

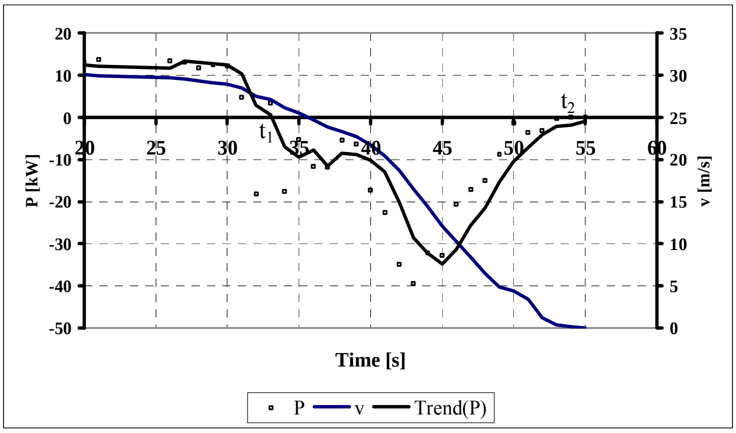

Figure 1: Parameters simulation model (table) and speed and power during braking period

The energy available for regeneration is the area where P≤0 (see Figure 1):

$$E_{DEC} = \int_{t=t_1}^{t=t_2} F_R(t) * v(t) * dt$$

with t_1: P=f(t)≤0 and t_2: P=f(t)≥0.

The available energy can either be regenerated or dissipated in the brakes. Vehicles with alternative drivelines are usually equipped with a regenerating possibilities, the regenerated energy is than stored in an accumulator.

Braking can be performed by different entities:
1. Mechanical: disc and/or drum brakes;
2. Electric:
   2.1. Batteries;
   2.2. Flywheel;
   2.3. Super capacitor.

The braking strategy defines the energy through the front axle and the rear axle, but also the vehicle configuration has its influence. With regards to the driven axle, the following regeneration configurations can be defined:
1. No regeneration;
2. Regeneration:
   2.1. Front axle driven;
   2.2. Rear axle driven.

Whether to regenerate or not and up to what level is determined by the regeneration strategy:
1. Sequential regeneration;
2. Parallel regeneration.

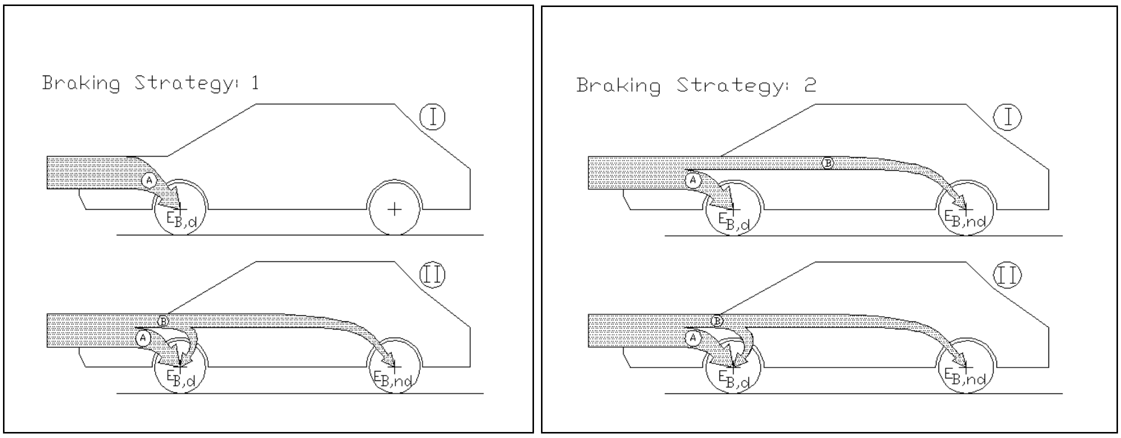

Figure 2: Braking strategies: Sequential (left) and Parallel (right)

N.B. $E_{B,d}$: braking energy driven wheels, $E_{B,nd}$: braking energy non-driven wheels.
A: Regenerative part of the braking energy; B: Heat dissipating part of the braking energy

In Figure 2 (left) sequential regeneration (SRB) is illustrated: just a single system regenerates the braking energy. The electric engine initially regenerates the braking energy up to a certain limit (I_R, a, n or v_{LIMIT}), beyond this limit the "main" mechanical braking system is activated and energy is dissipated in the conventional (mechanical) braking system.

In Figure 2 (right) parallel regeneration (PRB) is illustrated: additional to sequential regeneration, a mechanical braking system is activated. The mechanical brake can be (or is) necessary for maintaining, or guarantee, driving stability. The ratio A over B, can be a part of the braking strategy (constant or dependent of a predefined parameter (I_R, a, n or v).

A design parameter for vehicles is the ratio of dissipating braking energy over the front/rear axle, a ratio value 75% front and 25% rear is common.
Thus it is logical to assume that the regenerating system is dimensioned for regenerating, not exceeding 100% of the available 75% braking energy. With respect to the driving stability it is sensible to regenerate energy on a relatively low level during accelerator release and increase the regenerating capabilities when the brake pedal is used.

2.1 Problem definition

When testing a vehicle on a 2 Wheel Drive Dynamometer (2WD), the wheels of the non-driven axle are not rotating, thus no energy can be dissipated in the braking system of this axle. Hence, the load simulation on a 2WD is always thourgh the driven axle, which means that the energy which can be regenerated, is transferred through this axle. This can generate a difference in the simulated road load on the roller bench (RB) and the actual road load on the road.

When the performance, or the energy consumption, of a vehicle is tested, the vehicle is always driven according a defined speed cycle (HYZEM, NEDC, USFTP, Etc.). During these cycles there are predefined deceleration periods. When the level of deceleration during such a period is beyond a certain limit the additional braking system will (actually must) be activated and the braking system of the driven axle (i.e. wheels) will dissipate a certain **additional** amount of energy, in order to meet the required speed limit.
Since the non-driven wheels can not dissipate energy, an error **may** occur in the load simulation of the vehicle during the test, in comparison with road tests.

From this can be concluded that in the following modes there will be **no problem** if:

1. The deceleration due to the regeneration process satisfies the required braking capabilities to meet the required speed profile and;
2. Additional braking is necessary and the regeneration process is **not** influenced by the braking strategy, i.e. regenerative braking is only dependent on the vehicle speed.

There will be an error in load simulation when regenerative braking capabilities are changed due to the use of:

1. The additional mechanical braking system;
2. The brake pedal and thus the position of the pedal.

Basically the regeneration of braking energy is not constant, it depends primarily on the vehicle speed. Secondary parameters can be: the required braking level, temperature and SOC of the battery pack.
An intelligent braking system can change the ratio electric versus mechanical braking ratio as well as the ratio front versus rear braking capacity.

3 Braking strategies on existing vehicles

In order to get an overview of the problem and the impact on testing, an inventory has been made of the braking strategies of several vehicles:

1. Battery electric vehicles (BEVs):
   1.1. Spijkstaal Caravelle II[E];
   1.2. Mercedes Benz MB100E;
   1.3. Renault Master;
   1.4. Renault Express Electrique;
   1.5. Passenger car (confidential data);
2. Hybrid vehicles (HEVs):
   2.1. Series hybrid: Toyota Prius (more specifically: a combined hybrid);
   2.2. Parallel Hybrid: Audi Duo.

For the Caravelle, MB100E, Master, and the Express, the regenerative braking is, given during testing according to the NEDC cycle, Urban part and during a "coast down"-like (coast down (+R)) test on the dynamometer. The coast down (+R) test was the decelerating period with just regenerative braking, generating maximum regeneration possibilities, **without** the use of the mechanical brakes. These results are given in Appendix I to IV; Ib(D1) up to Ib(D4), indicates the regenerative braking current during the four consequent braking periods in the NEDC cycle. Dx = deceleration period, with:

1. D1: 15 km/u to standstill;
2. D2: 32 km/u to standstill;
3. D3: 50 km/u to 35 km/h;
4. D4: 35 km/u to standstill.

The deceleration during these periods can be performed with different speeds, since some of the vehicles are automatic and some have a manual speed selector.

One of the parameters during regenerative braking is de level of decelerating during the drive cycle. In Table 1 the minimum (deceleration or regenerative braking) and maximum (accelerating) value is given for a number of well known driving cycles (see Appendix V).

Table 1: Minimum and maximum accelerations during defined driving cycles

Cycle definition		a_{MAX} [m/s²]	a_{MIN} [m/s²]
NECD		1,0	**-1,4**
JAP10-15		0,8	**-0,8**
UDDS		1,9	**-1,8**
USFTP		1,9	**-1,8**
HFEDC		1,4	**-1,5**
US06		3,8	**-3,1**
SC03		2,3	**-2,7**
Modem		3,2	**-2,4**
Hyzem	Urban	2,2	**-2,1**
	Rural	2,4	**-4,6**
	Highway	3,2	**-4,0**

In the next part, the braking strategy and the behaviour of the braking system on both, the road and the dynamometer will be discussed regarding the previously mentioned vehicles. One has to bear in mind that the regenerative capability of a vehicle exists of at least two factors, the:

1. Braking strategy and;
2. Physical electric motor and/or battery limitations.

The regenerative possibilities of a vehicle exists of at least two factors, the:

1. Time length of the braking period and;
2. Deceleration level.

3.1 Spijkstaal Caravelle II^E

According to the manufacturer, the Spijkstaal Caravelle II^E has a two-phase regenerative braking strategy:

1. decelerator release: IR = 30 – 0 A;
2. Using the brake pedal:
   2.1. I_R = 30 – 150 A;
   2.2. I_R = typical 70A (approximately: 60 – 80A): additional mechanical braking;
3. The maximum deceleration through regenerative braking is 1,5 to 2 m/s².

In Appendix I, the regenerative braking strategy has been illustrated. In Figure 9, the regenerative current as a function of the vehicle speed has been given for the four braking periods of the NEDC (urban part only). The deceleration during these periods is not exceeding ≈1,0 m/s².
In Figure 10, this has been given for the coast down (+R) period on the roller bench, the deceleration during these periods is not exceeding ≈0,35 m/s².

In general: the regenerative braking strategy of the Spijkstaal Caravelle II^E is a linear function of the vehicle speed: $I_R = f(v)$.
There is no interaction between the mechanical brake system and the regenerative braking system, regarding the functionality of the regenerating system. The mechanical brake has an additional functionality, with an offset: when the deceleration level is higher than ≈1,0 m/s² (I_R = 70A, typical), the mechanical braking system is used additionally.

3.2 Mercedes Benz MB100E

Appendix II shows the regenerative strategy of the Mercedes Benz MB100E. Figure 11 shows the results during the braking periods, while driving the NEDC (urban part only), the deceleration during these periods does not exceed ≈1,0 m/s². Figure 12 shows the results during the coast down (+R) period on the roller bench, the deceleration during these periods is not exceeding ≈0,39 m/s².
The regeneration strategy for the MB100E is:

1. I_R = 35 - 0A decreasing, speed range: v = 40-0 km/h;
2. I_R = 35 A constant, speed range: v = v_{MAX}-40 km/h.

In general: the regenerative braking strategy of the MB100E is in the lower speed range ($v \leq 40$ km/h) a function of the vehicle speed: $I_R = f(v)$. Above this speed it is independent of the vehicle speed, i.e. I_R = constant.
The mechanical brake system has no influence on the regenerative braking, its functionality is additional to the regenerating system (or vice versa). When the deceleration level is higher than can be reached by just releasing the gas pedal (≈0,39 m/s²), the mechanical braking system is used additionally.

3.3 Renault Express Electrique and Renault Master

The regeneration strategy of the Express Electrique and Renault Master are similar. The regeneration current is linear dependent on the vehicle speed. The maximum regeneration current of the Renault Express Electrique is 145 A.

Appendix III shows the regenerative strategy of the Renault Express Electrique. Figure 13 shows the results during the braking periods, while driving the NEDC (urban part only), the deceleration during these periods is not exceeding ≈1,0 m/s². Figure 14 shows the results during the coast down (+R) period on the roller bench, the deceleration during these periods is not exceeding ≈0,80 m/s².
The regeneration strategy for the Express Electrique is:

1. I_R = 145- 0A decreasing, speed range: v = 75-0 km/h;
2. I_R = 145A constant, speed range: v = v_{MAX}-75 km/h.

Appendix iv shows the regenerative strategy of the Renault Master. Figure 15 shows the results during the braking periods, while driving the NEDC (urban part only), the deceleration during these periods is maximal ≈1,0 m/s². Figure 16 shows the results during the coast down (+R) period on the roller bench, the deceleration during these periods is maximal ≈0,34 m/s².
The regeneration strategy for the Master is:

1. I_R = 50- 0A decreasing, speed range: v = v_{MAX}-0 km/h.

3.4 A modern vehicle

(CONFIDENTIAL INFORMATION)
Some confidential information is available for a modern Battery Electric Vehicle. For the regeneration of the braking energy a “look up” table is used. In the table the engine torque is given as a function of the rotational speed of the engine.
The engine power is linear to the regenerative current, so the regenerative braking power is linear proportional to the vehicle speed, up to 94 km/h (r_{DYN}=0.3m, i_{TOTAL}=9). Above this speed the regenerative current remains constant. This is presented in Figure 3.

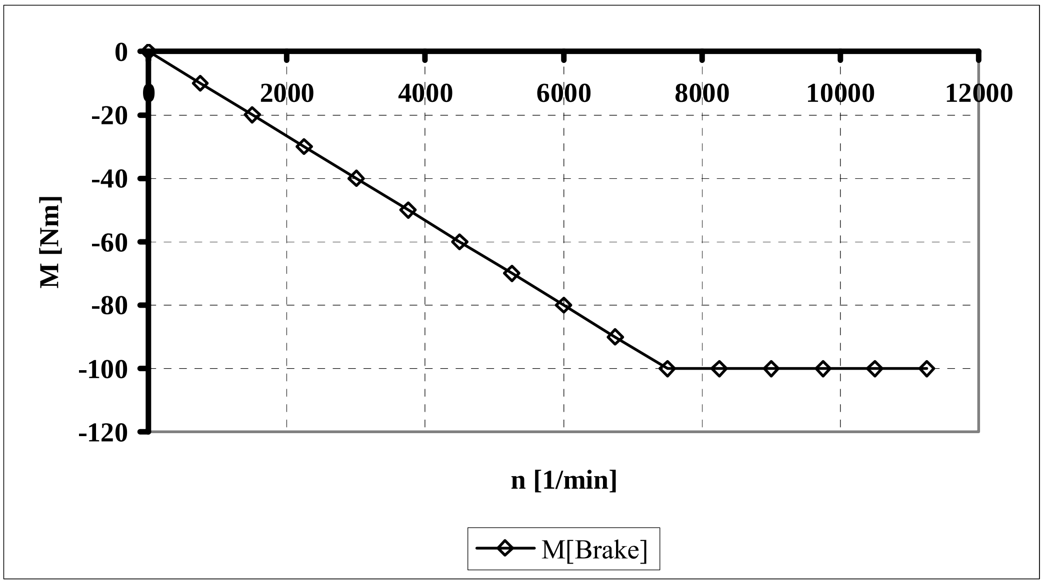

Figure 3: Regenerative torque as function of angular velocity

3.5 Toyota Prius

The Toyota Prius has a combined hybrid drive line and an optimal braking strategy. The driver requests a braking torque or a deceleration rate with the brake pedal. The vehicle tries to meet this request initially by regenerative braking. If the braking torque does satisfy the required braking level, the brake system applies the mechanical brakes itself as much as necessary. It works by reducing the hydraulic pressure to the brakes by an amount that corresponds to the electric brake torque.

To investigate the regeneration capabilities the Prius has been driven on a 2WD at TNO Automotive, using the NEDC. During 18 deceleration periods with 6 different deceleration levels, the amount of regenerated energy has been determined and compared to similar deceleration periods on the road.
Though a small difference in vehicle mass had to be permitted (m_{ROAD}: 1440 kg versus m_{2WD}: 1360kg), the energy regeneration level was significantly different (Table 2):

Table 2: Regenerated energy: Difference: Road versus 2WD

Deceleration period	ΔE_{ROAD} [Wh]	ΔE_{ROAD} [Wh]	ΔE_{RATED} [-] (Road = 1)
1: 15 – 0 km/h	-0,4	-0,6	-1,6
2: 32 – 0 km/h	2,7	4,9	1,8
3: 50 – 35 km/h	3,0	4,6	1,5
4: 35 – 0 km/h	3,3	5,9	1,8
5: 70 – 50 km/h	7,6	10,6	1,4
6: 12 – 0 km/h	35,0	69,1	2,0
Total	77,1	138,7	1,8

Figure 4 shows the difference in cumulative regenerated energy on the road and on the 2WD, during the braking period from 120 km/h to standstill. The total difference between road- and 2WD measurements is 61.7 Wh, which corresponds to 1% of the fuel consumption (with hot start), according to the NEDC procedure.

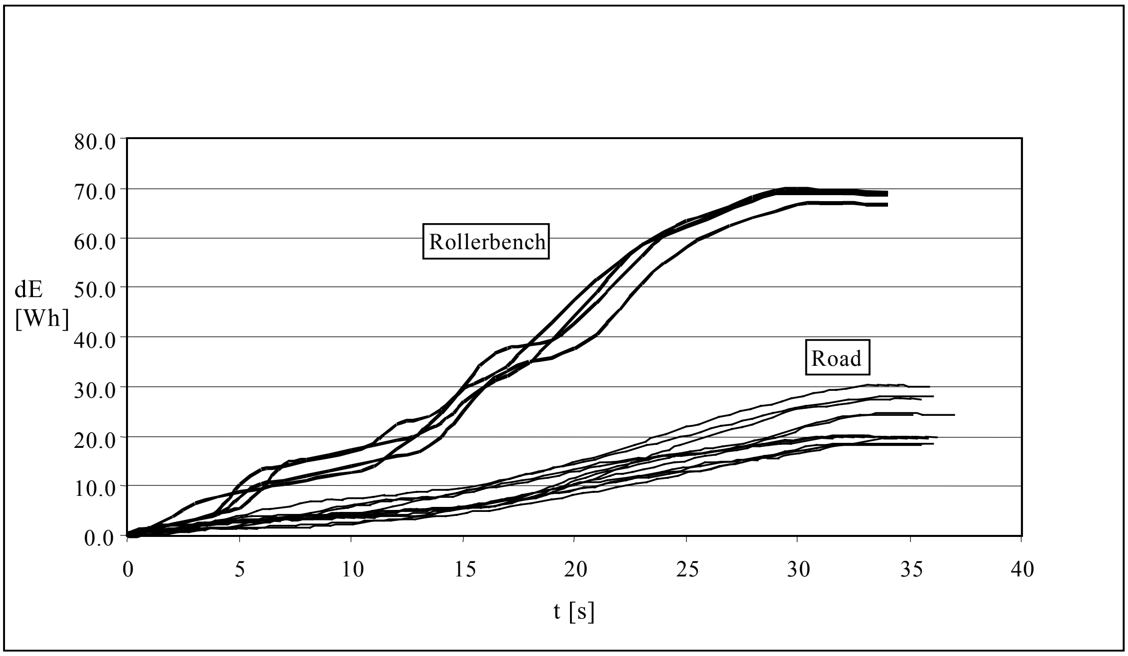

Figure 4: Differences in cumulative braking energy

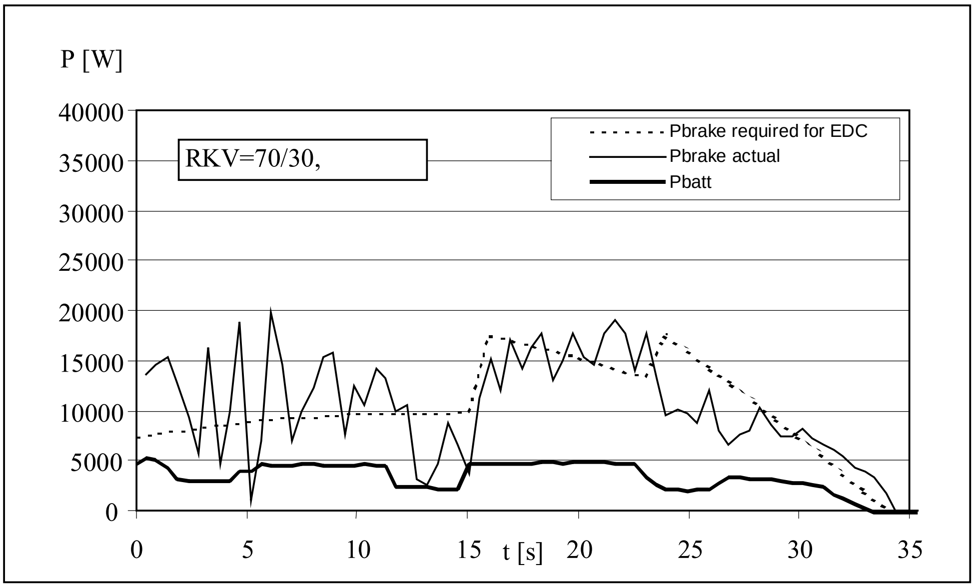

Figure 5: Road; deceleration 120 → 0 km/h

The difference in roller bench tests and road test is additionally illustrated in Figure 5 and Figure 6. These figures are showing the power flow to the battery, the required (based on the nominal speed and deceleration) and the actual (based on the measured speed and deceleration) braking energy, during the deceleration of 120 km/h to standstill.

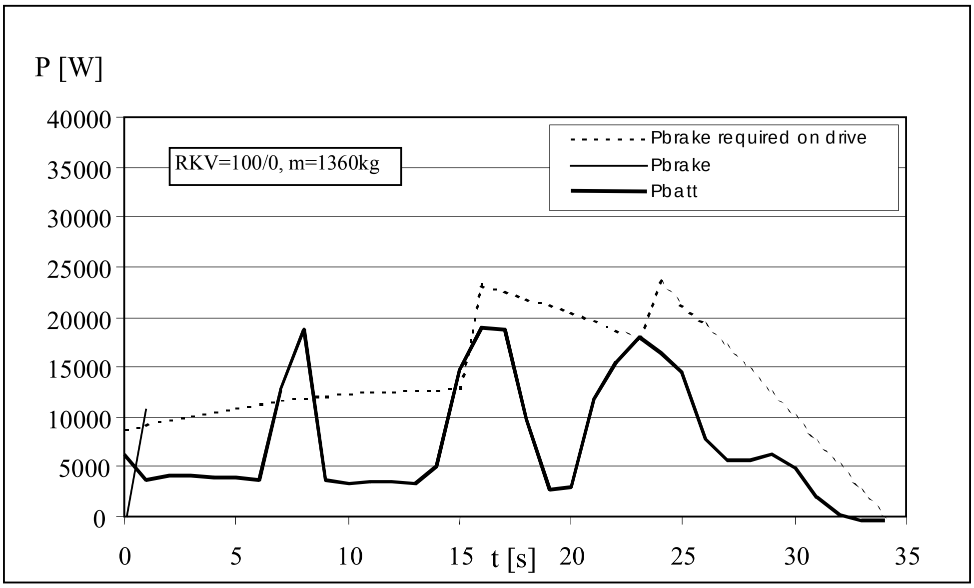

Figure 6: 2WD; deceleration 120 → 0 km/h

In Figure 6 the actual and battery power are similar, the difference is probably due to efficiency losses. The differences between actual and required braking power is due to the driver, though the vehicle speed remained within the prescribed bandwidth. The difference in battery power on the road and on the 2WD is not completely due to difference in distribution of the braking power over the front and rear axle.

The SOC and the battery temperature are also parameters who have a positive/negative effect on the braking strategy.

3.6 Audi Duo

The drive line configuration of the Audi Duo is parallel hybrid: the ICE is a 66kW, 1.9l, TDI Diesel and the electric motor is a 21 kW, synchronous motor with a permanent magnet.
There are two different regeneration strategies:

1. ICE mode:
   - 1.1. No regeneration or battery charging at SOC ≥ x%;
   - 1.2. Limited progressive regeneration at v=20 – 25 km/h: I_R: 0 – 15A;
   - 1.3. Constant regeneration at v≥25 km/h: I_R =15A;
   - 1.4. Constant regeneration at SOC < 40%
2. EM mode:
   - 2.1. I_R: 0 – 15A, with: 20 ≤v≤50 km/h, torque is constant;
   - 2.2. I_R = 15A, with: v≥50 km/h, power is constant.

The mechanical brake system has no influence on the regenerative braking, its functionality is additional to the regenerating system (or vice versa).

