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**TNO report**

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# Emission testing methods for the Dutch In-Service Testing Programme for Heavy-Duty vehicles

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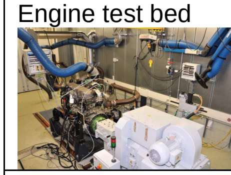
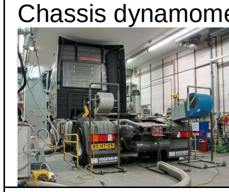
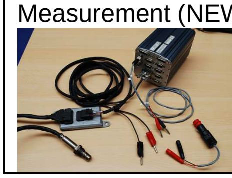
# Summary

Commissioned by the Ministry of Infrastructure and Environment of The Netherlands, TNO Sustainable Transport and Logistics regularly performs measurements to determine the in-service performance and durability of the pollutant emissions of heavy-duty vehicles under representative conditions. Several vehicle and engine testing methods are at disposal to fulfil the goals of the programme. The testing methods, however are all different.

The purpose of this investigation is to assess the emission testing methods against the most important requirements. In this way and with the different testing options at hand, the current and future in-service, heavy-duty testing programs can be tailored exactly to the goals of the programme, hereby maintaining maximum efficiency and minimum costs and effort.

The most important requirements considered are reproducibility, repeatability, accuracy and representativeness, but also the ease of operation, robustness and costs are important factors to consider when one chooses a method for a certain purpose. This assessment leads to clear conclusions regarding the capabilities of the testing methods. Namely, each emission testing method has strengths and or weaknesses and can therefore only serve specific purposes. The findings are summarised in the table below.

| | Reproducibility/ Repeatability | Accuracy | Representativeness | Purpose, comments |
|---|---|---|---|---|
| Engine test bed  | ++ | ++ | - | R&D<br>Type Approval |
| Chassis dynamometer  | + | + | + | Emission factors<br>R&D<br>Comparative assessment |
| Powertrain test bed  | ++ | + | +/- | R&D<br>Comparative assessment<br>In-Service Conformity checking |
| PEMS (Portable Emission Measurement System)  | - | +/- | ++ | Emission factors<br>In-service Conformity checking<br>Real Driving Emissions |
| Remote Emission Sensing  | -- | -- | +/- | Emission inventory / statistics<br>Detection of (share of) high emitters<br>Emission factor validation |
| Simplified Emission Measurement (NEW)  | ? | ? | ? | Due to the potential low costs and low effort to operate this system it is recommended to assess this system for it's possible application as in-service emission checking tool |

*Engine Test Bed*
The engine bed was and still is the instrument for R&D and also for Type Approval. It is accurate and once an engine and accompanying systems are installed it can run for days or weeks to perform very accurate and reproducible durability testing and much more.

*Chassis dynamometer*
A chassis dyno is a relative easy tool to perform tests on complete vehicles, almost under real world driving conditions. Depending on the type of chassis dynamometer, driving cycles and or steady state engine test cycles can be simulated. A disadvantage is that the tires limit the repeatability of the tests to some extend and the tires limit the test time at higher engine loads because of overheating issues with the tires.

*Powertrain Test Bed*
The powertrain test bed is a rather new tool and much experience has been gained during the assessment programme. Accuracy and repeatability are its main merits. The possibility to test transient engine cycles in a vehicle makes it a relative easy tool to approximate all current and future legislative engine test bed test cycles with sufficient accuracy. Also real world driving cycles and even on-road recorded driving cycles can be simulated on the powertrain test bed. It is important, however, that losses in the powertrain and power absorbed by auxiliaries are compensated to arrive at a good approximation of the test cycle load. This requires both experienced lab personnel and detailed technical specifications of the test vehicles.

*PEMS*
PEMS was recently introduced as tool to check In Service Conformity (ISC) of HD vehicles and is currently also considered for ISC checking of other vehicle classes. The accuracy and reproducibility are limited. For instance, PEMS cannot be used to compare emissions of individual vehicles with high accuracy. However, it can produce valuable insight in the level of emission performance under real world driving conditions. This proves important for e.g. Governments, because they are mainly interested in (reductions of) real world emissions in the view of (local) air quality problems. PEMS also provides lots of data of one vehicle under various driving conditions. A disadvantage is that the tests and the test results are influenced by the conditions at the time of testing which cannot be controlled, like ambient conditions and traffic conditions. A final remark about PEMS is that the tool is not plug-and-play and needs dedicated and experienced lab personnel to be operated. Furthermore, experienced engineers are needed to process the data and judge the results within the constraints of the test method and under the test conditions given.

*Remote Emission Sensing*
Already for some decades this tool has evolved gradually in a complete and mature emission measurement system. However, it still requires experienced lab personnel to operate the tool and to prepare the large flow of data for use. The limited sensitivity of the overall system (given the limitation of testing at one spot at a time and vehicles behaving differently at that spot) may be not well suited for all the purposes one thinks to serve with this kind of instrument. For instance, although the system was able to detect high emitters, the checking of emission compliance at the road side with this tool has so much uncertainty that this will probably never get a

legal status. Furthermore, results of one test location are limited to that single road/traffic situation and the selection criteria of the location are strict. Also, the tool is not able to test on all types of roads, like roads with dual lanes, roads were cars decelerate or drive at steady speeds. This makes it hard to derive a complete set of emission factors for all vehicle classes at all conditions, because the tests only measure under isolated types of driving conditions limited to the test site. Another disadvantage is that the acquired system does not measure $NO_2$ and PM, both very important indicators for air-quality.
In the USA, the ARB and EPA investigate Remote Emission Sensing as an option in addition to traditional Inspection and Maintenance, like a pre-screening tool for the Californian SMOG check, but errors of omission and error of commission are relatively high and therefore the tool cannot be used as replacement for testing roadworthiness. Despite the disadvantages, the tool might be effectively deployed to detect the (share of) high emitters in the vehicle fleet and to support the process of the estimation and validation of emission factors by delivering statistical information about the fleet (emission) composition.

*Recommendations: simplified emission measurement*
Next to the instruments or the testing methods discussed in this report, other options exist to measure tail-pipe emission of vehicles. For instance, sensors as used for after treatment control and On-Board Diagnostics have become sufficiently accurate to be used as scanning or screening instrument for checking real world emissions. Merits would be that they are easy to install, in contrast to e.g. PEMS, and that they would be able to deliver huge amounts of data under real world driving which would be accurate enough to indicate if a vehicle is clean or not. This becomes especially interesting now that tail pipe emissions are and will be reduced drastically by after treatment systems and checking the functionality and efficiency of these systems becomes important. It is therefore recommended to investigate the option to use sensors as In-Service Testing tool.

# Contents

# 1 Introduction

Today, different Heavy Duty emission testing methods exist and are used by mainly two different user groups; engine or vehicle manufacturers and governments, the latter either local, national or supra national. For these groups emission testing of HD vehicles and engines may serve different purposes, namely;

- To develop real world emission factors for the exhaust emissions
- To gain insights in trends in test cycle and real world HD emission performance
- To check in-service conformity of the exhaust emissions
- To compare technologies and perform comparative assessments
- To apply for type-approval for exhaust emissions
- To perform research and development

In the Dutch Heavy Duty In-Service and In-Use Compliance Testing programme emission tests are performed for the Ministry of the Environment and Infrastructure on a regular basis and mainly focus on the first three goals. The vehicle or engine manufacturer will mainly focus on the last three. Local governments or fleet operators may be interested in comparative assessment e.g. to make a well founded environmental choice for a certain technology for a concession.

Around 1990 an emission testing method has been developed for the Netherlands In-Use Compliance programme (Diesel Control Method) [10] and has been applied until the end of 2008 to fulfil the specific needs of the programme. The method was developed, based on steady state measurements on a truck on a chassis dynamometer, simulating the legislative 13-mode test cycle and later on the ESC engine test cycle. This was a relatively quick and easy way to check in-service conformity and to gain insights in emission trends. Recent developments in emission legislation, but also a change in the focus of the HD in-service conformity Testing from laboratory to real world emissions, required the programme to change. For this transition the available old and new methods have been evaluated for their suitability for the new goals and requirements for the programme.

The main driver for a change of the testing method is the need to assess the emissions as close to reality as possible, yet maintaining a reproducible, accurate and robust procedure to establish and judge the emission data. Accurate and representative figures are required for emission models and for checking emission conformity over real life situations instead of over a predefined test cycle. In the past and still for Type Approval the engine test bed combined with an emission analysis system is used but was believed to be not representative for real world emissions and also proved to be exhaustive. In the last years a few new methods to test emissions of HD engine and vehicles have been developed, which are more than before able to test emissions not of an engine but of a whole HD vehicle under real life conditions.
Each testing method has its own strengths and weaknesses with regard to the demand to produce emission data representative for the real world and therefore it is good to investigate the test methods in more detail;

The available methods are;

- Engine test bed (ETB)
- Portable Emission Measurement System (PEMS)
- Power train test bed (PTTB)
- Chassis Dynamometer (CD)
- Remote Emission Sensing (RES)

Other methods which are not evaluated are;

- On Board Monitoring (a sensor on-board a vehicle able to measure a quantity over a long period of time (days, months, years). Examples are a GPS logger, NOx sensor, Oxygen sensor.
- On board IT systems. A simple example is a FCM (Fuel Consumption Meter) already often found on cars and trucks. The instrument is able to calculate trip average FC, actual FC and average from the vehicles computer. More sophisticated aftermarket systems also exist and are used in the transport sector.
- Fleet data analyses; data available from the administration of fleet or vehicle owners, usually per trip or per refuelling. For some fleets such data can be obtained via the registration of travel/fuelling cards.

This report presents an evaluation of the methods. The evaluation is based on an intensive testing programme applying and correlating the different methods and on desk research to investigate the issues related to the different testing options.

The available HD testing methods were evaluated and the following methods were compared to each other in a measurement program:

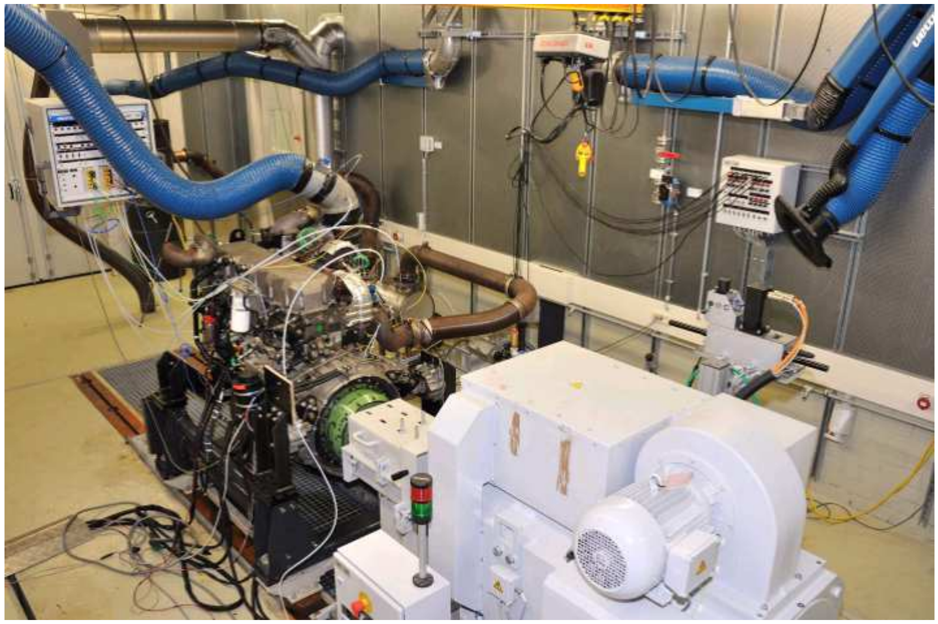
- Real world PEMS – PEMS on Power train test bed – Power train test bed;
- Real world PEMS – Remote Emission Sensing;
- Engine test bed – Power train test bed.

Additional items investigated are:

- Repeatability of PEMS
- Repeatability of the Power Train Test Bed

# 2 Available testing methods

## 2.1 Engine Test Bed (ETB)



The conventional tool to test HD engines is the engine test bed. On an engine test bed an engine's crankshaft/flywheel is mounted to a dynamometer which is able to brake (or accelerate) the engine directly. Normalised torque and engine speed cycles, either steady or transient, are applied to the engine.

The main advantage of the ETB is that the load and speed can be applied and measured very accurately and the other conditions, like intake air temperature, engine cooling can be controlled within narrow margins. Therefore in general the repeatability, reproducibility and accuracy are very good. Disadvantages are that the test is not regarded anymore as representative for real world operation and that preparation of a test is very time consuming and due to electronics sometimes even very hard to get a modern engine to run without the help of a manufacturer. Due to these characteristics the ETB is mainly suitable to perform in-depth research on the engine, its control and the after treatment system.

Summarized, the strengths and weaknesses of the ETB are:

+ accurate
+ repeatable
+ reproducible
+ long (durability) and automated testing

- expensive and time consuming to build up, especially if an engine needs to be dismantled from a vehicle and all complex controls need to be attached.
- not representative for real world operation. Trips have to be converted to engine tests. The engine is not mounted in a vehicle. Cooling is rather different.

The ETB is suitable for:
- Type approval; the value of this test method for assuring low real world emissions is questionable due to its low representativeness, however still used up till and including Euro VI, using the WHTC and WHSC as test cycles.
- R&D

## 2.2 Chassis Dynamometer (CD)


*Steady state chassis dynamometer*
A steady state chassis dynamometer or roller test bed was used in the Dutch In-Use Compliance testing programme until the end of 2008. Much experience was gained with this type of test bed. The chassis dynamometer was used to perform simulated steady state 13-mode and ESC cycles. A Diesel Control Method was especially developed to perform IUC checking on engines in a vehicle on a chassis dynamometer. The DCM checks whether a vehicle test matches the real engine test ESC points within a certain margin by measuring FC, air consumption, lambda based on emissions and the power developed by the engine in the vehicle. A model was used to calculate the power train losses (friction) and rolling resistance. In the case the fan could not be disengaged the fan speed was measured and used in a calculation to correct the engine power for fan operation. The engine power was also corrected for compressor operation.

Tyre slip has a significant influence on the total losses from dynamometer rolls to the engine. A model was developed to calculate tyre rolling resistance on the chassis dynamometer and special measures were taken to reduce slip to a minimum. Tyre temperature were monitored during tests and at the beginning of test programme the wheel slip was checked by measuring roll speed and wheel speed at the same time for the highest engine loads.

Summarized, the strengths and weaknesses of a steady state chassis dynamometer are:

+ easy set up
+ steady state engine test cycles can be approximated with an acceptable accuracy and repeatability for some type of investigations

- only steady cycles possible
- engine work is not measured directly but approximated using default functions or special tests for losses
- tyre slip makes the tests less repeatable and the work approximation more uncertain

The steady state chassis dynamometer is suitable for;

– IUC and ISC checking over approximated steady state engine tests
– R&D
– comparative assessment

*Transient chassis dynamometer*
A transient chassis dynamometer enables to drive driving cycles. But also engine cycles can be simulated to a certain extend. The drive cycle mode enables the simulation of real world operation of a truck or bus more closely than an engine test because the vehicle is driven with real gear shifting and follows real driving patterns. The driver follows this speed pattern and uses a specified gear shifting scheme to shift between gears.
The road load to be applied at the wheels by the rolls has to be calculated from formulae for drag and rolling resistance or can be determined by coast downs with a complete vehicle on a test track. The drawback of this type of test method is that the repeatability is not as good as on an engine test bed. On the other hand results are more representative for real world. An accurate simulation of engine cycles, especially the transient ones, is not possible. Only the vehicle speed cycle derivatives can be used to approximate an engine cycle.

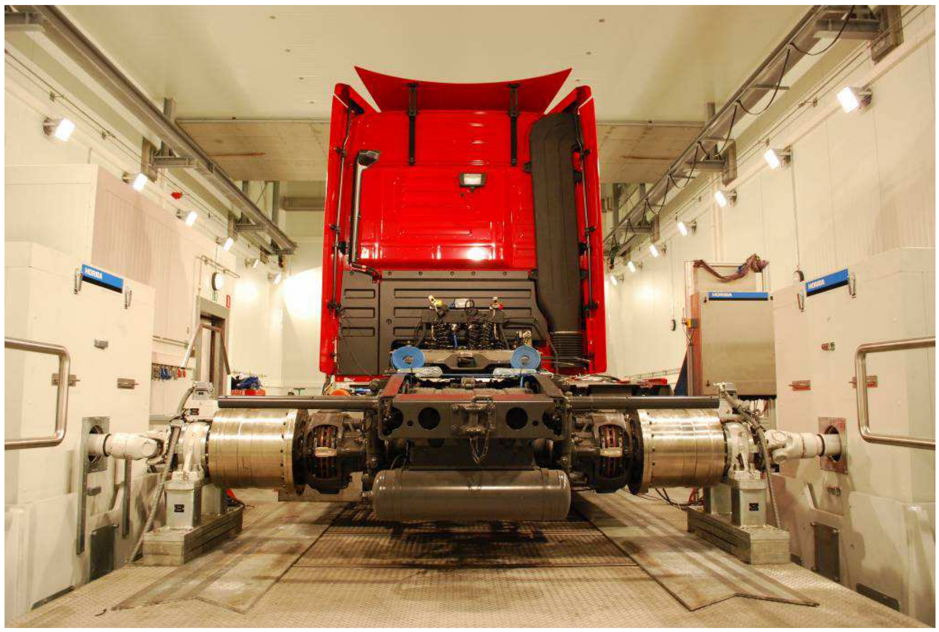
Summarized, the strengths and weaknesses of a transient chassis dynamometer are:

+ easy set up
+ representativeness; real world trips possible
+ steady state and transient engine cycles can be approximated with an acceptable accuracy for some investigations

- engine work is not measured directly but approximated using default functions or special tests for losses
- engine tests are simulated and less accurate
- tyre slip makes the tests less repeatable and the work approximation more uncertain

A transient chassis dynamometer is suitable for;
- IUC and ISC checking over approximated derivatives of transient engine tests and steady state engine tests
- Determination of real world emissions
- R&D
- comparative assessment

## 2.3 Power Train Test Bed (PTTB)



The power train test bed is a rather new tool for testing HD power trains. The complete vehicle is mounted to the test bed. The wheels of the powered axle are taken off. The load is applied by dyno's to the hubs of the wheels over the drive line to the engine. Any torque, engine speed cycle can be applied. Engine torque, engine speed cycles or wheel torque, engine speed cycles can be derivatives from vehicle speed cycles if the gear shifting points, transmission ratios and road load are determined. Additionally, it is possible to drive a vehicle speed time cycle. The test set-up at TNO is at the moment still limited to driving cycle and vehicle combinations where the wheel torque does not exceed 14 kNm (comparable to city busses and city operation).

The PTTB set up at TNO in Helmond is situated in a climate chamber which makes testing under controlled and extreme ambient conditions (temperatures between -40° C and +55° C and altitudes up to 4000m above sea level) possible.

For an accurate simulation of a formal engine test cycle of the engine in the vehicle on the PTTB the dyno control should compensate for;
- drive line losses;
- drive line inertia;
- active auxiliaries.

