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Summary

The reduction of real-world fuel consumption of new passenger cars does not keep the same trend as the reduction of the type-approval values of the same cars. The difference between the real-world fuel consumption and the type-approval fuel consumption is growing. This divergence is well known but poorly understood. A large number of possible causes have been mentioned and examined in separate studies.

They fall mainly in one of the following (interlinked) categories:

- The inappropriate NEDC test procedure for the representation of the type-approval fuel consumption.
- The exploitation of test flexibilities by vehicle manufacturers to achieve low test results.
- The application of vehicle technologies which achieve low CO₂ values on the type-approval test but give limited reduction of real world fuel consumption, such as stop-start systems.
- The additional real-world fuel consumption due to auxiliary systems, excluded from the type-approval test, such as air-conditioning.
- The external conditions affecting real-world fuel consumption, which are not properly represented on the NEDC test, such as ambient temperature, wind, road surface, congestion, and market fuel properties.
- The car maintenance state and the real-world driving behaviour leading to an increase in the fuel consumption.

None of the individual categories above can fully explain the increasing gap between the type-approval value and the real-world fuel consumption. Many of the above aspects, such as the weather, have not changed much over time and are therefore excluded from the analysis of the gap.

The European Commission has contracted TNO and ICCT to examine the divergence and attribute it to the different contributing factors. This resulting study is an attempt of synthesis. Moreover, it looks forward to the WLTP as the new test protocol for type-approval of fuel consumption and to similar USA legislation. The complexity of the study has two main reasons. First, effects are a combination of many factors which influence each other, such that a comparison of two numbers for fuel consumption cannot be understood without providing their full context. Second, the study only relies on fleet-relevant data for comparisons, i.e. the type-approval values and the fuel consumption monitoring. Some manufacturers may exploit some flexibilities for the type-approval test of some models, but such results cannot be extrapolated to all vehicles.. The use of such anecdotal and technology-specific information is therefore avoided to the extent possible.

One conclusion of this study is that the small difference between the type-approval value and the real-world fuel consumption in the past is accidental and not a proof of the representativeness of the type-approval test for the real-world fuel consumption. Therefore, it is not surprising that the effects on real-world emissions of technologies which are reducing CO₂ emissions on the type-approval test are often limited.

Basically, higher CO₂ emissions on the NEDC test are related with low velocity and low engine load, a large amount of idling, and the cold start. In real-world, the effect of these factors is less outspoken, while driving at constant high velocities, lower temperatures, higher rolling resistance, use of auxiliaries, and a higher vehicle weight are the most important factors affecting emissions.

As a result, the emission reductions effective on the type-approval test are mainly achieved by aspects such as stop-start systems, reducing engine losses, and cold-start engine strategies. Moreover, reducing test weight, a low rolling resistance, optimised test execution, and minimizing alternator use (exploiting flexibilities), are additional gains on the type-approval test which are not affecting the real-world fuel consumption.

Other factors often linked to the increasing gap, such as the improper exploitation of test flexibilities, the use of air conditioning, and specially prepared vehicles and tyres may have a certain effect but do not explain the most part of the gap for the average fleet. For air-conditioning, a small effect is established from two independent data sources. The variation in tyres fitted to test vehicles, production vehicles, and available in the aftermarket is substantial, but this effect is limited in the total fuel consumption.

One main cause for the gap is the additional real-world fuel consumption related to high velocities. For example, small vehicles, with reduced weight and engine size do not have a relatively lower fuel consumption with this usage, but they do have a relatively lower type-approval fuel consumption. The precise nature and magnitude of the gap depend very much on the real world usage: the fraction of the urban distance and of the motorway distance determine most of the net effect and it is strongly affected by the vehicle and engine characteristics. A further important element are the low ambient temperatures adding to this effect due to the increased air-drag with lower temperatures.

In summary, the difference between the current type-approval and real-world fuel consumption can be attributed to four factors of similar magnitude: 1) different ambient conditions and vehicle usage and weight, 2) excluded factors from the type-approval test, 3) optimised testing within the test bandwidth, 4) NEDC test specific vehicle technology. The last two items have increased from 2007 onward and they are at the basis of the increasing divergence.

The WLTP is meant to limit the gap, and is expected do so for current vehicles optimised on the NEDC. Three effects are important: The higher vehicle velocities on the WLTP test, the higher vehicle weight on the test, and the more appropriate tyre prescription and conditioning. The retention of this improvement with the WLTP-based type approval will require continued attention. However, these factors account for less than half of the total gap. As the low load associated with constant driving and the cold start effect are limited under WLTP with respect to the NEDC, this will lower the CO₂ emissions on the WLTP.

The main conclusion from this study is that a test protocol alone cannot ensure a proper representation of the real-world fuel consumption due to the numerous interacting factors and their very large variability. The monitoring of vehicles in real-world usage would help to streamline the relation between type-approval and real-world fuel consumption. Vehicle state, vehicle usage, auxiliaries usage, and

ambient conditions are all known to affect fuel consumption beyond the test flexibilities. Monitoring these factors on randomly selected vehicles would facilitate a better understanding and assessment of the reasons behind the gap. Consequently, on the basis of such information, measures can be decided to reduce and limit the divergence.

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1 Introduction

1.1 Context

On 1 October 2014, the European Commission filed Service Request 6 (SR6), “Supporting analysis on real world light duty vehicle CO₂ emissions” under the “Framework contract for services in the field of analysis, assessment and policy development in relation to climate forcing impacts of light-duty road vehicles” (CLIMA.C.2/FRA/2012/0006).

The Service Request addresses the substantial and growing gap between the passenger car CO₂ emissions reported on the basis of type approval testing and the performance experienced in real world driving. Updated analyses suggest that there has been a continued increase of the divergence between type approval and real world CO₂ emissions, while also pointing to a possible difference between company and privately owned cars.

The measurement of fuel consumption at type-approval is an instrument to enable legislation to require the reduction of CO₂ emissions from road transport in Europe. It is not to be expected that precisely the same reduction is achieved for the real-world emission as in type-approval, but the two could be expected to follow similar trends. Evidence is accumulating, however, that type-approval and real-world fuel consumption are diverging, in all possible metrics: as absolute difference and relative or proportional to the type approval fuel consumption. Aspects not covered by the current type-approval test (like electrical consumers), cannot explain alone the current trends in fuel-consumption monitoring data. In this report this data is presented, and the attribution of the CO₂ emissions to different causes is made explicit as far as the data allow. Insight is provided on the aspects influencing fuel consumption and CO₂ emissions, and the intricate interplay between vehicle technology, vehicle usage, and circumstances, to arrive at a given fuel consumption in the variety of circumstances and tests.