3.7 Concluding remarks

The regeneration strategy of the Caravelle, the MB100E, The Express, The Master and the Duo is either a constant regeneration current (I_R = c) dependent on the vehicle speed (I_R = f(v)), but not affected by the mechanical brakes.

Concluding from chapter 3.1 – 3.6, the following review may be shown:
The ratio for dissipating breaking energy over the front/rear axle is R=X/Y:

1. A = 100-X (e.g. 75%) for the front axle and
2. B = 100-Y (e.g. 25%) for the rear is common.

Table 3: Energy distribution during braking

<table>
<tr><th colspan="2" rowspan="2">Deceleration level</th><th colspan="2">Dynamometers</th><th colspan="2">Road</th></tr>
<tr><th>Front</th><th>Rear</th><th>Front</th><th>Rear</th></tr>
<tr><td>No brake pedal</td><td>$0 \le I_R \le I_{LIMIT,1}$</td><td>$E_{M,D} = 0$
$E_{B,F} = E_B$
$E_R = E_{B,F}$</td><td rowspan="3">$E_{B,R}$
=
0%</td><td>$E_{M,R} = 0$
$E_{B,F} = E_B$
$E_R = E_{B,F}$</td><td>$E_{B,R} = 0$</td></tr>
<tr><td>Use of brake pedal</td><td>$I_{LIMIT,1} \le I_R \le I_{LIMIT,2}$</td><td>$E_{M,D} = 0$
$E_{B,F} = E_B$
$E_R = E_{B,F}$</td><td>$E_{M,R} = 0$
$E_{B,F} = E_B$
$E_R = E_{B,F}$</td><td rowspan="2">$0 \le B \le E_{B,R}$</td></tr>
<tr><td></td><td>$I_R = I_{MAX}$</td><td>$E_{M,D} = E_{B,F} - E_R$
E_R = Max</td><td>E_R = Max
$E_{M,R} = E_{B,F} - E_R$</td></tr>
</table>

N.B. The Spijkstaal Caravelle II[E] has an additional option: when using the brake pedal the mechanical brakes will be used not before a certain pedal position has been reached.

Concluding (for these vehicles): no difference should be found between the energy consumption found with road tests compared to tests on the dynamometer, assuming the braking strategy in not changed. The regenerating current is limited for all vehicles, but below the limit of the electric motor.

The only difference between road measurements and dynamometer measurements is extra energy dissipation in the mechanical brake system.
An "exception to this rule", is the Prius; TNO tests showed a relatively small difference in road and dynamometer tests (< 1% in energy consumption).

4 Literature

In the literature, which in essence is based on test procedures, little is known or described on the phenomena of regenerative braking on 2WD.
During the literature survey, it became obvious that the regenerative problem is under discussion, or perhaps better, under construction:

> In [5], there are proceedings with regards to the 2WD-problem, but in [3] and [4], which are especially for testing on dynamometers of pure and hybrid electrical vehicles, there are no remarks related to this problem.
> In [9], a terminology list with regards to electrically propelled road vehicles, the term: REGENERATIVE, is completely absent.

In the available test procedures, see reference [1] through [9], only in [5] there is a correction method mentioned, which is described below.

In [11], an EVs-16, publication is given regarding the subject on regenerative braking and dynamometer testing. Professor Shimizu of the JARI Institute in Tsukuba Japan has carried out this study.

SAE J1634; electric vehicle energy consumption and range test procedure
These test proceedings contains a test procedure for pure electric vehicles on dynamometers and describes an approximate correction method for the regenerating brake energy.
In these proceedings it is clearly stated that:

> "For dynamometer testing, regenerative braking shall be representative of regenerative braking on the road for the applicable driving cycle, and the methodology for matching regeneration shall be described".

Then an example is given:

1. Road versus Dynamometer:
   - 1.1. Assume:
     - 1.1.1. 70% of braking energy is absorbed by the vehicle's driven axle and 30% by the non-driven axle;
     - 1.1.2. 80% of the drive axle braking is from regenerative braking;
2. Proposal for Simulation Regenerative braking on the dynamometer, under the assumption that the dynamometer can apply a constant retarding force when the vehicle brakes are applied, by:
   - 2.1. Driver operated push button;
   - 2.2. Switch controlled by the taillights or brake pedal;

   The desired braking force could be calculated prior to the test for each vehicle and used test cycle:
   $F_D = m * \bar{a} * k$. k is the fraction of the non-driven axle (here: k = 0,30).

Hence, this correction method can only be applied when the braking ratio over the front and rear axle is either constant or can be predefined.

A few remarks on a bench Test for Re-generative Energy Evaluation
In the study reported in [11], by Ken-ichi SHIMIZU, and presented during EVS-16 in China, a comparison has been made of regenerated braking energy, of a Toyota Prius on a 2WD and a 4WD chassis dynamometer.

The used chassis dynamometer has a 2- and a 4WD mode:

1. The 2WD mode: during both, acceleration and deceleration period, the road load and inertia mass, are simulated over the driven axle. During a test in this mode, the wheels of the non-driven axle are rotating on free rotating, non-controlled, drums;
2. The 4WD mode: during acceleration the road load and inertia mass are simulated over the driven axle. During deceleration the road load and inertia mass are set separately on the two dynamometer axles.

In preparation of the comparison of the regenerated energy on 2WD and 4WD, a series of tests have been executed in the Shinagawa district, under real road load conditions. Figure 7 shows the velocity, acceleration and battery current during this period.

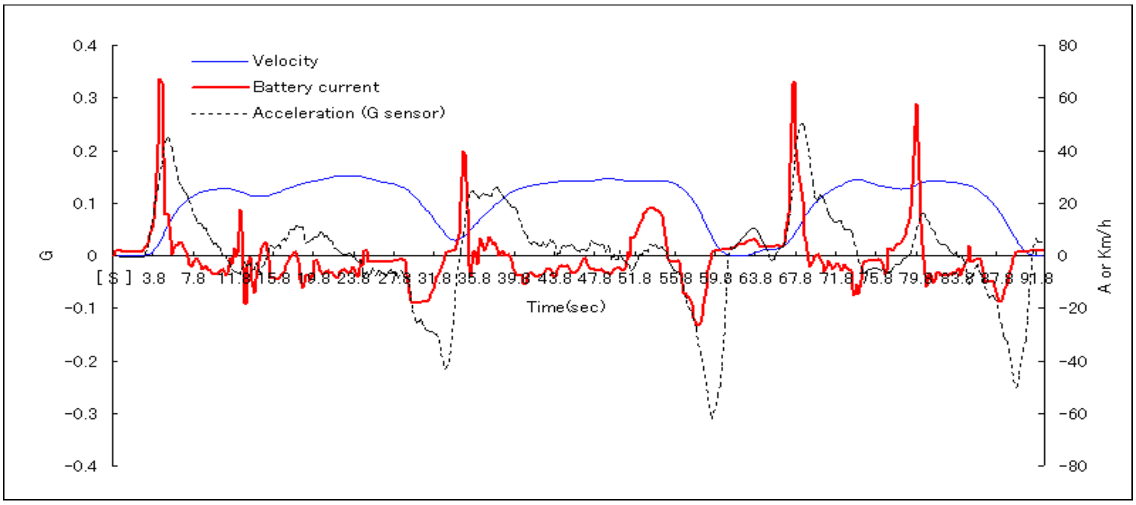

Figure 7: Variation of battery current, velocity and acceleration, during actual driving

These test have been reproduced on the 2WD and 4WD test rigs. The maximum level of deceleration during the braking periods of these tests is 0.2g, for both road and test rig tests. Considering the previous, the two different chassis dynamometer test showed similar results. The main issue of [11] is that there is no significant difference in the regenerated energy on a 2WD and a 4WD and thus the tested HEV (Toyota Prius) can be evaluated on a single roller chassis dynamometer.

5 Simulation results

5.1 Introduction

In this chapter the simulation results are described, as the have been obtained by TNO.
The BEV vehicle model represents a front wheel driven battery electric vehicle. Two electric motors provide propulsion power and, dependent on the braking strategy, are used for the regenerative braking. Three different braking strategies have been applied for these simulations:

1. 1ST Strategy: Mechanical braking only. The electric motors are only used for the propulsion of the vehicle, no regenerative braking;
2. 2ND Strategy: Optimal regenerative braking: as much energy is regenerated as possible, the mechanical brakes are not applied on the driven wheels;
3. 3RD Strategy: Proportional braking distribution: a fixed distribution over the mechanical brakes and the electric motors, the mechanical brakes are addressed more heavily when the electric motor runs into its limitations.

With the three braking strategies simulations have been performed for both road and dynamometer conditions. Figure 8 shows the powertrain configuration.

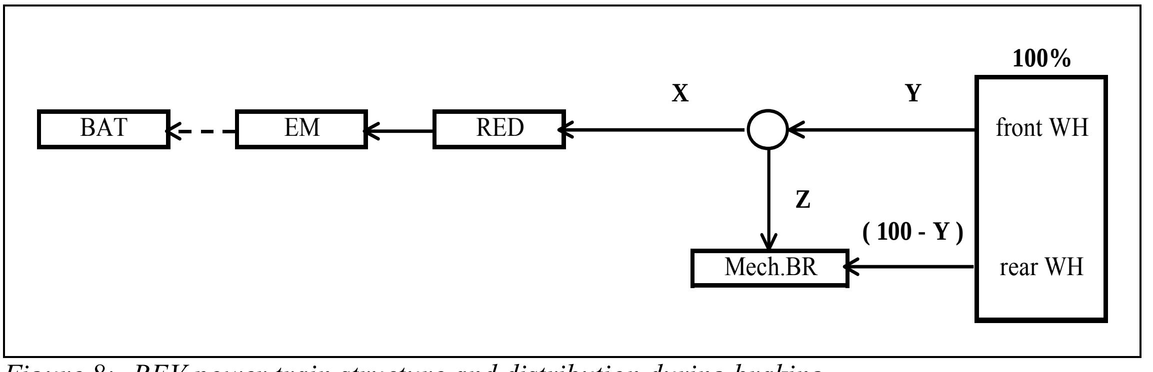

Figure 8: BEV power train structure and distribution during braking

The symbols used in Figure 8, represent the braking distribution according to the following operating conditions during braking:

1. X: Variable;
2. Y: 75%; for road simulation and 100%; for dynamometer simulation;
3. Z: =Y for mechanical, =(Y – X); for maximum regenerative braking and =(½Y) for proportional braking.

The data for the components used in the BEV model is listed in Table 4. The model is described in detail in the Subtask 2.2 report on ‘*Development of simulation models*’.

Table 4: Component parameters BEV model

Battery		**Reduction gear**	
Type	NiCd	i [-]	5.25
Capacity [Ah]	65	**Wheels**	
Cell voltage [V]	1.2	R dynamic [m]	0.295
Number of cells [-]	240	Number of wheels (front/rear)	2 / 2
Cell internal resistance [mΩ]	0.72		
Electric motor		**Vehicle**	
Type	Permanent magnet	Mass [kg]	1350
Power (nom/max) [kW]	(2x) 25 / 37.5	C_w [-]	0.3
Base speed [rpm]	3000	A [m^2]	2

Two driving cycles are used to determine the influence of the braking strategy and the behaviour on the road and dynamometer. The New European Driving Cycle (NEDC) and Hyzem Rural are chosen, due to their opposite deceleration levels: the NEDC can be distinguished for it's low level deceleration periods and it is **the** legislative cycle for Europe. And the Hyzem Rural cycle has been selected for it's high level deceleration periods and since it is representative for actual driving patterns.

5.2 Results

The most significant difference between the road and dynamometer simulation is that the braking energy flow on the dynamometer is100% through the driven axle. This implicates that there is 25% more energy available for regenerative braking and thus an extreme situation.

A comparison of the braking strategies and the road or dynamometer situation is made on the basis of the complete cycle. The energy consumption for the vehicle is calculated from the simulation results. In Table 5 and Table 6, the parameters are listed, which are used to characterise the differences between braking strategies and which are related to the vehicle's energy consumption.

Table 5: Simulation results, NEDC cycle

Braking strategy	**NEDC**				
	EC [MJ/100km]		ΔEC	E_R/E_B [-]	
	Road	Dynamometer		Road	Dynamometer
No regeneration	51.7	51.6	**0%**	0%	0%
Optimal regeneration	37.8	34.7	**9%**	73%	97%
Proportional regeneration	42.6	41.0	**4%**	32%	46%

Table 6: Simulation results, Hyzem Rural cycle

Braking strategy	**HYZEM RURAL**				
	EC [MJ/100km]		ΔEC	E_R/E_B [-]	
	Road	Dynamometer		Road	Dynamometer
no regeneration	62.9	62.9	**0%**	0%	0%
Optimal regeneration	42.4	37.6	**13%**	72%	94%
Proportional regeneration	50.8	48.1	**6%**	34%	47%

Remark: ΔSOC is negative, since this means that energy has been drawn from the battery. Ratio of regeneration energy versus drive energy is negative since the sign convention implies that regeneration gives negative values and propulsion positive. The ratio of regeneration and braking is positive, because for both negative values are found.

From Table 5 and Table 6 conclusions can be drawn with respect to:
1. Comparison of road and dynamometer simulation;
2. Differences between braking strategies;
3. Driving cycle influence.

Road versus dynamometer
Simulations confirm that mechanical braking only, generates no significant difference in energy consumption between the dynamometer and the road.

Dependent on which regenerative braking strategy is applied, the vehicle in road simulation consumes 4 or 9 % extra energy (ΔEC) for the proportional and optimal strategies respectively. The trend is that the higher the regenerative capability, the larger the difference between road and dynamometer results, which can be used for the evaluation of a correction method.

Braking strategies
Three different braking strategies have been applied (5.1). Quite logically, the energy consumption of the BEV without regenerative braking is the highest. The energy consumption decreases in proportion with the regenerative capability and is for the three selected strategies the lowest for the optimal strategy.

The ratio of regenerative versus total braking energy shows the differences between regenerative braking strategies. The optimum braking strategy is designed to regenerate as much energy as possible. In Table 5 and Table 6 can be seen that over 90% of the desired braking energy on the dynamometer (100% offered) and more than 70% on the road is regenerated (offered 75%).
In case of the proportional strategy the braking energy offer is actually 50% of the offer in the optimum strategy. This can be seen in the achieved performance; more than 45% is achieved on the dynamometer (while 50% is requested), and almost 35% is obtained on the road (where 37.5% is offered, due to the front/rear and proportional braking ratios). The differences between road and dynamometer thus can be seen here clearly too.

N.B. The optimal braking strategy implies that a minimum of no additional mechanical braking is assumed. Thus, the deceleration of the vehicle is depends of the regenerative braking process, limited by the drive line specifications. This strategy is different from the strategies found in Chapter 3, were mechanical braking is still possible and additionally used. But the simulation model has similarities to these strategies used in BEVs, with the restriction that the regenerating current is limited to a (much) lower

value.
Thus, during the simulation 25% more energy is offered to the driving axle, which can be (and is) used for regeneration. In the previously mentioned strategies, most of the extra braking energy is dissipated through the mechanical brakes, since they work additionally.
Translating these strategies into the before mentioned variables:

1. $X = f(v)$;
2. $Z = Z_0 – X(v)$, Z_0 is additional and dependent on the (driver and) desired speed profile.

Driving cycles
It will be clear that the amount of regenerated energy is dependent of the:

1. Time length of the deceleration period and;
2. Level of deceleration.

For the simulation two driving patterns were selected, the NEDC and Hyzem Rural. The NEDC is the current legislative cycle in Europe and has moderate accelerations and decelerations. And the Hyzem Rural cycle is significantly different from the NEDC, with respect to the two previously mentioned aspects. In consequence of this it will be clear that the energy consumption of the BEV model on the more demanding Hyzem Rural cycle is higher than on the NEDC.

With respect to the braking strategies and the differences between road and dynamometer, it is noted that the differences between road and dynamometer are larger on the more dynamic and more demanding Hyzem Rural cycle.
The regenerative energy in comparison to the total braking energy holds the same ratio for both cycles, which is probably achieved due to the fact that the braking is done by the electric motor, as it does not run into its limitations.

Concluding remarks:

1. When 100% of the available braking energy is regenerated, a virtual energy saving is generated of 9% for a moderate cycle and 13% for a more demanding cycle;
2. When a more sophisticated regeneration strategy is assumed: 50% of the available braking energy is regenerated, a virtual energy saving is generated of 4% for a moderate cycle and 6% for a more demanding cycle;
3. The 3RD Strategy (proportional) has a better correlation with the “reality” (chapter 3), than the 1ST and 2ND strategy. Therefore it is to be expected that the virtual energy saving during testing on a 2WD dynamometer of vehicles with a more complex regeneration strategy, will be approximately 5%.

6 Correction methods

The literature study showed that the Regenerative Problem is “Unknown”, which means it is a known problem, but the answer is a four-wheel drive dynamometer, a very expensive piece of equipment. Most of the tests are therefore performed on a two-wheel drive dynamometer, ignoring the problem.

The evaluation of the existing braking strategies (chapter 3), showed that the vehicles discussed here and mainly used today will have similar energy consumption on the dynamometer as on the road, assuming an identical speed sequence (profile) is used. Thus, a correction method is not applicable.

To some extent a correction method can be defined. In chapter 3 a “standard” method is described and given in the SAE J1634 standard: electric vehicle energy consumption and range test procedure.

A possible correction method for more sophisticated braking strategies is indicated by the TNO simulation results:

> Measure the energy consumption according a relevant test proceeding, e.g. NEDC or USFTP, etc, and when possible with and without regenerative braking on both road and test rig (a two-wheel drive dynamometer).
> By using a user defined braking strategy during simulations and setting regeneration parameters of engine and battery to user defined values, the maximum difference can be calculated between the energy consumption on the road and the dynamometer.

The energy consumption can be calculated by simulation of
1. No regeneration;
2. Optimal strategy (1ST strategy, chapter 5), and;
3. The best estimation of the braking strategy of the actual vehicle.

In this way a good impression can be obtained of the error due to the “Regeneration Problem” (a parallel can be seen with the ΔSOC problem.

7 Summary

Problem definition

When testing a vehicle on a 2 Wheel Drive Dynamometer, the wheels of the non-driven axle are not rotating, thus no energy can be dissipated in the braking system on this axle. Hence, the load simulation on a 2 Wheel Drive Dynamometer is always through the driven axle, which means that the energy, which can be regenerated, is transferred through this axle. This can generate a difference in the simulated road load on the roller bench (RB) and the actual road load on the road:

> When the performance (or energy consumption) of a vehicle is tested, the vehicle is always driven according to a predefined speed cycle. During these cycles there are predefined deceleration periods. During such a period the available amount of energy, which can potentially be regenerated, is significantly higher then under identical road conditions, since the mass simulation is only through the driven axle.
> For example, compared to identical road conditions the following consequences can be identified:
> 1. The additional braking system will be activated and the braking system of the driven axle (i.e. wheels) will dissipate a certain **additional** amount of energy, in order to meet the required speed limit.
> 2. Another consequence could be that the regenerating system would regenerate more energy, when an adaptive braking strategy is applied.

Concluding: Due to the fact that the non-driven wheels cannot dissipate energy, an error **may** occur in the load simulation of the vehicle during the test, in comparison with road tests.

The problem previously described is in this report referred to as: “The 2 Wheel Drive Dynamometer Regeneration Error” (2WDEr).

Quantification of the problem

In general it can be concluded that:

1. The commercially and presently available conventional BEVs are not affected by “The 2 Wheel Drive Dynamometer Regeneration Error”, due to the fact that regeneration capabilities are controlled by vehicle speed;
2. With an advanced hybrid drive train configuration, like the Toyota Prius, the influence can be neglected (using the results of the currently conducted tests).
   - 2.1. The error is approximately 1% for fuel consumption, on the NEDC (with hot start) on a 2 Wheel Drive Dynamometer.
   - 2.2. The influence appeared to be zero during a test where the energy consumption was compared between a random driven cycle (and simultaneously recorded) in a typical Japanese urban surrounding and afterwards simulated on a 2 **and** 4 Wheel Drive Dynamometer, separately;
3. Simulations using the model in figure I, showed that a maximum regenerative braking strategy (MAX: Z=Y–X) resulted in a 2WDEr of 13% difference in energy consumption. For the proportional regenerative braking strategy (PROP: Z=½Y) this resulted in a 2WDEr of 6%. Both using the demanding HYZEM Rural cycle.

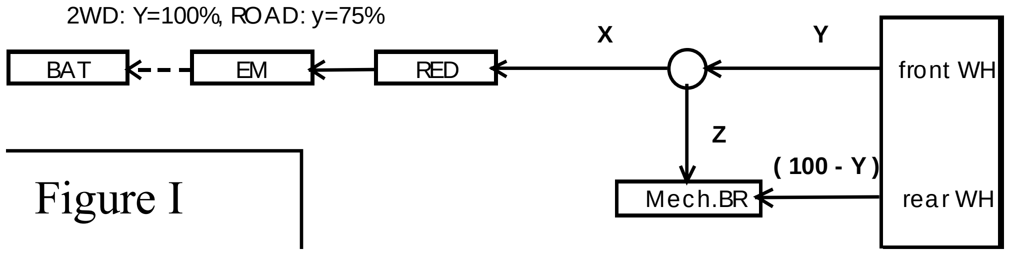

Figure I

The simulation model MAX is quit similar to the strategy used in BEVs evaluated here, with the restriction that the regenerating current is limited to a lower value.

Existing standards

In the existing standards there are no correction methods indicated. An exception to this “rule” is the test proceeding J1634, which contains a mechanical correction procedure for vehicles with regenerative capacities on 2 wheel dynamometers. The correction is established by applying a constant retarding force when the vehicle brakes are applied. Either operated by push button or switch controlled by the taillights or brake pedal. The desired braking force could be calculated prior to the test for each vehicle and used test cycle: $F_D = m * \bar{a} * k$. k is the fraction to the non-driven axle.

Possible solutions (studied)

For the vehicles that are presently (commercially) available, there is no need for a correction method. Since these vehicles are using a more elementary regeneration strategy, which is dependent on the vehicle speed only, maintaining a limited regeneration current.
However, simulations indicate that braking strategies may lead to an influence on the energy consumption when more sophisticated strategies are applied.

The literature study indicates that a correction method can be found in an additional braking force during deceleration periods.

The simulations indicate that a correction procedure might be found in a numerical correction method. Comparing the energy consumption with and without regeneration, obtained from road and test rig measurements, with simulation results, obtained through different braking strategies. In this way a good impression can be obtained of the error due to the “Regeneration Problem”. A parallel can be seen with the ΔSOC problem.

Restrictions and remarks for the (studied) solutions

Simulations showed a significant influence of the regeneration problem. But the simulated braking strategies appeared not to correspond to the strategies applied in the presently available vehicles. The Toyota Prius, however, has a braking strategy, which has certain similarities with the proportional user defined strategy, used in the simulations.

The mechanical correction method as indicated in the J1634 standard, can only be applied when the braking ratio over the front and rear axle is either constant or can be predefined.

The advantages of this system are:
1. It can be applied on the available 2 Wheel Drive Dynamometers;
2. The control of the braking force can be sophisticated and (in principal) dependent on several parameters.

N.B. The correction method can be implemented relatively easy in an electronic dynamometer (no mechanical mass simulation). The vehicle mass is then an input parameter for the controlling system, and can thus (again relatively easy) be made dependent on (other) parameters.

The disadvantage is general: every additional system introduces an extra error. But the error is inherently significant when the additional system is dependent on measured parameters, in this case e.g. vehicle mass (constant), speed (variable), braking strategy (dependent of SOC, deceleration, etc.).

Another disadvantage is the definition of the actual braking strategy of the vehicle to be tested, which is obviously necessary. Since this aspect is a part of the total driving strategy, it most likely is not available. Which means that either it must be made available by the manufacturer, or it must be obtained by testing. In the latter case there always is the relevant question "Is the obtained strategy complete and adequate for the simulation process".

Homologation testing versus technology assessment

Since the error, which is introduced by the difference in road load simulation on a 2-wheel drive dynamometer compared to the real road load (due to the fact that the non-driven axle will not dissipate braking energy) has not been quantified yet. It is advised to neglect this influence for both homologation testing and technology assessment.
This proposal is justified by the fact that the evaluated and currently available vehicles with alternative drivelines, are negligibly affected by the phenomena.