Summarized, the strengths and weaknesses of the PTTB are:
+ (formal) engine tests can be approximated accurately
+ more representative than an engine test bed due to integration of the drive line and after treatment in the vehicle
+ accuracy
+ repeatability

- at the moment no real driving is possible for high powered heavy duty vehicles, because the maximum wheel torque is limited at 14 kNm. For these vehicles, trips have to converted to engine cycles, cycles are then driven in one gear.
- engine work is not measured directly but approximated using default functions or special tests for driveline losses and / or activity of auxiliaries. Pre- and post-test checks are required for verification of the approximated engine work.
- testing a hybrid vehicle is complicated; actual wheel torques can only be applied to  up to14kNm to drive a vehicle cycle. A compensation model is required to calculate dynamic axle load and brake energy to simulate regenerative braking as realistic as possible, this has already proven to work.
- mounting the vehicle and the vehicle commissioning can be more time consuming compared to a chassis dynamometer.
- a vehicle with an automated gear box requires special control of the idle speed. Often a higher idle speed then the one prescribed is required to prevent the gear box from shifting to neutral during an engine test cycle.

The PTTB is suitable for;
– ISC checking over approximated engine tests
– R&D
– Comparative assessment
– The climate chamber enables checking emissions under a wide range of environmental conditions.

## 2.4 Portable Emission Measurement System (PEMS)


Around 2006 in the EU and in the US Pilot Programmes were started in which PEMS was investigated as a possible tool for checking In-Use Compliance (IUC for the US) and In-Service Conformity (for the EU). In 2011 legislation came into force

(582/2011/EC) in which PEMS is the alternative tool for checking ISC of Euro V engines and the exclusive tool for checking ISC of Euro VI engines.

A PEMS is a system which has analysers for the regulated gaseous components (with calibration gasses), an exhaust flow meter, a GPS, CAN communication and a weather station. The system can be mounted in a HDV or even a LDV or passenger car. However, the install and operation is not plug and play. During a trip on the road, exhaust gas concentrations and tail pipe exhaust gas flow are measured continuously and calculated (ISO 16183, ECE-R49) as mass emissions per unit of time. Next to emissions the vehicle speed is measured by a GPS and vehicle and engine parameters are sampled from the CAN bus. The CAN signals, if available, allow an approximation of the engines torque. With this value and engine speed, the engine work can be calculated over periods of time in a trip. The engine torque is however not specified with regard to its accuracy and thus calculated work has a certain amount of uncertainty.

At TNO an alternative method was developed to analyse emission behaviour over the speed range of a vehicle. This method is the called the speed binning method. The method calculates average emissions per speed bin. To judge absolute levels of emissions they are not related to engine work but to the $CO_2$ emission.
The advantage is that by dividing a certain emission components average mass emission by the average mass emission of $CO_2$ possible errors of the flow measurement are minimised. However, to judge absolute levels and to make them understandable one should convert them for instance to units like used in legislation (g/kWh) or emission models (g/km).

Summarized, the strengths and weaknesses of PEMS are:
+ representativeness for real world
+ relatively cheap
+ delivers hours of data in a few test days

- reproducibility
- repeatability
- accuracy
- accuracy of engine work
- still complex, requires good test program, data interpretation and control and operation of the equipment

Suitable for;
– Gaining insights in real world emissions
– ISC, if accompanied by a robust data evaluation method and well defined boundary conditions
– Comparative assessment, but only limited to very well controlled tests and comparable conditions, e.g. applying SORT test cycles on a test circuit or fixed test trips limiting the allowed variation of ambient conditions

## 2.5 Remote Emission Sensing (RES)

*Background*
Vehicle tail pipe emissions have been investigated and measured over more than three decades now. The result of extensive measurement programmes and gathered knowledge has, amongst others, been used to develop a vehicle emission model called VERSIT+. The VERSIT+ model is capable of calculating vehicle tailpipe emissions for specific vehicle categories, based on speed-time profiles. Accurate emission models of vehicles emissions are used for emission inventories, trend predictions, comparative assessment of technologies and are used as input for air quality models.

Both light- and heavy duty vehicles have always been tested in the emission laboratories. For light duty vehicles, real world vehicle driving behaviour (speed-time patterns) was investigated and used to create driving cycles. These driving cycles were used to simulate real world driving behaviour on the chassis dynamometer in the laboratory. In this way light duty vehicle emissions were measured under “real world” driving conditions. TNO has also tests heavy duty vehicle tail pipe emissions on a chassis dynamometer. Recently, a new test facility has been introduced to test heavy duty vehicles under transient loads under a wide range of ambient conditions. The results of such measurement programmes were used to check the in service conformity of the tested vehicles and used as input for emission models.

Since a few years, heavy duty vehicle tail pipe emissions are also measured on the road using a Portable Emission Measurement System (PEMS) which can be installed in a vehicle. This allows recording vehicle tail pipe emissions of this specific vehicle under real world driving conditions. The results of these measurements are reasonably accurate and provide valuable information of vehicle emissions under real world (dynamic) conditions. PEMS is the new standard for In-

Service Conformity Testing of Heavy Duty Engines and Vehicles in the EU and the US. The PEMS approach is reasonably accurate, but still time consuming and not plug and play. Therefore, just as tests in the laboratory, it is a relative expensive test method.

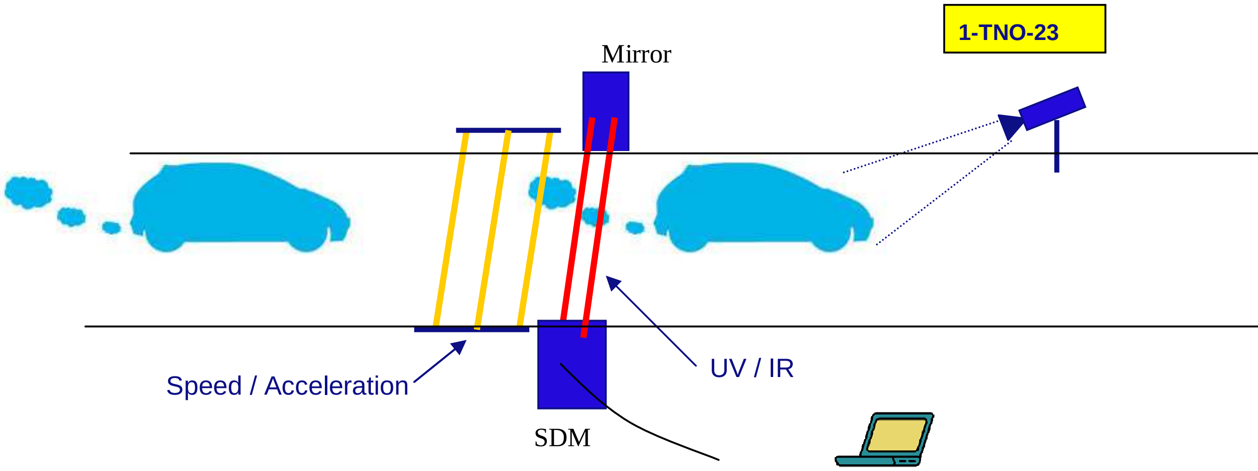
The aim of the Dutch In Service Testing programme is to verify the conformity of vehicles in-service and to gather information of the emission performance of vehicles from the (Dutch) vehicle fleet. Modern vehicle engines and exhaust gas after treatment systems have become complex systems. In order to understand and evaluate the emission behaviour of these modern vehicles, rather complex measurements and test equipment are necessary. As mentioned before, the emission laboratory and PEMS measurements, enabling these required detailed analyses, are relatively time consuming and expensive.
Due to the increasing variety of engine and exhaust gas after treatment technology a large amount of vehicles should be measured to derive accurate emission values. Furthermore, large amounts of vehicles should be tested to gather information of the real world emission performance of the vehicle fleet, not just of a few individual vehicles. An alternative testing method may provide insight in the emission performance of large numbers of vehicles.

The “remote emission sensing system” is introduced to fulfil the need of testing large numbers of vehicles. The system is installed next to a road and measures exhaust gasses in the exhaust plume of the vehicle passing the site. However, the system provides information of the emission behaviour of vehicles on only one particular moment under one specific driving condition. Remote emission sensing is therefore not an alternative method for the accurate vehicle measurements in the laboratory or with the Portable Emission Measurement System. It is an important additional testing method or scanning tool to gather information of the tail pipe emissions of large numbers of vehicles.
In the US the remote emission sensing system is also used to investigate the emission behaviour of large numbers of vehicles. If the vehicle emissions exceed certain thresholds, vehicle owners are contacted and asked to visit a workshop. When vehicles perform well, the annual vehicle’s exhaust gas inspection is even postponed.

*Remote Emission Sensing System RSD4600*
In the past decades many companies have tried to develop a remote emission sensing system. However, remote emission sensing (RES) appears to be rather complex and most of the companies/projects failed to deliver a reliable measurement system. In the 1980’s the University of Denver (USA) started the development of a remote sensor unit. This system was tested and improved substantially over ten years and finally in the 1990’s the system became commercially available. Since then still many new improvements have been made and the system has been tested by many different companies over the world. At this moment, this system is still the only commercially available system on the market and is sold by the company ESP (USA) under the name RSD4600. TNO purchased an RSD4600 system in 2009.

*Remote Emission Sensing Setup*
Vehicle emissions vary amongst others depending on the specific vehicle technology (fuel, after treatment etc.) and vary in relation to speed and acceleration. To be able to evaluate exhaust emissions measured by RES, of individual passing vehicles, these parameters need to be recorded.

The system setup of remote emission sensing is shown in the following figure:



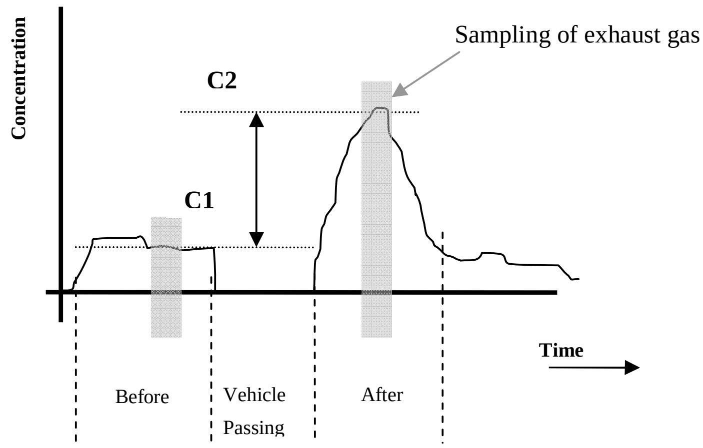

The remote emission sensing equipment detects and measures vehicle emissions as the vehicle passes. The process of measuring emissions remotely begins when the vehicle breaks the infrared (IR) and ultraviolet (UV) beam sent across a single lane road from the source/detector module (SDM) to a special mirror. This mirror reflects the UV/IR beam of the source exactly on the detector of the SDM. The reflected UV/IR light spectrum is analysed in the SDM. Based on the absorption of specific parts of the UV/IR light it is possible to identify the type of gasses present in the light beam. Furthermore, the amount of absorption is also representative for the amount of gasses (number of molecules) in the light beam.


Source/detector module Speed acceleration unit Vehicle detection

*Remote emission sensing measurements*
Fuel specific concentrations of HC, CO, $CO_2$, NO and black smoke are calculated in the vehicle exhaust plumes based on their absorption of IR/UV light in the dual beam path. During this process, the speed and acceleration of each single passing vehicle as well as the license plate of each vehicle is recorded. The license plate is stored for the technical identification of the vehicle using the database of the road administration authority.

The remote emission sensing system measures exhaust gas concentrations of a vehicle in following steps, see also the graph below;

1. air in front of the vehicle is measured to determine the background pollutant levels
2. air at the rear of the vehicle is measured to determine the vehicles exhaust emissions
3. The differences between the rear and front measurements represent the emissions of the vehicle.




The measurement values do not represent absolute emissions of the vehicle. Only a part of the total exhaust plume is measured. The tail pipe position and meteorological conditions like wind, influence the dispersion of the gases. The measurements therefore represent the amount (number of molecules) of gases in the path of the measurement beam (no concentrations). Based on the measurements of the RSD4600 system, three separate gas ratios can be calculated:

1. $CO/CO_2$ ratio
2. $HC/CO_2$ ratio
3. $NO/CO_2$ ratio

These ratios are calculated as follows (CO example):

$$(COrear - COfront)/(CO2rear - CO2\,front)$$

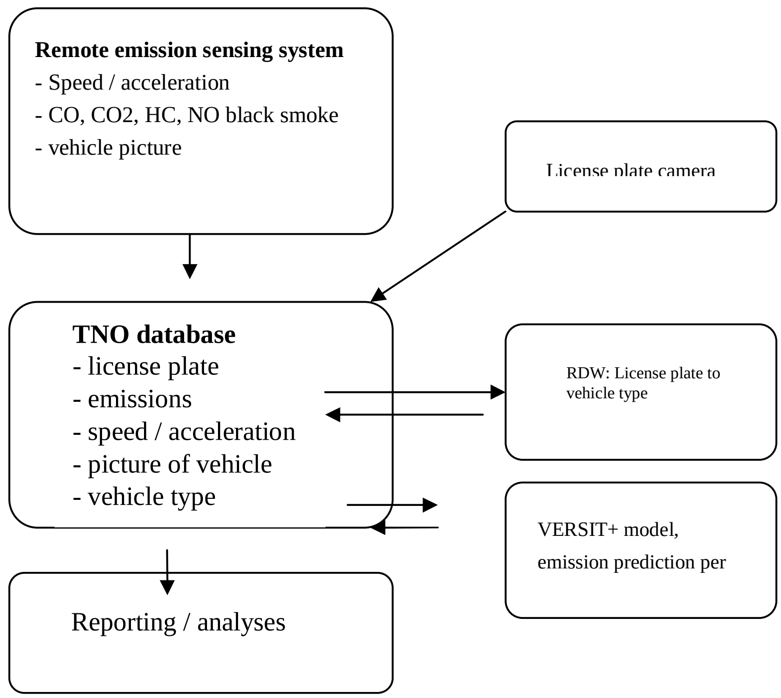
The rationale behind this calculation is the following. The air always contains a certain amount of the gases due to cars that have passed before. This amount is enhanced by the exhaust gasses of the car under study. To determine the amount caused by the car, one has to correct the measured amount at the rear of the car, for the amount already present. The latter is estimated by the amount in front of the car. So, the amount of gas is estimated by (gas_rear – gas_front). The ratios are used to evaluate the vehicle emission performance: it is not unknown to what extent the exhaust plume has diluted, so only a ratio of emissions is a relevant quantity.

The RSD 4600 system is also able to measure a smoke factor. The smoke factor is the ratio of the measured exhaust plume opacity and the amount of fuel being used by the vehicle. This amount of fuel being used is determined by measuring the sum of three carbon based gases in the exhaust ($CO_2$, CO and HC's). A volumetric sum of these gases represents an equivalent volume of the fuel being burned. The smoke factor can be described as "opacity per unit fuel".

*Data processing*
Once the RSD4600 system has been installed next to a road, the system can measure the vehicle emissions of thousands of passing vehicles on a single day. To

be able to evaluate every single vehicle detected by the system, software has been developed to process the large amount of data. The software also allows the comparison of the measured ratios to the predicted ratios of the TNO VERSIT+ emission model. Furthermore average emission levels per vehicle class can be calculated (for example euro 3 petrol vehicles). As the $CO_2$ emissions of each single passing vehicle can be calculated by the VERSIT+ model, the absolute emission levels of the passing vehicles can be calculated as well by multiplying the measured ratios of HC, CO and NO per $CO_2$ by the absolute amount of $CO_2$. This absolute rate, e.g. for NO, is then partly empirical and partly theoretical (since the VERSIT+ model is employed to determine an absolute emission ratio for $CO_2$).

## Data processing:




The data flow is visualized in the Figure above. The data of the RES measurements is collected in a database, this database contains following information for each single vehicle:

- The vehicles speed and acceleration.
- The ratios of CO, HC, NO per $CO_2$ and black smoke as measured by the RSD system.
- The predicted emission values based on VERSIT+ calculations (by using speed, acceleration and relevant vehicle type): CO, $CO_2$, HC, NO, black smoke
- Vehicle license plate from which vehicle specifications follow (from the Netherlands national authority responsible for vehicle registration, the RDW).
- A picture of the vehicle

# 3 Assessment programme

## 3.1 Test programme

Several test programmes were combined to arrive at an overall programme that enables the comparison of several emission test methods.

*Vehicles*
The test vehicle of the HD assessment programme is a HD tractor unit with a Euro V (B2G) certified, 6 cylinders, 350 kW engine has 2200 Nm of torque and SCR as after treatment system. One conventional Euro III HD engine was used for a comparison between the HD engine test bed and the powertrain test bed. For RES measurements also a Euro IV 12t delivery truck was used and tested with both PEMS and RES. Furthermore, two passenger cars were tested on a chassis dynamometer and those results were used to compare them on road RES passes. Summarising, the following vehicles/engines were used for testing with the respective methods given;

*Tests*
HD Euro V Tractor-trailer; PEMS, PTTB, RES
HD Euro III Engine; PTTB, ETB
HD Euro IV delivery truck; PEMS, RES
LD (2) passenger cars; LD chassis dynamometer and RES

Here the tests with the HD tractor-trailer unit will be explained. The other vehicles and tests are explained further on in the report. At TNO the HD tractor-trailer was tested with PEMS on the road and of course without trailer on the PTTB. Over a number of tests on the PTTB the PEMS was mounted too and emissions were measured simultaneously to be able to compare the PEMS results with the emission lab results. From the road tests no CAN information could be obtained as the vehicle did not broadcast a readable data format for the PEMS. Instead, some additional sensors were mounted to the vehicle and measured;
- cardan torque
- engine speed
- fan speed
- rear axle oil temperature

The programme allows;
- Correlation of PEMS with the PTTB
- Correlation of PEMS road tests vs. PEMS test simulated on the PTTB
- Repeatability of PEMS on the road; for the ISC method, data binning, brake specific and distance specific results
- Repeatability of PEMS on the PTTB at fixed cycles
- Repeatability of the PTTB

The findings will be discussed in the chapters hereafter.