Real-world vehicle-based fuel consumption data for passenger cars is not available Europe-wide and the few existing sources are not standardised. Much of the subsequent analyses are based on Travelcard Nederland BV fuel consumption data, consisting of: current mileage, date, and type and amount of fuel. This is fuel pass data made available to TNO from 2009 onwards. It concerns mainly company cars, which are a common job benefit in the Netherlands for employees. The cars span most of the vehicle sales segment, and are used generally on a daily basis. Company cars are typically at most four years old, and the employees are allowed to select a new car in a given market segment, every couple of years. The usage pattern does not change that much over time, and the group of drivers is rather constant. The average age of the car in the fuel consumption monitoring is about two years. In the past it was slightly younger, as with the economic crisis, the selection of a new car is less frequent.

The data available through Spritmonitor.de has been used as an independent validation of the identified effects. Spritmonitor.de is a free web service from Germany that allows users to track their fuel consumption based on odometer

readings and fuelling data. For a detailed discussion of Spritmonitor.de, see Mock et al. (2014).

Travelcard fuel pass data for the Netherlands shows an increasing gap between the type-approval value and the real-world fuel consumption over time (see Figure 1). The average 10%-15% difference it showed between real-world fuel consumption and type-approval value in 2004 has been the typical deviation for a long time, since the first reporting in the 1990's. Evidence shows that from 2008 both petrol and diesel real world consumption starts to deviate upward from the historic 10-15% divergence from the test value. The underlying fleet which is monitored has a typical average age of two years such that the increase in divergence may have started already in 2006, maybe slightly earlier for petrol cars.

Figure 1 clearly shows the substantial and growing gap between type approval and real-world fuel consumption. In 2008, an average vehicle used approximately 12% more fuel than in the type approval test, whereas in 2014 the average additional fuel consumption increased to approximately 40%.

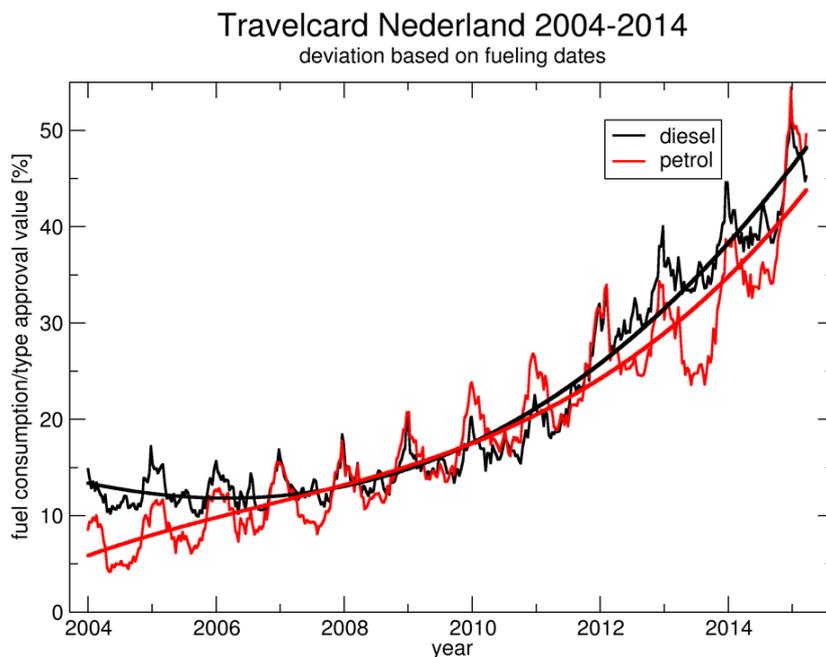


Figure 1 Average (per fortnight) of the additional fuel consumption per fuelling as percentage of the vehicles' type approval fuel consumption. Most vehicles are younger than four years and the monitored fleet has a typical average of two years.

This increasing divergence results in customer complaints to car manufacturers, a growing belief that the car labelling figures based on the test procedure are not relevant or misleading and that the CO₂ savings delivered under the EU car and light commercial vehicle Regulations are lower than expected.

In the past, a potential bias of this dataset regarding particular vehicle models which are considered sportive, or with varying behaviour with the annual mileage, has been examined. These effects are very minor. While the target group is a particular group of motorists who do not have to pay for their own fuel, it is large in the Netherlands accounting for almost half the total on-road mileage. The Netherlands have busy road and a rather strict enforcement of the speed limits. This reduces the variability of driving behaviour of the different road users. In many cases drivers must go with the traffic flow. For example, even in TNO test programs with specific instructions, such as eco-driving or sportive driving the variation in fuel consumption and average velocity over the same route is limited.

1.2 Goal of this study

In its Service Request, the Commission asked for:

1. an assessment of the contribution of the complete range of factors contributing to the divergence between test and real world CO₂ and fuel consumption performance. This assessment should also point out how these factors and their impact have changed and will change over time;
2. to build and verify a model – a mathematical approach - that better estimates the real-world fuel consumption and CO₂ emissions of specific vehicles under future LDV CO₂ standards.

This report aims to give a comprehensive and quantitative picture of the different aspects which result in the actual, or real-world, fuel consumption, and how this deviates from the type-approval value. It is not necessarily explaining the deviation for an individual driver in a specific vehicle, but will draw from the average real-world fuel consumption of large groups of car users, and the variation therein.

1.3 Approach

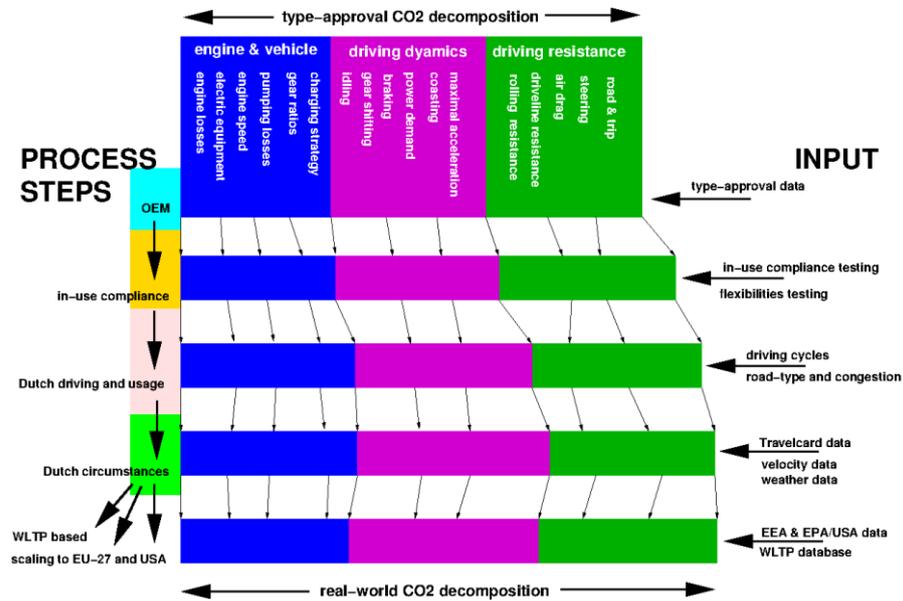


Figure 2 Between the factory type-approval values and the fuel consumption monitoring of car users there are many differences, which can be captured into steps for which independent verification exists. By “In-use compliance” it is meant independent NEDC testing.