Recommendations

Since a "hardware" solution is expected to be expensive the major recommendation is to aim at a numerical solution. Nevertheless, a "hardware" solution would be optimal, provided that the actual braking strategy is adequately known to meet the requirements of the simulated driving cycle.

Evaluation results showed that the comparison of energy consumption on the road versus test rig results of a modulated vehicle with a user defined braking strategy, is affected by the difference in regeneration of energy during a braking period. When it is tested on a two wheel drive dynamometer according to the low demanding NEDC cycle or the high demanding HYZEM Rural cycle definitions.

Since these first elementary simulations indicate that more sophisticated braking strategies can induce an error, it is advised to develop more relevant braking strategies for simulation models and study this phenomena more thoroughly.

In the near future it is to be expected that more intelligent regeneration systems will be developed, taking into account aspects like the:
1. Regeneration potential of the non-driven axle, or;
2. Interaction between an ABS-system and the driveline strategy (including regenerative braking).

8 References

[1] EN 1821-1: Electrically propelled road vehicles - road performances - Measurement of road operating ability – Part 1: Pure electric vehicles, 1995.
[2] EN 1821-2: Electrically propelled road vehicles - road performances - Measurement of road operating ability – Part 2: Thermal electric hybrid vehicles.
[3] EN 1986-1: Electrically propelled road vehicles -Measurement of energy performances; Part 1: Pure electric vehicles, 1997.
[4] EN 1986-2: Electrically propelled road vehicles -Measurement of energy performances; Part 2: Thermal electric hybrid vehicles, July 1999.
[5] SAE J1634: Surface vehicle recommended practice; Electric vehicle energy consumption and range test procedure, June 1995.
[6] SAE J1711: Recommended practice for measuring the exhaust emissions and fuel economy of hybrid-electric vehicles.
[7] ISO/DIS 8714-1: Electrically road vehicles - Reference energy consumption and range; Part 1: Test procedures for passenger cars and light commercial vehicles, 1994.
[8] EN 13444-1: Electrically propelled road vehicles – Measurement of emissions of hybrid vehicles; Part 1: Thermal electric hybrid vehicles.
[9] EN 13447: Electrically propelled road vehicles – Terminology, July 1999.
[10] Matador, Task 2: Testing methods for vehicles with conventional and alternative drive lines, Inventory of test procedures: State of the Art and Problems, participants: ENEA, HTA, IKA and TNO, September 1998.
[11] A few remarks on a bench Test for Re-generative Energy Evaluation, Ken-ichi SHIMIZU, Tetsu IWATSUKI, Nobumasa SHIRAI, Mechanical Engineering Laboratory, AIST, MITI, Japan, presented at EVs-16.

Appendix I REGENERATIVE BRAKING: SPIJKSTAAL, CARAVELLE IIE

Drive line specifications

Drive Line		**Vehicle Batteries**	
Engine Manufacturer	Thrige-Titan Electric	Manufacturer	Saft
Engine type	ttl 280 CV (proto type)	Type	STM5.180 (NiCd)
Driving axle	Front axle	Open battery voltage	192 V
Nominal Power	48 kW, 3 min. power: 60 kW	Capacity	180 Ah
Open battery voltage	192 V, ≈ 250 A	Weight	≈ 750 kg
Max. rotational speed	4000 1/min	Service facilities	Water controlling system
Controller		Battery heating	Battery cooling system
Manufacturer	ABB Norway	Lifetime	1500 Cycles
Controller	BA-60 electronic		
Recuperative deceleration, Recuperative braking			

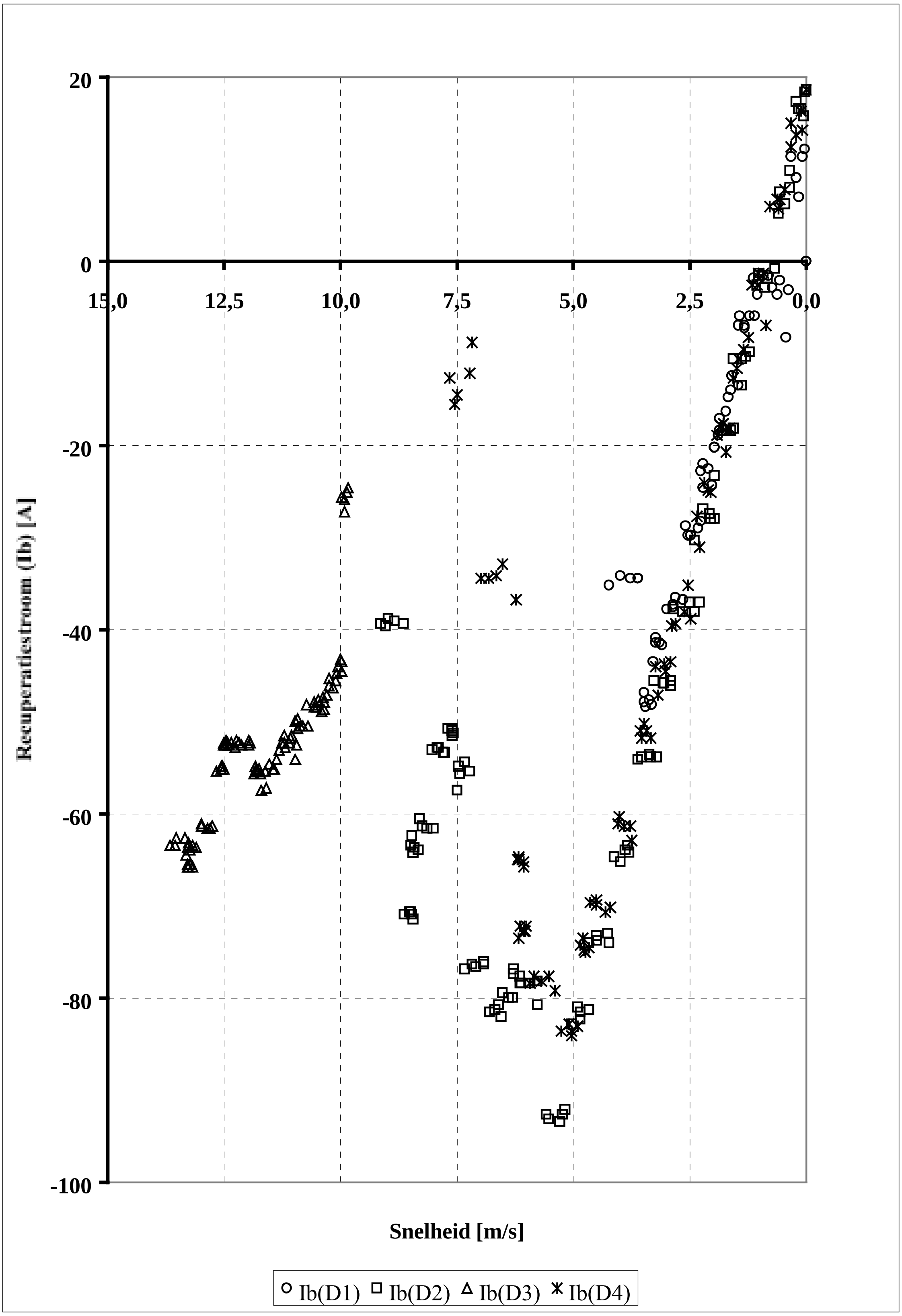

Figure 9: Regenerative current during partial braking periods in the ECE Part I (Urban) cycle

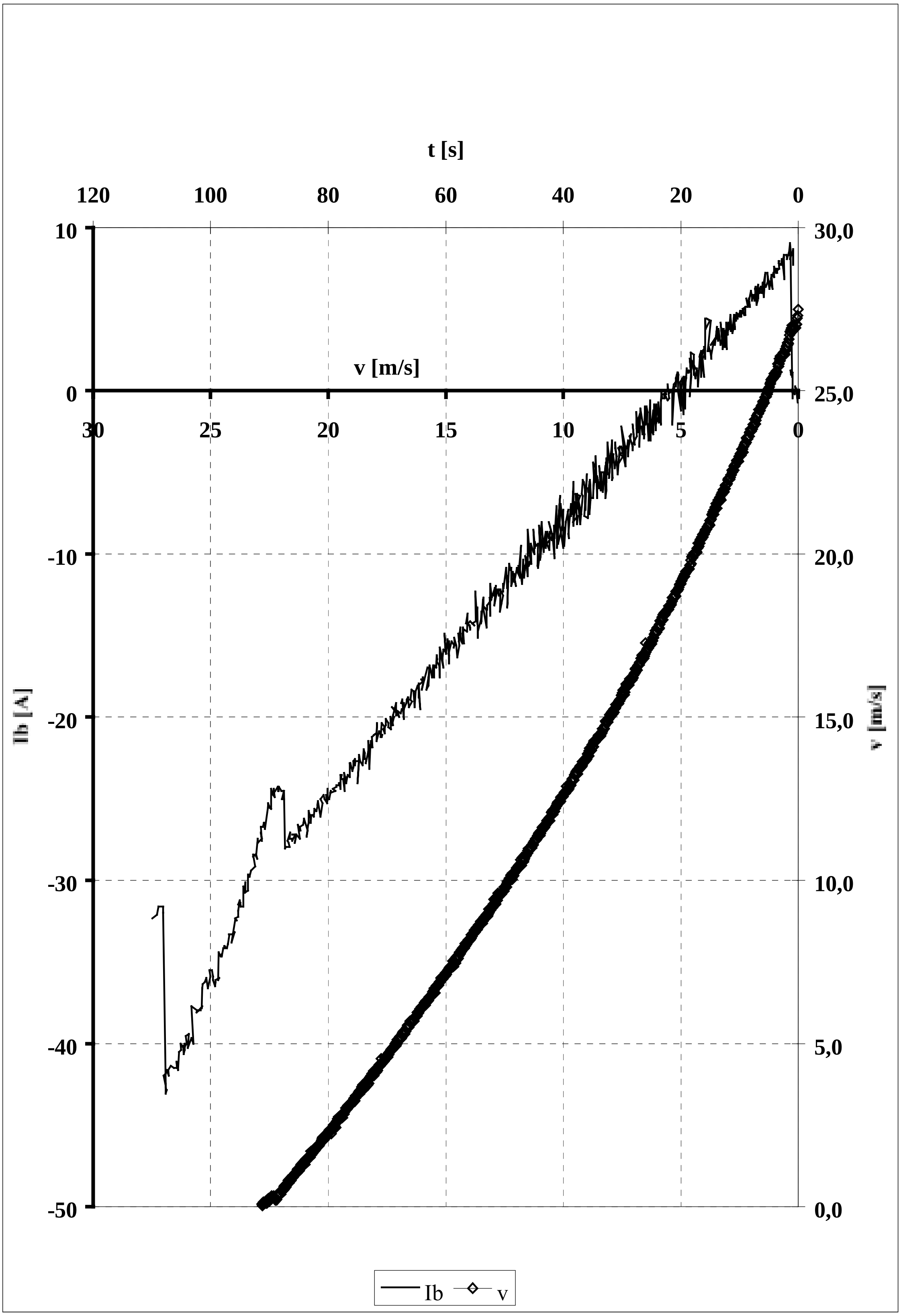

Figure 10: Regenerative braking: current (Ib) and speed (v) during coast down (+R) on the roller bench

Appendix II REGENERATIVE BRAKING: MERCEDES BENZ, MB100E

Drive line specifications

Drive Line		**Vehicle Batteries**	
Engine Manufacturer	LARAG	Manufacturer	-
Engine type	AC, squirrel cage	Type	Traction, Lead Gel
Driving axle	Front axle	Open battery voltage	180 V
Nominal Power	36 kW; 3 min. power: 36,0 kW	Capacity	160 Ah
Open battery voltage	180 V; ≈190 A	Weight	≈750 kg
Max. rotational speed	6500 1/min	Service facilities	None
Controller		Battery heating	None
Manufacturer	LARAG	Life time	- Cycles
Controller	High frequency chopper		
Recuperative deceleration, Recuperative braking			

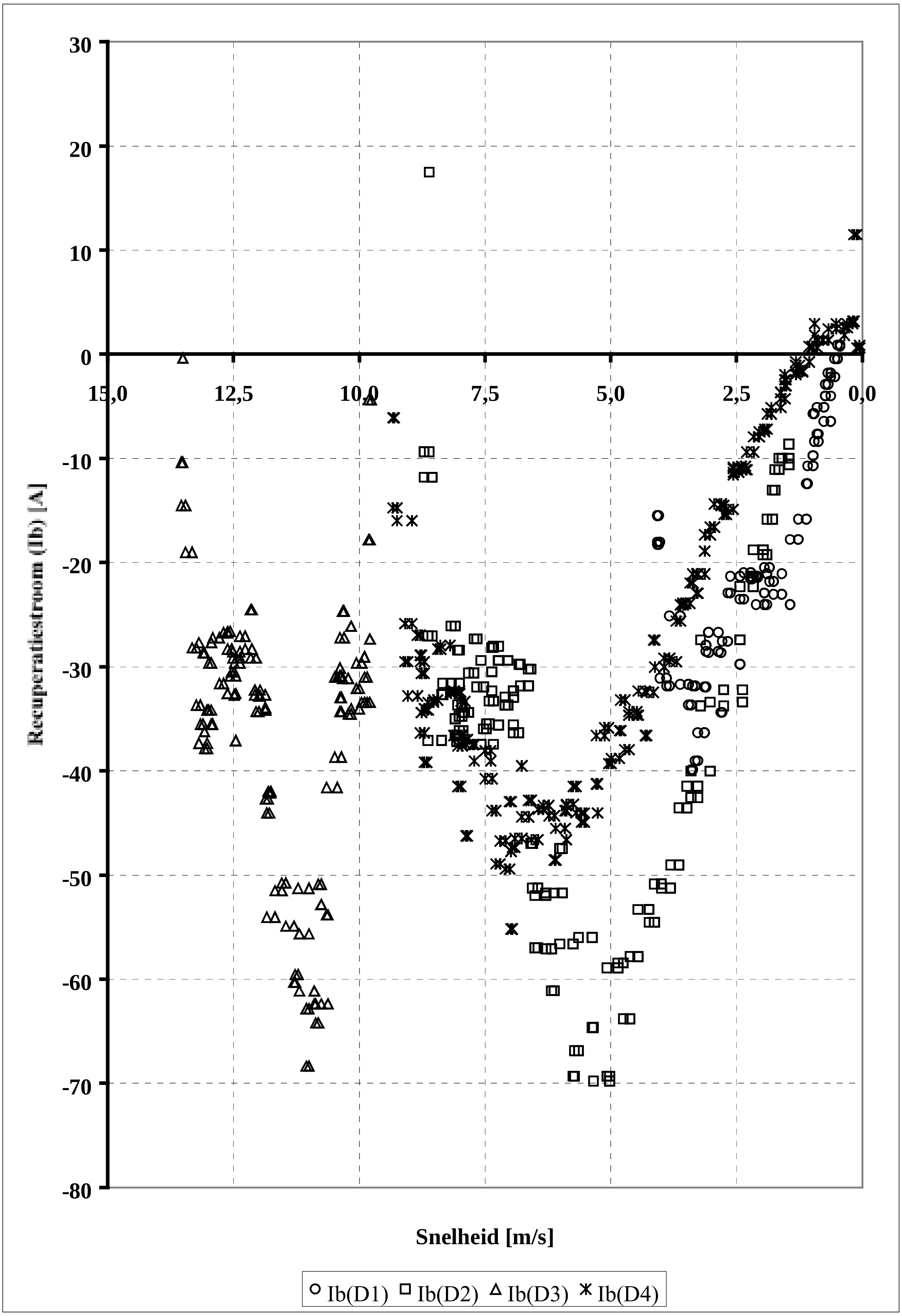

Figure 11: Regenerative current during partial braking periods in the ECE Part I (Urban) cycle

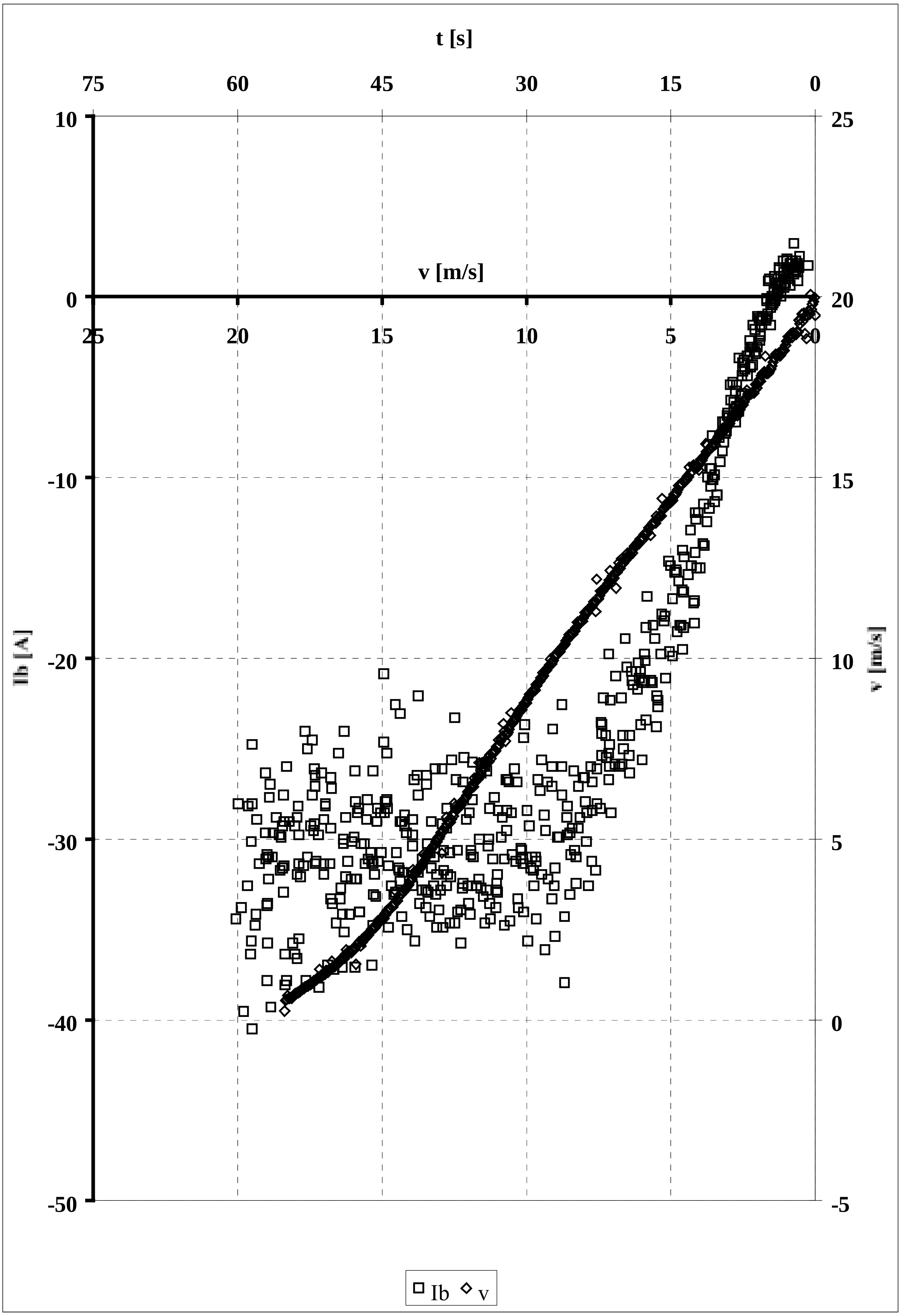

Figure 12: Regenerative braking: current (Ib) and speed (v) during coast down (+R) on the roller bench

Appendix III REGENERATIVE BRAKING: RENAULT EXPRESS Electrique

Drive line specifications

Drive Line		**Vehicle Batteries**	
Engine Manufacturer	ABB / GN 21	Manufacturer	SAFT
Engine type	DS - VB	Type	NiCd
Driving axle	Front axle	Open battery voltage	108 V
Nominal Power	16 kW, 3 min. power: 21 kW at 2000 1/min	Capacity	140 Ah
Open battery voltage	108 V, ≈ 250 A	Weight	325 kg
Max. rotational speed	7000 1/min	Service facilities	Ah counter
Controller		Battery heating	None
Manufacturer	ABB	Life time	1500 Cycles
Controller	High frequency chopper		
Recuperative deceleration Recuperative braking	0.86 m/s²,		

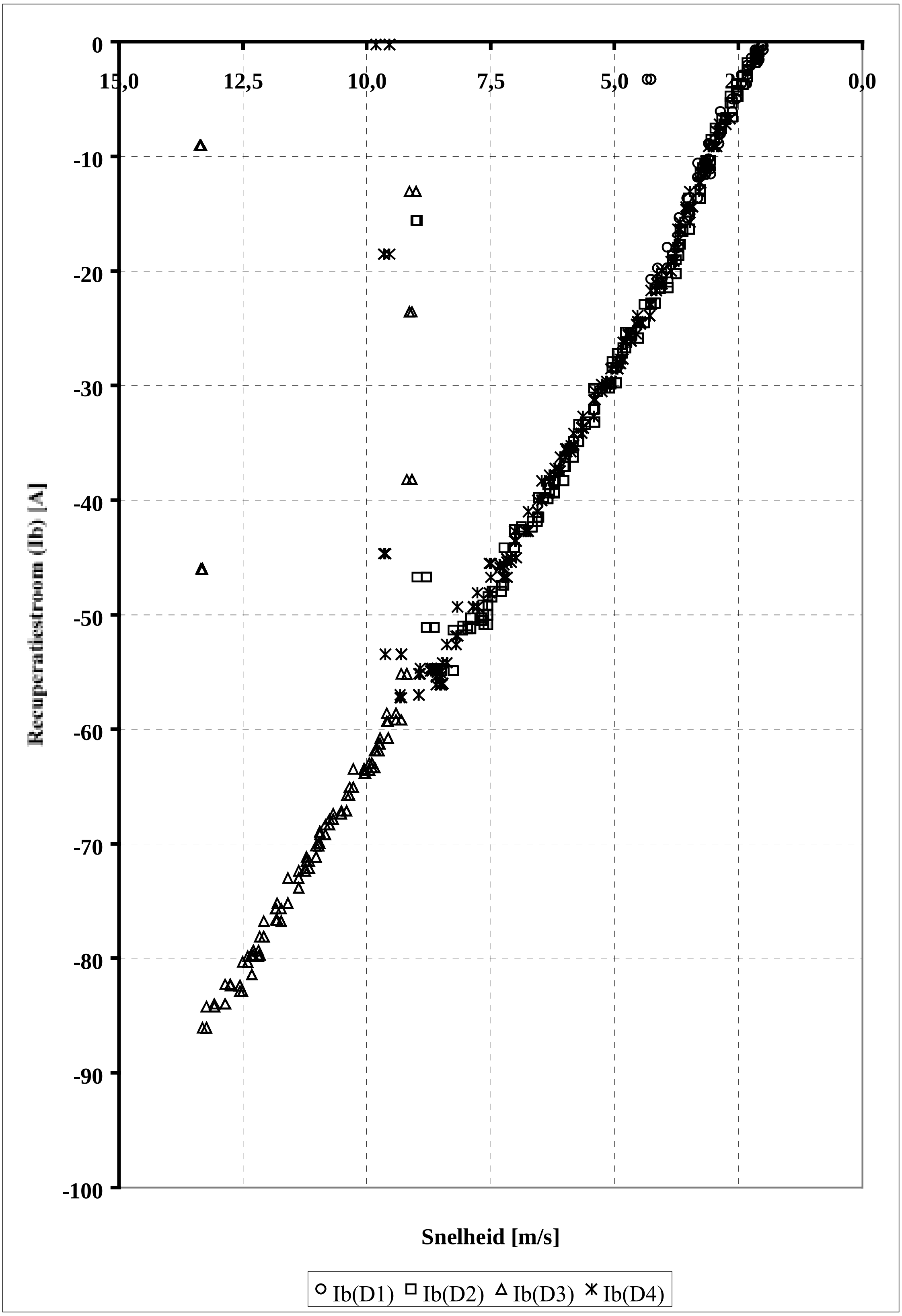

Figure 13: Regenerative current during partial braking periods in the ECE Part I (Urban) cycle