Test programme

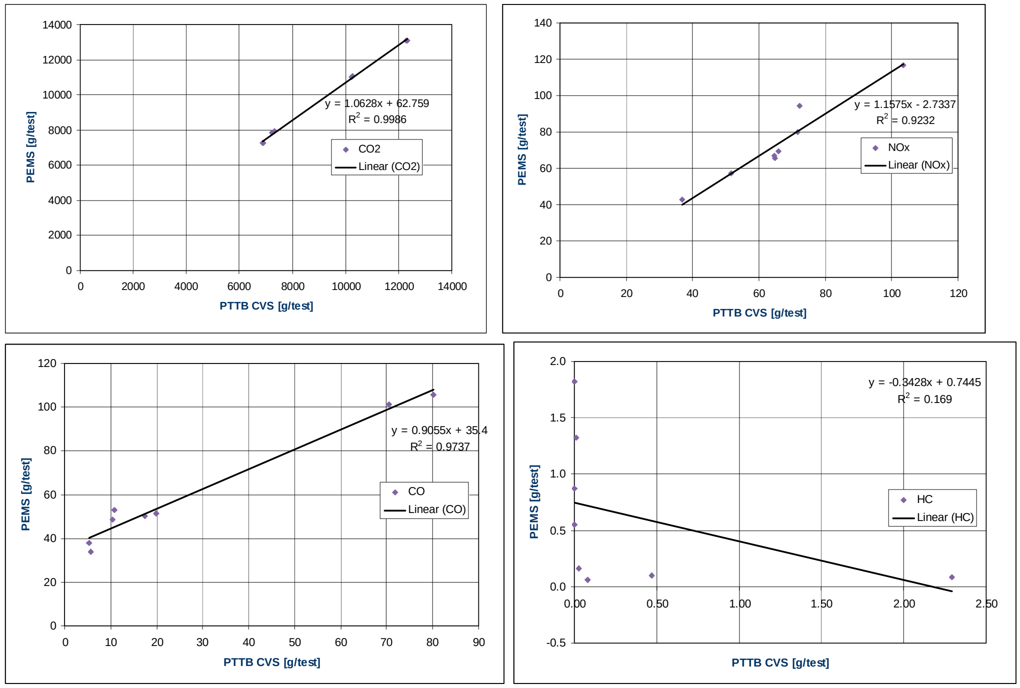
| **Day** | **Test** | **Remarks** |
|---|---|---|
| Day 1 | Preparation | Mounting PEMS, fan speed, cardan torque and engine speed sensors |
| Day 2 | Preparation<br>commissioning PEMS test | "<br>small test trip<br>weighing vehicle |
| Day 3 | Cold start reference trip until hot | payload 50% (29,7 t GVW) |
| Day 3 | Warm started reference trip 1 | payload 50% (29,7 t GVW) |
| | Warm started reference trip 2 | payload 50% (29,7 t GVW) |
| Day 4 | Preparation | Mounting vehicle on PTTB |
| Day 5 | Preparation<br>commissioning PTTB tests | Mounting vehicle on PTTB |
| Day 6 | transient full load curve | |
| Day 6 | ETC 1 | analyses PEMS + PTTB |
| Day 6 | ETC 2 | analyses PEMS + PTTB |
| Day 7 | ESC 1 | analyses PEMS + PTTB |
| Day 7 | ESC 1 | analyses PEMS + PTTB |
| Day 8 | WHTC cold | |
| Day 8 | WHTC hot after 20 min soak | |
| Day 8 | WHSC 1 | |
| Day 8 | WHSC 2 | |
| Day 9 | Steven cycle 1 | load and speed controlled at hub without loss compensation (derived from road load and gear shift model PHEM) |
| Day 9 | Steven cycle 2 | " |
| Day 9 | PEMS cycle 1 | simulation of the PEMS road cycle calculated from the cardan torque |
| Day 9 | PEMS cycle 2 | " |
| Day 9 | engine map | 29 Artemis points |
| Day 9 | engine coolant fan tests | fan ramps at different engine speeds |

## 3.2 PEMS compared with the Powertrain Test Bed and Constant Volume Sampler

The accumulated results over test cycles of PEMS emissions can be compared with the results of the CVS (Constant Volume Sampling) emissions from the PTTB. Also the online (instantaneous) emissions of both systems can be compared.

The Fuel Consumption and $CO_2$ emission are consistently higher for the PEMS results. The differences range from a few to about 8%. Also for $NO_x$ the PEMS values are consistently higher, but with more variation than $CO_2$. CO correlates linearly, but has a large offset at lower values. For HC the general trend is very bad.

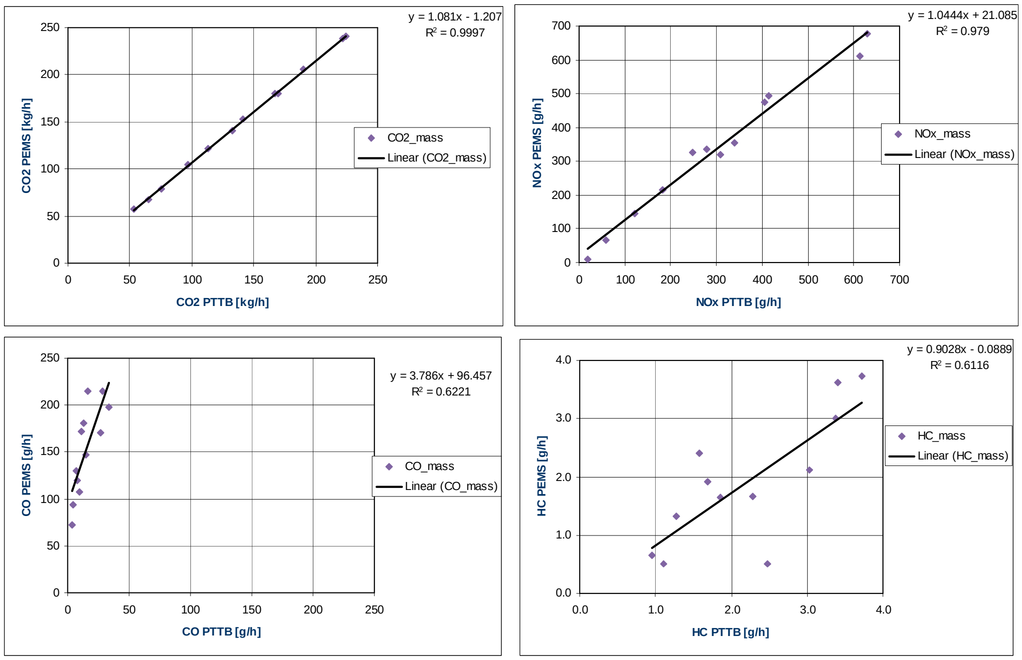
Figure 3.1: correlation of accumulated test results between PEMS and PTTB CVS




| Difference PEMS vs. PTTB CVS | FC | $NO_x$ | $NO_x/CO_2$ | CO | HC | $CO_2$ |
|---|---|---|---|---|---|---|
| ETC1 | 6.5% | -2.1% | -6.2% | 360% | 400% | 4.4% |
| ETC2 | 6.3% | 0.1% | -3.3% | 400% | >>> | 3.5% |
| WHTC cold | 8.7% | 11.0% | 6.5% | 32% | >>> | 4.2% |
| WHTC hot | 8.3% | 21.7% | 11% | 44% | -100% | 9.6% |
| Steven 1 | 5.9% | 8.3% | 1.9% | 600% | -80% | 6.3% |
| Steven 2 | 5.1% | 3.5% | -2.6% | 500% | -26% | 6.3% |
| PEMS 1 | 7.8% | 7.6% | -0.9% | 190% | >>> | 8.6% |
| PEMS 2 | 7.4% | 10.0% | 1.4% | 160% | -100% | 8.5% |

The individual steady state points from the ESC show a good correlation for $CO_2$ and $NO_x$, a poor correlation for HC and a very poor correlation for CO. For the CO measurement of this PEMS type it is known that the analysers range is not suited to measure the low CO emission levels of diesel vehicles. For HC this may be the case as well.

Figure 3.2: correlation of g/h emissions between PEMS and PTTB CVS over the ESC steady state points




The difference between the PEMS en the PTTB was further investigated to find the cause. For both systems the mass emissions over a test cycle are determined by:

1. the exhaust mass flow and
2. the emission concentrations.

*Exhaust mass flow*

With PEMS the exhaust mass flow is measured by an Exhaust Mass Flow Meter (EFM), at the PTTB the exhaust mass flow is calculated from measured intake air flow and fuel flow of which the air mass flow has the largest portion.

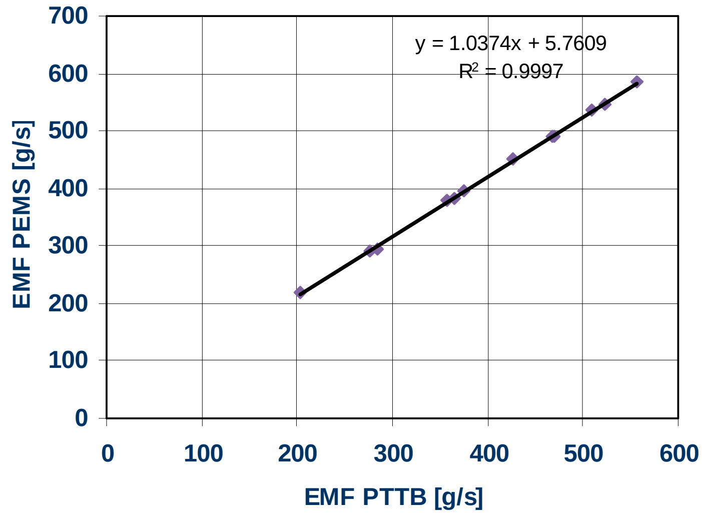
In the past the exhaust mass flow accuracy of PEMS has been investigated by EPA (EPA 2008). In particular effects of exhaust pulsation, uniformity of exhaust velocity on the exhaust mass flow (swirl effects) and tail pipe wind were investigated and quantified. Pulsation proved to cause positive errors up to about 2%. Non-uniformity of the velocity proved to cause an error up to 1 % and tail pipe wind had only very little effect which was neglected in the further investigation.
The linearity of the exhaust mass flow was also investigated; errors were found for the slope factor of most exhaust mass flows. The direction and size of the error of the slope varied from system tot system but generally remained within -5 to +5%, which is still larger than the instruments specification of 3% (Full Scale).

Here the cumulative exhaust mass of the EFM from the PEMS and from the air and fuel mass measurement of the PTTB are compared for three test cycles. A consistent difference of 4-6% can be noted.

| | ETC | WHTC cold | WHTC hot | Steven |
|---|---|---|---|---|
| PTTB emf [kg] | 483 | 334 | 333 | 344 |
| PEMS emf [kg] | 509 | 354 | 353 | 365 |
| Difference [%] | 5% | 6% | 6% | 6% |

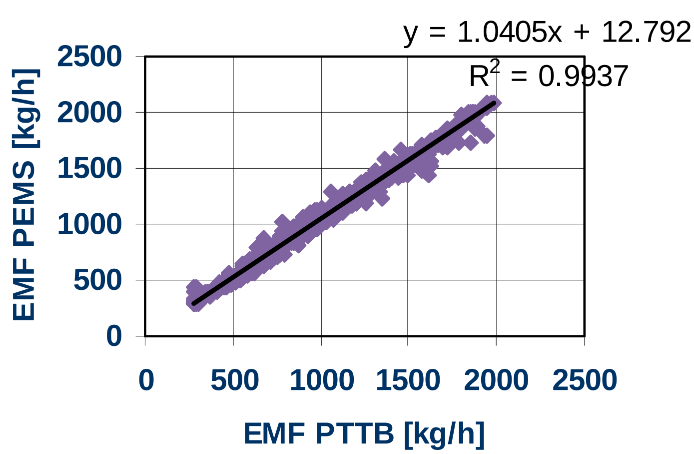
For the steady state points of the ESC test a positive deviation of the slope was found of about 4%.

Figure 3.3: deviation of the exhaust mass flow rate of the PEMS and PTTB over the ESC




Over a transient test (ETC) the slope of the instantaneous EMF is also at about 4%.

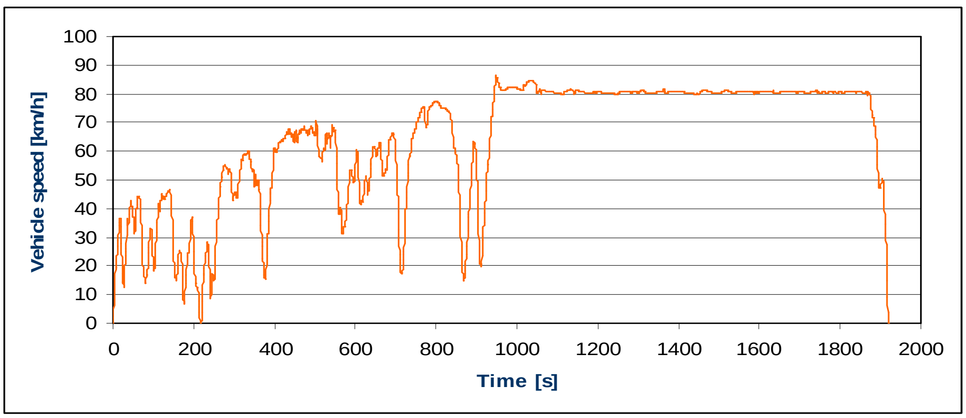
Figure 3.4: deviation of the exhaust mass flow rate of the PEMS and PTTB over the ETC

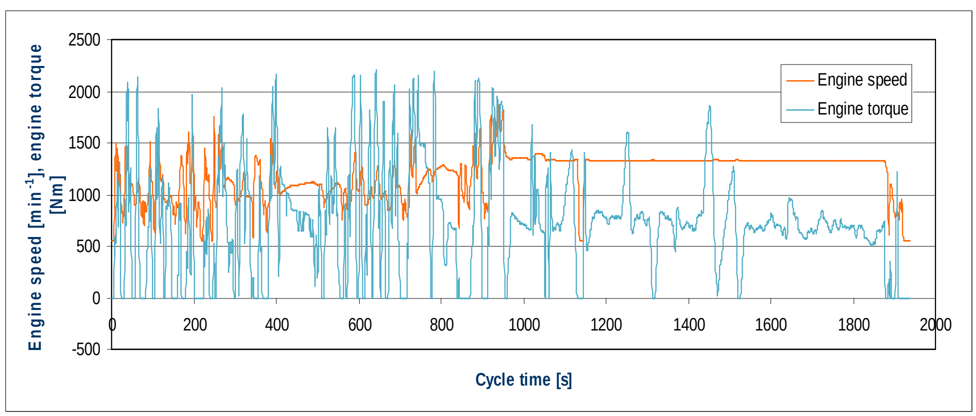


### 3.3 Real world PEMS vs. PEMS on the Powertrain Test Bed; simulation of a road trip on the Test Bed.

A part of a PEMS trip on the road was used to derive an engine test cycle to be performed on the Powertrain Test Bed (PTTB). Cardan torque was measured. The cardan torque was converted to engine torque by means of the gear ratios as calculated from the measured relation engine speed – vehicle speed. The use of the vehicles retarder caused high negative torque peaks in the cardan signal. The cardan torque signal had to be edited to make it suitable to convert it to an engine cycle. The high negative torque values caused by the retarder were replaced by 'motoring' which is a common indicator for a test bed control to propel the engine at given speed.

Figure 3.5: the PEMS vehicle cycle and the conversion to an engine cycle



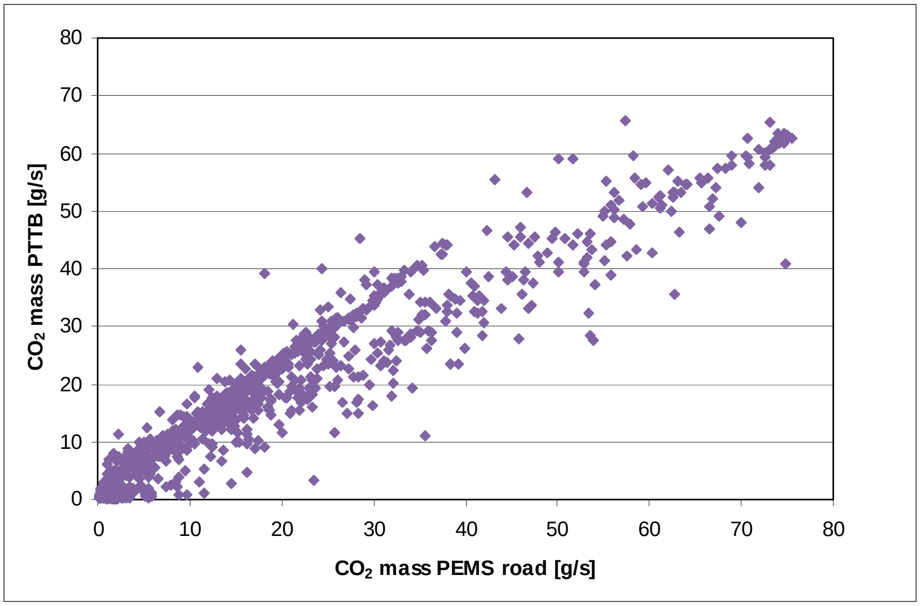

The tests resulted in a reasonable correlation between the road test and the test bed test for $CO_2$, $NO_x$ and HC and a poor correlation for CO. The $CO_2$ mass from the road test differs only 2% from the PTTB analyses but 10% from the PEMS analyses. The difference between the PEMS analyses of $CO_2$ and PTTB analyses of $CO_2$ was also observed for other test cycles.

Looking at possible causes for the differences the repeatability of the PEMS and PTTB, instruments plays a role, but mainly for the noxious emissions the repeatability (stability) of the vehicle plays a role as well. The duplicate tests on the PTTB show for instance a rather large variation for $NO_x$, indicating possible history effects of the SCR catalyst. Between consecutive duplicate tests on the PTTB the variation of $NO_x$ is larger than the difference between road test and PTTB test.

| | $CO_2$ | $NO_x$ | $NO_x$ / $CO_2$ | CO | HC |
|---|---|---|---|---|---|
| | kg/test | g/test | g/kg | g/test | g/test |
| **PEMS on Road** | **31.5** | **51** | **1.6** | **111** | **0.2** |
| | | | | | |
| PTTB instantaneous, test 1 | 32.1 | 64 | 2.0 | 19 | 0.3 |
| Deviation from Road | 2% | 26% | 23% | -83% | 22% |
| | | | | | |
| PTTB instantaneous, test 2 | 32.0 | 32 | 1.0 | 19.7 | 0.3 |
| Deviation from Road | 2% | -37% | -38% | -82% | 17% |
| | | | | | |
| PTTB CVS, test 1 | 32.2 | 71.6 | 2.2 | 17.4 | 0.0 |
| Deviation from Road | 2% | 40% | 37% | -84% | -100% |
| | | | | | |
| PTTB CVS, test 2 | 32.1 | 36.8 | 1.1 | 19.92 | 0.0 |
| Deviation from Road | 2% | -28% | -30% | -82% | -100% |
| | | | | | |
| PEMS on PTTB, test 1 | 34.7 | 80 | 2.3 | 50 | 0.5 |
| Deviation from Road | 10% | 56% | 42% | -55% | 122% |
| | | | | | |
| PEMS on PTTB, test 2 | 34.6 | 43 | 1.2 | 52 | 1.8 |
| Deviation from Road | 10% | -17% | -24% | -53% | 637% |

Although cardan torque was converted in engine torque using calculated gear ratio’s,  there is still a clear correlation between the instantaneous (second by second) $CO_2$ emission on the road and on the test bed. Differences occur from miscalculations of the selected gear and the resulting calculated engine torque and by differences between the measurement instruments (PEMS and CVS instantaneous emissions).

Figure 3.6: correlation of instantaneous PEMS and CVS emissions




For conversion of road cycles to engine cycles by means of cardan torque, variability is introduced by the uncertainty of the measured shifting points. More accurate engine cycles may be derived from measured CAN signals like % engine torque, reference torque and friction torque. However, gear shifting in the real world has influence on emissions and as long as gear shifting points are not fixed (a measured torque signal on the road from CAN represents only that cycle with the used gear shifting points) variations are possible. For noxious emissions the variations of the object seem to be even more important. Even if a cycle is reproduced well variations occur, possibly due to conditioning and history effects.