A proper assessment of the magnitude of the different contributing factors can only be made if the complete chain of effects from the type-approval value CO₂ emission to the real-world CO₂ monitoring is considered. The magnitude of every contributing factor must be combined with context data:

1. The type of test (driving cycle, on-road, velocity, test mass, etc.), and variation (e.g. only mass, or mass and resulting rolling resistance).
2. The type of test conditions and execution (“optimised”, i.e., type-approval values, normal, real-world, mass-in running order, additional payload, etc.)
3. The underlying physical cause or mechanism, such that the interaction of different effects and the external changes affecting the result can be determined.

In order to arrive at quantitative results, a “bootstrap” analysis, or re-iteration, is applied. This approach, and the underlying problem it solves, is most easily explained with an example. Air-conditioning is an important factor, contributing to real-world CO₂ emissions. However, the magnitude of its effect depends very much on the ambient conditions and usage. Its relatively constant power consumption will make a greater contribution to total energy use when driving at low velocity, as it uses a higher share of the energy consumed per kilometer at low velocity. Moreover, air-conditioning will not be on full-power in all circumstances. Typically, it is expected that air-conditioning power consumption increases with ambient temperature, relative humidity, and solar radiation. Hence, in monitoring data it is important to correlate fuel consumption with these ambient conditions. However, ambient conditions also affect fuel consumption in other ways: for example air-drag decreases with temperature and with relative humidity¹. This effect diminishes the

¹ Under standard conditions water vapour is 28% lighter than air.

fuel consumption increase due to air-conditioning usage at high temperatures. In this manner the data from test and monitoring and the physical model are visited four times to peel off the dependencies affecting fuel consumption related to air-condition usage:

- First the effect of the average velocity is determined to arrive at the proper [g/km] metric. This already disqualifies some of the NEDC-based air-conditioning testing for estimating real-world fuel consumption, as the effect on the NEDC is larger than in real-world, because of the lower test velocity.
- Secondly, the monitoring data is used to arrive at an overall fuel-consumption dependency on ambient temperature. On top of that, the effect of air-conditioning usage can be distinguished for uncomfortably high temperatures.
- Finally, the effect has to be related back as a contribution to the gap, where the difference in vehicle velocity between type-approval test and real-world driving, and their effects on engine efficiency, is accepted as part of the difference.

For example, the effect of temperature on air drag is not visible in the type-approval test, as the road load is determined independently in a separate coast-down test, which is normalized to a fixed 23° C. The temperature has a substantial effect on the air-drag. However, in the variation of the testing in the laboratory the air-drag is carried over from the coastdown test, and not subject to variation. Hence, the decomposition of the total fuel consumption requires moving back and forward between data and model many times to peel off the effects in order of their magnitude. Eventually, all trends should be explained or assigned and only minor random variation remains. After monitoring data is corrected for effects which can be quantified, the remainder may exhibit systematic variations, which can be assigned to other aspects. In the end, after correcting for effects, only small random variations in the monitoring data remain. At this point the fuel consumption from monitoring data is decomposed to its fullest extent currently possible.

This study takes a different perspective than other partial studies which try to establish the effect of a single influencing factor through dedicated testing, such as specific testing for air-conditioning. In many cases, such studies have limited value for understanding the true real-world contribution, as in general limited information is available on the true real-world conditions and usage. This only becomes visible when correlating variations seen in fuel consumption in real-world monitoring with real-world conditions, as performed in this study. The causal effect, such as a direct figure which incorporate the air-condition usage over the whole fleet and all weather conditions, and the associated additional fuel consumption, is therefore not a priori established. On the other hand magnitudes of certain effects can be given an upper bound based on the available monitoring data.

The mathematical models to establish the interaction of the different effects must be complete, yet not too specific to disqualify data from use. Hence, effects are grouped together on the basis of their dependencies, either in usage, circumstances, or technology. This model features prominently in report, as the quantifies result in their proper context. For example, the effect of ambient temperature relates to cold start and air drag. The vehicle use mixes these two aspects into the total fuel consumption in a manner related to the particular test or real-world usage. For example, cold start plays a larger role on the NEDC, while air-

drag has a larger role in real-world fuel consumption. Moreover, in the example above, the effect of air-conditioning is not an absolute number. It cannot be separated from average velocity, ambient temperature, or air-drag, which vary across the different numbers for fuel consumption in the range from type-approval value to monitoring data. The variability of the effect with the vehicle test and usage is the central theme of this report. A model combines the vehicle technology, vehicle use and the vehicle test in an intricate manner.

1.4 Structure and stages of the analysis

Figure 3 shows the different tasks as specified by the service request.

The problem description is simple: what is the cause of the (growing) difference between type-approval and real-world fuel consumption? The answer is not, as it depends strongly on the context. This makes presenting the results challenging. Different topics must be revisited several times to arrive at a final answer. Globally, the following aspects must be covered:

- First, the total system involved in fuel-consumption determination.
- Second, the separate factors which can be distinguished in this system.
- Third, the interdependencies between these factors.
- Fourth, a global quantitative assessment of the effects, to allow the data to be compared.
- Fifth, normalizing the effects of the separate influencing factors for comparison and combination of the data.
- Finally, a synthesis of all findings.

The last two stages are presented extensively in this report, so that the reader can independently evaluate the merits of the evidence provided.

While items are discussed several times in the report, this is done to make sequential reading of the report possible. The different stages of the analysis are condensed to three major steps, and parts of the report: inventory (factors), model, and data.

The structure is set up for the specific task at hand: combining the available evidence for the gap between real-world fuel consumption and the type-approval value against the effects which may explain this gap. Hence, one cannot find here many items featured in other reports. No attempt is made to decompose flexibilities into detail, like test circuit slope for the coastdown test, for which no independent data is available. This report is not based on anecdotal or very specific elements, but on the fleet level and the generic data available at that level.