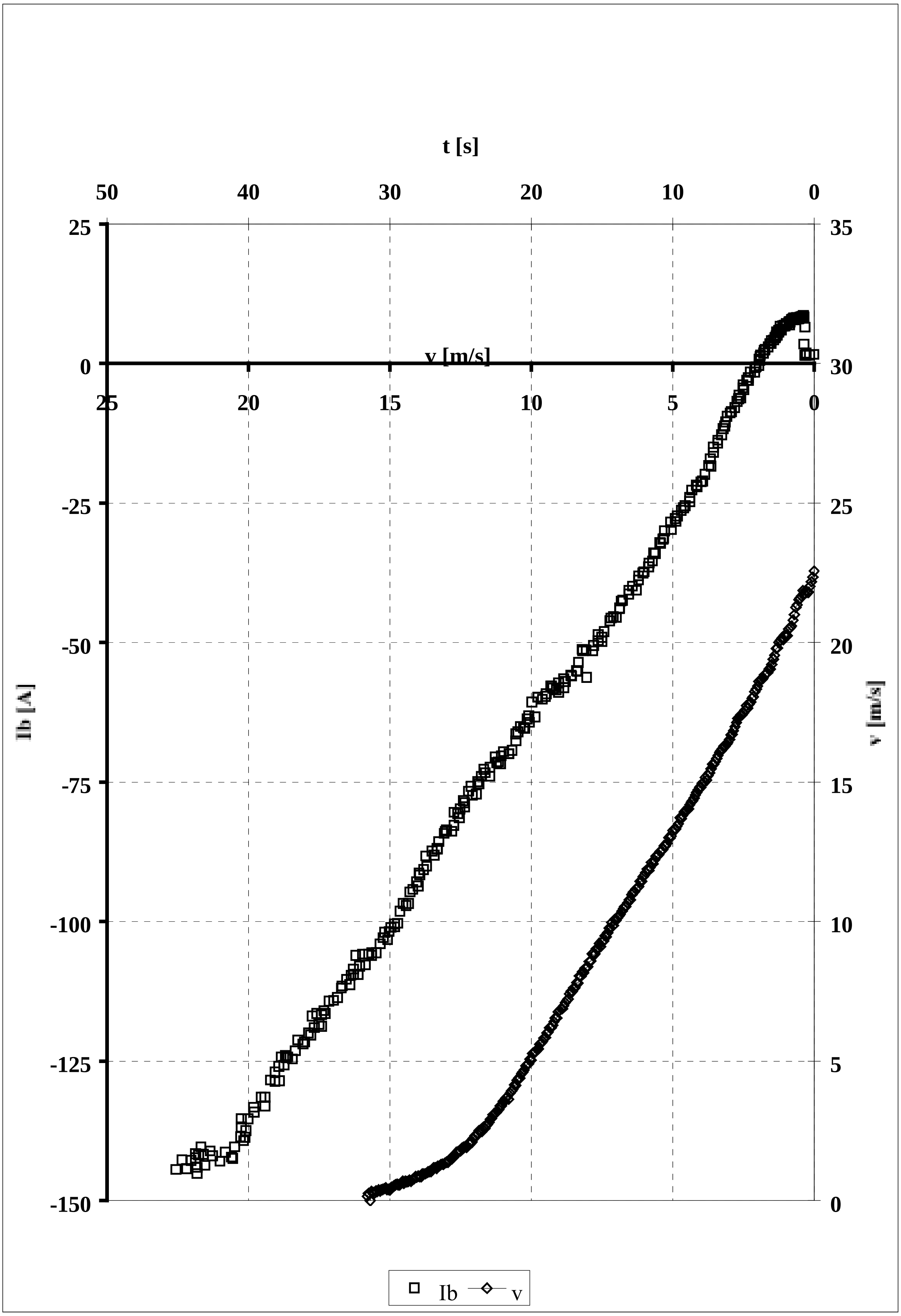

Figure 14: Regenerative braking: current (Ib) and speed (v) during coast down (+R) on the roller bench

Appendix IV REGENERATIVE BRAKING: RENAULT MASTER

Drive line specifications

Drive Line		**Vehicle Batteries**	
Engine Manufacturer	EPE (UK); MT 305 / 216	Manufacturer	Sonnenschein
Engine type	DC	Type	Lead Gel
Driving axle	Front axle	Open battery voltage	216 V
Nominal Power min. power: 42 kW	30 kW at 2500 - 3800 1/min, 3	Capacity	205 Ah
Open battery voltage	216 V, ≈ 350 A	Weight	1134 kg
Max. rotational speed	3800 1/min	Service facilities	None
Controller		Battery heating	None
Manufacturer	-	Life time Cycles	6 à 800
Controller	High frequency chopper		
Recuperative deceleration	-, Recuperative braking		

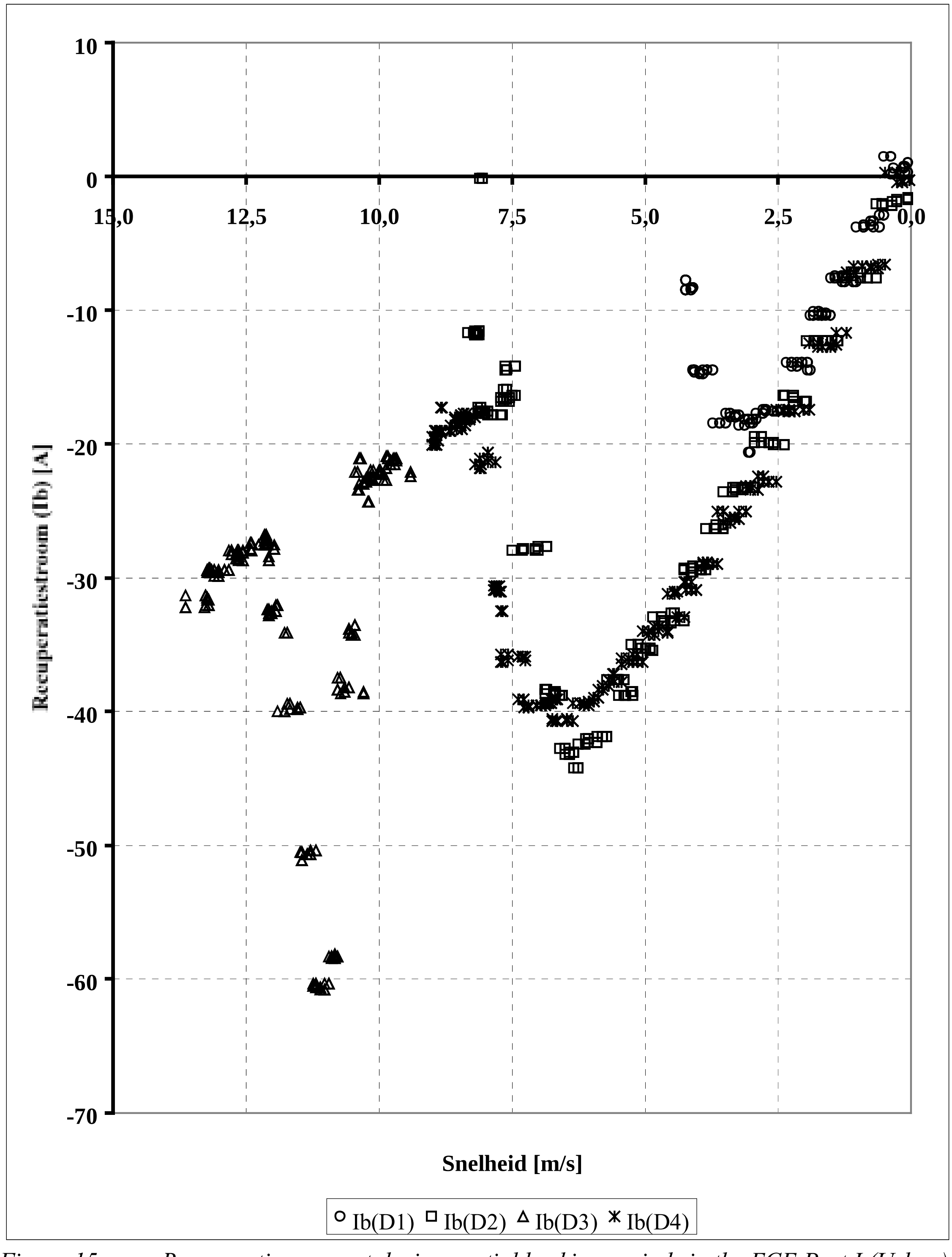

Figure 15: Regenerative current during partial braking periods in the ECE Part I (Urban) cycle

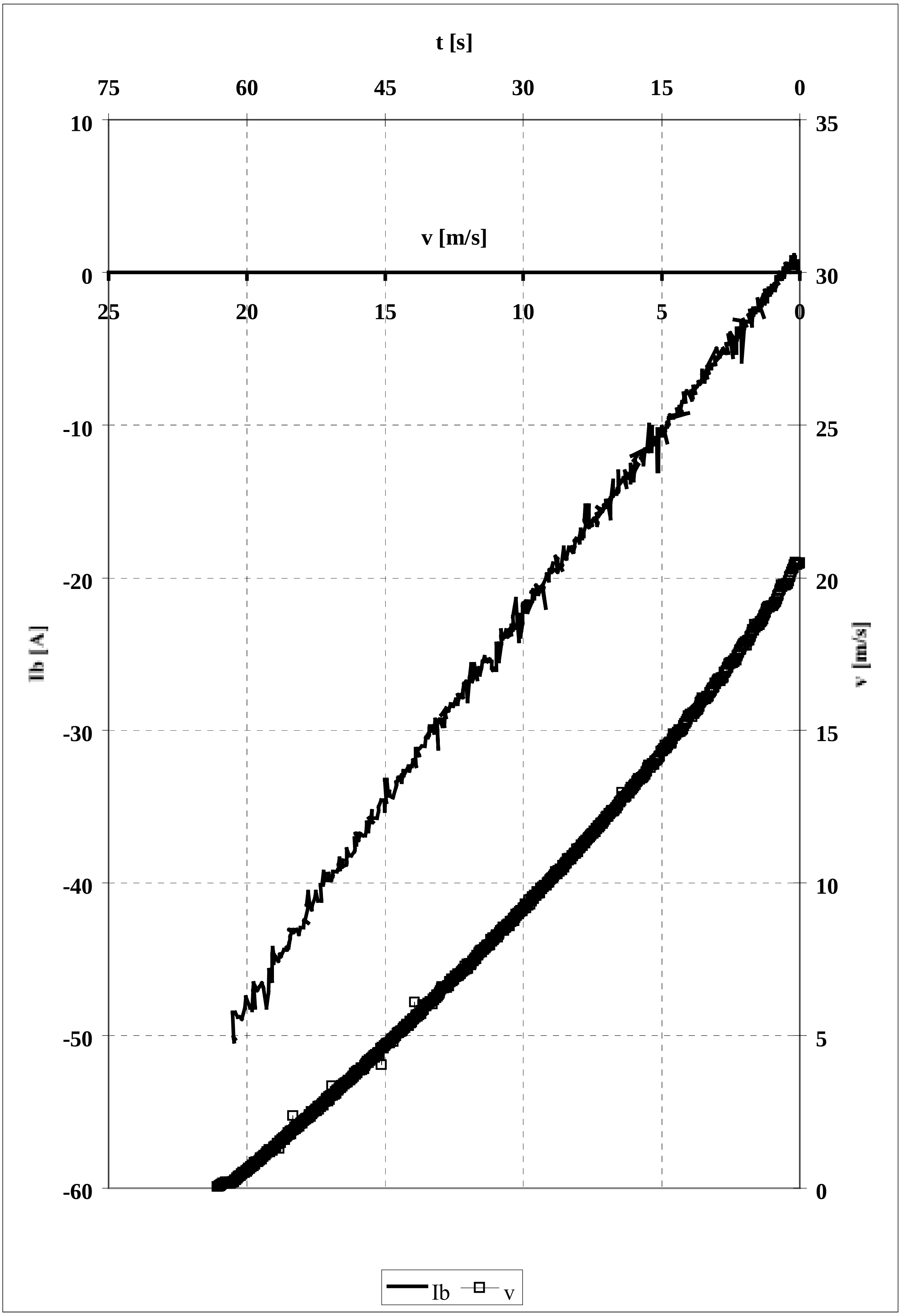

Figure 16: Regenerative braking: current (Ib) and speed (v) during coast down (+R) on the roller bench

Appendix V DRIVING CYCLE PARAMETERS

Table 7: Elementary specifications of drive cycles

Driving cycle	Time [s]	Distance [m]	Maximum speed [km/h]	Average speed [km/h]	Maximum acc / dec [m/s^2]	RPA [m/s^2]
New European Driving Cycle (NEDC)	1180	11007	120	33.6	1.04 / 1.39	0.12
Japanese 10-15 Mode Hot Cycle (Jap1015)	660	4171	70	22.7	0.79 / 0.83	0.17
US City Cycle (USFTP-75)	1877	17762	91.2	34.0	1.89 / 1.81	0.18
USFTP-72 / UDDS	1372	11986	91.2	31.4	1.89 / 1.81	0.19
US Highway Cycle (HWFET)	765	16507	96.4	77.4	1.43 / 1.48	0.07
SC03 Air Conditioning Cycle (SC03)	594	12887	88.2	34.9	2.28 / 2.73	0.22
US06 High Speed/High Load Cycle (US06)	600	5760	129.2	77.2	3.78 / 3.08	0.22
MODEM cycle	1946	25121	128.7	46.5	3.19 / 2.42	0.19
Hyzem Urban	559	3470	57.2	22.3	2.19 / 2.06	0.28
Hyzem Rural	842	11224	103.4	47.9	2.42 / 4.61	0.22
Hyzem Highway	1803	46205	138.1	92.2	3.19 / 4.03	0.13

MANAGEMENT TOOL for the ASSESSMENT of DRIVELINE TECHNOLOGIES and RESEARCH

MATADOR

Contract JOE3-CT97-0081

Task 2:

Testing methods for vehicles with conventional and alternative drivelines

Subtask 2.13

Non-rechargeable batteries

ENEA - Advanced Energy Technology Division

20 July, 2000

by
Mario Conte (ENEA)
Luigi De Andreis (ENEA)

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Energy Conservation and Utilisation

Nomenclature

Abbreviations

BEV	Battery Electric Vehicle
C	Battery storage Capacity in Ah measured or calculated during test sequence.
C_n	Battery storage Capacity in Ah. The subscript **n** indicates the discharge time in hours to completely discharge the battery under predefined conditions.
DOD	Depth Of Discharge. It is the ratio in percent of the capacity in Ah divided the nominal capacity of a battery
E_{zinc}	the energy required for converting the spent zinc in metallic zinc
EE	Electrochemical Equivalent (820 Ah/kg per zinc)
EOD	End of Discharge
E_{NRB}	energy consumption of an electric vehicle with a non-rechargeable battery
η_c	Charging /regeneration efficiency of zinc-air battery
η_{zinc}	the conversion efficiency to obtain 1 kg of metallic zinc from zinc oxide in a specific plant.
FCEV	Fuel Cell Electric Vehicle
MV	Medium Voltage
NC	Number of Cells of which the battery is composed.
V_{MAX}	Maximum vehicle speed during climbing
Zn-air	Zinc-air

Contents

1 Introduction

Task 2 of the MATADOR Project (**Ma**nagement **T**ool for the **A**ssessment of **D**riveline Techn**o**logies and **R**esearch, EU-contract JOE3-CT94-0081) is aimed at developing test methods for homologating and evaluating conventional and alternative vehicles and propulsion systems. These testing methods should also allow for a comparative assessment and benchmarking of such technologies. The testing methods, considered in Task 2, are restricted to the determination of energy consumption and emissions of various vehicles and powertrains. The definition of such testing procedures is strongly affected by the vehicle configuration, the required fuels and the specific driving patterns which may be real or simulated on test benches. In addition, the introduction of alternative technologies and fuels may pose measuring problems when compared with conventional vehicles and standardised procedures. Investigation and critical evaluation of technical issues in relation to the various technologies is the main scope of Task 2, from which specific recommendations for modified or new testing and measuring methods are derived.

This report aims to identify and suggest possible solutions to the problem of measuring the energy consumption of battery powered electric vehicles (BEV), when only mechanically rechargeable batteries are feeding the electric drivetrain. This type of problem mainly applies to metal-air batteries proposed in the last 20 years in BEVs. Of the metal-air batteries more commonly investigated for vehicular applications, only Aluminum-air and Zinc-air have been somehow experimentally verified. Since early 90' the Zinc-air (Zn-air) batteries have been more often than Al-air batteries applied in EV applications: The use of such battery has not been considered in existing standards, while in under development terminology and standards EVs powered by zinc-air are coupled with fuel cell vehicles (FCEV). The considerations and evaluations presented in this document mainly applies to non-rechargeable electrically zinc-air, because these batteries are still in development stage and, of course, for testing purposes can be treated as any other secondary rechargeable battery [1][2].

In this Subtask 2.13 report, specific analyses of the Zn-air use and regeneration processes are described, experience acquired during testing Zn-air BEVs are presented and conclusions are drawn up about possible impact on testing methods.

The document has been authorised by Edison ***to be circulated freely*** *in the framework of a Confidentiality Agreement signed between Edison and ENEA on 29 November 1999. This Agreement states that all the information and reports containing experimental data of the Edison batteries and vehicles must be classified CONFIDENTIAL to MATADOR Task 2 Members (and eventually to the EU) and circulated after written approval by Edison and ENEA. Most of the data comes from Reference [3]. For testing purposes, general conclusions can be anyhow used and disseminated outside Task 2 participants.*

2 Zinc-air batteries

The zinc-air battery is not recharged electrically, but rather is 'refueled' through a series of mechanical and electrochemical steps that will require a special infrastructure in commercial application. The cell comprises a central static replaceable anode bed of electrochemically generated zinc particles in a potassium hydroxide solution compacted onto a current collection frame and inserted into a separator envelope, flanked on two sides by the company's high-power air (oxygen reduction) cathodes.
During cell discharge, zinc at the anode is consumed by conversion to zinc oxide (ZnO), and at the cathode, oxygen from the air is electrochemically reduced to hydroxide ions. Nominal discharge voltage at the 5-h rate is about 1.15 V per cell.

The EV batteries, used in the Edison Carica van, are built from blocks of 22 cells connected in series, with blocks connected in suitable arrangements according the requirements of the vehicle, motor and controller. The battery contains subsystems for air provision and heat management. The on-board battery is "refueled" or mechanically recharged by exchanging spent electrodes - the zinc anode including current collector frame and separator envelope - with fresh "regenerated" anodes. This process is accomplished by an automated refueling machine (pilot battery exchange machines have been developed) that allows a zinc-air battery-powered EV to "refuel" in less than 10 minutes. The depleted electrodes are electrochemically recharged and mechanically recycled external to the battery. Figure 1 shows the zinc-air utilisation scheme.

2.1 Edison Carica Zn-air Battery

The Zn-air battery powering the Carica van (a prototype EV designed and built by Lamborghini in a development project of ENEL - Italian public Electricity company) is composed of 2 modules connected in series, each one constituted by 6 blocks for a total of 132 cell series connected. Due to the non-rechargeability of the battery, the regenerative braking function has been disabled in the EV in order to have exactly zero current going back into the battery. The configuration of the battery, closed in a dedicated tray, includes:

- The reaction air feeding circuit with one or two blowers, CO_2 scrubber and a CO_2 analyser. The flow of the reaction air is regulated according to the discharge current.
- An external (not in the tray) cooling system with a heat exchanger, a circulation pump of the cooling liquid and a piping system.

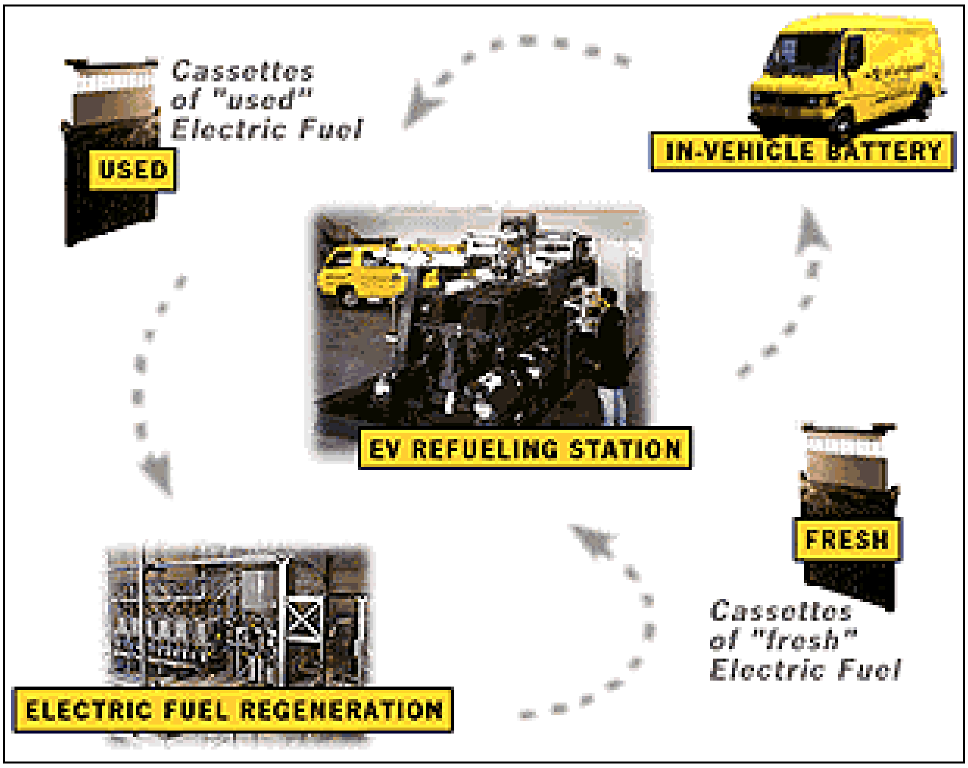

Figure 1: The electric fuel system [4]

- An air circuit for the battery cooling system working into the tray with dedicated valves and compressor.
- A battery and auxiliaries controller.

Table 1 shows the characteristics of one module of 132 cells.

Table 1: Performance characteristics of a Zinc-air module for the Carica van

Characteristics	**Value**
Nominal Capacity	249 Ah
Open Circuit Voltage, OCV	190 V
Nominal Working Voltage	140-150 V
EOD* Cut off Voltage	85 V
Max Continuous Current	60 A
Peak Current	160 A
Energy delivered @ CC 50 A	37.5 kWh
Thermal Power to be removed @ 60 A	5.3 kW

* EOD = End Of Discharge

The overall energy content in the battery is about 75 kWh with a practical specific energy close to 200 Wh/kg. The behaviour of the module at constant current discharges (only until 60 A, there complete continuous constant current discharges) is summarised in Table 2. It is useful to evaluate the effect of the discharge profiles on the available capacity (directly measured at the battery poles).

Table 2: Discharge voltage and capacity at various discharge currents

Discharged Capacity (Ah)	**DOD** (%)	**Discharge Current (A)**							
		20	40	60	80*	100*	120*	140*	160*
24,9	10	160,6	155,5	150,3	145,2	140,1	134,9	129,8	124,6
74,7	30	160,0	154,1	148,2	142,3	136,4	130,4	124,5	118,6
124,5	50	158,6	151,5	144,4	137,3	130,2	123,1	115,9	108,8
174,3	70	156,9	148,3	139,7	131,1	122,5	113,9	105,3	96,7
224,1	90	155,3	145,2	135,1	125,1	115,0	104,9	94,8	85,0
249	100	154,9	143,9	132,8	121,8	110,7	99,7	88,7	----

* Short discharge at constant current at defined discharged capacity (or DOD).

2.2 Torpedo Marbella Zn-air Battery

A new generation of zinc-air battery has been developed by Electric Fuel and made available from Edison on a second EV, SEAT Marbella Elettrica, which will be tested at ENEA in March 2000. The new generation is air-cooled and composed by 94 elementary cells. The main characteristics are listed in Table 3.

Table 3: Performance characteristics of a Zinc-air module for the SEAT Marbella.

Characteristics	**Value**
Nominal Capacity	282 Ah
Open Circuit Voltage, OCV	135 V
Nominal Working Voltage	100-110 V
EOD Cut off Voltage	60 V
Max Continuous Current	78 A
Peak Current	260 A
Energy delivered @ CC 60 A	30 kWh

According to Edison data, the battery contains a total weight of metal zinc of 40,4 kg (± 5%). When the battery is fully discharged of the nominal capacity of 282 Ah (corresponding to the conversion of 80% of the total zinc weight), the regeneration process requires 32,3 kWh of electrical energy (from MV lines) to transform zinc oxide in metal zinc.