## 3.4 Engine Test Bed vs. Powertrain Test Bed; the possibility to simulate engine cycles on the Powertrain Test Bed

Data of two programmes is used to demonstrate the possibility to simulate engine cycles on the PTTB;

- In one test programme legislative test cycles were executed on the PTTB. During the tests the driveline losses and effects of auxiliaries were measured and simulated to arrive at the best match of the engine cycle.
- During the commissioning phase of the PTTB a programme was executed where an engine was tested on an engine test bed and the same engine was tested in a truck on the PTTB.

The PTTB has two different modes in which the engine (speed, torque) cycle can be approached.

- simulation mode; the approximated driveline losses and inertia and power consumption of auxiliaries are used to calculate the required torque at the dyno's.

$$M_{solldyno}=M_{sollengine}-M_{inertia}-M_{losses}-M_{aux}$$

– normalised mode; on an engine test bed the actual torque cycle is determined at the flywheel and is calculated from given percentage values from the transient full load curve. It is assumed that the normalised test cycle applied to the hub torque as calculated from the full load curve determined at the hub will result in the same cycle as would have been obtained for the normalised flywheel torque, or;

  $Actual\_torque\_hub_i = \%\_torque_i \times maximum\_torque\_hub$

  results in the same engine torque as officially required in ;

  $Actual\_torque\_engine_i = \%\_torque_i \times maximum\_torque\_engine$
  (2005/55/EC, R49)

  The total cycle work at the engine is calculated after a test. During control of the dyno torque an online correction can be made e.g. if an auxiliaries becomes active and one knows the power demand of this auxiliary.

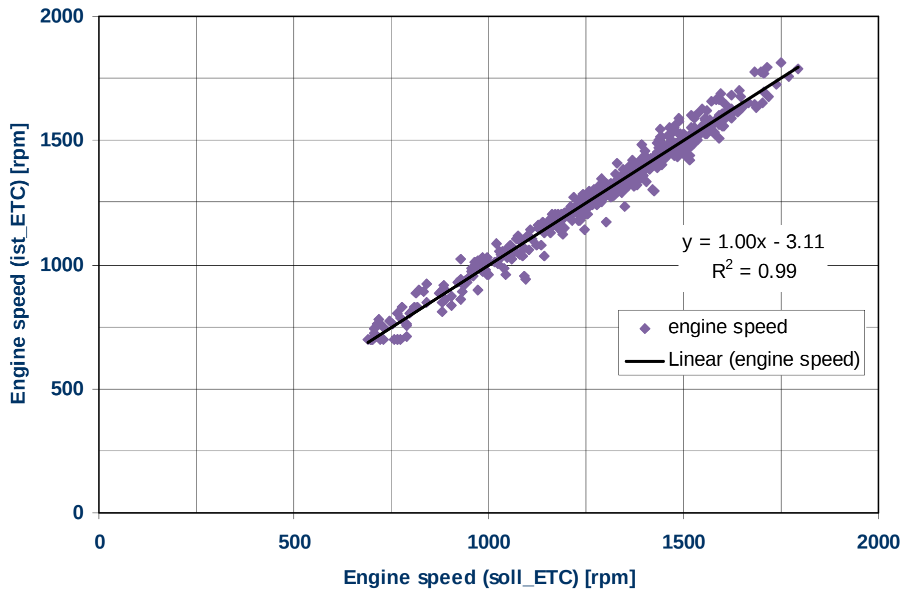
For both modes a few issues are relevant;
– How well is a cycle simulated momentarily (e.g. per second). This influences emissions per second, short offsets may have only minor influence.
– How well is the total cycle approached, looking at engine work and engine speed. This influences the overall brake specific emission results.
– How well are the ETC test conditions approached as would have occurred on the ETB. Parameters are important that might influence emissions, like intake/charge air temperature, exhaust gas temperature.

*Momentary cycle simulation*
An ETC cycle was used for the analyses. The In-Service Test procedure as used in the past for the Dutch In-Service Testing programme was only able to approach steady state 13-mode and ESC mode points. The PTTB is also able to simulate an ETC or any other transient cycle. To evaluate this capability, the measured (‘ist’) engine speed and engine torque are compared with the so called demand (‘soll’) values.

The official EU test procedure for HD engine emissions describes the transient ETC test cycle as a normalised speed torque pattern at 1 Hz, of 1800 seconds. Based on the lug curve the denormalised engine torque and engine speeds can be calculated and should be used to control the engine dyno of the ETB. At the PTTB the engine speed is controlled through the drive line with the gear box in a fixed gear. The engine torque can be controlled in the two modes as described above.

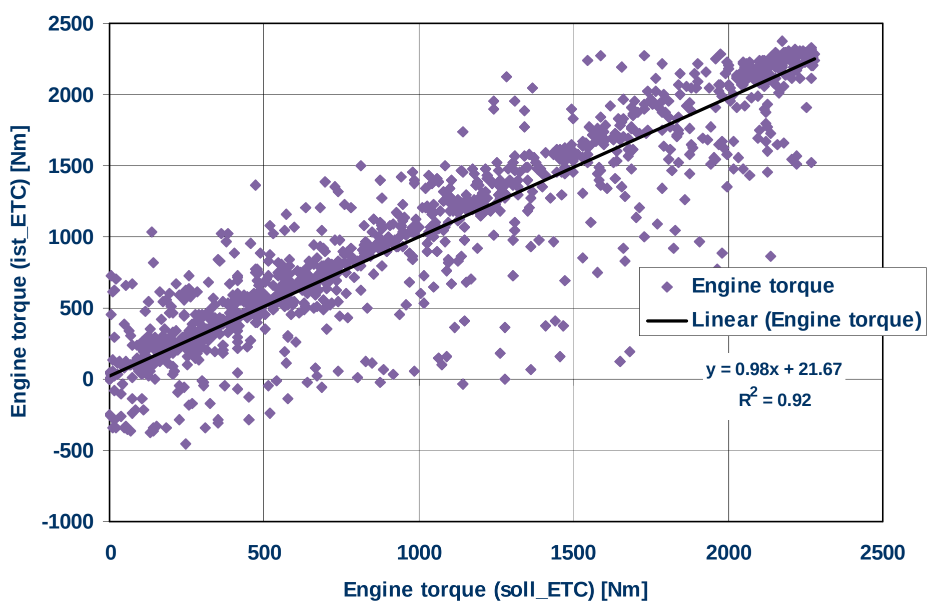
The engine speed is controlled very well. The relation between ‘soll’ and measured ‘ist’ speed is linear and 1. Momentarily, minor deviations occur. 90% of the points are within a band of +/- 2.5%. Almost 100% of the data lies within a band of 10% with only a few points exceeding the 10%. The average engine speed over the cycle differs 0.1% between ‘soll’ and ‘ist’.

Figure 3.7: deviations between 'soll' and 'ist' engine speed on the PTTB



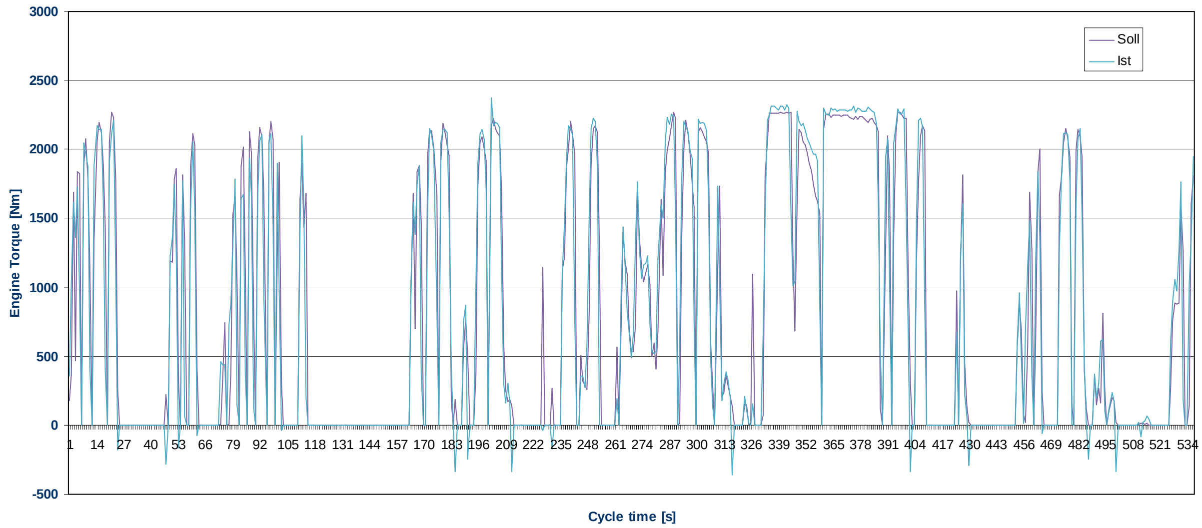

The following graphs demonstrate the PTTBs capability to simulate engine torque momentarily. Half of the data points are within 100Nm and 75% of the data are within 200Nm. 90% of the data is within 400Nm.

Figure 3.8: deviations between 'ist' and 'soll' engine torque on the PTTB



The correlation between ‘soll’ and ‘ist’ torque can also be shown over the cycle, as depicted in the figure below. It is clear that the ‘ist’ torque follows the ‘soll’ torque well but momentarily deviations may occur.

Figure 3.9: correlation of ‘soll’ and ‘ist’ torque, show over the cycle




The accumulated work calculated over a test cycle is an important value as in current emission legislation limits are defined as brake specific emissions; emission per engine work delivered. The table below shows the values for the engines work determined in a few different ways; on the left the available reference values and on the right the measured and calculated values. All values are within 1%. The largest difference occurs between the repetitions of the two ETCs.

| Work from denormalised cycle and manufacturers lug curve | Work from simplified rule of thumb $W_{ETC}$=0.17*Pmax | Work measured +calculated $W_{dyno}+W_{losses}$ ETC #1 | Work measured +calculated $W_{dyno}+W_{losses}$ ETC #2 |
|---|---|---|---|
| 59.8 | 60.2 | 60.3 | 59.4 |

## 3.5 Repeatability of PEMS

### *3.5.1 Duplicate PEMS tests on the road*

Two reference trips, both started with a warm engine, were driven with the vehicle on the same day; one in the morning and one in the afternoon. The PEMS results were analysed with the EMROAD tool applying the pass-fail ISC method as defined for Euro V engines and using the same tool to calculate the distance specific emissions (g/km) over a complete trip. The results were also analysed with the binning method. This is a method were the $CO_2$ specific emissions are calculated per speed interval of 5 km/h.

<u>Repeatability using the In-Service Conformity data-evaluation with EMROAD</u>

The pass fail evaluation as performed with the EMROAD tool shows a reasonable repeatability. For $NO_x$ the difference between two consecutive road tests and pass fail evaluations is about 20%. For CO this is about a few percent and for HC the values are very low. The trip criteria, presented below in the table vary somewhat.

| | | **Trip 1** | **Trip 2** |
|---|---|---|---|
| Reference Quantity | | $CO_2$ | $CO_2$ |
| Reference Value | | 39 kg | 39 kg |
| Threshold | | 3060 sec | 3060 sec |
| | | | |
| THC_AVG | [-] | 0.01 | 0.01 |
| THC_MIN | [-] | 0.01 | 0.01 |
| THC_MAX | [-] | 0.06 | 0.01 |
| **THC_90% CUMULATIVE PERCENTILE** | **[-]** | **0.02** | **0.01** |
| CO_AVG | [-] | 0.75 | 0.85 |
| CO_MIN | [-] | 0.54 | 0.68 |
| CO_MAX | [-] | 1.00 | 1.01 |
| **CO_90% CUMULATIVE PERCENTILE** | **[-]** | **0.92** | **0.95** |
| NOx_AVG | [-] | 0.63 | 0.54 |
| NOx_MIN | [-] | 0.58 | 0.50 |
| NOx_MAX | [-] | 0.84 | 0.73 |
| **NOx_90% CUMULATIVE PERCENTILE** | **[-]** | **0.67** | **0.56** |
| | | | |
| Window Max. Duration | [s] | 3060 | 3060 |
| Window Min. Duration | [s] | 2457 | 2503 |
| Number of valid windows | - | 3010 | 3002 |
| Percentage of valid windows | [%] | 90 | 98 |
| Data Coverage Index | [%] | 97 | 99 |

EMROAD v4 build 8. Settings; bsfc 200 g/kWh; data exclusion; engine coolant temperature <70C, altitudes >1500m.

<u>Repeatability of the trip</u>
The trip characteristics show very little variation. The most important difference observed is the small difference in average speed and hence the difference in trip duration.

| | | **Trip 1** | **Trip 2** | Difference |
|---|---|---|---|---|
| Trip duration | [s] | 6213 | 5903 | -5% |
| Trip distance | [km] | 74.729 | 74.766 | 0% |
| Average speed | [km/h] | 43 | 46 | 5% |
| Average temperature | [ºC] | 24.4 | 26.2 | 7% |
| Average humidity | [%] | 58 | 51 | 12% |

The distance specific emissions vary and may have been influenced by the average speed. Generally, at a higher average speed the $CO_2$ and the $NO_x$ emission are lower. The variation for $CO_2$ and fuel consumption is about 5% and for $NO_x$ 20%.

| | | **Trip 1** | **Trip 2** | Difference |
|---|---|---|---|---|
| HC | [g/km] | 0.1 | 0.0 | -100% |
| CO | [g/km] | 5.8 | 5.8 | 1% |
| $CO_2$ | [g/km] | 1078 | 1034 | -4% |
| $NO_x$ | [g/km] | 2.5 | 2.1 | -19% |

<u>Repeatability of the data-binning method</u>

The repeatability of the data-binning data processing method for both trips is demonstrated by the figures below. Trip 2 has a higher average speed which can be clearly explained by the shift towards higher speeds from 70 km/h onwards. The $CO_2$ specific emissions vary per speed bin and the amount of variation differs per emission component. For $CO_2$ and $NO_x$ the amount of variation is not so large, although for some bins even $CO_2$ emissions vary around 30%. The HC emission differs quite substantially between the trips. This is caused by a period of 10 minutes at the beginning of trip 1 were the HC emission is very high. Also the $NO_2$ emission varies. Mainly at lower speeds for trip 1 the $NO_2$ is substantially lower. Both trips were started with a warm engine after a warming up, but the data indicate a difference in catalyst temperature at test start. Maybe for test 1 the catalysts were not warmed up sufficiently, resulting in a lower $NO_2$ and a higher HC.

Figure 3.10: distribution of the data points of trip 1 and trip 2 over the speed bins

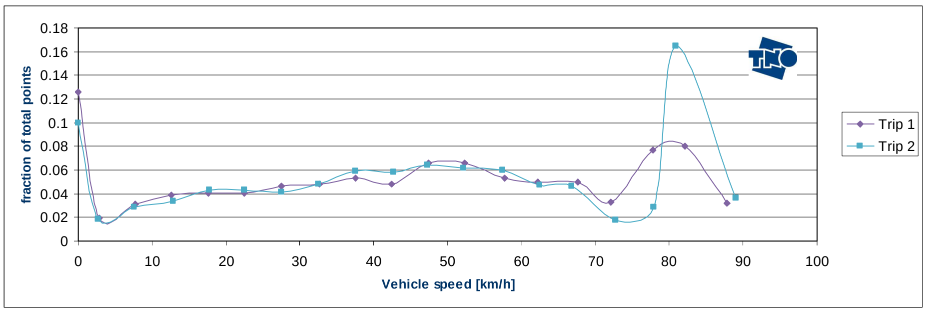



Figure 3.11: speed binned $CO_2$ emission of trip 1 and trip 2

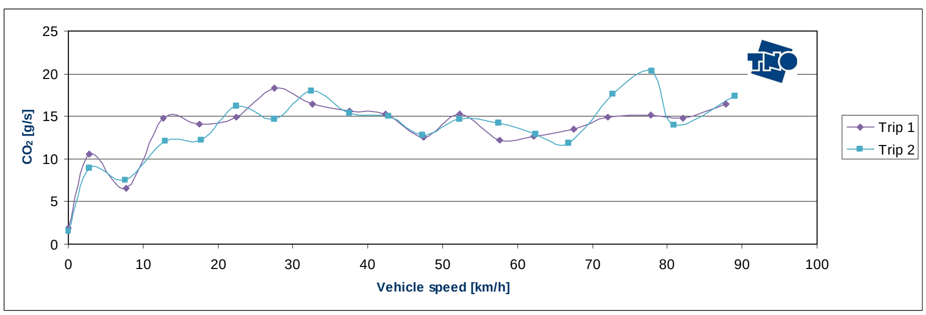



Figure 3.12: speed binned $CO_2$ specific $NO_x$ emission [g/kg] of trip 1 and trip 2

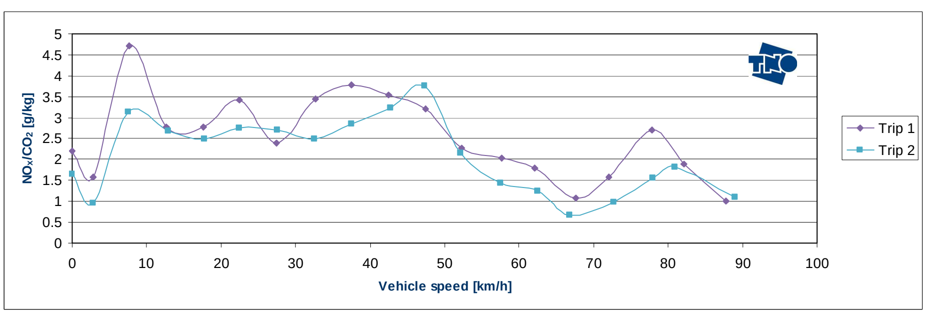


Figure 3.13: speed binned $CO_2$ specific $NO_2$ emission [g/kg] of trip 1 and trip 2

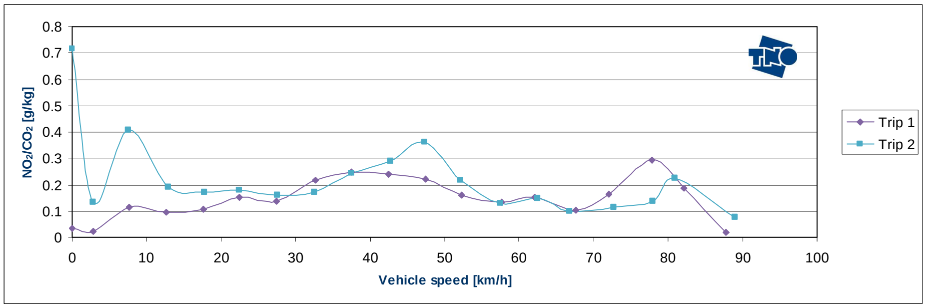



Figure 3.14: speed binned $CO_2$ specific CO emission [g/kg] of trip 1 and trip 2

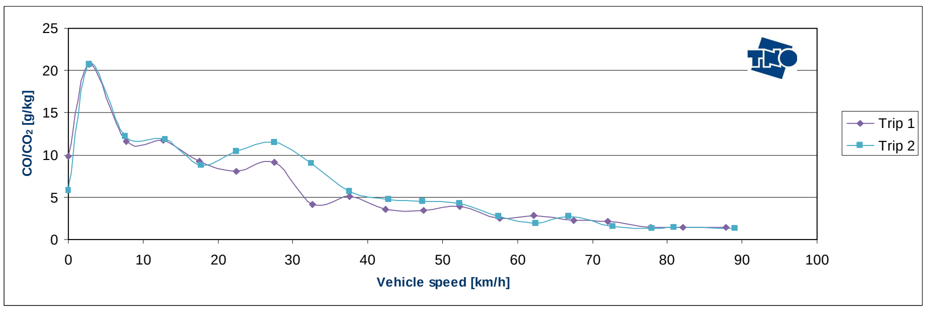
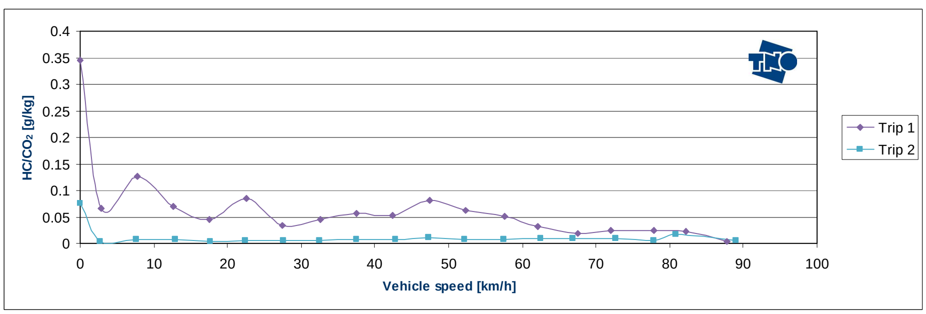



Figure 3.15: speed binned $CO_2$ specific HC emission [g/kg] of trip 1 and trip 2




### 3.5.2 *Duplicate tests with PEMS on the Powertrain Test Bed*

Most engine cycles on the PTTB were performed twice. The PEMS was mounted during these tests and thus these PEMS results allow an assessment of the repeatability of PEMS measurements under operation conditions that are far more repeatable than trips on the road.