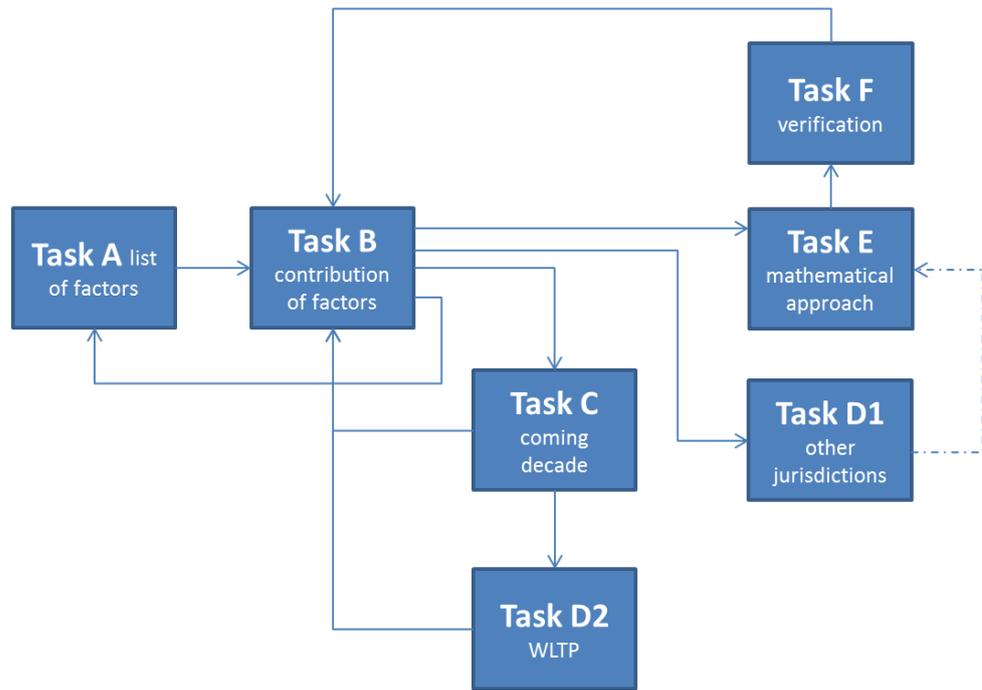


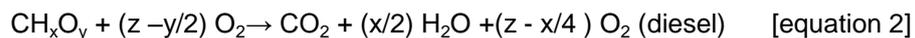
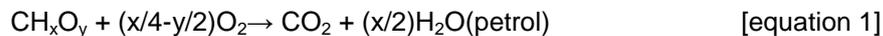
Figure 3 The relations among the tasks.

2 Type-approval versus real-world CO₂ emission

This chapter provides the reader with an introduction into the most important aspects regarding the difference between type-approval fuel consumption and real-world fuel consumption of passenger cars.

2.1 How are fuel consumption and CO₂ emission related?

Vehicles equipped with an internal combustion engine use a fuel, typically petrol or diesel, to drive the engine. Petrol and diesel are fossil fuels containing hydrocarbons (consisting of carbon (C) and hydrogen (H)), and currently also oxygen (O) due to the admixture of oxygenates, such as MTBE and ETBE, or biofuels, such as ethanol and FAME. When burning a fuel, carbon dioxide (CO₂) is formed. Formulas 1 and 2 show the reaction for the ideal combustion of oxygenated petrol and diesel, respectively.



Currently, with the bio-admixture in the Netherlands, i.e. relevant for the available Travelcard data, the carbon content of summer diesel is about 85% and of summer petrol it is 84%, with about 2% and 3% oxygen weight fraction in the fuel respectively.

The above results in a constant value for the amount of CO₂ emitted per unit of fuel burnt (either expressed in litres or in MJ), which depends on the specifications / contents of the fuel. The CO₂ emissions of a passenger car using an internal combustion engine are therefore directly related to its fuel consumption. Subsequently, these terms are used interchangeably throughout this report.

As a rule of thumb, the following relation between a car's CO₂ emission and its fuel consumption on the type approval test can be used:

$$\text{CO}_2 \text{ [g/km]} \sim 23.7 * \text{FC [litres/100km]} \text{ (petrol)} \quad \text{[equation 3]}$$

$$\text{CO}_2 \text{ [g/km]} \sim 26.5 * \text{FC [litres/100km]} \text{ (diesel)} \quad \text{[equation 4]}$$

The difference is mainly explained by the differences in density of diesel and petrol fuel, respectively 830 g/l and 745 g/l. Diesel and petrol have very similar heating values for one kilogram of fuel of around 43 MJ/kg.

These values are used throughout the report to translate between monitoring data, i.e., litres, and test data, i.e. CO₂. There is little knowledge how it may vary with market fuels. However, there is indication in the Netherlands that market petrol has lower heating values, which may indirectly increase both the fuel consumption and the CO₂ emission above the relations used here.

These fits are based on the type-approval fuel consumption and CO₂ emissions reported in the last years. Type-approval tests are carried out with well-specified

reference fuels which should represent the current market fuel, but may not do so. Hence with Euro-5 the requirement for reference fuels include a bio-admixture. The spread of a few percent is already within the reporting accuracy of a single decimal. Bio-admixture, in the form of ethanol lowers the coefficient of petrol somewhat from 23.7 to 23.6. in the type-approval test a 5% admixture is to be used, resulting in this change. For diesel hardly any noticeable effect of biofuel admixtures is observed in type-approval results for fuel consumption and CO₂ emissions. The admixture of FAME does not significantly alter the fuel specification. In the real-world it is unknown what the relation is between CO₂ and fuel consumption. Moreover, the amount of energy per litre of market fuel is not specified. Therefore the CO₂ emission may be higher due to a lower energy content.

2.2 Type-approval fuel consumption and how it is determined

According to Directive 2007/46/EC², every vehicle type to enter the market must be approved. One of the many aspects covered in the vehicle type approval testing procedure is the vehicle's fuel consumption and CO₂ emissions. They are measured in a chassis dynamometer test.

A chassis dynamometer has to be 'fed' with the vehicle's mass as well as characteristics of the vehicle's resistance, which are measured in a road-load test. In this test, the vehicle is coasted down from a velocity of 125 km/hr to 0 km/hr. By measuring the time intervals between specific speeds, the so-called road load curve is established, which is used as input to the chassis dynamometer.

Subsequently, on the chassis dynamometer, the vehicle is tested according to the prescribed test conditions.

- First of all, several vehicle parameters are prescribed to be in a certain range. For example, the vehicle's tyres must be inflated to a certain minimal pressure, there are rules for accessory use during the test and also the vehicle test mass is prescribed.
- Secondly, the environmental conditions should be within predefined bandwidths. The temperature in the laboratory, for example, must lie between 20 and 30 degrees Celsius. With the WLTP the bandwidth is smaller, but the temperature remains high compared to average European conditions. This will be corrected to 14° C.
- Thirdly, the type approval procedure dictates the test cycle that must be used to determine the vehicle's fuel consumption. The test cycle is the trip the vehicle must 'drive' while being tested on the chassis dynamometer. Currently, vehicles are tested on the New European Driving Cycle, or NEDC. The NEDC trip, a velocity-time profile which is shown in Figure 4, is a test trip of 11 km at an average speed of 33 km/hr. During the chassis dynamometer test, the vehicle is operated by an experienced highly-skilled automotive engineer used to driving test cycles.