2.3 Energy consumption for Zn-air EVs

In order to carry out calculations for the energy consumption, experimental data has been collected from various road testing activities. Furthermore, the bench tests carried out at ENEA were purposely planned to verify the methodology to directly measure the energy delivered by the battery and the energy discharge efficiency starting from the manufacturer data. Unfortunately, the first test was interrupted after a few days because of problem at the cooling system, but the second one, on a new BEV Marbella with a brand new Zn-air battery, was successful. Appendices A and B describe both test activities.

The effective specific energy of the battery depends on the vehicle and the working conditions. Experimental results supplied by Edison [3], IAE [7] and from literature [4] confirm such variations of the energy efficiency. Table 4 and Table 5 summarise data from some EVs of the Edison fleet having the same nominal specific energy (about 200 Wh/kg).

Table 4: Specific battery consumption and efficiency for 3 EVs and 2 discharge conditions

Vehicle Type	Driving Route			
	Urban		Mixed	
	Specific energy (Wh/kg)	Discharge efficiency (%)*	Specific energy (Wh/kg)	Discharge efficiency (%)*
Ducato van 1st Gen	**172,8**	**69,0**	**164,5**	**65,7**
Marbella Elettra	**177,8**	**68,4**	**172,8**	**66,5**
Ducato van 2nd Gen	**180,2**	**70,8**	**179,3**	**70,5**

*The efficiency is based on the theoretical energy content of the battery (Thermodynamic voltage 1,62 V multiplied by the electrochemical equivalent, 0,820 Ah/g, and the weight of zinc consumed).

Table 5: Specific vehicle consumption for 3 EVs and 2 discharge conditions

Vehicle Type	Driving Route			
	Urban		Mixed	
	Specific energy (Wh/kg)	Vehicle Specific Consumption (Wh/km*ton)	Specific energy (Wh/kg)	Vehicle Specific Consumption (Wh/km*ton)
Ducato van 1st Gen	**172,8**	**219,9**	**164,5**	**186,0**
Marbella Elettra	**177,8**	**171,6**	**172,8**	**137,1**
Ducato van 2nd Gen	**180,2**	**217,1**	**179,3**	**179,9**

The variations, apart from the slight self-discharge (due to parasitic corrosion processes developing hydrogen and estimated by Edison in 1,5% of the available energy in about 7 days of continuous operations), are mainly due to the voltage changes during discharge. In fact, Figure 2 shows the voltage profile during discharges at constant current. Similar behaviour is expected for profile with varying currents. As a consequence, in consideration of the constant energy consumption of the vehicle during standardised profiles, the change of voltages imply the variation of discharged capacities at various DOD for equal intervals of the discharge cycle.

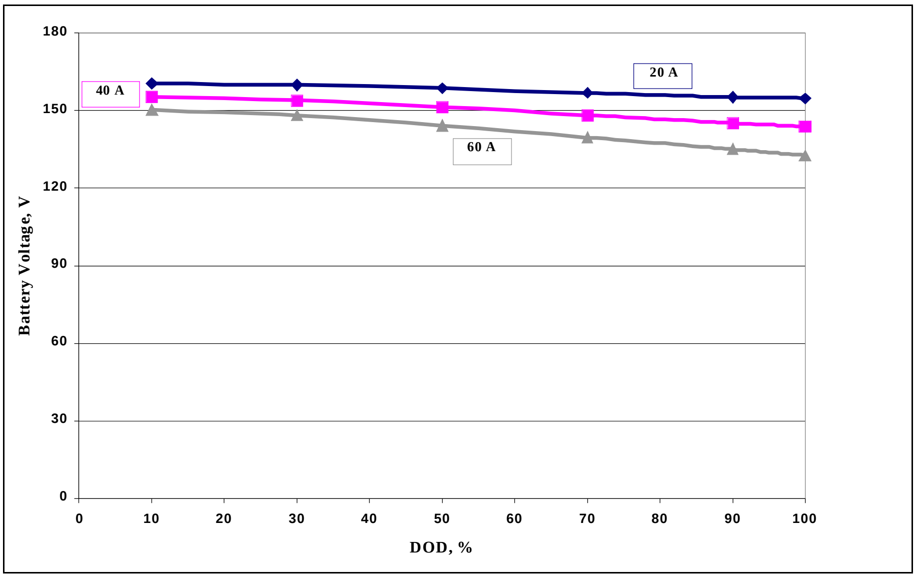

Figure 2: Voltage vs. DOD during discharges at various constant currents

3 Regeneration Process

Due to the impossibility of the direct measurement of the energy charged into the battery at the end of the discharge cycle, a short analysis of the regeneration process is necessary to determine the amount of energy needed for producing zinc electrodes and refueling the batteries. For uniformity with the standardised procedure for BEV energy consumption determination, only the energy needed for "recharging" the spent zinc electrodes should be considered.

3.1 The Technology

Figure 3 shows the complete logistics of the Electric Fuel Zinc-air Scheme, while Figure 4 schematically describes the complete regeneration process, presented by Electric Fuel in [4].

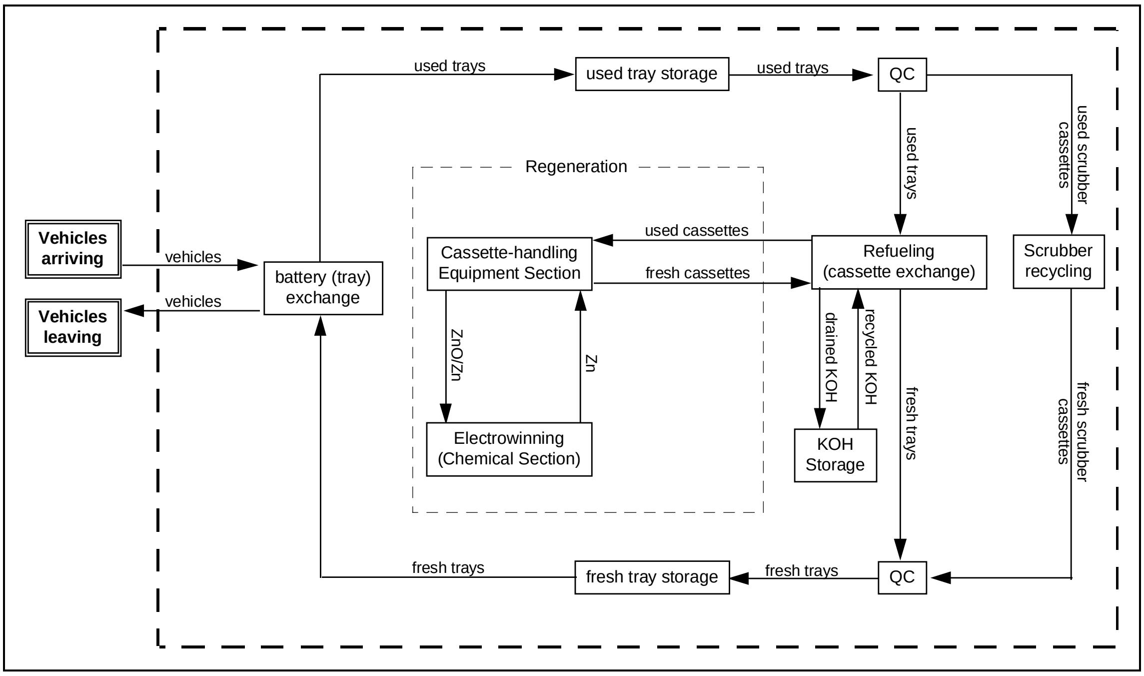

Figure 3: Logistics of Electric Fuel System

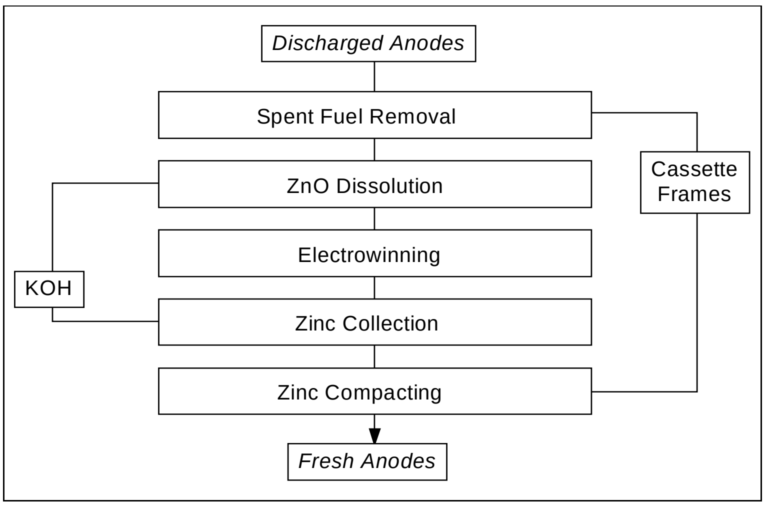

Figure 4: Scheme of the regeneration process

The regeneration includes the following steps:

a. Disassembly, in which separator bags are removed from the anodes, and the zinc oxide discharge product (along with residual, undischarged zinc) is removed from the current collector frames. Frames and separators are cleaned and reused.
b. Dissolution, in which zinc oxide is dissolved in a KOH solution to form a zincate-rich feed, according to the following equation:
$$ZnO + 2KOH + H_2O = K_2Zn(OH)_4$$
c. Electrowinning, in which the zincate solution is electrolyzed in an electrowinning bath according to the following equation:
$$K_2Zn(OH)_4 = Zn + 2KOH + H_2O + ½O_2$$
d. Reassembly, in which the electrowon zinc, together with residual (charged) metallic zinc, is compacted in metered quantities onto the current collector frame and the anode is inserted into a separator envelope.

4 Energy Balance for "refueling" Zinc-air batteries

The evaluation of the overall energy balance is strongly dependent on the production level of the regeneration plant, a typical electrochemical factory. The evaluations presented hereafter are then related to the characteristics of the production plant (at pilot size). Three pilot regeneration plants are presently known: the Trofarello plant, near Turin (Italy), built in 1994 and managed by Edison; the Bet Shemesh Plant in Israel, built in 1995 and managed by Electric Fuel; the Bremen Regeneration Plant put in service in 1996 and used in the German Post Project. The first two plants have a regeneration capacity of ***10 kg zinc per hour*** and will be used as the basis (extrapolated by Edison to 50-100 kg/h) for (Edison) MATADOR energy calculation. A fourth plant was planned to be built in Sweden in 1998.

The basic characteristics of the zinc-air systems are the theoretical cell voltage, ***1,62 V***, and the electrochemical equivalent, ***820 Ah/kg$_{zinc}$***.

4.1 Edison calculation

Edison has systematically collected data on their regeneration plant, even for an EU LIFE Project, installed at the R&D Facility of Trofarello. The analysis is based upon a complete characterisation of the Zn-air Transport System, including the environmental and energy balance. Table 6 presents the efficiency and energy data of all the phases of the regeneration and substitution process.

Table 6: Efficiency and energy data for regeneration and substitution of zinc-air system [3]

Parameter	Value
Faradic (or Coulombic) efficiency of the zinc electrowinning process, %	**97,5**
Voltaic efficiency of the zinc electrowinning process, %	**65,5**
Energy efficiency of the zinc electrowinning process, %	**63,9**
Overall efficiency of the regeneration process, %	**57,5**
Energy consumption of the regeneration process (from MV electricity station), kWh/kg$_{zinc}$	**2,32**
Overall energy efficiency of recharging/anode substitution process, %	**57,4**

The calculation and estimations are based upon a small-scale regeneration plant of zinc (up to 50-100 kg zinc/h) operating on three shifts per day without any losses for thermal management of the electrolyte (working at 50-60 °C).

For exemplification, the zinc-air battery of the CARICA van contains 100,32 (±5%) kg of zinc and 75 kWh (at defined constant current discharge of 50 A). The nominal capacity of 249 Ah corresponds to the use of 80% of the available zinc. In fact, the following equation calculates the capacity available from the zinc electrodes:

Cell/Battery Capacity (Ah) =

$$\frac{\text{ZincWeight} \times \text{ElectrochemicalEquivalent} \times 0{,}80}{\text{n°cells}} = \frac{100{,}32 \times 820 \times 0{,}80}{264} = 249{,}3\text{Ah}$$

Consequently, the zinc oxide amount to be regenerated in metallic zinc is 80,26 kg, corresponding to an energy consumption from mains of (see Table 6) 186,20 kWh (neglecting the energy consumption for substituting the electrodes*)*. The regeneration process only converts zinc oxides in metallic zinc: the energy consumption is then only related to such conversion.

The conversion/charging efficiency to be considered for the recharging/regeneration process is:

$$\eta c = \frac{75 \cdot kWh}{186.20 \cdot kWh} = 0.40$$

This value is not constant and not univocally determined. It includes self-discharge and discharge efficiency of the battery (at defined discharge profiles, 75 kWh corresponds to the energy delivered under a constant current discharge of 50 A). It is based on the energy values measured for converting metallic zinc in zinc oxide during battery discharge, which depends on the discharge profile, and, vice-versa, for regenerating metallic zinc from zinc oxide, which depends on the regeneration plant characteristics.

4.2 Electric Fuel calculation

A similar calculation has been made by Electric Fuel in [6] and is reported in Table 7.

Table 7: Electric Fuel Calculation for zinc-air energy efficiency [6]

#	Parameter	Value
1	Net of losses in the electric utility grid to the regeneration, %	94
2	Multi-MW power converters, %	98
3	**Net of power consumption for regeneration operation, %**	**63,9**
4	Battery/regeneration DC/DC round trip efficiency, %	57
5	Net of self-discharge losses on-stand, on-board energy use, %	97
6	**Net of energy usage of Electric Fuel distribution, %**	**97**
7	Net energy efficiency, %	47

For the scope of the MATADOR and testing methods evaluation, only the efficiencies 3 and 6 are useful. A regeneration and substitution efficiency of **62 %** is then obtained. This value is higher than **57,4%** calculated by Edison. Some of the values presented in Table 7 are quite questionable or specific: some are electricity grid dependent (1 and 2) and others are not clear for which uses are measured (4 and 5).

5 Test results

In MATADOR Task 2 activities, two Zn-air BEVs have been tested at ENEA Roller Dynamometer Facility. The two BEVs and battery characteristics have been described in paragraphs 2.1 and 2.2. The two tests were completed in March 2000. The first test was discontinued after about 20% of partial discharge of the battery, due to vehicle ancillaries problems (see Appendix A for test results). The second test was almost completed after about 80% of the nominal capacity was discharged (see Appendix B for test results). The second battery was then fully discharged at Edison Facility. Furthermore, results from Zn-air BEV used by KEMA in Netherlands have been also used for extrapolating some conclusions. For testing purposes, a few aspects can be stressed as results of the testing activity:

1. The current and voltage of the battery and then the energy consumption have been directly measured.
2. The driving cycle ECE-15 was applied without modifications even if no regenerative braking was possible due to the non-rechargeability of the Zn-air battery.
3. The energy consumption from the battery depends on the driving profile, as expected for any BEV.
4. No specific problems were encountered in testing the BEVs.

6 Calculations of energy consumption for Zn-air BEVs

6.1 1st Measuring and calculation method

The energy delivered by the battery should be measured or calculated (by using current and voltage sensors) over a standardised number of cycles, according to EN 1986-1:1997, along with the discharged capacity. This measurement is not considered in EN 1986-1, but it is technically feasible and quite inexpensive in testing laboratories: this has been verified in testing work.

The calculation of the energy consumption can be done by dividing the delivered energy by a substitution/regeneration efficiency (**0,4** from Edison data in defined operating and regeneration conditions). Edison declares that the energy delivered by the battery in a mixed route (urban/extra-urban not clearly identified) at a discharge regime of 50 A, is equal to **0,93 kWh** per each kg of metal zinc transformed in zinc oxide.

During the ENEA complete discharge test with Marbella van (Appendix B), the Zn-air battery delivered a total energy of 20,69 kWh (69 % of the nominal capacity) and the vehicle had an energy consumption from the battery storage tank of 140 Wh/km. These two values can be used to estimate the energy consumption from mains in two different ways: by dividing 140 Wh/km by 0,4, the regeneration efficiency, we obtain **350 Wh/km**. In the second way, with the ratio 20,69/0,93, we achieve the weight of zinc oxide to be regenerated of 22,25 kg (55 % of the total weight of zinc in the battery). This value multiplied by 2,32 kWh/kg and divided by the travelled distance (147,62 km) gives as energy consumption from mains **349,7 Wh/km**.

6.2 2nd Measuring and calculation method

The capacity (or charge) (Ah) delivered by the battery should be measured over a standardised number of cycles, according to EN 1986-1:1997. This measurement is not considered in EN 1986-1, but it seems to be technically feasible and quite inexpensive in the testing laboratories.

The calculation of the energy consumption from mains requires various steps:

- The amount of metallic zinc consumed can be determined by using the electrochemical equivalent of the discharged capacity C. For example, in the case of the CARICA van battery, the discharge of 24,9 Ah corresponds to 10% (10,03 kg) of metallic zinc converted in zinc oxide. For the Marbella test (see Appendix B) we have 198,15 Ah (70% of the nominal capacity).
- The regeneration process of zinc oxide requires 2,32 kWh/kg (Edison calculation for a defined regeneration plant). Consequently, the energy consumption of the BEV is obtained by multiplying the consumed metallic zinc by the regeneration energy consumption. In the case of the CARICA van, the energy consumption should be 23,3 kWh divided by the travelled distance. For the Marbella we have a weight of 22,71 kg of spent zinc to be regenerated, which multiplied by 2,32 gives 52,7 kWh. The energy consumption from mains for Marbella then becomes **356,0 Wh/km**.

7 Conclusions and recommendations

Problem definition

The testing of BEV powered by non-electrically rechargeable batteries (e.g. metal-air systems, such as zinc-air and aluminium-air batteries) poses various fundamental problems related to the measurement of the energy consumption:

1) In which vehicle category can such a vehicle be classified? As a result of the discussion by CEN TC301 Working Group 1 (European Standard Setting body, WG1), for the moment, zinc-air electric vehicles are classified in the group of Pure Fuel Cell Electric Vehicle. This classification seems to be rather inadequate for testing and homologation purposes, because the parameters to be measured for determining the energy consumption of a zinc-air-propelled vehicle are similar to those of a BEV.
2) Can all parameters needed for determining the energy consumption be measured? The testing procedure to be applied in such a case is not yet defined in existing standards. In fact, such a battery, by definition, cannot be electrically recharged from the mains, as required by BEV standards. The batteries are "mechanically recharged" (more properly: regenerated) by exchanging the fully used electrodes (e.g. zinc oxide electrodes in zinc-air batteries) with “fresh” ones (e.g. zinc metal electrodes in zinc-air batteries). The only energy data that can, eventually, be determined during testing is the energy delivered by the battery: this measurement is not included in existing standards, which excludes intrusive measurements.
3) Can the energy required to regenerate the spent zinc electrodes be measured? The regeneration process is carried out in dedicated chemical regeneration plants. Currently there are a few pilot regeneration plants that cannot be surely controlled during the testing procedures. The energy data depends on the characteristics and the production level of the regeneration plant and can only be supplied by the electrode manufacturers.
4) Can the energy needed for zinc regeneration by means of electrochemical reactions be calculated? The basic chemical reactions and electrochemistry cannot be used to calculate the consumed energy from the mains in the regeneration plant, because the value depends on the plant characteristics.

The difference between the energy delivered by the battery and that needed from the mains to regenerate the spent electrodes is relevant. Depending on the characteristics of the regeneration plant, experimental results confirm that the energy consumption (calculated as Wh/km) of the zinc-air battery during bench test with BEV is much less than 50% of the overall energy consumption, if the regeneration energy is taken into account.

Status of standard procedures

Current official (and draft) test procedures do not take into account this specific problem, because it is impossible to measure the energy consumption in a conventional way, that is, directly from the energy meters. CEN WG1 has considered zinc-air batteries in recent meetings and has asked the MATADOR Members to prepare a technical note, in which the elaboration of related principles and a proposal for a procedure for measuring the energy consumption. The basic idea is not, for the moment, to amend any standard or to propose a brand new standard, but to add a technical note describing the test procedure for zinc-air battery vehicles as an Appendix to the appropriate standard (EN1986-1). Furthermore, the classification of zinc-air vehicles should also be clarified, because in terms of test methods, according to previous considerations, seems more appropriate to list zinc-air vehicles as BEV, rather than as Pure Fuel Cell Electric Vehicle.

Possible solutions for measuring energy consumption

The literature survey, the analysis and testing activities suggest, with some warnings about the reliability of the reference data about the regeneration process, two possible methods for the determination of the energy consumption BEV with Zn-air. Both methods require further information from the manufacturers about the zinc content (in kg) of the battery and the energy needed for regenerating 1 kg of zinc in a defined regeneration plant (for comparison the efficiency data of the regeneration process could be valuable to compare different plants).

The first method is based upon data from manufacturers during regeneration of zinc electrode and the specific discharge data of the battery in real service. This solution presents many sources of inaccuracy:

1. The energy delivered by the battery depends on the discharge profile. The number of discharge cycles will affect the discharge efficiency and the specific energy consumption (from the battery). In particular, the energy conversion factor associated with the zinc conversion depends on the driving profile and normally the manufacturer refers to a specific discharge condition.
2. The final result strongly depends on the calculation of battery manufacturers and is plant-specific.
3. The battery should be fully discharged according to a standardised Test Sequence, as in a range test, in order to have the actual overall energy. This allows the determination of the energy delivered and compared to the actual one, and directly associated to the amount of zinc oxide to be regenerated.

The second method presents some positive aspects along with some warnings still related to the information from the regeneration process. In fact, its inaccuracy mainly depends on regeneration process data.

1. The measurement and the calculations are straightforward and based on general constants with the exception of the regeneration consumption.
2. The test sequence and then the DOD influence the final results, because the current increases with increasing DOD when a power profile is used. Figure 5 and Table 2 clearly show the dependency of the voltage on the DOD and discharge conditions.
3. The EN 1986-1 Test Sequences should be applied in order to have an inexpensive and affordable test method.
4. The final result strongly depends on the calculation of battery manufacturers and is plant-specific.

Both measuring and calculation methods, still requiring a complete verification with specific manufacturer data, offer the possibility to just estimate and make comparable the energy consumption of BEV even including Zn-air batteries. The second method has more easy to measure characteristics and is less dependent on reference data during service. Nevertheless, the existing technological fluctuations in the realisation and construction of zinc anode and complete batteries (the variation of weight in zinc content is around 5 %), as well as the not-yet-fixed regeneration process energy balance makes the accuracy obtainable far from that required in standard procedures.

These alternative test methods, with the above mentioned warnings, can be both applied in homologation testing as well as for comparative assessment.

Recommendations for a test procedure

A complete and detailed description of the test procedure is described in Appendix C of Subtask 2.13. This Appendix, according to the request of CEN TC 301, has been written as an Annex (or technical note) for the existing standard EN 1986-1.

A test method and a technical attachment to the Standard EN 1986-1, *specific for non-rechargeable batteries*, must consider the following sequence for measuring the energy consumption:

- The capacity (or charge) (Ah) delivered by the battery should be measured over a standardised number of cycles, according to EN 1986-1:1997. This measurement is not considered in EN 1986-1, but it is mandatory and seems to be technically feasible and quite inexpensive in various testing laboratories. This measurement is necessary to determine the metallic zinc converted in zinc oxide during discharge.

- The calculation of the energy consumption from the mains requires various steps:
  - The amount of metallic zinc consumed can be determined by using the electrochemical equivalent of the discharged capacity. The calculation is based on the following equation:

    $$\text{Zinc} \cdot \text{Weight} = \frac{C \times NC}{EE} \qquad (1)$$

    where C is the battery capacity measured during the test, NC is the number of cells composing the entire zinc-air battery and EE is the electrochemical equivalent for the zinc (820 Ah/kg_{zinc}).
  - The regeneration process of zinc oxide requires 2.32 kWh/kg (this value only represents the Edison calculation for a defined regeneration plant). Consequently, the energy consumption of the BEV is obtained by multiplying the consumed metallic zinc by the regeneration energy consumption:

    $$E_{zinc} = \text{Zinc.Weight} \times \eta_{zinc} \qquad (2)$$

    where E_{zinc} is the energy required for converting the spent zinc in metallic zinc and η_{zinc} is the conversion efficiency to obtain 1 kg of metallic zinc and is plant specific (the value to be used should be certified by the battery manufacturer and indicated in the battery).
  - The vehicle energy consumption is obtained by dividing the energy consumption for producing the metallic zinc divided by the travelled distance.

8 References

[1] NEDO, "The investigation of the development trend and the social adoption evaluation for the system regarding Zn/air battery", Technical Report, April 1997.