For $CO_2$ the variations of the PEMS are small. For $NO_x$ the same variations were noted for the measurement with PEMS and the PTTB (CVS) which indicates that the variations are mainly caused by the vehicle and that the PEMS equipment itself has little variation and a good repeatability. For HC the relative variation is high but caused by the low emission levels. The min-max variations of PEMS and the PTTB CVS during the identical tests are demonstrated in the table below.

| Min-max variation PEMS | FC | $NO_x$ | CO | HC | $CO_2$ |
|---|---|---|---|---|---|
| ETC | -0.2% | -2.1% | -9.1% | -140% | -0.1% |
| Steven | 0.4% | -20% | 10.4% | 54% | 0.4% |
| PEMS cycle | 0.5% | 61% | -2.8% | -110% | 0.5% |
| | | | | | |
| Min-max variation PTTB | | | | | |
| ETC | -0.2% | 0.0% | -3.3% | 200% | -0.8% |
| Steven | 0.4% | -24% | -8.5% | 140% | 0.4% |
| PEMS cycle | 0.2% | 64% | -14% | #DIV/0! | 0.3% |

## 3.6 Repeatability of the Powertrain Test Bed

The repeatability of the PTTB could be determined from two different test programmes. Repeatability in this case consists of the variation of both the test method and the test object (test vehicle).

Results available of two test programmes were used to investigate repeatability. One programme contained several driving cycles which were tested in duplicate. For another test program two fuels were compared. Each test was performed in triplicate.

The engine work is generally well within 1%, with exception of the ETC cycle of the first test programme (1.5%). Here the engine work may have been influenced by active auxiliaries. The exact cause is not known. Variations for BSFC and $CO_2$ are around one percent and lower, with one outlier at almost 2%. This is the same test were the engine work deviates the same amount.

For $NO_x$ the variations are mostly a few percent higher, but with some strong variations in the first test programme over two cycles. With an SCR system on board, a test object may become less stable in terms of emission variation. An SCR system stores and uses urea to reduce $NO_x$. Such storage effects may influence emission levels from test to test for $NO_x$ and $NO_2$.

For HC and CO the relative variation is high but caused by the low emission levels of the vehicles concerned. For PM the relative variation is some 10-40%.

Table 3.1: test variation of the first test programme over various duplicate driving cycles

| | Work engine | Work dyno | BSFC | $CO_2$ | $NO_x$ | CO | HC | PM |
|---|---|---|---|---|---|---|---|---|
| ESC | 0.7% | 0.1% | 0.2% | 0.2% | 6% | 5% | 11% | 8% |
| ETC | 1.5% | -0.1% | -1.8% | -2.4% | -1% | -5% | -100% | -3% |
| Steven | 0.5% | -0.3% | -0.9% | -0.2% | -25% | -9% | 140% | 19% |
| PEMS | 0.1% | 0.0% | 0.0% | 0.3% | 64% | -14% | -46% | 16% |

Table 3.2: test variation of the second test programme over triplicate ETC cycles; absolute and percentage standard deviation and absolute and percentage min-max variation

| | | Work dyno | BSFC meter | $CO_2$ | $NO_x$ | CO | HC | PM |
|---|---|---|---|---|---|---|---|---|
| STDEV kWh, g/kWh | Fuel A | 0.04 | 0.4 | 0.4 | 0.03 | 0.03 | 0.002 | 0.002 |
| | Fuel B | 0.06 | 0.2 | 2 | 0.01 | 0.01 | 0.001 | 0.005 |
| STDEV % | Fuel A | 0.1% | 0.2% | 0.1% | 2.1% | 11.9% | 145% | 8% |
| | Fuel B | 0.1% | 0.1% | 0.3% | 0.5% | 3.2% | 173% | 20% |
| | | | | | | | | |
| Min-max kWh, g/kWh | Fuel A | 0.07 | 0.7 | 0.8 | 0.06 | 0.05 | 0.005 | 0.004 |
| | Fuel B | 0.12 | 0.3 | 4.1 | 0.02 | 0.01 | 0.002 | 0.009 |
| Min-max % | Fuel A | 0.1% | 0.3% | 0.1% | 4.3% | 22.1% | 266% | 14% |
| | Fuel B | 0.2% | 0.2% | 0.6% | 1.0% | 6.3% | 300% | 40% |

## 3.7 Powertrain Test Bed driveline and auxiliary losses handling

An engine test differs from a PTTB test in the fact that at the PTTB additional losses or loads occur in the driveline and from auxiliaries. To simulate an engine test on a PTTB these losses should therefore be either compensated online by the dyno control or minimized to an agreeable extend.

Differences between an engine test and a PTTB test occur from:
- Operation of auxiliaries like the engines cooling fan, the compressed air system, generator, HVAC, etc.
- Inertia of the driveline from hub to and including the gear box
- Friction of the driveline; kinetic joints, bearings, gear friction, pumping losses (diff/transmission oil).

ECE R24 describes which auxiliaries should be active during an engine test. In general those are the auxiliaries that are needed to operate the engine, like a cooling water pump, fuel pump, injection system, electrical system including ECU, the exhaust line, pollutant control devices, intake, including flow measurement devices, EGR, intercooler and the engines coolant fan, etc. Generally, however the engine coolant fan is not used at an engine test and engine coolant is provided from an external source. The air compressor may provide air for an SCR system, but an air compressor is never included in an engine test.

### *3.7.1 Auxiliaries; electrical load*

There is a difference in electrical load if an engine is run on an ETB or runs as mounted in its vehicle on a PTTB. Differences occur from the equipment that needs to be electrically powered to operate the vehicle instead of the engine alone. This includes for example the operation of cabin lighting, instruments, on-board systems, vehicle related ECU’s (e.g. gear box ECU), control and actuation.

For a test procedure where an accurate simulation of engine load according to a normalized engine test cycle is important one could decide to minimize and accept a minimal electrical load of the on-board systems; here it is recommended to first investigate the contribution to work and load over the test cycle by measuring current from the battery/alternator. Another option is to feed the battery from an external source so that the alternator does not need to deliver power to the electrical system of the vehicle.

### 3.7.2 *Auxiliaries; compressed air system*

The compressed air system usually consists of a compressor, an accumulator (air tank) and valves with control to operate the pneumatic systems on board, like the brakes, suspension, gear box operation, clutch operation and air assist for the SCR system. On a PTTB the brakes, suspension, clutch and gear box normally take little to no air from the system during a test cycle. An air assisted SCR system, if mounted, may use some air during a test. The compressors capacity depends on the demand for air on board for the various systems; the compressors load and duty cycles determine the actual contribution to auxiliary work. The compressor work was investigated and power losses formulae have been developed in the project “Diesel controle methode” (DCM) [10]. They have been redefined in the in-use compliance project of 1994-1995 [11] and again in the project of 1998-2000 [12]. The final power loss formula that can be used for compensating the work for the compressor work is.

$$P_{compressor} = P_{engine,max} \times (N_c \times 0{,}0090 \times (n/n_{max}))$$

with:

| | | |
|---|---|---|
| Nc | = number of cylinders of the air compressor |
| n | = actual engine speed |
| n | = nominal engine speed |

On a PTTB most of the systems require little to no air during a test cycle, with exception of the air assisted SCR system. For a test procedure where an accurate simulation of engine load according to a normalized engine test cycle is important one could decide to accept a minimal compressor load if an SCR system is active; here it is recommended to first investigate the contribution to work and momentary load. One could also compensate the contribution to the work, using the above mentioned formula. Another option is to feed the air system from an external source which keeps the system pressure above the compressors threshold at which it switches on.

Even at no compressor activity a compressor may put an additional load to the engine by the friction torque at compressor ‘idle’ or stand-by.

### 3.7.3 *Auxiliaries; air conditioner*

The mobile air conditioner may take off a significant amount of power under real operation. At the PTTB the MAC and other climate functions can be switched off. Still there may be some additional friction if the MAC compressor is operated over a fixed belt-pulley-clutch construction of belt and pulley under zero load if the MAC clutch is open.

### 3.7.4 *Auxiliaries; engine cooling fan*

Next to other auxiliaries an engine cooling fan consumes a certain amount of energy during normal operation on the road. The fans energy consumption may be required for including it in the total energy balance of a vehicle.

To determine the fans contribution to the energy consumption one would like to know its input power in relation to its speed and also its activity over time. To determine the power in relation to speed one can measure the engine output with and without the fan. Fan activity would namely cause the engines output to decrease as some of the engines output is required to propel the fan.

During an emission test on a HDV (e.g. on a chassis dynamometer) the fan may be uncoupled in some cases, but depending on the actual construction of the fan drive clutch this may not always be possible. Often a fan can be uncoupled from the crankshaft if it is fixed drive with an on and off type of clutch. In such a case the electrical clutch actuator can be controlled to achieve an 'on' or 'off' situation. If a clutch is of a viscous type the fan speed behaves partly independent from the engine speed. Some fan drives also have a distribution ratio.

The fan drive and clutch of the tested Mercedes has a fixed drive ratio and has a viscous clutch. The fan could not be uncoupled during the tests to achieve a pure on or off situation to be able to calculate the fan load.

*Tests*

To calculate the fans power over speed, steady state points where run with the vehicle on the power train test bed. During the tests engine torque and fuel consumption were monitored accurately. During these steady state points the fan speed fluctuates due to the cooling demand. Resultantly, the power output measured at the dyno's and the FC change. The power balance of these signals determines the power absorbed by the fan and the fan drive. In some cases the cooling fan in front of the vehicle was used to increase or decrease the cooling demand to force the fan to switch either 'on' or 'off'.

Figure 3.16: a 350 kW Heavy Duty vehicle at the power train test bed. Note the external cooling fan, with a maximum capacity of 100.000 $m^3$/hour, that was used to influence the cooling

*Fan clutch slip*

The graphs below show the fan speed in relation to the engine speed during three different tests. These pictures clearly show the amount of slip of the viscous clutch. The pictures show a low fan speed (maximum slip) of the fan of about 150 $min^{-1}$ increasing to above 200 $min^{-1}$ towards higher engine speeds. It should be noted that the fan in front of the vehicle might have influenced this speed a little. Although during the tests the cooling fan in front of the vehicle was shut off a few times no fan speed drops were detected towards zero meaning that there is indeed a maximum slip condition where the fan stays above a certain speed. From the graphs a maximum slip of about 85-90% can be noted.

For the steady state Artemis points and the ETC the fan did not reach very high speeds and all of the time there was a certain amount of slip. The highest fan speeds were measured during the fan test where the external cooling was reduced on purpose to force the fan to operate at maximum. During that test the maximum fan speed was at engine speed (slip ratio of 1 or 0% slip) but there still is some slippage at the highest engine speed. It is not sure if for these speeds also a zero slip situation would have been reached at an even higher cooling demand.

Figure 3.17: fan speed a different engine speeds during the fan test, indicating the slip of the viscous clutch

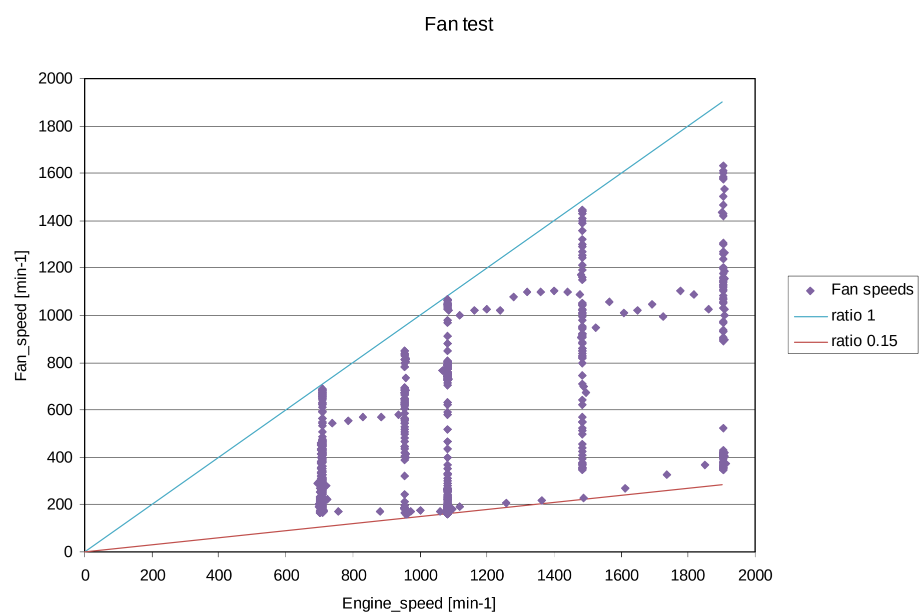


Figure 3.18: fan speed a different steady state engine speed of the Artemis test, indicating the slip of the viscous clutch

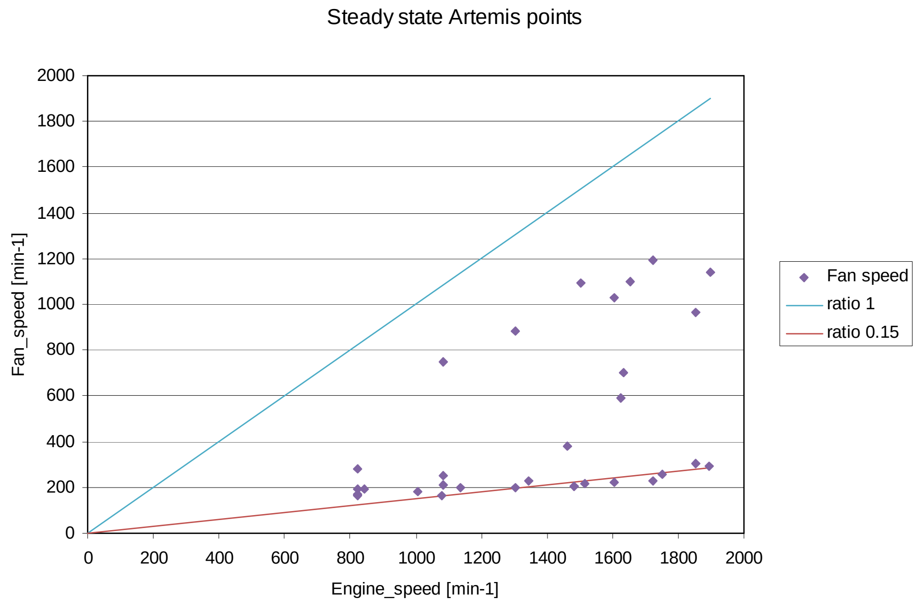
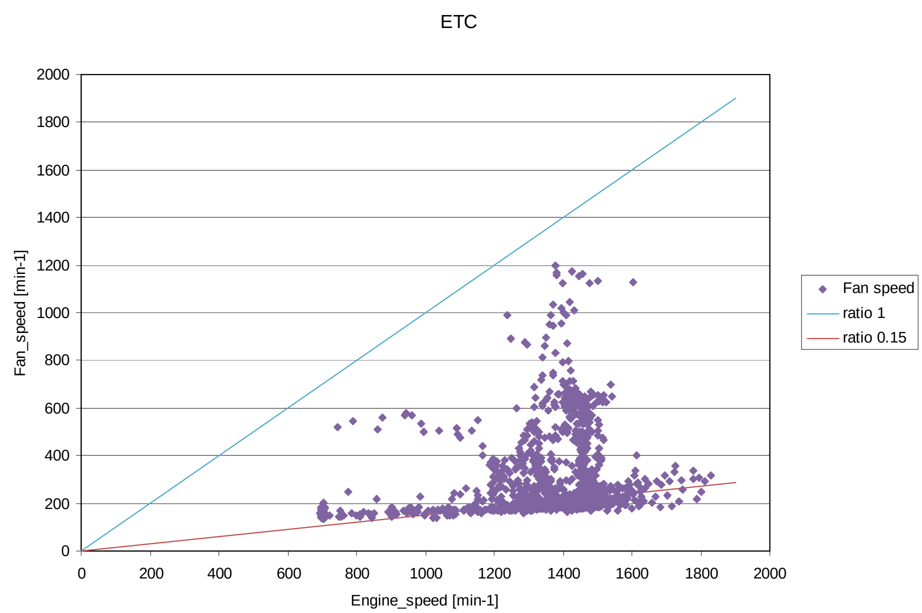



Figure 3.19: fan speed and engine speeds during the ETC, indicating the slip of the viscous clutch




*Fan power*

The fan input power is composed of;

- the actual fan power
- (viscous) clutch slip
- friction/drag in drive belts, bearings
- inertia

SAE J1342 (Method for Determining Power Consumption of Engine Cooling Fan Drive Systems) [13] describes a method to calculate the Fan power. SAE J1339 (Test Method for Measuring Performance of Engine Cooling Fans) [14] describes a test method to measure the fans power on a dedicated test bed.

In SAE J1342 the fan input power is determined by

$$\text{Total Power} = (N_i - N_0)(N_0^2)(K) + (N_0^3)(K) + P_1$$

with;

- $(N_i - N_0)(N_0^2)(K)$ = Slip/drag power
- $(N_0^3)(K)$ = Fan power
- $N_i$ = Input speed
- $N_0$ = Fan speed
- K = Fan constant
- $P_1$ = Power loss associated with the fan drive system minus the fan and clutch but including belts, pulleys, and pulley bearings
- “K“ fan constant is obtained by dividing fan power by the (fan speed)3 required to consume that power.