² DIRECTIVE 2007/46/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 5 September 2007 establishing a framework for the approval of motor vehicles and their trailers, and of systems, components and separate technical units intended for such vehicles.

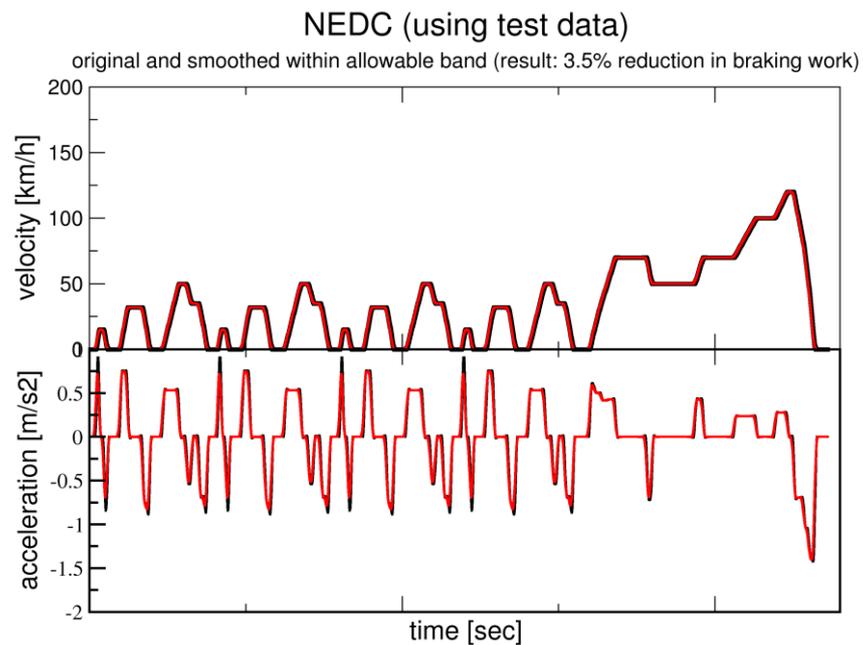


Figure 4 The NEDC test cycle velocity and acceleration. The red line is an actual velocity trace from a test execution. The cycle is stylized with some freedom in the test to reduce the braking, as illustrated by the red line “cutting corners”. Given its higher dynamics, this potential is larger under the WLTC unless correction algorithms are applied.

The fuel consumption, and thus the CO₂ emission, of the tested vehicle during the NEDC forms a basis for the official, or type approval, fuel consumption and CO₂ emission of the vehicle type. This is the value used by Member States in CO₂ labelling of cars as well as in CO₂-differentiated tax regimes.

Due to technological developments, the real-world fuel consumption of new passenger cars shown in the Travelcard data has decreased by approximately 16% in the period 2000-2013 in the Netherlands. The corresponding type-approval value made a more dramatic drop of 55%. (See Figure 5.)

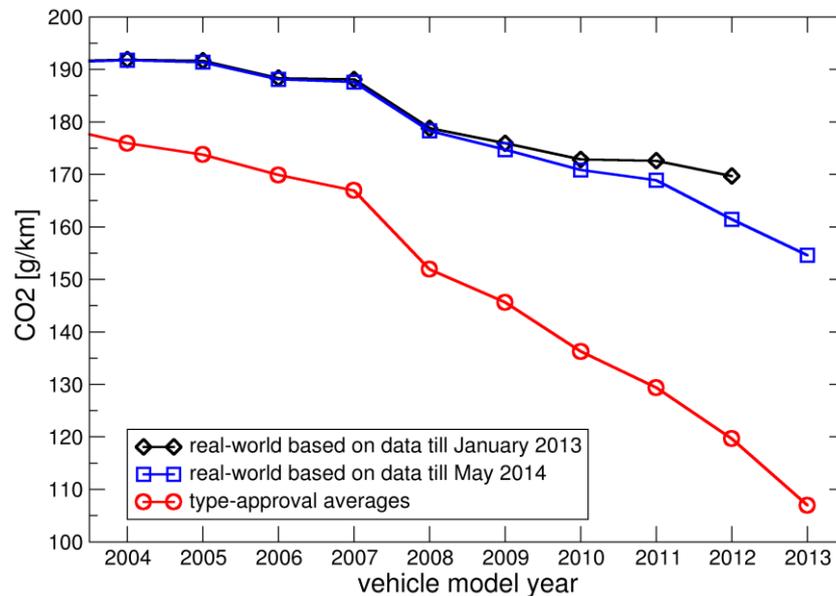


Figure 5 The change in type-approval and real-world fuel consumption over time for the Travelcard data. In 2014 a change was observed in for vehicles from 2010-2013. This was examined in [Ligterink 2014].

2.3 Real-world fuel consumption differs from type-approval fuel consumption

The day-to-day operation of a passenger car differs from the type approval test. Both the test cycle and the test conditions on the test are only partly representative of real-world circumstances, and the way the vehicle is used differs from one owner to the next. It is for this reason that real-world fuel consumption is not equal to the type approval fuel consumption, and different for each individual driver. The fact that in past the average fuel consumption of drivers was close to the average type-approval fuel consumption may have been more-or-less accidental rather than the result of appropriate representativeness of the test for real-world usage at that time.

If the type-approval test would be representative for average real-world driving, one might expect that the real-world fuel consumption would evenly vary around the type approval value, i.e. that some cars in real world operation have a lower fuel consumption than measured in the NEDC, and others have a higher real-world fuel consumption. In practice, however, real-world fuel consumption is almost always higher than the fuel consumption measured in the type approval test. Moreover, the difference between real-world fuel consumption and type approval fuel consumption, or “the gap”, has grown significantly over the last years.

2.4 Why the gap is growing

There are two main causes for the increasing absolute difference in g/km between type approval fuel consumption and real-world consumption.

First of all, vehicles have changed. Comparing the first 1974 Volkswagen Golf with a Golf of present day makes this perfectly clear.



Figure 6 The current Volkswagen Golf weighs 1125-1210 kg and has a rated power of 77-90 kW, while in 1990, the weight was 855-920 kg and the power 40-66 kW.

Vehicles have literally ‘grown’: they have become larger and as a consequence have a larger frontal area. Also, vehicles nowadays are safer. Apart from structural improvement for better crashworthiness, cars of present day are usually equipped with multiple airbags, ABS and so on. Finally, the level of comfort of a modern car is almost incomparable with vehicles of a couple of decades ago. Better seats, climate control systems with air-conditioning and solid *hifi* equipment are frequently encountered in cars of modern age. These auxiliary systems have increased the vehicle weight considerably. This, together with car buyers asking for better performance, required larger engines. The additional weight is more than compensated by the extra increase in power, such that the power-to-mass ratio has grown as well.