[2] ZINCAIR Power Corporation, Presentation to USABC, 1996.

[3] LIFE Project 94/IT/A171/IT/00330/PIE, Final Report, excerpts, Private Communication from Edison.

[4] B. Koretz and J. R. Goldstein, "Regeneration of zinc anodes for the Electric Fuel© Zinc-air refuelable EV battery system", 32nd IECEC, Honolulu, Hawaii, 1997.

[5] R.A. Putt and G: W: Merry, "Zinc air battery development for Electric Vehicles", Technical Report, LBL-31184, 1991.

[6] B. Koretz, Y. Harats, J. Goldstein, "Operational aspects of the Electric Fuel™ Zinc-Air battery system for EV's", 12th International Seminar on Primary and Secondary Battery Technology and Application, Deerfield Beach, Florida, 1995.

[7] L. Buning, MATADOR/IAE/Task2/1999/3/PU, 1999.

[8] CEN, "Electrically propelled road vehicles - Terminology", prEN 13447, January 1999.

[9] CEN, "Electrically propelled road vehicles - Measurement of energy performances - Part 1: Pure electric vehicles", EN 1986-1, July 1997.

Appendix A Zn-air BEV Test: Carica Van

The test on the Carica was organised in two phases, the first one aimed to verify vehicle's performances in terms of acceleration, gradeability, energy consumption on urban cycle, the second one, on a new battery pack, aimed to measure the range. Unfortunately, during the first phase, the battery cooling system, which on the Carica is not incorporated in the battery system, broke down, and the test was interrupted. So, in the following, only the test results of a part of the first phase are reported, and the test will be repeated on a new vehicle, a Panda. However, the experience was very useful to develop the test procedure and to get used with zinc-air equipped electric vehicle's problems.

A1 The test vehicle

Table A.1 summarises the main specifications of the BEV van.

Table A.1: Technical specifications of the Electric Carica van with Zinc-air battery

Vehicle Type	**Carica 11/52**
Manufacturer	EMILIANAUTO
Kerb-weight	1700
DC electric motor	SIEMENS
Nominal Power	30 kW
Battery charger	

A2 The battery

Table A.2 summarises the main specifications of the Zinc-air battery BEV van.

Table A.2: Technical specifications of Zinc-air battery for the Electric Carica van

Manufacturer	**Edison (Electric Fuel Ltd.)**
Type	Zn/Air
Nominal voltage	300 V
Cell voltage	1,13 V
n° of elements	264
Capacity (C_5)	249 Ah
Battery weight	220 kg
System weight	440 kg
Dimensions	711x960x362 mm

A3 Test Preparation and Drag Force Measurements

The drag force curve is an input of the roller dynamometer and has been calculated using the data from the manufacturer:

Kerb weight: 1775 kg
Frontal area : 2,5 m^2
Air drag coefficient C_x: 0,4

The measurement of losses due the rolling friction of tyres onto the bench rollers has been performed after a preheating with drawn tyres at 20 km/h per 600 sec, at 40 km/h per 600 sec and at 60 km/h per 600 sec.
Table A.3 reports the tyre temperature after the heating process.

Table A.3: Tyre temperature after vehicle preconditioning

	Right Tyre	**Left Tyre**
Tread Temperature	40,0°C	49,0°C
Sidewall Temperature	27°C	28°C

Table A.4 presents the value of the force needed to keep moving the tyres at various speeds.

Table A.4: Force at various speeds

Speed (km/h)	**Force (N)**
10	193
20	208
30	220
40	228
50	238
60	242
50	230
40	219
30	214
20	201
10	193

With such data, the drag force curve has been calculated in function of the speed. The parabola approximating the calculated curve has the following formula and coefficients:

$$F = F_0 + F_1 V + F_2 V^2 \text{ [V in km/h]},$$

with F_0=208, F_1=0 and F_2=0,046.

The tyre losses due to the rolling resistance are represented by another parabola with the coefficients:

F_0 = 30,9 F_1 = -1,93 F_2 = 0,057

The brake force of the roller bench is obtained by difference from the two parabolas. Figure shows three different curves:

- *Theoretical*: calculated from the vehicle data;
- *Losses*: obtained from tyre rolling resistance on the dynamometer rollers;
- *Brake*: summing up the roller bench dynamo resistance and the losses to obtain the theoretical curve :

F_0=177,9 F_1=1,934 F_2=-0,011

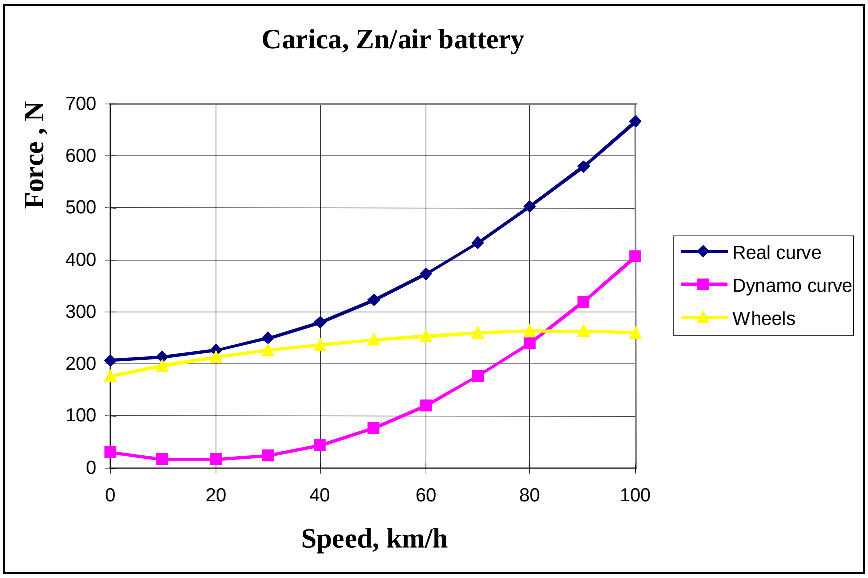

Figure A1: Drag force curve of Carica van

The drag force obtained from the dynamometer is practically the brake force summed to a small share of the vehicle mass running on slopes and the inertia force when acceleration is involved. The simulation of the inertia force is done by means of flywheels up to 907 kg and after that by controlling adequately the dynamometer.

A4 Test Results

A4.1 Energy consumption at various speeds

The energy consumption test has been performed for comparison even at various constant speeds. The test allows the determination of the vehicle consumption from the battery, at various speeds in one discharge cycle. Table A5 shows the test results that are plotted in Figure A6.

Table A5: Energy from the battery at various speeds

Speed km/h	Energy consumption from the battery (Wh/km)
10	170
20	130
30	125
40	130
50	150
60	155

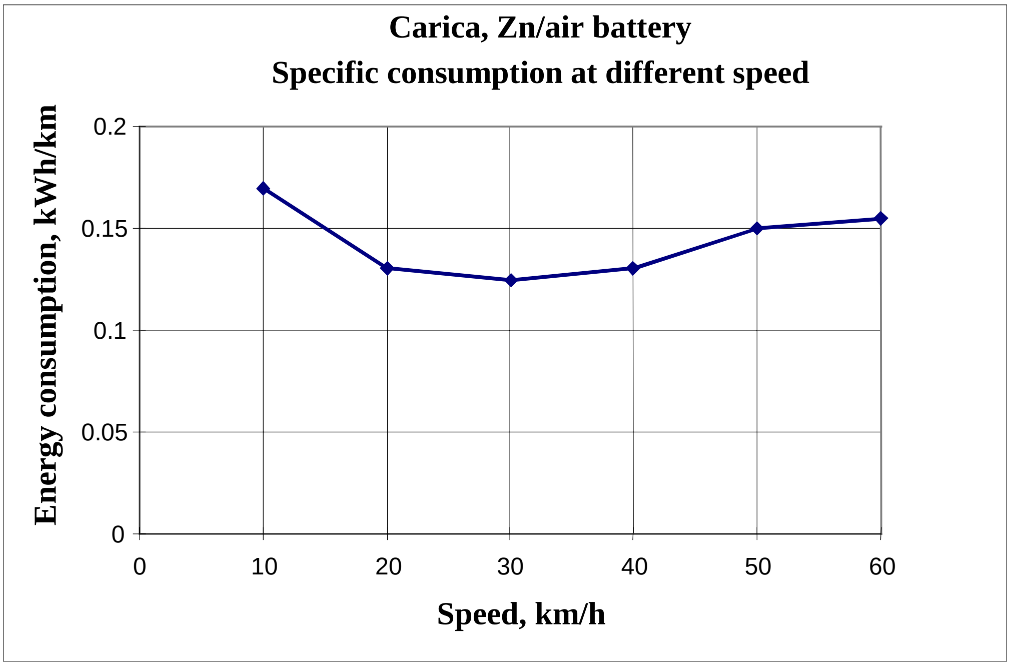

Figure A2: Energy consumption from the battery at various speeds

A4.2 Total discharge performance test

Non-rechargeable batteries need of a special testing procedure, to reduce time and costs associated with the battery substitution. So, the decay of vehicle's performances during the discharge was explored by coupling three different tests (energy consumption, gradeability and acceleration) in a single test. The performances are measured in consecutive periods of the battery discharging process, by alternating these tests with a discharge at constant speed (50 km/h). Time intervals and speeds (power) are chosen so that the discharged capacity is about 10% of the total battery nominal capacity, 20 Ah. Table A.6 reports only the results of a partial test, because the cooling system failure prevented to complete the test.

First discharging at 50 km/h: 0→14,252 km; 0→5,01 kWh

1) Energy consumption on urban cycle

Table A.6: Energy consumption (from the battery) test results for Carica

Cycle	Distance	Energy consumption
1-4	15,259 km	2,5 kWh
1-2	16,286 km	2,75 kWh
1-3	17.290 km	2,99 kWh
1-4	18,304 km	3,44 kWh

2) Acceleration

Best time	14,40 sec

3) Gradeability, 4% and 12 %

O.K.

Appendix B Zn-air BEV Test: Marbella

B1 The test vehicle

Table B1 summarises the main specifications of the Marbella EV.

Table B1: Description of the vehicle under test.

Vehicle Type	Van (2 seats)
Manufacturer	Seat
Model	Marbella (modified by Edison)
Plate number	TO 09341N
Kerb Vehicle weight with driver	1050 kg

B2 Test results

B2.1 Energy consumption at various speeds

The test has been carried out at the ambient conditions listed in Table B2.

Table B2: Test ambient conditions

Ambient temperature	**Minimum night temperature**
13 °C	13 °C

The energy consumption test has been performed for comparison even at various constant speeds. The test allows the determination of the vehicle consumption from the battery, at various speeds in one discharge cycle. Table B3 shows the test results that are plotted in Figure B1.

Table B3: Energy consumption (from the battery) at various speeds

Speed km/h	**Energy consumption Wh/km**
10	112
20	89
30	100
40	90
50	91
60	106
70	126

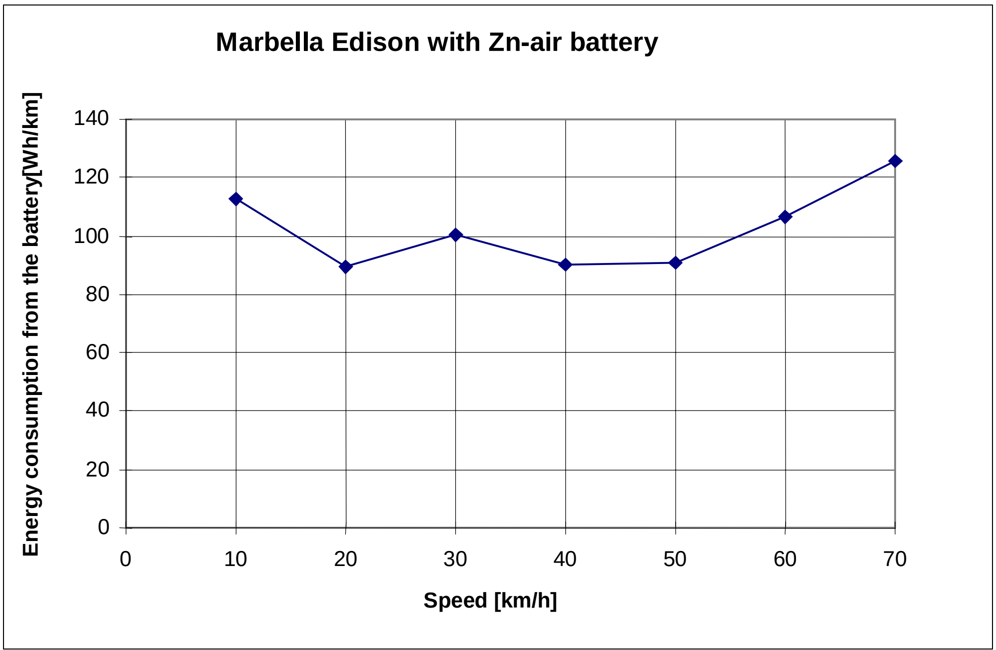

Figure B1: Energy consumption (from the battery) at various speeds

B2.2 Complete discharge of the Zn-air battery

The non- electrical rechargeability of the Zn-air battery required to modify the test sequence normally applied to conventional electrically rechargeable batteries in order to obtain various data and information during a complete discharge test.
A special full discharge test was then defined to measure energy consumption during ECE-15 driving cycles, acceleration, gradeability at 4% and 12% at various DOD. The vehicle has been driven, between each group of tests, at constant speed of 60 km/ in order to discharge the battery of 20 Ah (10% of the useful capacity, which is 80% of the C_5 nominal capacity).
Tables B4 and B5 report some of the test results.
The battery arrived at ENEA not fully charged (discharged only 10 Ah).

Table B4: Constant speed test data

Distance/cycle km	Energy/cycl ekWh	Cumulative distance km	Cumulativ e energy kWh
11,000	1,220	11,980	1,264

Table B5: Complete discharge test results

Cycle # ECE15	km/ cycle	kWh/ cycle	V_{max} 4% km/h	V_{max} 12% km/h	t_{0-50} km/h sec	Ah at Constan t speed	Cumulative * km	Cumulative kWh
1	4,041	0,575	48,8	22,3	14,23	20,0	38,857	5,03
2	4,044	0,636	46,2	20,8	16,64	20,1	60,961	8,42
3	4,041	0,645	43,3	18,0	17,63	20,1	85,658	11,73
4	4,102	0,590	27,9	13,3	21,42	20,2	109,42	14,85
5	4,108	0,620	40,1	16,3	21,75	20,0	136,59*	18,57
6	4,094	0,640	33,6	15,6	24,94	9,4	147,62	20,69

*It includes 2,916 km driven for testing Edison instrumentation.

The overall travelled distance during the discharge test is 147,62 km. The 18 acceleration tests (from 0 to 50 km/h) are not included in this value.
The overall performances of the battery during the discharge test were the following:

- Energy consumption of the battery: 20,69 kWh
- Discharged capacity: 208,15 Ah

The average specific energy consumption (from the battery) of the vehicle was 140 Wh/km.

After the test, Edison further discharged the battery at constant power (7 kW per 40 minutes) with a cycler, with a delivery of 4,6 kWh. Therefore, the total energy consumed before, during and after the test was **25,29 kWh** (84,3% of the nominal capacity).

Appendix C Proposal for an Annex F to EN 1986-1

Annex F (normative)

Determination of the energy consumption of an electrically propelled road vehicle powered by a non-electrically rechargeable battery (e.g. zinc-air or aluminum-air).

F.1 Introduction

The purpose of this annex is to define the method of measuring the energy consumption of a vehicle powered by non-electrically rechargeable when tested on a chassis dynamometer.

F.2 Reference conditions

Testing shall be performed according to the test sequence described in 4. The step described in There is no modification of the test sequence and vehicle preparation.

F.3 Test procedure modifications

The test procedure for measuring the energy consumption described in 5.5 shall be modified in the following way:

- *Initial charge of the battery (CANCELLED*);
- **Application of the test sequence as defined in 4.1;**
- *Charge of the battery (CANCELLED);*
- Calculation of the energy consumption.

The bold step remains partially unchanged as in 5.5.2. In fact during the test sequence, the current (or the capacity) delivered by the battery shall be measured. This type of measurement is not provided in the procedure for pure electric vehicles. The accuracy of the current (or capacity) measurement should be ± 1%.

F.3.1 Initial charge

The non-electrically rechargeable batteries cannot be recharged by the mains, but are normally mechanically rechargeable, that is, the spent electrodes are substituted by fresh ones. This step of the test sequence is then omitted. Consequently, for the test of these specific vehicles 5.5.1 and 5.5.3 cannot be applied.

F.3.2 Calculation of the energy consumption

The energy consumption E_{NRB} of an electric vehicle with a non-rechargeable battery is defined by the formula:

$$E_{NRB} = \frac{E_C}{d}$$

where E_C is the electric energy consumed at regeneration plant for regenerating the spent electrodes and d is the distance travelled in km recorded during the test. The value E_C does not include the energy consumed for handling the electrodes.

- The calculation of the energy consumption from mains E_{NRB} requires various steps:
  - The amount of metal (e.g. metallic zinc in zinc-air batteries) consumed can be determined by using the electrochemical equivalent of the discharged capacity. The calculation is based on the following equation:

$$Zinc \cdot Weight = \frac{C \times NC}{EE} \qquad (1)$$

where C is the battery capacity measured during the test, NC is the number of cells composing the entire zinc-air battery and EE is the electrochemical equivalent for the zinc (820 Ah/kg_{zinc}).

- The regeneration process of the zinc oxide in zinc-air requires 2,32 kWh/kg (this value only represents the Edison calculation for a defined regeneration plant of zinc oxide). Consequently, the energy consumption from mains is obtained by multiplying the consumed metallic zinc by the regeneration energy consumption:

$$E_C = \text{Zinc.Weight} \times \eta_{zinc} \qquad (2)$$

where E_C is the energy required for converting the spent zinc in metallic zinc and η_{zinc} is the conversion efficiency to obtain 1 kg of metallic zinc and is plant specific (the value to be used should be certified by the battery manufacturer and indicated in the battery).

MANAGEMENT TOOL for the ASSESSMENT of DRIVELINE TECHNOLOGIES and RESEARCH

MATADOR

Contract JOE3-CT97-0081

Task 2:

Testing methods for vehicles with conventional and alternative drivelines

Subtask 2.14

Self-discharge and heating energy

ENEA – Advanced Energy Technology Division

20 July, 2000

by

Mario Conte (ENEA)

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Energy Conservation and Utilisation

Nomenclature

Abbreviations

BEV	Battery Electric Vehicle
C	Battery storage Capacity in Ah measured or calculated during test sequence.
C_5	Battery storage Capacity in Ah. The subscript **5** indicates the discharge time in hours to completely discharge the battery under predefined conditions.
DOD	Depth Of Discharge. It is the ratio in percent of the capacity in Ah divided the nominal capacity of a battery
ΔSOC	The variation of State of Charge, calculated between the final SOC and the initial SOC. Initial and final refer to the starting and the completion of a test sequence.
E_{zinc}	the energy required for converting the spent zinc in metallic zinc
EN	European Norm
EUCAR	European Car Research Committee
FCEV	Fuel Cell Electric Vehicle
HEV	Hybrid Electric Vehicle
HSFW	High Speed FlyWheel.
IKA	Institut für Kraftfahrwesen - Aachen.
LSFW	Low Speed FlyWheel.
Macrocycle	Definition of a driving/test cycle including test sequence, standstill and charging phase
Ni-Cd	Nickel-Cadmium Battery
NiMH	Nickel-Metal Hydride Battery
Ni-Zn	Nickel-Zinc Battery
OCV	Open circuit voltage
SAE	Society of Automotive Engineers.
SOC	State of Charge. It is given in percent and is equal to 100-DOD.
UPS	Uninterruptable Power Systems.
USABC	United States Advanced Battery Consortium
VRLA	Valve Regulated Lead- Acid batteries.

Contents

1 Introduction

In the Task 2 activities of the Matador Project, storage systems (electrochemical batteries, supercapacitors and flywheels), used in electric and hybrid vehicles (BEV and HEV), may have a high self-discharge or may work at high temperatures. In both cases, the amount of energy implied may be high and common to many storage technologies (batteries, supercapacitors and flywheels). In present standards EN 1986-1 and prEN 1986-2 these sources of energy losses are not quantitatively considered and then are not included in the calculation of the overall energy consumption. These standard procedures only oblige to maintain the storage systems at their operating temperature, neglecting the energy spent to accommodate such condition.
Furthermore, the current test cycles are substantially time-limited and rigidly performed, giving interesting opportunities for relative comparison of similar technologies, but discarding some dynamic aspects, as self-discharge and real duty cycles. Investigation of the other energy losses can give interesting data for comparing technologies, proposing modified testing methods and taking decisions on the real impacts of new transport technologies.
All in all, Sub Task 14 of Task 2 had the scope to investigate the effects of self-discharge and heating of storage systems, that are mainly related to the driving cycles/patterns (use conditions) per day and/or per week, and analyse possible solutions to be proposed for testing methods. Experimental tests of components and vehicles have been performed or used to evaluate the amount of various energy losses. Self-discharge and heating energy losses are an intrinsic property of various storage systems (batteries, supercapacitors, flywheels). The amount of energy losses normally depends on operating conditions (external temperature, state of health) and is time-dependent. For homologation and comparative assessment, the losses depend on the test condition and the driving cycles: the duration of standstill times before, after or between tests may significantly modify the amount of energy consumption. For the same storage, the longer standstill times, the higher is the energy consumption, exactly in the same working. For example, the standstill time between the charging phase and the testing phase surely affects the final energy consumption.

The work performed in this Subtask has been to investigate the amount of energy losses (self-discharge, heating energy) for various storage systems, the existence of methods for accounting them, and then the possibility to propose measurements or even calculation procedures to incorporate in testing methods. In addition, some considerations have been made on possible effects of changing battery efficiency of high-energy batteries with the depth-of-discharge (DOD) on the energy consumption for BEVs and, consequently, on the driving cycles (2 or 7 in standardised test sequences). This Subtask report is divided in three parts, each one referred to the specific topics of self-discharge, heating energy and high capacity batteries. Conclusions are drawn and recommendations given about when and how take into account and measure energy losses or variation of efficiency in modified testing procedures.

2 Self-discharge

This process normally indicates the spontaneous losses of capacity (or even energy) of a storage system due to local actions (irreversible chemical reactions for electrochemical batteries, side reactions or static losses in supercapacitors and mechanical friction or electromechanical losses in flywheels). Two main parameters are to be considered in testing procedures for the determination of the energy consumption: *the amount of the losses* and *the time constant* during which the capacity or energy is lost. Such parameters may have a strong influence on the driving cycle and the measurement accuracy.

2.1 Battery self-discharge

The self-discharge is a process by which the available capacity of a battery is spontaneously reduced by undesirable chemical reactions [1][2]. If the capacity or energy loss includes the electrical leakage between cells, it is called charge or capacity retention. As it is evident by these definitions that the thermal energy needed to heat the battery at its operating temperature is not included in the self-discharge, but should be considered in energy losses due to heating energy (or, preferably, thermal conditioning energy). USABC and EUCAR Battery test procedures include in Stand and in Self-discharge tests all the losses (including heating energy) during open-circuit standing time (period during which the vehicle is not used). According to the definition in this document, the heating energy is not considered in self-discharge losses and, consequently, Zebra battery has no self-discharge but only heating energy losses. Apart from specific tests for components, as mentioned above, the self-discharge losses are not considered in vehicle testing.

2.1.1 Lead-acid batteries

The self-discharge parameters vary with the type of the batteries and the working conditions. Figure 1 shows the self-discharge curve of a lead-acid battery (OPTIMA Yellow TOP 52Ah) in function of the cycle number, that is the decline of battery performances.