On a power train test bed all variables can be determined with exception of the fan constant K, because the power absorbed by the fan alone cannot be distracted from the total input power. To determine K one should test a fan on a dedicated test bed (J1339). For the purpose of a simplified emission model for the energy balance of a vehicle a less accurate approach may suffice.

The steady state fan input power in relation with fan speed has been approximated from the transient fan behaviour using the change in measured engine power, the power (heat) caused by a change in FC and the power caused by inertia of the fan during the fan transients at a fixed engine speed (1900 $min^{-1}$).

$$P_{fan\_steady} = \Delta P_{engine} - \Delta P_{fuel} - P_{inertia\_fan}$$

Because the engine speed is fixed during the tests, all fan speeds below the engine speed include loss due to slip. At lower engine speeds the same fan speed may therefore be achieved with less slip and thus less loss.

In the graph below the steady state fan power in relation to engine speed is approximated by the red polynomial trend line. The inertia of the fan, although it can reach momentarily high values, had a minimal influence (difference blue and red line) on average.

Using the resulting function for the power absorption by the fan in relation to fan speed e.g. during the ETC the total work amounts about 0.6 kWh which is 1% of the total engine work of that cycle. For other cycles the work ranges from about 0.3 to about 0.6 kWh depending on the cycle.

Figure 3.20: total power absorbed by steady state fan power operation (red line), approximated using the change in measured engine power (purple line), the change in power from the fuel (brown line) and inertia of the fan

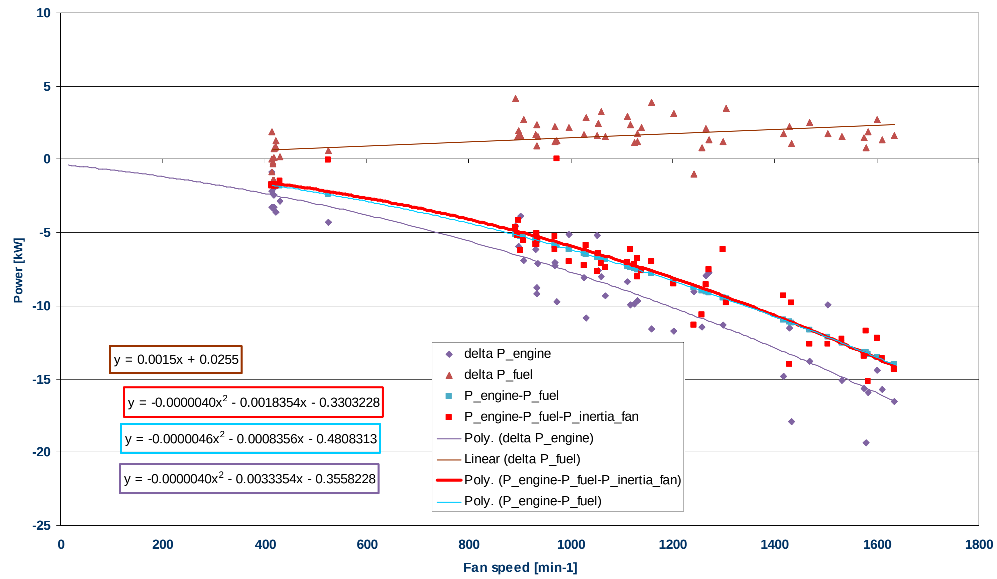
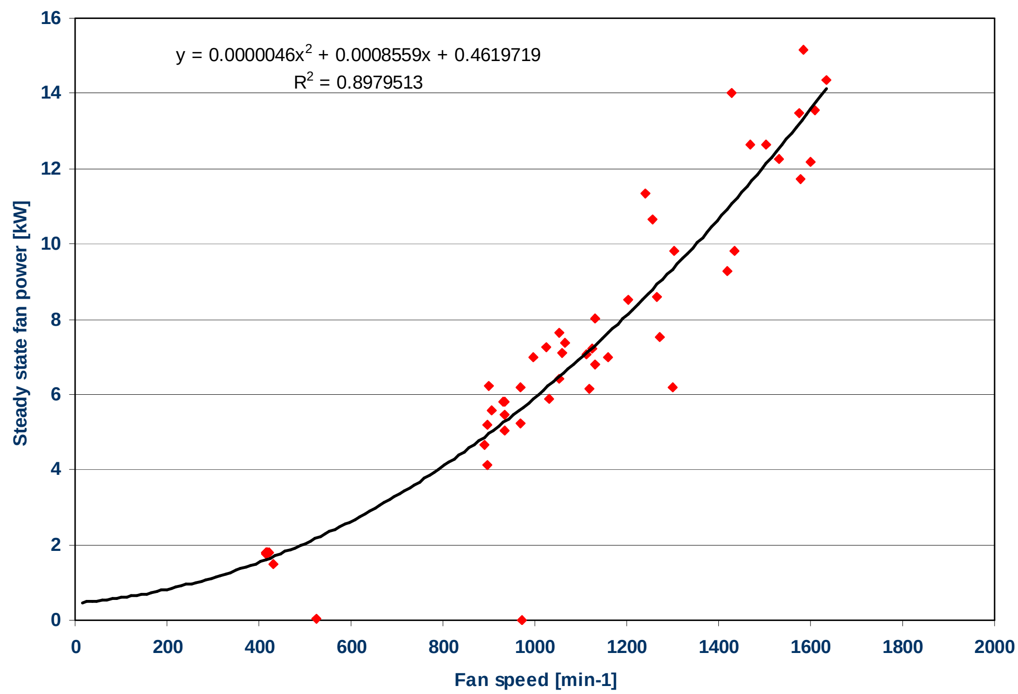



Figure 3.21: approximated absorbed total steady state fan power as a function of fan speed, including slip from the viscous clutch



*Conclusions:*

- An engine cooling fan drive absorbs a significant amount of energy over a driving cycle. The contribution to total cycle work was in the range of 0,5 to 1 %.
- A simple fan model may suffice to model the absorbed fan power. For the fans contribution to the total energy balance, however, it is not yet clear if engine and technology type influence the required cooling power or operational activity and as such it is not clear if they should be compensated for if this influence becomes significant.
- To drive a legislative normalised engine cycle accurately with the engine mounted in a vehicle a cooling fan should be deactivated or online compensated for in the dyno control.
- If fan activity is not compensated when testing a vehicle on a chassis dyno, driving a normalised engine cycle, the simulated engine load may become somewhat too high during occasions with fan activity (Torque_soll = Torque_engine_ist - Torque_fan - Torque_other_losses). Compensation afterwards (to correct the measured work) requires fan speed to be measured online and requires the fans power absorption curve.
- The engine cooling fan activity probably depends on the actual cooling provided by an external cooling device (drive wind simulation), ambient conditions and load on the engine.
- The actual fan activity on the road may also differ depending on the conditions mentioned.
- For the determination of fan power over fan speed of a fan in a vehicle on a chassis dyno, steady conditions and a clear ‘on and off’ segregation are preferred. For a fan with a viscous clutch such conditions are hard to achieve.
- If a viscous clutch is mounted there is loss due to slip. This loss and the contribution to total engine work over a test cycle is not known.

### *3.7.5 Inertia losses*

To calculate and to control the flywheel torque for an accurate engine test with the engine mounted in the vehicle the drivelines inertia should be known. Sometimes this value is known through the manufacturer, but the driveline inertia can also be approximated by a special procedure.

The Work required to accelerate the drive line and to decelerate the driveline by the dyno is measured by the dyno’s and is of course as much as two times the work caused by inertia. Knowing the dyno’s work by measurement, the inertia work and hence the inertia itself can be calculated.

To accelerate: $W_{friction}+W_{inertia}=W_{dyno(acc)}$
To decelerate: $W_{friction}-W_{inertia}= -W_{dyno(dec)}$

$$W_{friction}+W_{inertia}-W_{dyno(acc)} = W_{friction}-W_{inertia}+W_{dyno(dec)}$$
$$W_{inertia}-W_{dyno(acc)} = - W_{inertia}+W_{dyno(dec)}$$
$$2*W_{inertia} = W_{dyno(acc)} + W_{dyno(dec)}$$

With the vehicles clutch open, the dyno’s accelerate and decelerate the driveline. The work at the dyno’s and the angular accelerations are measured so that the unknown inertia J can be calculated;

$$J = W_{inertia} / (dw/dt * w_{avg} * dt)$$
$$J = 0.5 * (W_{dyno(acc)} + W_{dyno(dec)}) / (dw/dt * w_{avg} * dt)$$

### 3.7.6 *Friction losses*

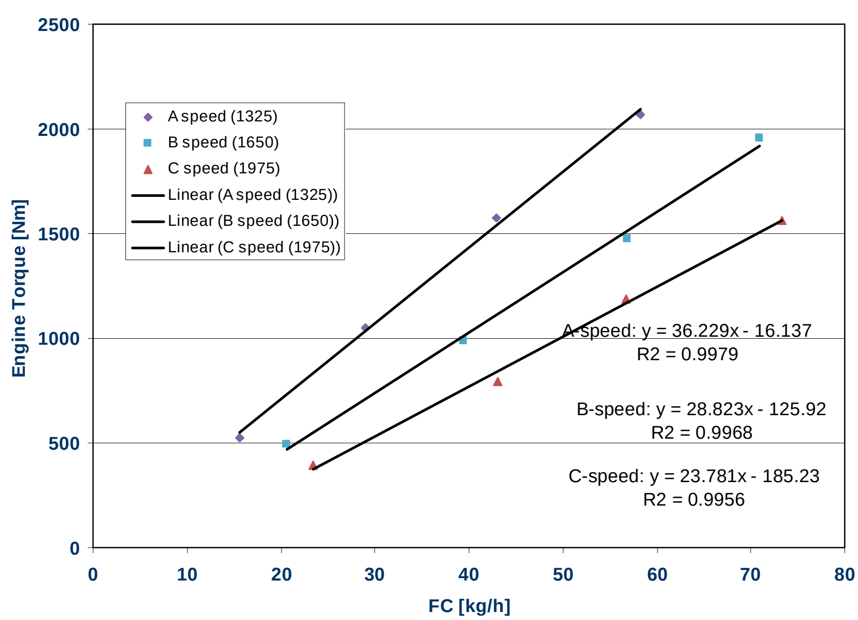
The friction losses cannot be measured on the PTTB under heavy load.
The steady state friction losses under no load can be determined by propelling the driveline with the clutch open, a gear engaged and measuring the dyno torque. The dyno torque measured is representative for the free spinning friction of the driveline in the given gear.

An experiment was done with an engine mounted on the engine test bed and an engine mounted in a vehicle on the PTTB to compare both situations. If it is assumed that the engine has a stable behaviour considering power delivery and BSFC, one can deduct the power train friction by comparing both situations. For both situations the dyno torque and fuel consumption were measured accurately over steady state points.

At full load at the engine test bed the dyno torque is more than the dyno torque measured at the PTTB; the difference is the friction of the drive line.

At partial load the dyno torque was kept the same for both situations. Resultantly, the engine as mounted in the vehicle experiences more load because the drive line adds friction. The additional load at the engine on the PTTB can be calculated from the difference in fuel consumption for the given individual partial load points and the relation between torque and fuel consumption (Willans lines) at fixed engine speeds, as measured on the engine test bed.

Figure 3.22: relation between measured engine torque and fuel consumption




The following graph shows the calculated static drive line friction losses for a DAF XE Euro III engine mounted in a chassis with a manual gear box. The friction under load is heavily related to engine speed and only little to engine load. This means that at light loads the relative importance of this friction becomes substantial, see the second graph.

Figure 3.23: calculated absolute static drive line friction losses

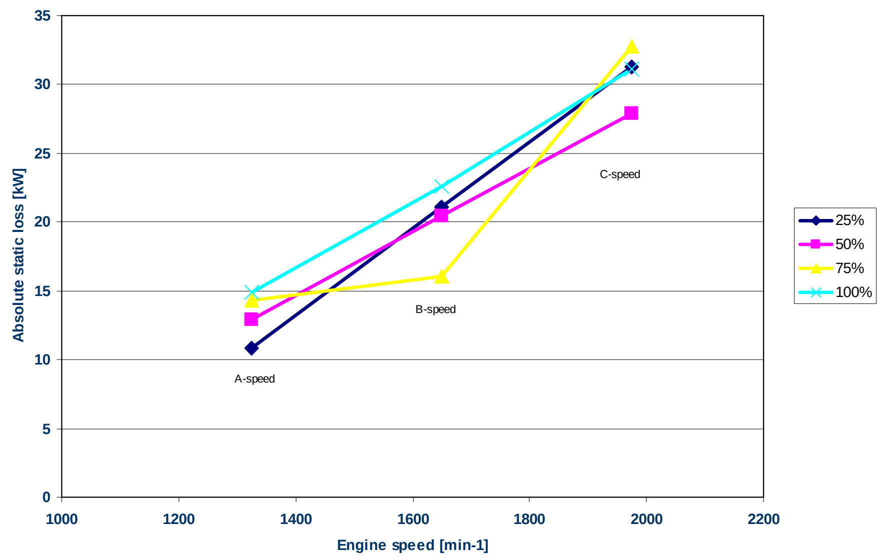
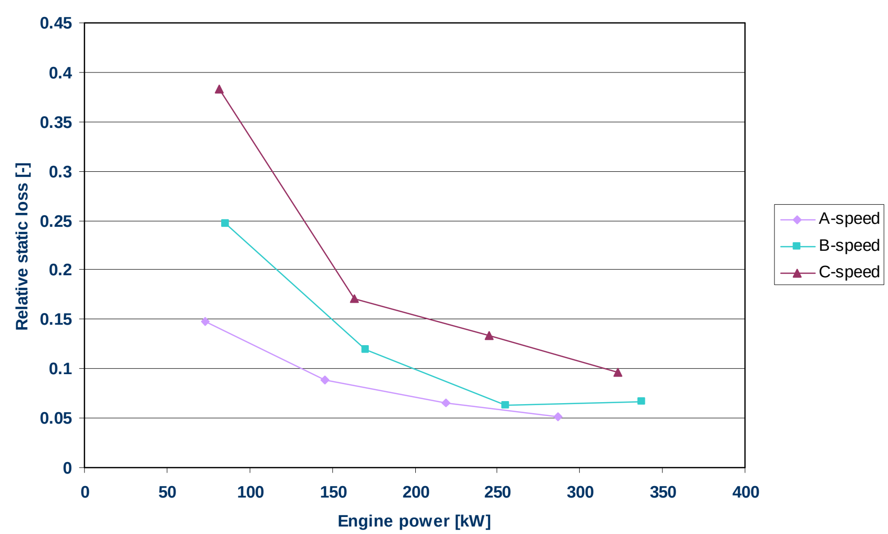
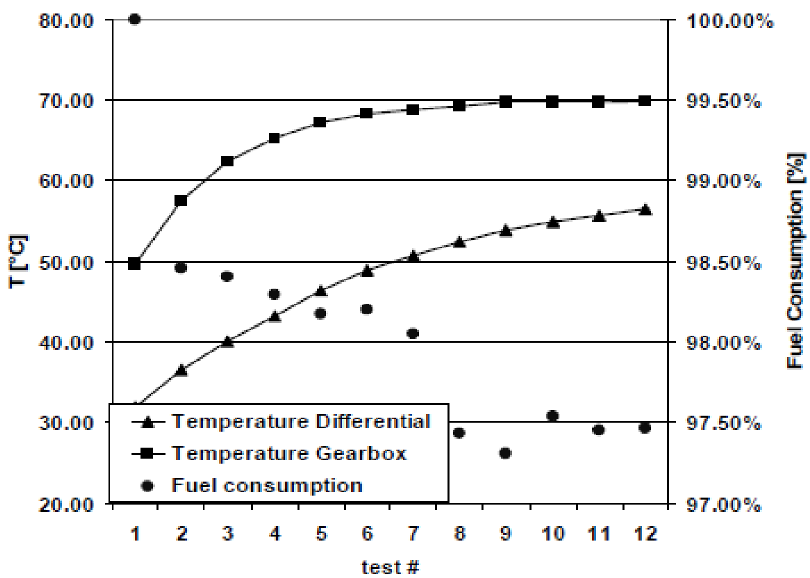



Figure 3.24: relative static friction loss of the drive line




Another test programme, which has to remain anonymous, shows the importance of the warming up of the drive line for the determination of fuel consumption and $CO_2$ emission. After 12 successive tests of the ETC highway part, which in total lasted 2 hours, the gear box temperature is stabilised and the rear axle temperature is almost stabilised. The fuel consumption drops one percent due to the decrease of the friction over this two hours testing period.

Figure 3.25: driveline temperature during 12 successive tests, and its influence on fuel consumption




*3.7.7 Other factors to take into account*

- Intake or charge air temperature
- Temperature of the cooling medium

For an engine test on an engine test bed there are requirements for the intake air temperature or charge air temperature if the engine has charge air cooling. On an engine test the intake air temperature factor 'fa' is calculated and must be within certain limits. The charge air temperature must be within 5K of the temperature as defined at max power. The cooling medium must be at least 293K. If a legislative test has to be simulated on a PTTB these conditions have to be met. Otherwise deviations from these conditions may influence the emission results.

## 3.8 Remote Emission Sampling

*3.8.1 Test programme*

Despite the fact that the RSD 4600 system is used in the USA very frequently, there are many reasons to validate the results. The remote emission measurement system still is a new test method for TNO.
First of all, before the measurement results of the RES system can be used for validating vehicles exhaust gas emissions or modelling purposes one needs to have a clear understanding of

- accuracy of the measurements
- repeatability and reproducibility
- relation to PEMS or laboratory tests

In order to investigate the results of the RES system, various different measurements have been performed. The measurement programme allows the comparison of the RES results directly to the PEMS and laboratory measurement results and to VERSIT+ emission predictions:

1) **Traffic compared with VERSIT+ predictions:** On a location in a large city in the Netherlands the RSD4600 system was installed on two subsequent days. The traffic on this specific location was travelling at almost constant speeds between 30 and 50 km/h. The results have been analysed and compared to the TNO emission model (VERSIT+) predictions.
2) **Light duty RES and laboratory measurements:** Two light duty vehicles have been tested on the chassis dynamometer. Subsequently, the exhaust gases of these vehicles were frequently measured by the RSD4600 system under various speed and acceleration conditions. The technical details of these vehicles are described in Table 3.3.

Table 3.3: Light duty vehicles tested in the laboratory and with RES

| | BMW | Citroen |
|---|---|---|
| Model | 3 series | Picasso |
| Engine | 1995 CC | 1560 CC |
| After treatment | Catalyst | DPF |
| Fuel | Diesel | Petrol |
| Euro Class | Euro 4 | Euro 4 |
| First registration | 01.07.2008 | 07.06.2007 |

3) **Heavy duty RES and PEMS measurements.** Two heavy duty vehicles, a Euro V Tractor and a Euro IV 12t delivery truck, were equipped with the PEMS (Semtech DS) system. The vehicles passed the RSD4600 system under various speed and acceleration conditions. The exhaust gases were measured with the PEMS and RSD4600 system simultaneously.