Large engines typically have larger engine losses. The relatively low average velocity and acceleration in the NEDC, however, lead to low engine loads. As a consequence, engine losses are a large contribution to the type approval fuel consumption and very likely much more so than in the real world. Currently applied specific improvements to lower these CO₂ emissions due to engine losses in the NEDC, such as turbo’s, CVT (Continuous Variable Transmission), hybridization, controlled valves and stop-start systems, have no or limited consequence in real-world operation. An example of this is the engine stop-start system, which has a larger effect on the NEDC with its idling time of over 267 seconds, amounting to 23% of the total test cycle driving time. In real-world operation, however, a stop-start system has a significantly smaller effect as idling time represents far less than 10% of the total driving time. Moreover, normal drivers generally less quickly and less frequently put the gear in neutral during idling than an NEDC test operator. This is a first hint as to why the gap has grown over the years.

Secondly, during the last decade or so, new legislation requiring compliance with fleet-average CO₂ emission targets has emerged. This has, in part, driven the fuel efficiency measures described above. Moreover, several European Member States have fiscal regimes in place stimulating people to buy fuel-efficient cars. These fleet-average CO₂ emissions, as well as most of the fiscal incentives, are based on the type approval CO₂ emission of the vehicles. As a result, the type approval CO₂ emissions and fuel consumption of a passenger car have become more and more important. The lower the type approval fuel consumption of the car, the better its chances to be eligible for stimulating programs and/or subsidies. Various studies have indicated that car manufacturers are increasingly using the flexibilities in the

type approval test procedure and optimise the vehicle to achieve an as low as possible fuel consumption during type approval [Kadijk 2012b]. As many of these optimisation measures and utilizations of flexibilities, such as over-inflating tyres, removing the spare wheel or taping up the seams around the doors, move the test conditions away from the 'real world' even further, this also contributes to the growing difference between type approval fuel and real-world fuel consumption.

This study aims to provide in chapter 3 a list of all factors that contribute to the gap, and to quantify them in chapter 4.

2.5 Will the gap decrease in the future?

The NEDC was introduced in 1992 and it has remained virtually the same since then, as an extension on the ECE or UDC test developed in 1970. Cars, and their usage from the 1970's were however completely different than today. Therefore, currently the Worldwide harmonized Light vehicles Test Procedures (WLTP) is being developed. This new type approval test procedure incorporates a new driving cycle, the Worldwide harmonized Light vehicles Test Cycle, or WLTC. The WLTP is intended to come into force as of 2017 and aims at 'better reflecting the real conditions in which cars are used' [EU 2013].

Whether the WLTP better reflects real-world average vehicle operation and will help to decrease the gap, cannot be conclusively judged at present time. There are aspects of the WLTP/C that are likely to yield more representative type approval CO₂ emissions:

- in the WLTP, the vehicle must be tested with a higher test mass,
- tyres and tyre conditions are better prescribed and
- the average velocity is higher.

It will only be possible to determine the actual effects of the WLTP introduction afterwards and this will depend on both the technological development, the type-approval process and the control thereof.

To be able to estimate the *real-world* CO₂ savings of future EU Regulations, a set of models was developed to better estimate the real-world fuel consumption and CO₂ emissions of passenger cars. Therefore, this study takes into account the status quo of the WLTP to do so. It will incorporate the actual changes in the test protocol, such as test weight and tyre choice and preparation. This study does not reflect on the change in exploitation of potential flexibilities on the WLTP. This will depend strongly on other aspects of the legislative framework, such as the Conformity of Production, which are not completed yet.

3 List of factors

Chapter 2 provided the reader with a basic understanding of the most important aspects related to the difference between type-approval and real-world fuel consumption. The current chapter further elaborates on the factors that contribute to the CO₂ emissions of a passenger car.

As stated in the introduction, the first goal of this work is to assess the contribution of the complete range of factors contributing to the divergence between test and real-world CO₂ and fuel consumption performance. In order to be able to do so, this chapter first describes all factors that contribute to the real-world fuel consumption, and thus the CO₂ emissions, of a passenger car.

This is done in two ways. Firstly, section 3.1 groups the various energy consuming factors that determine the CO₂ emission of passenger cars into classes, which allow one to scale the effects with particular vehicle use, vehicle state and circumstances. Then, in section 3.2, various factors influencing the observed CO₂ emission are assigned to the different categories defined in section 3.1.

Furtheron in this report evidence is collected for the major contributions to the differences in CO₂ emissions. Not every separate effect described in section 3.2 will be quantified, but generic groups of effects will be. For example, the evidence shows that holiday periods lead to a limited increase in fuel consumption. Therefore, towing of caravans, use of roof racks, additional passengers and luggage, all associated with higher fuel consumption and holiday periods, can be estimated to have a small effect on the total annual fuel consumption. Another example is the rolling resistance at low velocity. This is a combination of driveline losses and losses due to tyre rolling resistance which are difficult to decompose. However, the combined effect is measured and variations between official type approval values and independent measurements can give an estimate of the effect of driveline losses and losses due to tyre rolling resistance on CO₂ without knowing the detailed technical cause.

3.1 Decomposing CO₂ in terms of energy

The analysis starts with the ideal situation. This situation is dictated by the laws of physics for a conventional engine. In the conversion of heat to work heat losses are related to the engine cycle; compression engine or positive engine. These heat losses are not included in the analysis. Possibly with waste heat recovery some additional mechanical or electric energy can be recovered, but this lies outside the current scope. Moreover, the kinetic energy of the vehicle is not considered as “lost” but just a “conversion”. Only when the mechanical brake is applied the energy is lost.

Moving a vehicle from one place to another requires energy. As Figure 7 shows, the energy the engine has to provide is related to either the velocity and acceleration of the vehicle or to the operation of the vehicle and its auxiliary equipment, and of the engine itself. The energy required for vehicle operations are commonly termed ‘losses’.

engine	work (velocity related)	rolling resistance	
		air drag	
		braking losses	
	losses (operation related)	friction	cold start
		pumping	
		auxiliaries	

Figure 7 Decomposing a vehicle's energy consumption into factors.

The work to be done and the losses to be overcome are further decomposed in sections 3.1.1 and 3.1.2 respectively.

3.1.1 Work

The velocity-related energy the engine has to provide can be divided into rolling resistance, air drag and braking losses. Braking losses are associated with work, as the kinetic energy or the work of acceleration is dissipated once the vehicle brakes. Crudely said, the work was done earlier, but at the moment of braking no longer put in good use.

3.1.1.1 Rolling resistance (R)

The rolling resistance is mainly due to the tyre rolling resistance, but it includes all resistance of the moving parts which are coupled to the rotation of the wheels. The drivetrain losses after the transmission, at the same speed as the wheels, can be included in the rolling resistance. Such elements rotate with the velocity of the wheels and they are included in the road-load in coast down tests. Depending on the velocity and variation of velocity, the contribution will vary.