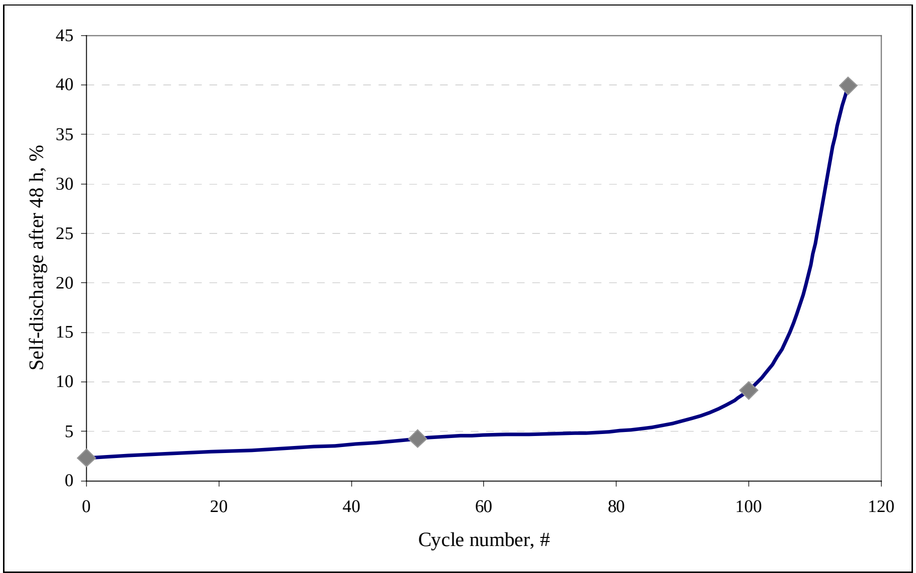

Figure 1: Self-discharge of a lead-acid battery vs. cycle number at RT [3]

The self-discharge has been measured after a fixed number of charge-discharge cycles (0,50, 100, and 115), by a complete test sequence, which considers the C_5 capacity before and after a rest time of 48 hours. It is apparent in Figure 1 that even if the initial capacity losses due to self-discharge is very limited (about 0.05%/h, assuming a linear behaviour), after only 100 macrocycles it becomes about 0.2 %/h and at the end of life (after 115 macrocycles) about 0.8 %/h.
This situation is practically valid for any lead-acid battery type (vented or sealed with starved or flooded electrolyte). Of course, the absolute values are extremely varying depending on the design, electrolyte concentration, grid types and working temperature. Lead-acid batteries with low antimony and maintenance-free designs may have a self-discharge in the range of 10-30 %/year.

2.1.2 Nickel-cadmium

Self-discharge trend of such batteries depends on temperature and stand time. For example, the capacity loss at 45 °C is almost three times higher than that at 25 °C. Experimental results for different battery types show that the charge retained depends on the OCV stand time (time constant) in a semilogarithmic relationship:

$$\text{Retained charge}\,(\%) = 100 \times e^{-D/tc}$$

where D is the number of days and t_c is the time to retention, depending on the storage temperature, of 36.8% of initial capacity. Table 1 presents the self-discharge of the same battery at room temperature (RT = 23 °C) as a function of stand time, whereas Figure 2 shows the self-discharge of a SAFT Ni-Cd battery for EV applications (STM-5 200).

Table 1: Self-discharge of a Ni-Cd at RT [5]

Capacity Loss (% of nominal capacity)	Stand time (Days)
7	10
10	20
18	30

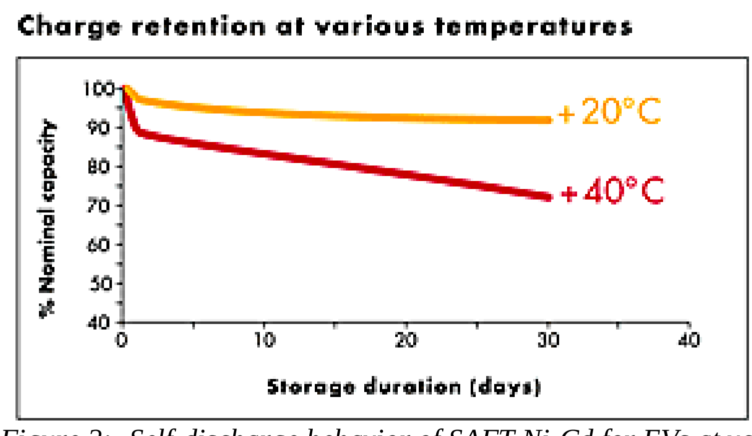

Figure 2: Self-discharge behavior of SAFT Ni-Cd for EVs at various temperatures

It is apparent that the storage temperature significantly affects the self-discharge rate, but in any case the self-discharge is limited to a few percent in a time frame lower than 1 day.

2.1.3 Nickel-metal hydride batteries (NiMH)

This system, derived from Ni-Cd system, has a self-discharge behavior quite similar to that of Ni-Cd, but the causes are completely different. The involved phenomena are mainly related to the reaction of hydrogen with the positive electrode and the slow decomposition of both electrodes: these processes are completely reversible [1]. The rate of self-discharge still depends on temperature and storage time: an increasing temperature increases self-discharge rates. Figure 3 and Figure 4 show the charge retention of two different NiMH batteries: Figure 3 refers to a GM-OVONIC NiMH [5][6] and Figure 4 to a SAFT NiMH.

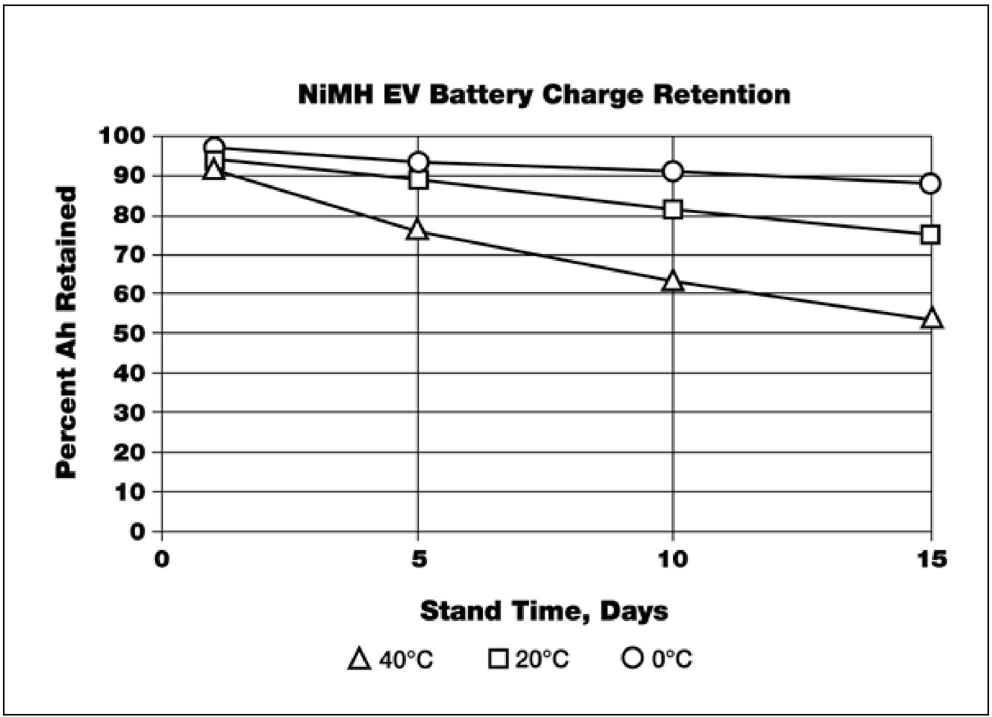

Figure 3: GM-OVONIC NiMH charge retention curve vs storage temperature [6]

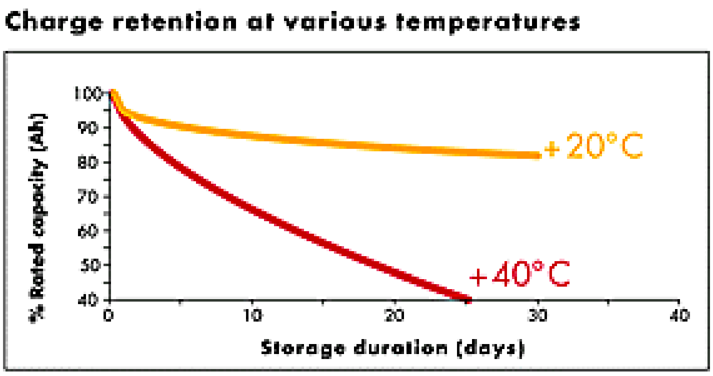

Figure 4: SAFT NiMH self-discharge at various temperatures [7]

A direct comparison of Figure 4 with Figure 2 clearly demonstrates the greater self-discharge rate of NiMH batteries with respect to a Ni-Cd of the same manufacturer. In both cases, the self-discharge remains limited to a few percent in a short time (less than 1 day).

2.1.4 Lithium Batteries

Lithium batteries are available and under development in a variety of types, which can be roughly classified in two big categories: with metallic lithium and with lithium alloys or lithiated carbon as anode. For the purpose of charge or energy loss determination, currently lithium-metal rechargeable batteries work at a temperature higher than 60 ° C, when polymer electrolyte are used [8]. The other types, normally called lithium-ion or rocking chair, are able to work at RT. The first type requires insulation systems to limit heat losses (this part will be treated in the paragraph on heating energy), while the latter comes with thermal management system for smoothing external temperature variations.
The lithium metal polymer type cell is very stable thermally and chemically, with practically 100% of coulombic efficiency: the coulombic (or Ah) efficiency is the ratio .of the output of a battery, in Ah, to the input to restore the initial SOC. The self-discharge resulted very low in stand test, according to USABC procedures, never exceeding 0.75% per day only in the first two days [8]. Figure 5 shows the voltage curve with no self-discharge after the first two days.

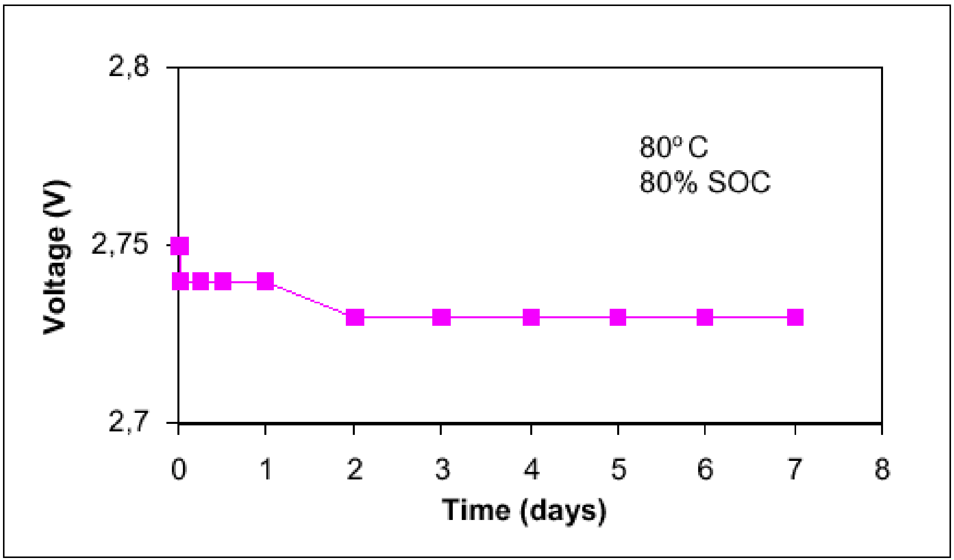

Figure 5: Voltage curve during stand test [8]

The situation is slightly worst for lithium-ion systems for which charge losses due to self-discharge can be higher than 10% per month.

2.2 Supercapacitors self-discharge

The self-discharge of a supercapacitor considers the decrease of voltage and, consequently, the associated energy when it is full charged at working voltage and then open-circuited. This value is not to be confused with the Inflow or Leakage Current, which takes care of internal dissipation during on-load operation and then causes a reduction of efficiency. Figure 6 presents the results of a self-discharge test, carried out at ENEA Laboratory, at various operating temperatures on a PANASONIC supercapacitor [9].

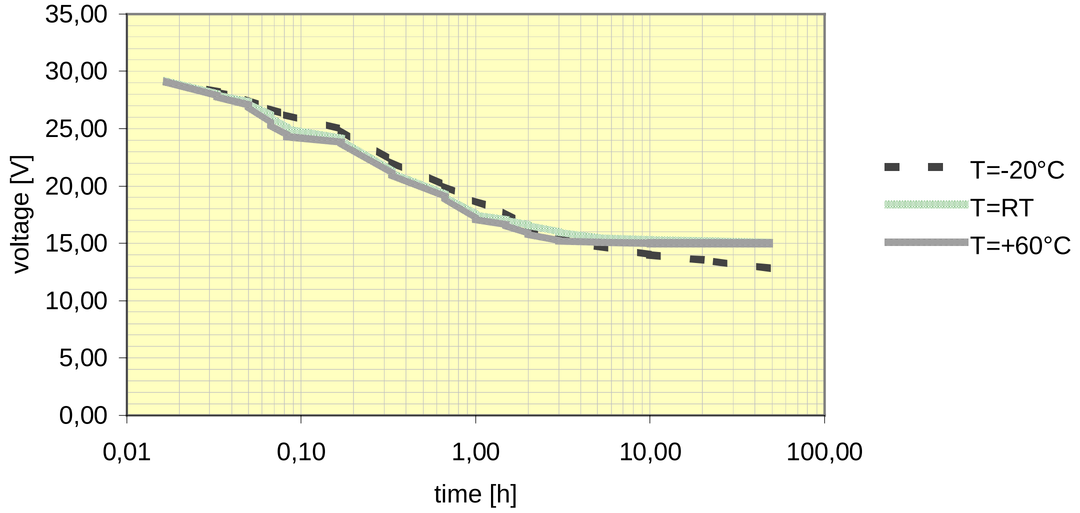

Figure 6: *Voltage decrease of a supercapacitor at various temperatures as a measure of self-discharge*

The decrease of voltage (V_{72h}) experienced after the device is monitored for 72 hours, as an indicator of the extent of the occurrence of non-ideal energy storage/transfer mechanisms. The results of the tests for two double layer (carbon-based) supercapacitors are given as a percentage:

$$S\%(1500F) = \left(1-\frac{V_{72h}}{V_W}\right)\cdot 100 = 27.3\%,$$

$$S\%(800F) = \left(1-\frac{14.873}{20.5}\right)\cdot 100 = 28.4\%$$

Based on these results, the self-discharge energy loss factor (SDLF) should be calculated from the relationships [10]:

$$SDLF(1500F) = \left[1-\left(\frac{V_{72h}}{V_W}\right)^2\right] = 0.467$$

$$SDLF(800F) = \left[1-\left(\frac{14.873}{20.5}\right)^2\right] = 0.473$$

where V_{72h} is the open circuit voltage measured after 72 hours and V_w is the initial working voltage. It is apparent how can be significant the self-discharge loss for long standstill time. On the other side, the vehicle designs with supercapacitors normally consider a small energy content and a high power capability for the supercapacitor subsystem, greatly limiting the direct energy contribution to the overall consumption of the vehicles.

2.3 Flywheel self-discharge

The energy can be mechanically stored in a flywheel (mechanical battery) by converting electrical energy in kinetic energy. The kinetic energy is accumulated in a rotor (flywheel) spinning at very high speed (up to 100.000 rpm). The main cause of energy losses is due to the mechanical friction of the rotor, which can be eliminate by putting the rotating system in a vacuum chamber and suspending it in the vacuum space with supporting bearings. The most advanced flywheels are electromechanical systems with magnetic bearings that strongly minimise losses. For a flywheel developed under EU Projects, when supplying maximum power and rotating at 60,000 rpm, the overall loss has been estimated in about 110 W [11]. The AVCON, Advanced Controls Technology of California, claimed that the energy stored in a flywheel with magnetic bearings during idle time is reduced less than 1% over a ten-hour period [12][13].

2.4 Preliminary remarks on self-discharge (excluding thermal losses) issue

Table 2 lists self-discharge characteristics of major candidates for energy storage in electric and hybrid electric vehicles.

Table 2: Self-discharge of storage systems at RT, adapted from [1]

Storage system	**Self-discharge (%) per month ***
Lead-acid	3
Nickel-cadmium	30
Nickel-metal hydride	30
Nickel-zinc	15
Zinc-bromine	12-15
Zinc-air	---
Sodium-nickel chloride	---
Lithium metal polymer	< 0,75 per day
Lithium ion	> 10
Supercapacitors	≈ 30 per 3 days
Flywheels	< 3 per day
USABC Mid-term goal	*<15 (48h)*
USABC Long-term goal	*<15*

* For the batteries, the self-discharge rate refers to the initial charge or capacity and for the others refers to the initial energy content.

Data about self-discharge losses (or even charge retention) are surely an area of concern with many EV storage technologies. Standard test sequences only take 39,3 min (2 complete NEDC cycles) or 91 min (7 Urban ECE cycles). Self-discharge becomes a concern only when a vehicle stands for an extended period of time between cycling. For electric vehicle externally rechargeable (both BEV and HEV), the energy losses for self-discharge are included in the energy consumption measured according to the actual testing procedures, because it is anyhow measured during recharging. Meanwhile, there are two considerations for BEV testing methods, which can justify the need of a separate measurement of self-discharge losses instead of a calculation/correction procedure:

1. The self-discharge losses depend on storage technology, temperature, working conditions and age, and then can make inaccurate the comparative assessment of alternative drivelines in real operating conditions. The error varies with the storage technology.

2. The calculation of energy losses from charge or capacity self-discharge is not straightforward. Only for flywheels and supercapacitors the energy losses are directly determined by self-discharge percentage, while for batteries the energy losses cannot be simply calculated. In practice, the supercapacitors self-discharge is measured by measuring the variation of working voltage

For HEV testing methods, apart from efficiency variations due to the SOC and current rate [15], the determination of ΔSOC can be further affected by the self-discharge losses. In fact, the ΔSOC corresponds to the variations of the absolute values of SOC at beginning and at the end of the test sequence. Self-discharge losses are part of the energy consumption and can be accounted for only in the case of externally rechargeable HEV, because the recharging from mains allows the calculation of the real SOC. The use of Ah-counting for calculating ΔSOC does not include the self-discharge losses in calculated values, which are only based on the measurement of the charge received from or delivered by battery during the test sequence: the final value of SOC may be modified because of the self-discharge losses.
For sake of comparison, self-discharge losses have been determined in UPS applications, when the storage systems are fully charged. The idle (self-discharge) losses are in stand-by mode and are reported in Table 3 per unit energy stored in the system [16].

Table 3: Self-discharge losses per unit stored energy of storage systems

Storage system	**Self-discharge Losses per Wh**
Low speed flywheel (LSFW)	2,2 W
High speed flywheel (HSFW)	1,2 W
Supercapacitor	0,026 W
Valve-regulated lead-acid (VRLA) battery	0,023 W

From the data in Table 3, it is possible to estimate the error occurring when self-discharge loss is not measured or not included in the energy consumption during a specific driving range.

3 Heating Energy

The thermal heating of batteries best operating above the ambient temperature pose different problems in testing EVs and HEVs. The first problem is related to the determination of the time needed for having the battery fully operational, which affect the preparation of the test and the impact of various driving cycles. A second problem regards the amount of energy needed to heat the battery before starting the test, which is normally not account for in present testing procedures. Finally, a third problem, similar to the self-discharge, is related to the thermal losses during standstill, which reduce battery capacity when not connected to the mains. These problems have been treated separately and only referred to the sodium-nickel chloride (Zebra) and Lithium metal polymer batteries, presently available systems.

3.1 Zebra battery

The Zebra battery works at an operating temperature between 270 and 320 °C. The system is contained in a sealed and insulated vacuum case. The system is electronically controlled by a Battery Management System (BMS) that controls thermal and electrical behaviour of the system. The heat capacity of the system is high as well as the thermal insulation [16]. As a consequence, the time that is required to freeze and thaw (cooling and heating) the battery is very long. Figure 7 presents the result of thermal cycle testing performed at ENEA under an EU contract. The test results showed that the complete thermal cycle duration varied from 7 to 12 days, depending on the state-of-charge of the battery and its contribution to the thermal conditioning. It is evident in the curve the phase transition from liquid to solid occurring at about 150 °C.

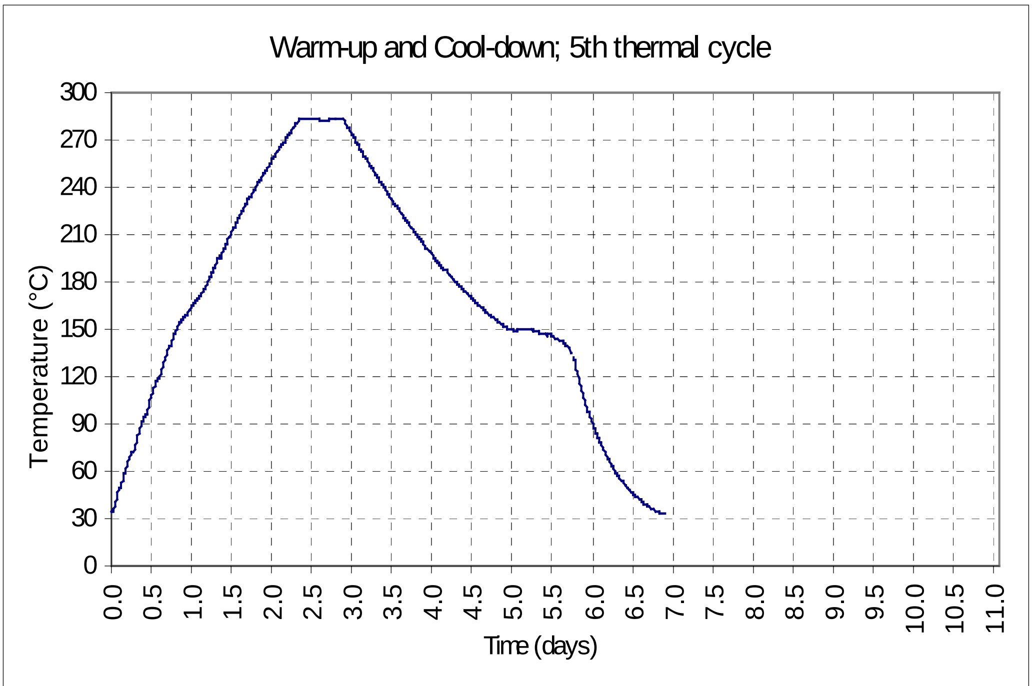

Figure 7: Thermal cycling of a Zebra battery

The amount of energy in the heating process has been measured by IKA in a comparative analysis of driving cycles with a VW BORA BEV [17]. Figure 8 shows energy consumption for the VW Bora with and without heating energy. There is no doubt from the range test data (by driving the EV up to the complete discharge of the battery over a standardised driving cycle) that the longer the test, the smaller is the effect of heating energy on the overall energy consumption (the initial one used for the first heating of the battery).

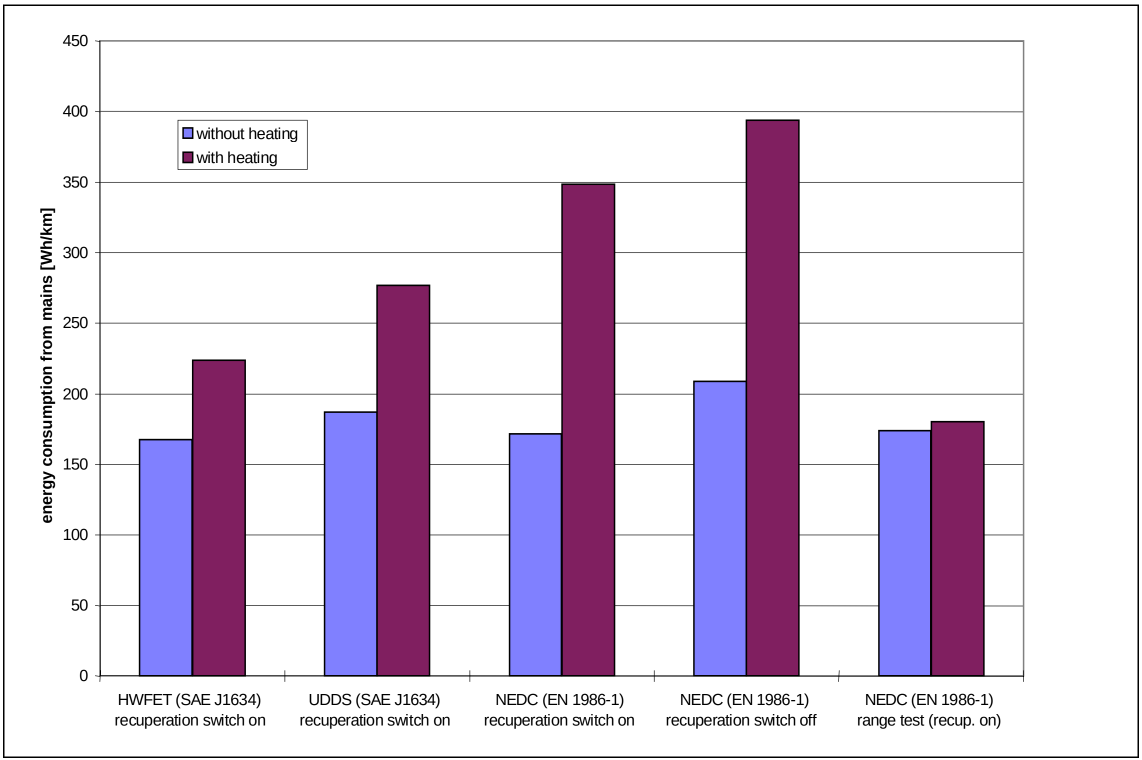

Figure 8: IKA Data for a VW Bora with Zebra battery [17]

Table 4 derived from [17] shows the effect of idle time (during driving cycles) and the test sequence on the energy consumption. In the data presented the heating energy only refers to the initial energy spent to warm up the battery from ambient temperature to the internal working temperature (about 300 °C). Heating energy substantially contributes to increase energy consumption up to more than doubling the energy consumed for moving the EV. In the last column, the energy consumption after a range test shows that the longer the travelled distance, the shorter is the energy consumption per travelled km. From the test results, it is possible to conclude that only when the Zebra battery is standstill for long periods the heating energy significantly affects the specific energy consumption.