Table 3.4: Heavy Duty Vehicles tested with PEMS and RES

| | Vehicle 1 | Vehicle 2 |
|---|---|---|
| Vehicle type | Tractor trailer 40t GVM | Rigid delivery truck 12t GVM |
| Engine | 350 kW | 132 kW |
| After treatment | SCR | EGR |
| Legislative Category | N3 Euro V | N2 Euro IV |

The Euro V Tractor passed the remote emission sensing equipment frequently. The speed of the truck was chosen from 10 to 50 km/h with intervals of 10 km/h. At each speed, the truck passed with constant speed, moderate acceleration, nearly full acceleration and under decelerating conditions. Every measurement was repeated three times to investigate repeatability and to increase the reliability of the measurement value.
The Euro IV 12t delivery truck was also measured by RES and PEMS and made frequent passes of RSD 4600 system. These measurements were performed in a city centre and therefore the speed range is limited.

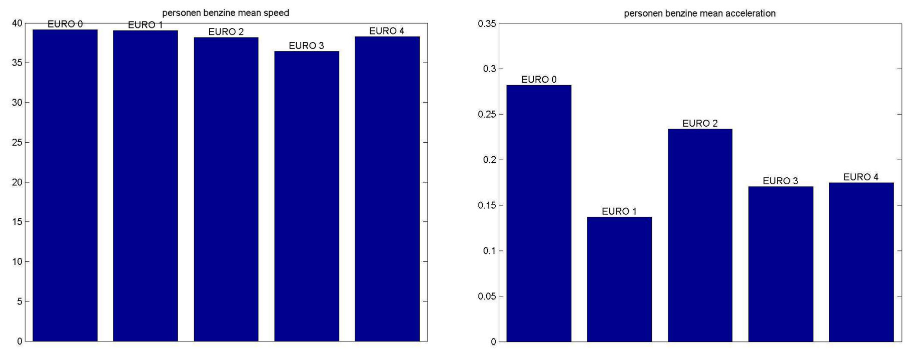
Figure 3.26: Euro IV 12t delivery truck passing the remote emission sensing equipment


### *3.8.2 Results light duty measurements*

On a location in The Hague (the Netherlands) the RSD system was installed on two subsequent days. The location behind this crossing is not very favourable for a RES measurement session as vehicles have low dynamics (low speeds, limited accelerations). This causes a low signal for the RES measurement when a car passes the RSD system. Therefore, there might be a relatively small number of valid RES measurements. Nevertheless, exhaust gases of approximately 4500 light duty vehicles have been measured. A total of approximately 7000 light duty vehicles have passed the remote emission sensing system during the measurements, so the detection ratio of the RES measurement at this specific location was around 65%. For each single vehicle, the remote emission sensing results are linked to the technical details of the specific vehicles. In this way the speed, acceleration, ratios of $NO/CO_2$, $HC/CO_2$ and $CO/CO_2$ and vehicle specifications such as fuel type and Euro class are known. The VERSIT+ emission model was used to calculate the emissions of HC, CO and NO for each individual vehicle as well. In this way the RES results for different Euro classes and different fuel types can be compared to the VERSIT+ predictions. The measurement uncertainties as well as the fluctuations arising from using the $CO_2$ emission rate of the VERSIT+ class of the cars measured rather than that of the car itself (which is not available), are expected to average out when aggregates per VERSIT+ class are considered, provided the various classes are sufficiently populated.

First of all the average speeds and accelerations per Euro class are compared. The figure below shows that the observed average speeds are similar, the average acceleration of especially Euro 0 en Euro 1 differ from the other Euro classes. The differences in accelerations influence the average emissions per Euro class. As the VERSIT+ emission model takes into account speed and accelerations, the comparison between RES measurements and VERSIT+ results is still well possible.

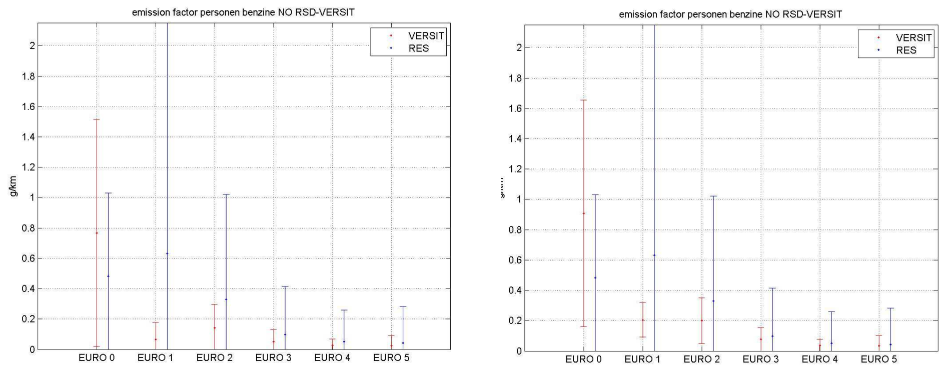
Figure 3.27: comparison of the average drive by speed and acceleration of the petrol vehicles of different Euro classes




The $NO/CO_2$ ratios of the petrol vehicles have been measured by the RES system. Based on the measured speed and acceleration the NO and $CO_2$ emission of each individual vehicle was calculated with the VERSIT+ emission model as well. The measured $NO/CO_2$ ratio was multiplied by the VERSIT+ predicted $CO_2$ emission. In this way, the NO emission of all passing petrol vehicles has been calculated. The figures below shows the measured and (VERSIT+) predicted emission values. Two different calculated values are shown, one without cold start correction (left picture) and one which takes into account the cold start effects (right picture). The average values and the range $\pm 1\sigma$ are shown for Euro 0 to Euro 5 petrol fuelled vehicles.
For Euro 2 to Euro 5 the VERSIT+ predicted NO values (with and without cold start effect) correspond well to the RES measurements. The average values are very similar. The range of the RES NO measurements is larger. This can be explained by variation of real world vehicle emissions compared to the “average” emission model values. The RES measurements will also suffer from noise on the measurement values.
For Euro 0 and Euro 1, the VERSIT+ predictions without cold start effect correction are within the range of RES measurements, but the average values differ. After cold start correction the average values of the VERSIT+ prediction and the RES emission for Euro 1 petrol vehicles matches slightly better. The average of the VERSIT+ NO calculation for Euro 1 vehicles is significantly lower than the average NO value based on the RES results.
The results of the RES measurements also contain negative values. This is the result of noise on the measurements and a result of the method to calculate the emission values, because the emission value is calculated by subtraction of the measured ‘after- minus before’ values.

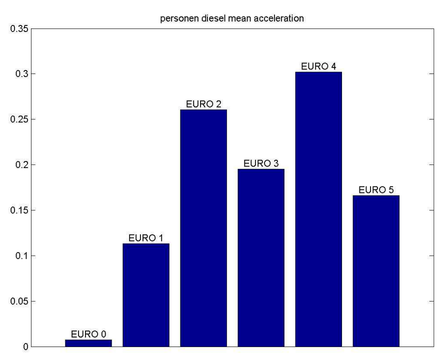
In the plots, the error bars (+/-) correspond with an assumed Gaussian distribution of the measured values around the mean. In reality, the distribution is skewed since emissions are always positive and can attain very high positive values as well (caused by high emitters).

Figure 3.28: VERSIT+ predictions versus RES measurements of petrol passenger cars, left without, right with cold start correction



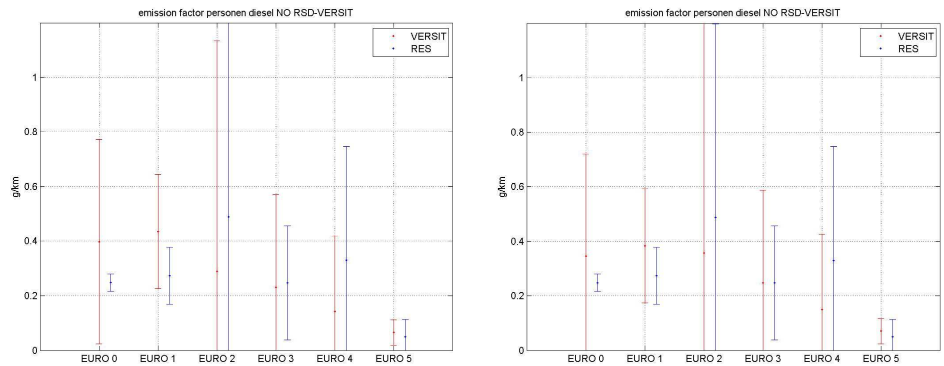

For diesel vehicles, the same analysis was made. The average acceleration per diesel Euro class does vary significantly. Especially for Euro 0 (pre Euro 1) vehicles the average acceleration is very low. As explained before, this does not influence the comparison between the VERSIT+ emission values and the RES measurement results.

Figure 3.29: average acceleration for light duty diesel Euro classes




The VERSIT+ emission model predictions do match the RES emission measurement values reasonably well, especially after cold start correction.

Figure 3.30: VERSIT+ predictions versus RES measurements of diesel passenger cars for the given measurement location. The left picture without and the right picture with cold start correction




*Light duty laboratory measurements compared to RES measurements*

Two light duty vehicles have been tested in the emission laboratory on the chassis dynamometer. These vehicles have passed the remote emission sensing unit frequently as well. This allows a back to back comparison between the RES measurement results and test results on a chassis dynamometer. Both vehicles have passed the RES system under various speed and acceleration conditions. The figures below depict the driving speed/acceleration conditions of both vehicles when passing the RES system.

Figure 3.31: speed and acceleration of the BMW when passing the RSD system

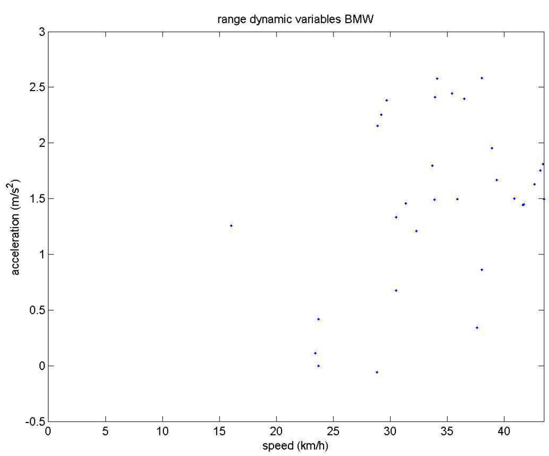
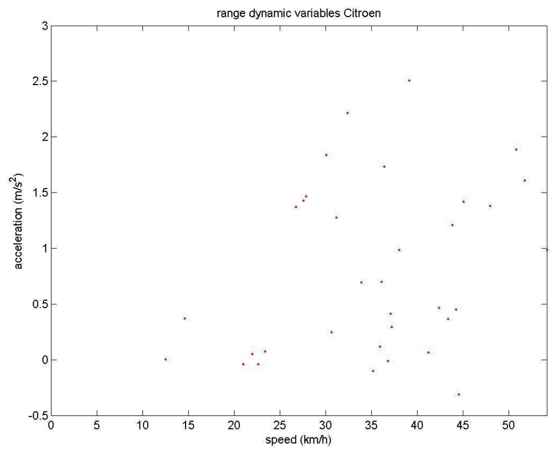
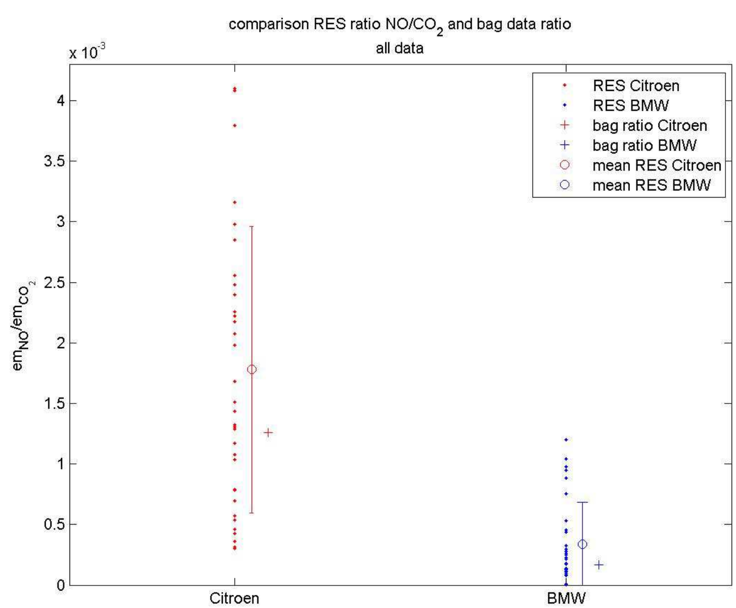


Figure 3.32: speed and acceleration of the Citroën when passing the RSD system




*Comparison of RES measurements with modal mass laboratory measurements*
Though specific gas emissions may vary largely, depending on the dynamic quantities, ratios of gas emission rates are usually more universal. Especially, there is a strong correlation between the NO and $CO_2$ emission rate. In the figure below, the $NO/CO_2$ ratios for the various passages of the Citroën and the BMW (dots: RES measurements), as well as the average for each car (open circle) and an error bar corresponding to +/- one standard deviation are depicted. The ratio of the bag result of the laboratory measurement is indicated with a plus-sign (+).

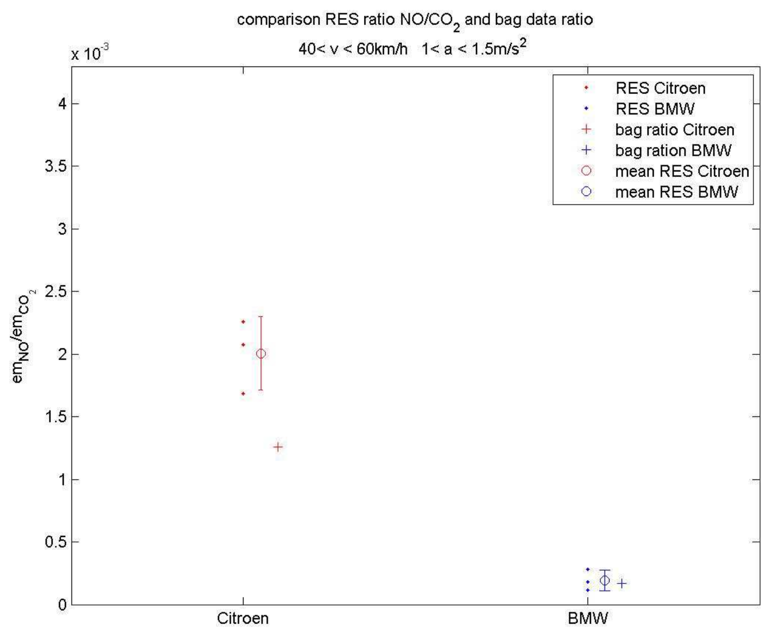
Figure 3.33: comparison of RES measurement results and the average $NO/CO_2$ ratio of laboratory measurements




It can be concluded that the orders of magnitude for average RES ratio, average modal mass ratio and modal mass proportionality factor are comparable. It can also be concluded that there is a large spread between individual measurements. This makes a distinction between the Citroen and the BMW based on the RES ratio for $NO/CO_2$ solely difficult.

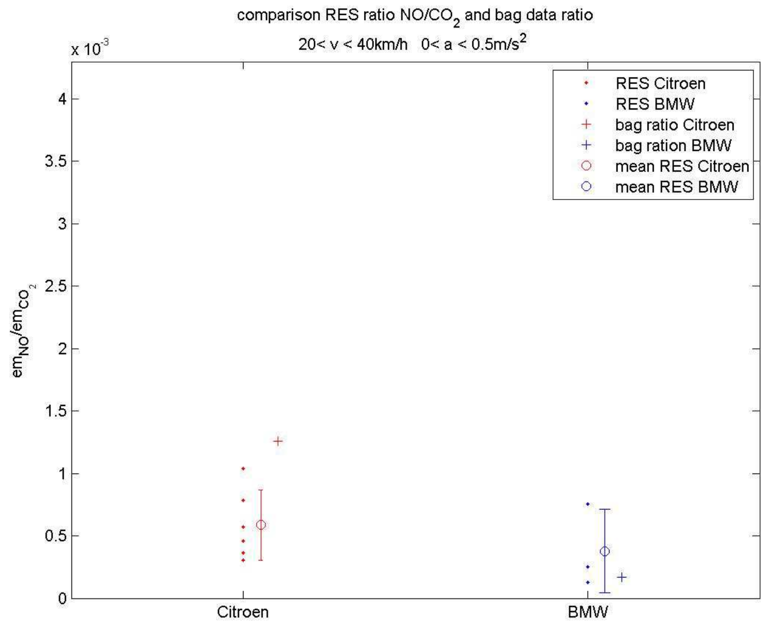
A distinction between the vehicles becomes considerably easier if dynamic variables are included. In the figure below, the RES measurements are plotted for which the dynamical parameters of the passing car are in the v-a window 40 km/h < v < 60 km/h and 1 m/s < a < 1.5 m/s (dots).

Figure 3.34: comparison of RES measurement results and the average $NO/CO_2$ ratio of laboratory measurements




Based on this picture, the Citroën and the BMW can now be distinguished based on their emission behaviour, if speed and acceleration are taken into account as well. The RES ratios in the v-a bins are in good correspondence with the modal mass mean ratios. However, if the speeds and accelerations are low, the distinction cannot longer be made, even when v-a bins are employed, as can be seen from the figure below, for 20 km/u < v < 40 km/u and 0 m/s < a < 0.5 m/s.

Figure 3.35: comparison of RES measurement results and the average NO/CO2 ratio of the laboratory measurements




The figure shows that within this v-a bin the measured ratios for Citroën and BMW are more or less the same within the measurement error.

This seems to confine the uses of the RES techniques to situations where there is a lot of dynamics, i.e. when the cars are accelerating and emissions are generally high (thus guaranteeing a high signal to noise ratio.) This corresponds to the recommendation of the manufacturer of the RES equipment, to perform RES measurements on a ramp.

### *3.8.3 Results heavy-duty measurements*

*Comparison of RES measurements with PEMS measurements.*
Heavy duty trucks, a Euro V Tractor and a Euro IV 12t delivery truck, were tested with RES and PEMS at the simultaneously. Using the license plate information, passage times for the trucks could be retrieved from the RES data files. The corresponding data points in the PEMS data (speed, gas rates) were obtained and for each passage past the RES equipment, the RES emission ratios and the PEMS emission ratios were determined.

The figure below depicts measured $NO/CO_2$ ratio of RES and PEMS of measurement of the Euro V Tractor and the Euro IV 12t delivery truck during acceleration. The connection between the data points is a guide to the eye and has no physical significance.