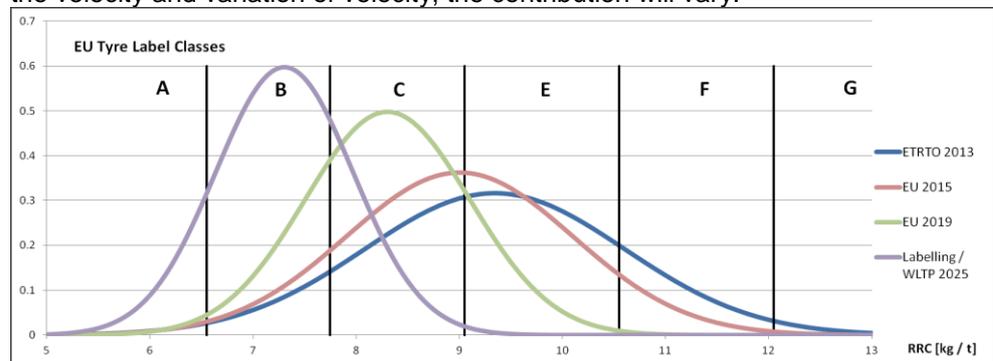


Figure 8 The aftermarket sales of tyres, and the forward prediction of reducing rolling resistance. There are indications that the RRC on production vehicles is slightly higher. (source ICCT)

Rolling resistance is a more-or-less constant force, with a limited dependence on velocity. Hence, it requires a constant work to drive a certain distance. It can therefore be associated with a fixed g/km CO₂ emission, independent of driving style. Variation in engine efficiency are factored in independently, In order for this assignment to work, the engine losses must be attributed separately.³

Tyre labels provide a rough estimate of the total rolling resistance, however, other driveline resistances can contribute 10% to 20% to the total rolling resistance , i.e.,

³ The rolling resistance coefficient RRC (or C_{rr}) is the ratio of vertical force, or weight, and the associated horizontal force or rolling resistance. A vehicle of 1400 kg total weight and an RRC of 8 [kg/ton] will have a rolling resistance force of $110 \text{ N} = 1400 \text{ kg} * 9.8 \text{ (g)} * 8 \text{ (RRC)} / 1000 \text{ [kg/ton]}$.

assumed constant for each velocity. However, tyre labels are measured at 80 km/h, while at higher velocity the resistance may increase somewhat. Typical RRC values of tyres on production models sold in Europe are around 9 kg/ton, which means that for a vehicle of 1300 kg including driver, the unavoidable CO₂ emissions related to the total rolling resistance are at least 21 g/km, based on 650 gCO₂/kWh (see section 5.1.1). For aftersales tyres the RRC in the past has been even slightly higher, but this may be affected lately by the tyre energy label. Likely the total rolling resistance in real-world on normal roads, including driveline, is more in the order of 30 g/km CO₂, associated with a combined RRC value of 11 to 12, i.e., 0.12 N/ton. In type-approval, road-load values of 0.06 N/ton are not uncommon. In part, this is due to the low weight of the car tested compared to the kerb weight of the vehicle sold, but in part this must be due to tyre choice and treatment for optimal road load in coast down testing. A third large contribution of the difference is due to the choice of test track: sloping test tracks cause a reduction of the measured force in the order of 0.02 N/ton, which is substantial, yet limited for real-world vehicle road loads or resistances. On the very low type-approval values for rolling resistance, it makes a large difference, however.⁴ Moreover, rolling resistance is also affected by the road surface. The effects are estimated up to 20% of the total rolling resistance. Even test tracks are advertised with a reduced rolling resistance from resurfacing the track, with a reduction of 0.02 RRC, which is an additional effect of 5% on an already smooth track.

The reduction of rolling resistance in road-load values from a common real-world value of 11 kg/ton to an optimised result of 6 kg/ton on the type approval test will thus yield an attributable reduction in CO₂ emission of 11 grams for an average vehicle of 1300 kg in running order. It is expected that this can be attributed to:

- Tyre choice (narrow, A-label)
- Tyre preparation (heat treatment, low tread, surface grinding etc.)
- Tyre conditioning (high pressure, run-in execution)
- Track (slope, road texture)

The tyre choice and preparation for type approval testing will become more realistic with the WLTP legislation. The test track slope effect will be removed although there will be no account taken of the track surface. For the other attributions, such as reference tyre pressure and actual tyre pressure during the test, some effect is expected with the WLTP, however, without open comparison between the vehicle tested and the vehicle sold it is expected that the test optimisation will remain significant.

3.1.1.2 *Air drag (A)*

Air drag increases rapidly with velocity. Therefore, unlike rolling resistance, the CO₂ emissions associated with air drag are strongly dependent on the actual driving. On all the tests, NEDC and CADC⁵ alike, the driving constant at high velocity is limited, compared to Dutch driving. A modern car drives about half its annual distance on the motorway, and mainly so at velocities between 100 km/h and 110 km/h, in the

⁴ A sloping track adds a constant force to the uphill run, and removes the same force on the downhill run. The coast-down time is approximately inverse proportional to the force. Hence, for a slope of 0.3% and a vehicle weight of 1400 kg, this force is 40 N. For a resistance of 150 N, the average $(2/(150+40) + 1/(150-40))^{-1} = 139$ N instead of the proper average force of 150 N. The effect is the largest for the low velocities, hence very relevant for the NEDC.

⁵ The Common Artemis Driving Cycle has been used by many test laboratories as a representative cycle for real-world driving prior to the development of the WLTP test cycle.

Netherlands. In other countries this fraction is somewhat lower (30%-50%), but still substantial. This is reflected in the average air-drag force. Driving at 60 km/h constantly yields a much lower average air drag, than a combination of urban driving at 25 km/h and motorway driving at 100 km/h, yielding the same 60 km/h average.

3.1.1.3 *Braking losses (B)*

Braking losses are a typical feature of urban driving and of driving in congested traffic, where 30% or more of the energy generated at the wheels is lost again in braking. Weight plays an important role in the total energy lost in braking. It is frequently assumed that fuel consumption is associated with acceleration. However, this energy is not lost during acceleration: it may be used for coasting, or motoring, in which the vehicle decelerates without braking or further fuel consumption. Only if the brakes are applied is the energy lost (over and above the energy that was required to move the vehicle).

3.1.2 *Losses*

Losses are grouped together by their relation with engine speed and vehicle propulsion.