Table 4: Experimental data for VW BORA about energy consumption with and without heating energy over various driving cycles

Cycle/procedure / Test data	HWFET	UDDS	NEDC recuperation switch on	NEDC recuperation switch off	NEDC range test
Distance driven, km	33,992	24,054	22,129	22,049	177,458
Cycle duration, sec	765	1372	1180	1180	9450 (estimated)
Total idle time, sec	5	259	293	293	2358 (estimated)
AC energy consumption (without heating), Wh/km	163	187	172	212	174
AC energy consumption (with heating), Wh/km	217	277	348	394	180

The thermal loss during standstill is able to cool down the battery. In normal operation, thermal losses are most compensated by reaction heat and Joule's effect, while in operational stand-by an electrical heating system keeps warm the system by discharging the battery with electrical heaters. This heat loss depends on the battery size and is practically insensitive to the variation of ambient temperature. Zebra data sheet shows that the heat loss varies between 80 W and 150 W. In relative terms, these values have been made consistent with the USABC goal of less than 3.2 W/kWh (equivalent to a self-discharge of less than 15% in 48 hours). The Zebra Z11 has a measured thermal loss of 5,5 W/kWh [16].

3.2 Lithium metal polymer battery

The lithium metal with polymer components currently under development operate at temperatures between 60-90°C. The present designs use an insulated case and a battery management system. The only available complete data are those supplied by the consortium Hydro-Quebec and 3M [18]. The energy for this thermal control is provided by the battery or from an external source when the battery is plugged-in for recharge. Conventional insulation is added around the pack, minimising the energy loss. A full-sized 40 kWh pack loses around 200 W for a 60°C temperature gradient from the battery operating temperature to ambient conditions. During a three-hour drive, this amounts to only a 1,5% energy loss. During a twenty-four hour stand, this amounts to a 12% energy loss (or equivalent to a 35 km range loss over a total range of 300 km). This energy loss can be recovered in less than 45 minutes at a six hour charge rate (the battery is recovering roughly 50 km range per hour of charging). Occasionally, the end-user will leave the vehicle unplugged for a long period of time. The pack can then be put in sleep mode or it can be automatically switched-off after a designated standstill period depending on the battery SOC (for example about 48 hours). If the ambient temperature is around 15°C, the battery pack will then slowly cool down to 20°C in about 36 hours. Heat-up from this temperature can be achieved in less than two hours using the battery energy (less than 10%) or in less than one hour from an external energy source, such as the charging unit. The heat-up mode can be easily programmed [18].

3.3 Preliminary remarks on heating energy issue

Thermal losses of high temperature batteries may significantly impact the measurement of energy consumption in BEVs and even in HEVs.

1. The thermal energy required to warm up the batteries can be neglected only when long test runs without unplugged standstill periods are considered (range tests or continuous operations).
2. The heating energy, when measured, can be up to 50% of the overall energy consumed in a standard test (see Table 4 for VW Bora with various driving cycles).
3. Thermal losses are small for Zebra and Lithium batteries, but in 48 h may reduce the battery energy content up to 15% (goal of USABC). Presently up to 40-50% of the energy consumed by a BEV with a Zebra battery can be due to the heating energy; whereas prototypes of lithium batteries may loose in 48 h up to 25% of the stored energy.
4. Battery losses normally depend on the configurations and construction parameters, which do not allow defining general calculation procedures, suitable for any high temperature battery. A possibility could be the use of battery test data, normally available from battery test procedures (e.g. battery tests of USABC and EUCAR). In such procedure stand (or self-discharge) tests are carried out to determine the battery capacity loss after 2 days or 30 days. These values (in absolute and percentage) can be made available for calculating battery-by-battery the effect on energy consumption.
5. Another source of significant error is the variability in existing standards (EN 1986-1) of the time duration between the end of charge and the start of driving cycle. EN 1986-1 states that the test sequence on the chassis dynamometer must start within 4 h from the battery disconnection from mains, whereas SAE J1634 fixed this time in 1 h. This problem is common to all the batteries with high heating or self-discharge losses.

4 High capacity batteries

The last technical issue, not included in Subtask 14, regards the possible variation of BEV specific energy consumption, measured with current standard EN 1986-1. The test procedure for the measurement of energy consumption considers only two test sequences, mainly related to the vehicle performances: 2 complete NEDC cycles (including extra-urban part) or 7 ECE cycles (made of 4 urban microcycles). The total distance travelled is, respectively, about 22 km for the first sequence and about 28 km for the other. If we compare the energy content of conventional batteries (e.g. lead-acid) with high capacity batteries (Lithium, Zebra, Zn-air), equipping the same reference vehicle, the proposed test sequences discharge differently the battery. Table 5 compares performance (only indicative losses and efficiencies not included) and test conditions for various batteries used in a hypothetical reference vehicle.

Table 5: Indicative comparison of performances of a reference vehicle with 300 kg of different batteries

Performances	Lead acid 35 Wh/kg	Ni-Cd 50 Wh/kg	Ni-Mh 70 Wh/kg	Zebra 86 Wh/kg	Li-ion 120 Wh/kg	Zn-air 180 Wh/kg
Vehicle range, km	60	90	130	160	220	330
DOD Test Sequence 1, %	35	22	16	13	10	7
DOD Test Sequence 2, %	48	30	21	18	13	9

With the exclusion of mechanically rechargeable zinc-air batteries (the regeneration energy is proportional to the spent zinc), the charging efficiency of electrochemical batteries depends, among other factors, by the DOD. The rough calculation in Table 5 can be also applied to different vehicles with the same battery type but with different capacities. Experimental results from IKA test on VW Electric Bora (energy consumption test, 172 Wh/km, compared with range test, 174 Wh/km) show that there is no significant variation of energy consumption for Zebra battery only related to energy efficiency during charge. In fact, Zebra batteries, as expected, have a coulombic efficiency, and energy efficiency, practically constant [17] with the DOD. For lead-acid and alkaline batteries, the variation of the efficiency with DOD is more significant. Results from HTA [19], IEA [20] and ENEA [21] tests show variations of energy consumption under different testing conditions giving varying DODs.

Figure 9 presents test results for two different BEV and batteries: IKA data from VW Electric with Zebra battery and ENEA test data with Panda, powered by NiMH battery. Data refers to the results of test sequences applied according to EN 1986-1: the energy consumption is determined by recharging the batteries from mains after about 22 km and more than 100 km (range tests) of travelled distances.

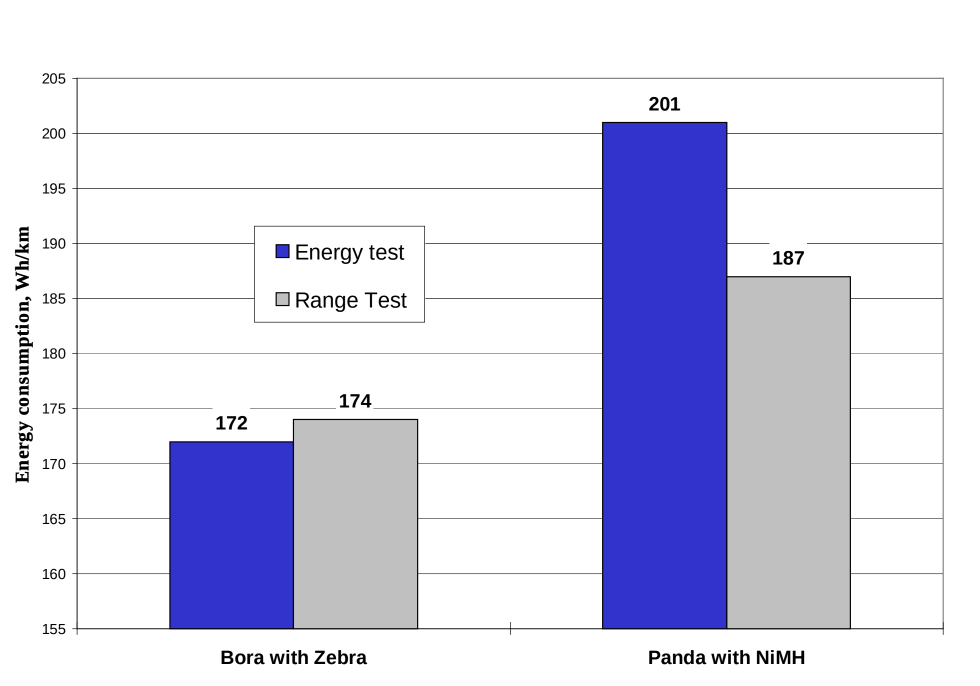

Figure 9: Energy consumption of various BEV at various DOD

There is no doubt that the energy consumption depends, for NiMH, on the DOD at the end of the test sequence. The results presented are representative of extreme conditions, due to the fact that the alkaline batteries (Ni-Cd and NiMH) have the lower efficiency, while Zebra battery has the highest one.

No clear data are available for lithium batteries in this direction, even if the battery presents a high coulombic efficiency: a behaviour similar to that of the Zebra battery can be expected. Further analysis and investigation are needed on this aspect to more quantitatively evaluate the amount of the variations.

A possible modification to current BEV test sequences would be the determination of the energy consumption from the mains, even when a range test is performed: EN 1986-1 does not include the measurement of the charging energy from mains at the end of the range test. A combination of energy consumption achieved with energy and range tests may avoid overestimating or neglecting charge efficiency variations, depending on DOD.

For comparative assessment, the impact of charging efficiency over energy consumption will, of course, depends on the driving patterns, which are the real operating modes (the entire vehicle duties including, e.g., standstill, driving cycles, off operations) in opposition with driving cycles, which try to simulate the real world in a general, simplified manner. The recommendation could be to measure the energy consumption according to the driving patterns, independently on the DOD, and use, as a reference, the energy consumption measured at the end of a complete discharge of the battery.

5 Conclusions and recommendations

Problem definition

There are various energy losses during battery use, which may significantly affect energy consumption of BEVs and HEVs. Storage systems (electrochemical batteries, supercapacitors and flywheels) may have high self-discharge and/or may work at high temperatures. In all these cases, the amount of energy involved may be high, strongly dependent on the use of the vehicle (daily travelled distance, km/day, number of chargings per day or per week), and is not always accounted for in existing testing procedures. Furthermore, high temperature batteries require energy to reach the high operating temperatures. In general, all the energy losses occur during standstill periods. Three separate phases may be considered during which standstill periods, and related energy losses, may be present:

1. Initial battery heating to have the battery at its working temperature before starting the test;
2. Standstill periods before and after driving cycles; (charging, preconditioning and preparation and recharging);
3. Idle times included in driving cycles.

The amount of losses due to self-discharge and heating may significantly impact the energy consumption calculation in BEV and HEV, depending on the measuring conditions and test sequences. Currently, the dimension of such losses may vary from about 50% of the overall vehicle energy consumption (heating energy of $NiCl_2$-Zebra battery for short working time) up to about 45% of the store energy of supercapacitors and 3% for flywheels after 72 h.

Finally, another source of error in energy consumption determination is in BEV with high capacity batteries, suitable to improve up to 4-5 time the present ranges of BEV, which, during standard energy test procedures (SAE and CEN), are only shallowly discharged. The DOD (depth of discharge) reached at the end of the energy consumption test is below 20% with respect to other BEVs reaching up 40-50% of DOD. In such cases, the measured energy consumption may be affected by the variation of charging efficiency of batteries with DOD. This phenomenon is more significant for high-energy batteries with extremely varying efficiency with DOD, such as alkaline (Ni-Cd, NiMH, Ni-Zn) and lead-acid batteries. Experimental results have given variations in energy consumption of about 15% (dynamometer tests with a NiMH battery BEV) when the battery is discharged at 20% DOD or at 100% DOD. This variation is due to differences in charging efficiency with DOD, while similar tests performed with a BEV powered by a Zebra battery gave no significant variation of energy consumption, due to the high charging efficiency.

All these sources of losses, and then inaccuracy in energy determination, may have impact on testing methods.
The behaviour of high temperature batteries is representative for various problems:

1. The first problem is related to the determination of the time needed for getting the battery fully operational, which affects the preparation of the test and the impact of various driving cycles.
2. A second problem regards the amount of energy needed to heat the battery before starting the test, which is normally not account for in present testing procedures.
3. Finally, a third problem, similar to the self-discharge, is related to the thermal losses during standstill, which reduce battery capacity when not connected to the mains.

For self-discharge losses, further problems are:

1. the lack of a general relationship suitable for calculating the energy losses for any storage system; the limited availability of self-discharge data;

2. the large number of storage systems (batteries, supercapacitors, flywheels);
3. the impossibility to measure the energy remained in the battery when a non-externally rechargeable battery is used.

Finally, the variation in energy consumption values due to charging efficiency may require, depending on the battery type, a modification of the existing test sequence including at least two measurements at two different DOD.

Status of standard procedures

Existing standard test procedures do not specifically address the problems of self-discharge and heating energy losses. As mentioned above, the amount of losses depends on the duration of standstill in various moments of the test sequence. An analysis of CEN (EN 1986-1) and SAE (J1634) standard procedures for BEVs can be done in relation to the three phases of the test sequence identified: initial battery heating; standstill before and after driving cycles; idle time during driving cycles.

Initial battery heating and charging

Both procedures do not measure the energy spent to warm up the battery at its operating temperature. The heating process is included in the test preparation, also said preconditioning. CEN states that the test operator must follow the procedure recommended by the vehicle manufacturer to maintain the battery temperature in the normal operating range. SAE standard only stipulates that the battery shall remain on charge for the duration of soak and until the full charge of the battery is achieved: there is the obligation to verify the battery capacity (Ah) before starting testing. In SAE J1634 the charging period ranges between 12 and 36 hours before the start of the test, while EN 1986-1 does not state any specific duration for vehicle preconditioning. SAE standard requires that the soak and charging duration be recorded.

Standstill before and after driving cycles

After the vehicle, and the battery, is unplugged from mains and before starting the test, there is no measurement carried out in both existing standards. In addition, the same occurs at the end of the test before recharging the battery. In SAE J1634, there is an interval of 1 h available before the start of the test, whereas EN 1986-1 leaves a maximum of 4 h between the battery disconnection and the start of the test. A minor difference between the two standards after the end of test cycle and before recharging the battery: SAE has a flexibility of 1 hour, whereas CEN has only 30 minutes.
Combining the energy required during the initial heating with the energy losses due to battery temperature regulation (after unplugging the battery), the difference in charging and standstill times before and after test cycles gives place to high variations of energy consumption between SAE and CEN test procedures: measurements on the VW Bora with a high temperature battery (Zebra) have shown differences up to 9% (without initial heating energy) and up to 38% (with initial heating energy). This large discrepancy, partially depending on the driving cycles, but mostly related to test procedure, justifies the recommendation of a unified pre-test (and after test) procedure for both standards.

Idle time during driving cycles

The energy losses occurring during driving cycles are inherently related to the energy economy of the cycles. These losses (self-discharge and heating energy) during BEV tests are normally accounted for in present standards at the end of the test, when the battery is externally recharged from the mains. A problem may rise for non-externally rechargeable HEVs: present (draft) standards (CEN 1986-2 and SAE J1711) do not include any method for measuring losses from the storage systems (battery, supercapacitors, and flywheels).

High capacity batteries

Standard procedures for BEVs (CEN 1986-1 and SAE J1634) allow the measurement of energy consumption by driving a fixed number of defined driving cycles (2 or 7 in CEN and 2 or 4 in SAE). The different test sequences may be chosen alternatively and only SAE standard leaves the possibility to use one or more of them, which may allow the comparison of results from various test sequences corresponding to varying DOD. Both standards also have range tests, which aim to determine the overall range of a BEV over repeated standard driving cycles until the battery is fully discharged. At the end of the range tests, the energy consumption is not measured in CEN standard, whereas SAE standard leaves it optional. The combination of the two tests (energy consumption and range), if energy consumption is measured in any case, may be sufficient to take into account the variation of the measured values, without increasing complexity and costs of the test sequence.

Possible (studied) solutions and principal constraints for their application

There are various options investigated during the analysis of the self-discharge and heating losses of storage systems. The identified options all looked at determining the actual contribution of the energy losses on the energy consumption values and their impact on testing methods.

First of all has been ascertained whether it was possible to have *reliable and repeatable relationships* for self-discharge and heating energy losses of the various systems, which could be easily used for correcting the energy consumption values, by, for example, measuring standstill periods. The technological survey and analysis of current and future storage systems shows a variety of behaviours related to several technologies and configurations developed and produced. General relationships between self-discharge times and capacity losses are available only for a few battery types (Ni-Cd and NiMH) and for supercapacitors (in specific cases). For the other storage systems there are experimental data obtained in specific self-discharge tests.

Another possibility should be the measurement of energy losses from batteries (and other storage systems) separately from the vehicle. There are testing procedures defined by EUCAR and USABC for measuring such losses for batteries and supercapacitors, but there are not yet mandatory for component and vehicle manufacturers.

A third way could be the direct measurement of standstill losses during vehicle tests or to modify test sequence in order to include standstill time in a controlled manner: e.g. reducing time flexibility in all the test phases not included in the driving cycles. This option seems reasonable to avoid mismatching of present standards, in which different charging and preparation times are defined (see the subsection on *Standstill before and after driving cycle*).

For the case of BEV powered with high capacity battery, the only direct way to account for the energy consumption variation with DOD is to have two tests at two different DOD. A straightforward suggestion is to measure the energy consumption from the mains also during range tests and then compare them with the values from energy consumption tests. In this way, only a minor modification of existing standards would be required.

Homologation tests versus comparative assessment

The nature of energy losses, related to self-discharge and heating energy, might strongly modify the results of specific tests, particularly if they are aimed at homologation or comparative (technology) assessment. In general, such losses strongly depend on the use of the vehicle: e.g. km/day, number of parking hours far from charging stations and weekends included in the real service. The energy consumption for homologation purposes is based on the measurement during a defined driving cycle, including idle time typical of a continuous service. The discrepancy between CEN and SAE standards mostly depends on the use of different driving cycles, which also contain different idle times. For technological (comparative) assessment, it is much more representative to use real service duties that are called driving patterns (the entire vehicle duties including, e.g. standstill, driving cycles, off operation stops) in contrast to driving cycles, which try to simulate the real world in a general, simplified manner. In comparative assessment tests, energy losses during standstill are objectively part of the overall energy consumption of the specific technology used if they are included in a specific driving pattern. The proposal for both test procedures is to assure that all the energy consumption can be selectively and separately measured, and to limit as much as possible the time during which the vehicle behaviour is not recorded. The weight of standstill times in various driving patterns should be determined by measuring independently from the energy test the related losses (alternatively self-discharge or heating data, in W/kWh, for the specific storage systems should be supplied by the vehicle manufacturer). The calculation of the real energy consumption will then be weighted using the results from driving cycles and standstill tests.

Recommendations for testing methods

The possible solutions for accounting for energy losses or significant energy determination differences are a combination of *hardware* and *software* routes. The hardware routes have a larger impact on existing testing procedures (mainly, cost, complexity and duration), while the software ones will make easy adaptation of existing procedures or even a compromised utilisation of manufacturer data.

Recommendations for self-discharge and heating losses

A software recommendation to modify existing standard test procedure (CEN EN1986-1) is to strongly limit the time during which the vehicle is not measured and losses occur. The present flexibility of 4 hours in EN 1986-1 between test starting and vehicle unplugging from mains is not acceptable: 1 h is regarded as a good compromise and is also consistent with SAE J1634.

A hardware correction to EN 1986-1 may be to extend the measuring period also to the charging and soaking time and perform a new test: a specific self-discharge (or initial heating for high temperature batteries) test should be carried out separately from the energy consumption test. The proposal is to keep separated energy consumption during driving cycles from energy losses before and after driving cycles. In this way, it will always be possible to weigh the contribution of energy losses in any testing procedure (either for homologation or for comparative assessment). SAE J1634 already requires measuring battery capacity, soak and charge duration and energy consumption at the input (AC energy) and the output (DC energy) of the battery charger. The same data can be recorded even in the CEN EN 1986-1.

A temporary compromise (before the recommended revision of present standards) should be the use of experimental results (Ah or energy per unit of time), achieved by the application of EUCAR and USABC testing procedures for batteries and supercapacitors. Vehicle manufacturers, in collaboration with storage system manufacturers, may supply self-discharge and heating data along with vehicle data profile already required in present standards.

Recommendations for testing BEV with high capacity batteries

A software recommendation to modify existing standard test procedure (CEN EN1986-1) is to measure the energy consumption also during range test. The hardware suggestion is to use the same test sequence applied in energy consumption test: EN 1986-1 allows two test sequences in energy consumption measurement and only one in range test. In case the tests sequence applied in energy consumption test is different from that used in range test, another range test should be done to have the same discharge conditions. The calculation of the energy consumption could be referred to the DOD or at the specific variation among the two tests.

References

[1] D. Linden, “Handbook of Batteries”, Second edition, 1994.

[2] INEL, “USABC EV Battery Test Procedures Manual”, revision 2, DOE/ID-10479, 1996.

[3] “ENEA Test Report for EUCAR”, CONFIDENTIAL, 1999.

[4] SAFT Manual, “Accumulatori al Ni-Cd per applicazioni su veicoli elettrici ed ibridi - Accumulatori al Ni-Cd serie STM”.

[5] VARTA, “NiMH and Li-ion Batteries for Automotive Applications”, Special Report, September 1998.

[6] GM-Ovonic Brochure, “The NiMH Choice”, 1998.

[7] SAFT Brochure, 1998.

[8] C. St-Pierre et alii, “Lithium Polymer battery for electric vehicle and hybrid electric vehicle applications”, EVS-16, Beijing, 1999.

[9] ENEA Internal Report, 1998.

[10] F. Brucchi et alii, “Ultracapacitor tests for EV applications: introduction of new equalisation coefficient”, EVS-16, Beijing, 1999.

[11] P. Mason et alii, “Flywheel peak power buffer for electric vehicles”, EVS-15, Brussels, October 1998.

[12] AVCON Brochures, 1997.

[13] G. Anerdi et alii, “Technology potential of flywheel storage and application impact on electric vehicles”, personal paper.

[14] L. Cervati, M. Conte, L. De Andreis, G. Pede, “Determination of SOC and ΔSOC in general”, EU MATADOR Project, ENEA SubTask 2.5 Report, June 2000.

[15] H. Darrelmann, “Comparison of alternative short time storage systems”, 6^{th} International conference "Batteries for Utility Energy Storage", Gelsenkirchen, Germany, September 1999.

[16] AEG Zebra, “Zebra Power”, E&HV Technology, 1997.

[17] C. Renner, S. Ploumen, M. Schüssler, “Testing Methods for vehicles with conventional and alternative drivelines: Evaluation of existing (draft) standards”, EU MATADOR Project, IKA SubTask 2.3 Report, March 2000.

[18] C. Letourneau et alii, “Progress in lithium polymer battery system for electric vehicles”, EVS-15, 1998.

[19] K. Meier-Engel, "Failure time and energy consumption of vehicles", EU MATADOR Project, HTA Biel SubTask 2.10 Report, June 2000.

[20] L. Buning, "Inventory of test results: Vehicles tested at IAE", EU MATADOR Project, IAE Report, March 1999.

[21] L. De Andreis, "Prove a banco a rulli Panda con NiMH", ENEA Test Report, March 2000.