Figure 3.36: Euro V tractor Remote Emission Sensing (RES) data compared to PEMS data (right: moving average of 5 seconds)

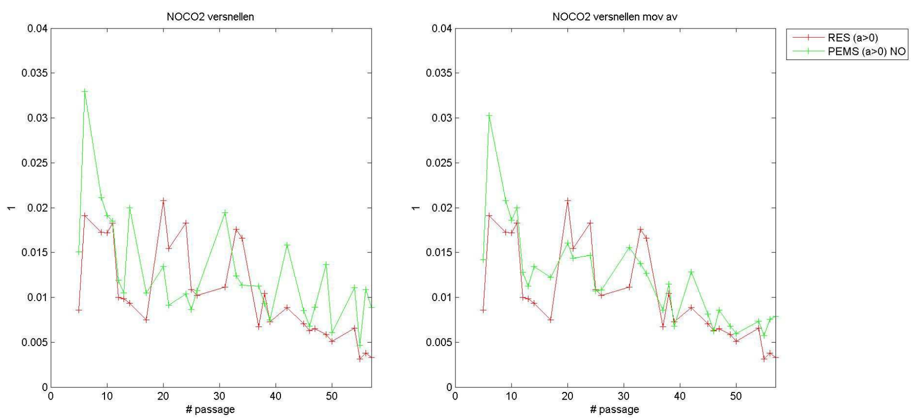
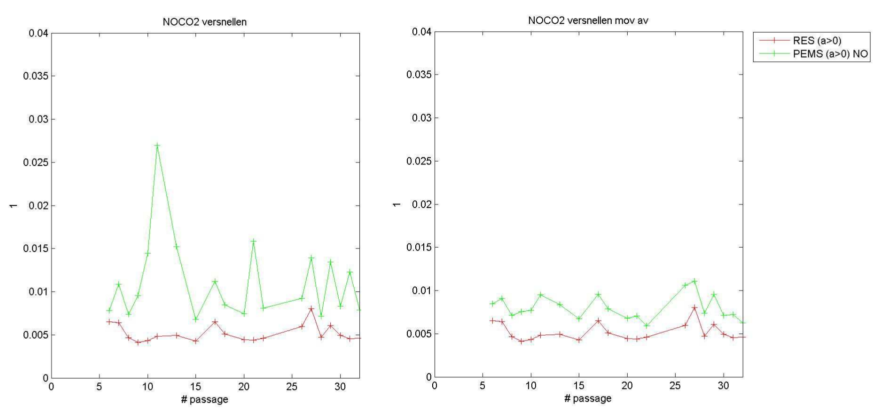


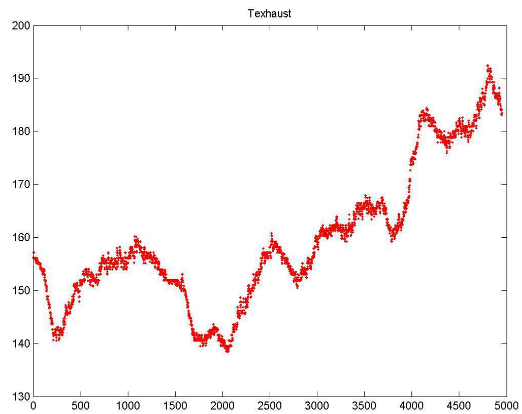

Figure 3.37: Euro IV 12t delivery truck Remote Emission Sensing (RES) data compared to PEMS data (right: moving average of 5 seconds)




From this results comparison it can be concluded that the NO/$CO_2$ ratios of the PEMS and RES measurements are in the same order of magnitude but show a weak correlation.

Further, the results show that the Euro V tractor is not performing better than the Euro IV 12t delivery truck, though this was expected based on the emission reduction technology of both vehicles. This phenomenon might be attributed to the catalyst of the Euro V tractor not having reached its working temperature of 200-250 degrees C during the simultaneous measurements with RES and PEMS, as depicted in the figure below.

Figure 3.38: exhaust gas temperature of the Euro V tractor, measured with PEMS during the simultaneous PEMS and RES measurements

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The Euro IV 12t delivery truck is equipped with EGR emission reduction technology, which efficiency depends less on exhaust gas temperature than the SCR technology of the Euro V tractor.

Another way to depict the correlation between PEMS and RES data of one vehicle measured at the same time, is to plot RES data against PEMS data, as in the graphs below. Especially when the calculated 5 second moving average values of the PEMS measurements are compared to the Remote Emission Sensing measurement values, a reasonably good correlation is found. The improvement of the correlation of the data when a 5 second moving average is applied to the PEMS data, can be explained with some knowledge of the PEMS measurement principle. PEMS measures exhaust gas flow and pollutant concentrations with separate devices with a sample frequency of 1 Hz. Both values are used to calculate gram emissions, where the flow and concentration data should be time aligned. The quality of the time alignment fluctuates during the measurements, the application of a moving average on the emission results, improves the overall quality of the results.

Figure 3.39: comparison of Euro V tractor RES and PEMS measurement data, left: second based PEMS data, right: 5 second moving average PEMS data.

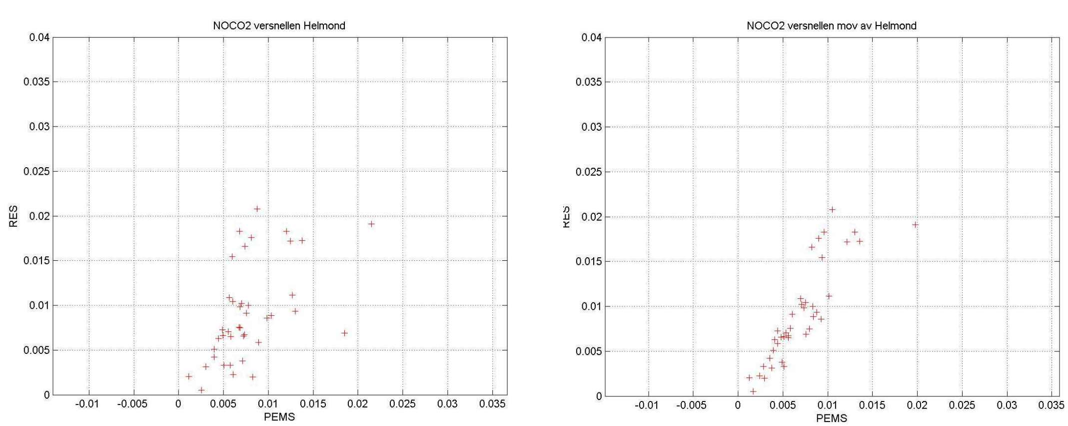
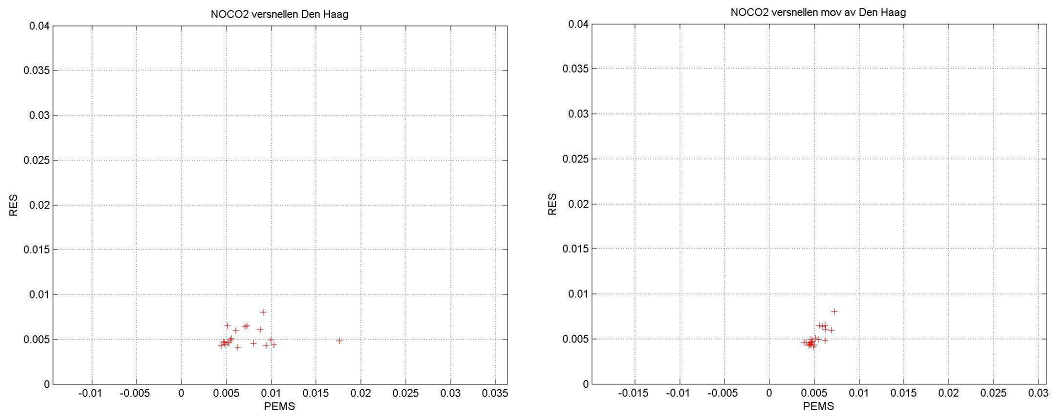


Figure 3.40: comparison of Euro IV 12t delivery truck RES and PEMS measurement data, lhs second based PEMS data, rhs 5 second moving average PEMS data



# 4 Discussion; suitability and recommended practises

It was found that clear differences exist between the available emission testing methods. The main differences between the test methods exist for accuracy and repeatability/reproducibility and for (real world) representativeness. It is therefore very important that the test method is chosen which best suits the goal of the test programme. Furthermore, results of tests should always be judged in the light of the capabilities of the test method used.

Clear procedures should be established if accurate and representative values for emissions are required. Possibilities are to accurately define the preconditioning and to perform multiple tests, the latter to determine the variability of the test object or to correct for accumulation effects in e.g. modern after treatment systems or batteries.

## 4.1 General issues for emission testing of modern HD vehicles

Emission data of recent tests on Euro V HD trucks showed emission variations caused by variation of the test object itself rather than variations from the test. For instance, the instantaneous and cumulative $NO_x$ emission levels over test cycles or even complete PEMS trips of about two hours are affected substantially by the thermal state of the SCR catalyst but possibly also by the catalysts actual urea load (chemical state).

It was found that both the conditioning of the vehicle and after treatment influence the results substantially. The test object in this investigation, a Euro V HD tractor with an SCR system, showed substantial variation from test to test. For $NO_x$ the warming up of the after treatment has a large influence, but also the history of the after treatment seems to play a role if an SCR system is mounted.

For PM it was already known that the conditioning of the after treatment and the measuring equipment may influence the result substantially.

For an accurate determination of $CO_2$ or FC the warming up time of the driveline and engine influences the result.

A generally accepted method to condition an engine or a vehicle for a warm emission test in a laboratory is to drive the same test cycle in advance of the emission test cycle over which emissions are sampled. The first preconditioning cycle allows to stabilize engine and after treatment to a given and reproducible state as obtained after that cycle. Still, this may lead to a result with a bias for $NO_x$. If the preconditioning ended with very warm highway driving, the first part of the real test cycle over which emissions are sampled, may be started very warm and lead to a negative $NO_x$ bias for vehicles equipped with SCR. An option is to perform consecutive tests of only urban cycles, then rural cycles, etc. or to precondition with the first part of a test cycle or multiplications of that part (often an urban driving cycle). Then, a vehicle can stabilize thermally for the given driving conditions. Still, accumulation or history effects may interfere. The same problem exists for hybrid vehicles where the battery acts as an accumulator for energy. However, the State of Charge of the battery can be measured and can be corrected for. The chemical state of an SCR catalyst (or the soot loading of a DPF or DOC) cannot be measured objectively and when a certain accuracy of the emission level is required it becomes inevitable to perform multiple tests to learn as much as possible about the emission stability of the test object.

For cold started tests the thermal condition of the SCR catalyst at test start can be reproduced very well. The chemical condition of the SCR, however, may still vary, depending on the (recent) driving history.

## 4.2 Portable Emission Measurement System (PEMS)

PEMS is versatile tool. However, it has to be used with care. Main points for attention for use of PEMS in the Netherlands In Service Testing Programme are;

Safety
Driving around with bottles of combustible gas (FID fuel), high pressure bottles, hot and sharp modified flow meter / tail pipe constructions and taped down lines, all temporarily mounted on a vehicle under time pressure leads to safety risks. The risks need to be known and dealt with to minimize them to a level which is agreeable for the lab in service.

Accuracy
The PEMS used for this investigation is less accurate then a laboratory set-up.

The EFM of the PEMS shows a significant deviation of about +5% from the exhaust mass flow as calculated from the measured air and fuel flow at a laboratory set-up.

The mass emissions can be substantially influenced by the time alignment between the EFM (Exhaust Flow Meter) and the measured concentrations at the analysers. The alignment should always be checked. For further analyses of the data where e.g. actual vehicle speed or torque is used, further checking of the alignment between GPS / CAN signals is important as well.

From experience it was found that the CO and $NO_2$ analyser may drift up to 20ppm. When emission levels get very low this drift may be a substantial part of the result. For very clean Euro V HD engines with $NO_x$ levels around 100-200 ppm the level may be acceptable. If a Euro VI engine would have levels lower than 50ppm the error would become so substantial that it can be doubted if it still is accurate enough for detailed analyses of $NO_x$ performance. According the ISC rules the drift may be corrected linearly over a trip. At the moment newer and also more stable analysers are available when one wishes to measure very clean trucks more accurately.

The $CO_2$ analyser showed a deviation of about 2% from the lab analysers. Together with the difference of the measured exhaust flow of about 5% this added up to differences in $CO_2$ mass emission between PEMS and lab of about 5-9%.

The CO analyser of the PEMS is not suitable for HD diesel vehicles. The measuring range and resolution are too high and better suitable for gasoline vehicles for instance. However, considering the low levels of the CO emission of HD diesel vehicles, one may question the importance of this measurement.

The THC measurement showed relatively large variations between PEMS and lab, but like for CO the measured level was low.

Repeatability and reproducibility
A PEMS has limitations with regard to repeatability. A PEMS trip lasting about 6000seconds, like the TNO reference trip, can be repeated within approximately 5-10% for average speed, FC and $CO_2$ emission. The $NO_x$ emission varies more and may vary about 20-40% between two of the same trips. It has to be noted that this may also have been caused partially by the earlier mentioned variability of the vehicle. The Conformity factor also varies 20-40% between two trips. Somewhat lower variations have been observed in the laboratory as well. These tests were well reproduced test cycles. Probably, the conditioning of the SCR and driving history play a large role and influence the result substantially.

CAN signals
For one brand no CAN communication could be established. In that case the engine power cannot be calculated and one can only calculate distance specific and $CO_2$ specific results. For a lot of vehicles there is not a complete set of CAN signals available. Also in those cases the engine power cannot be calculated. Often, some of the CAN signals have to be converted to metric units. This issue shall be addressed in future legislation, to secure the e.g. the possibility for national authorities to perform stand alone in service testing with all vehicle types and brands.

Procedure
Clear and strict procedures should be established for PEMS to ascertain the best outcome and to avoid risks of misuse and misinterpretation. The procedures are required to ensure the correct use of PEMS and the correct application of a test, including application of the trip, conditioning and also e.g. correct application of driving style. Important is the moment of calibration of the instruments, preferably this is done before and after a trip. Also important, as for other testing methods, is the conditioning of the vehicle. Furthermore, the trip composition and order of sub-trips influences the result and as such should be chosen and analysed with care. Data-management becomes important with the large amount of data coming from PEMS. But not only the measurement data itself is important also, clear descriptions of the test object, test conditions, OBD checks, logs of error codes, liquid samples and a log book are important to obtain and store in a consistent manner.

For the calculation of the in-service Conformity Factor (CF) a tool (EMRoad) can be used. This is an excel macro which allows to import measurement data in the sheet to perform a pass-fail calculation according the applicable pass-fail method for in-service conformity. The use of this tool is not without risks for making mistakes. There are many settings and variables can be changed manually. This can result in different outcomes of the pass-fail result (CF). It is recommended to integrate the checking of the tool in the (laboratories) quality system and to include the checking of the settings in the standard procedure of the test programme.

## 4.3 Powertrain Test Bed

Here the main issues are described that should be considered for the development of a testing method using the power train test bed applied in the Netherlands In Service Testing programme.

The main function of the PTTB for the NL HD In Service Testing programme will be the simulation of legislative cycles to check the conformity of the emissions over these cycles. Engine tests of Euro V engines on an ETB remain decisive for real ISC but like done in the past an alternative procedure can supply enough information to screen emission performance. In the past only the simulation of steady cycles was possible. Nowadays, the new PTTB enables the simulation of all legislative test cycles, including the transient ones, given the condition that the power train losses and auxiliaries are approximated accurate enough and corrected for.

<u>Repeatability and reproducibility</u>
For $CO_2$ and FC the repeatability is generally within 1% and can be further improved when the test object is conditioned to a fully warmed up drive line. Fully warming up a drive line takes more than an hour and the consumption of time is a factor to take into account when defining a testing programme.

For $NO_x$ and PM the test object may show variability from test to test. For both components variations of about 20-40% were observed. It has to be noted that this may also have been caused partially by the earlier mentioned variability of the vehicle, as was also observed during the PEMS tests. To establish accurate figures a repetition of tests is required, preferably starting with a preconditioning with the same test cycle.

<u>Power train losses and auxiliaries</u>
Clear procedures should be established to compensate for these losses.

## 4.4 Remote Emission Sensing

Vehicle emissions were measured with the Remote Emissions Equipment. Large numbers of light duty vehicles were tested at the road side and the results were compared to the output of the TNO VERSIT+ emission model. The emission model is based on thousands of emission measurements performed in an emission laboratory, is extensively validated and can be used as a reference. In this report remote emission sensing results were also compared directly to emission measurements performed on a chassis dynamometer and to measurements performed with Portable Emission Measurement System;

<u>Heavy duty PEMS-RES comparison results</u>
With the two trucks that were equipped with PEMS and that passed the RES system frequently, it was demonstrated that the results of both systems correlate reasonably well. However, in quite some occasions also significant differences can be found. Time alignment of the PEMS and RES signals proved to be rather complex and very critical. When a moving average of 3 or 5 seconds is used on the PEMS emission data, the correlation between PEMS and RES becomes substantially better.

Results of light duty vehicles tested with RES and on the chassis dynamometer
Two vehicles were tested in the laboratory and the results were directly compared to the RES results for the same vehicles. This comparison showed a good correlation, especially for acceleration conditions.

Results of the light duty emission model compared with RES
The RES system measured emission of thousands of light duty vehicles. These results have been compared to the VERSIT+ emission model. The results correlate well on average. For some vehicle classes, especially petrol vehicles the RES results vary a lot more than the predictions of the emissions model. This is probably caused by a large variation in real world emissions of the specific vehicle fleet passing the RES system. Another explanation can be the limitation of the emission model; in the specific vehicle speed/acceleration range (accelerations are very limited) the model is not very sensitive to small changes in speed or accelerations. In future projects, the available laboratory measurements will be analysed to better understand these differences. And if necessary, the emission model will be tested and improved.

Most vehicles did pass the remote emission measurement system at low speeds with very moderate driving style. This is both for the RES equipment and for emission models an unfavourable situation because under these conditions, most vehicles emit only small quantities of exhaust gases. Under these circumstances the RES system has proven not to be sensitive enough to measure emission of all passing vehicles.

Taken into the account of the complexity of the different measurement systems, the unfavourable conditions at the remote emission test site (low speeds and very low accelerations of vehicles) the study still provides good insight in the capabilities of the RES system.

Main conclusions for suitability and recommended practice of RES
Based on all measurements and comparisons, the following can be concluded:

- The large number of light duty vehicle RES measurements were used to calculate average emission levels of vehicle classes, differentiated to fuel type and Euro classes. Taking into account the speed and acceleration conditions the average emission levels of HC, CO and NO measured by the RES system on average correlate very well with the VERSIT+ emission model predictions. Some individual vehicles showed high deviation from the VERSIT+ prediction, which might be caused by the spread of the emissions of the vehicles in de fleet. This indicates that RES might be a suitable tool to distinguish (the fraction of) high emitters in the vehicle fleet.
- The direct comparison of two light duty vehicles tested on the chassis dynamometer and with RES equipment shows comparable results. Especially when the vehicles accelerate ($a>0.5ms^2$) RES measurement results match well with laboratory test results. This indicates that in future measurement sessions the RES system should preferably be installed at a location where passing vehicles accelerate, in order to secure the most accurate results.

- When large numbers of vehicles are measured, the remote emission measurement system proofs to be a valuable source for validation of emission factors.
- The results of the heavy duty PEMS and the RES system measurements are quite well comparable for NO. In future measurement sessions, it should be investigated if RES has the capability of distinguishing (the fraction of) high emitters in the heavy duty vehicle fleet, and if RES can contribute to heavy duty emission factor models.

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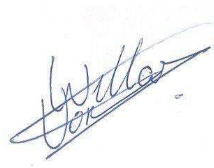
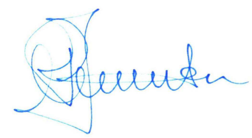
# 6 Signature

Delft, 21 August 2012





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