3.1.2.1 *Friction(E)*

In the NEDC, engine losses above the losses in the waste heat, account for about half of the total fuel consumption. These losses are defined as additional fuel consumption compared to the optimal efficiency. The engine losses can be half of the lowest CO₂/kWh at the optimal efficiency. Idling plays an important role in that, which is not even visible in an engine map, as no work is associated with idling, and the engine efficiency is technically zero. These losses can be decomposed into two main parts: the internal losses proportional with the engine speed, of which the friction is a major part, and the losses proportional with the square of the engine speed, of which the air-flow resistance through the engine is the major part. Although the friction is by far the most important part, all sorts of CO₂ emissions that are proportional to the engine speed are grouped together. For example, the back-pressure of the DPF (Diesel Particulates Filter) of a diesel engine is grouped with friction although it is really a pumping loss. However, due to the linear flow in the micro-channels of the filter, losses in the DPF grow linearly with flow, rather than in a quadratic manner.

3.1.2.2 *Cold start effects (C)*

Cold start effects, as defined here, were traditionally associated with higher friction losses due to cold, viscous lubricants. However, nowadays more and more parts of the engine and after-treatment require a higher operating temperature for optimal operation. From 70° C coolant temperature, the engine starts to 'feel comfortable'. Traditionally, cold start effects on fuel consumption could be determined by subtracting fuel consumption measured in a test starting with a warm engine from the fuel consumption measured in the same test starting with a cold engine. This, however, is no longer the case with modern vehicles. Since nowadays the engine control is very sophisticated, i.e. such that a traditional "cold start" effect, with a "mechanical engine"(Euro-2 and earlier) is difficult to spot, the data of modern cars on cold start effects cannot be used. In light of the recent diesel scandal it was already observed that modern vehicles, from 2010 yield lower CO₂ emission at a cold start test, than at the same warm test in laboratory tests, due to a different

control strategy, rendering this data useless for the determination of real-world cold start emissions. [Ligterink 2012b] But that does not mean that the underlying physical mechanisms are no longer playing a role. Older data indicate a cold start effect from 23° C for the NEDC, FTP, or WLTP test, of 140 g of CO₂ for petrol and 100 g of CO₂ for diesel. The cold start duration (τ) varies somewhat, but the total Urban Driving Cycle, the urban part of the NEDC, is affected by the cold start. Therefore a τ of 500 seconds seems appropriate. Moreover, since 500 seconds is shorter than any real-world trip, the actual duration is of limited relevance. The cold start effect is almost always completely absorbed and just “smeared” over the length of the trip to add to the total fuel consumption.

The colder ambient temperatures are however important. In normal type approval testing, the appropriate laboratory temperature is used, lying between 20° C and 30° C. Outdoors, and especially in the morning, temperatures are lower. The difference between the laboratory temperature and the ambient temperature should be taken into account, with respect to the offset temperature of the warm engine at 340 K, or 67° C (also refer to section 3.2.1.1.1).

3.1.2.3 *Pumping and cooling losses (P)*

Pumping losses are typically the losses generated by pumping the gas through the engine from inlet to exhaust pipe. However, the air used for cooling the engine by means of the radiator can be considered as a pumping loss as well, either from an increase in air-drag or the operation of a fan. The total losses are expected to be minimal when the car is idling with a warm engine. This will give a lower estimate on the losses to be expected. At high engine loads the losses are more difficult to determine, but it is physically sound to assume the increase with engine speed to be somewhere between linear (\sim RPM) and quadratic (\sim RPM²). Friction and pumping losses both have these kind of dependencies on the engine speed. Analyses of a large number of emission results reveal a large variation between engines, but an equal share of effects proportional with RPM and RPM² related losses at idling seems to be a reasonable average for modern, non-optimised engines. This means the losses increase about sixfold when driving on the motorway with a compact car, with an idling RPM of 1000 min⁻¹ and an RPM on the motorway of 3000 min⁻¹. The low idling emissions are associated with the energy to keep only the engine running, i.e., fully attributed to the internal mechanical and pumping losses. Given an idling CO₂ emission of 0.2 g/s (0.3 litre per hour) as measured for a modern compact car, the losses on the motorway can be as high as 1.2 g/s or 43 g/km⁶. Clearly, this shows the case for vehicles where the engine speed can be controlled independent from the vehicle velocity, such as hybrid vehicles and CVT (Continuous Variable Transmission), where engine speed can be reduced when the engine load is limited, e.g. at constant driving.

For high-powered cars, increase in losses with higher velocity are expected to be relatively smaller, as the gear ratio is different. Gear ratios vary greatly from one car to the next, even for cars with similar engine power. Typical average values for a 5-gear manual transmission are: 0.007/0.014/0.023/0.031/0.042 [(km/h)/(min⁻¹)]. This corresponds for a typical engine speed of 2000 rpm to 14/28/46/62/84 km/h, values

⁶ A 75 kW engine with an idling speed of 1000 RPM is expected to have internal losses in the order of: $1.1 \cdot (\text{RPM}/1000) + 1.1 \cdot (\text{RPM}/1000)^2$ kW, which is 2.2 kW at idling speed. On the motorway the engine speed increases to 3000 RPM or more, which yields losses of $3.3 + 9.9 = 13$ kW. The losses of 1 kW are associated for such a vehicle with 750 g/kWh, or $750/3600 = 0.2$ g/s.

well in line with the traditional NEDC gear shifts of 15/35/50/70 km/h. Instead of 3000 rpm at 100 km/h for a compact car with a lower power engine, the average engine speed for medium power is likely to be 2500 rpm, with somewhat lower losses, although the baseline losses for larger engines are higher.

Losses are to first order proportional to the engine size. Old engines (built before the year 2000) will have idling losses in the order of 4%-5% of the rated power. For modern engines, losses are in the order of 3% of the rated power, mainly due to downsizing made partly possible by turbo. However, the larger the engine size, the larger the losses, even nowadays. On the NEDC test, the losses may dominate the result. An important reason for this effect is the low, yet fixed power requirement on the NEDC test, based on the typical power-to-mass ratio of vehicles from the 1970-1980 era. The NEDC cycle can be executed with a power-to-mass ratio as low as 20 kW/ton. The lowest power-to-mass ratio of modern cars is of the order of 35 kW/tonne, and the typical average value is 60 kW/tonne. The actual fleet average value depends on the country, as high motorway speed limits and mountains will increase consumer demands for higher rated power.

It is likely that current automatic gears are optimised for low type-approval fuel consumption. Unlike the manual gear-shift points on the NEDC, the automatic gear can shift up quickly in the NEDC as the velocity trace is known and the forward-looking power demand at a given velocity is often very limited, due to the constancy of the velocity and the frequent decelerations in the test.

3.1.2.4 *Electric and auxiliaries usage (X)*

The total electric power of a modern vehicle is substantial. However, most power is used very intermittently. Even an item such as air-conditioning is not likely to yield substantial power usage in a country like the Netherlands with a moderate climate. Lights are a typical common and continuous power usage. Taking into account the efficiency of the alternator and battery charging, 200 W to 300 W can be drained from the engine, by the lights. Measuring the alternator current in tests show a wide variation over time and with vehicles. The value is based on a typical average for 12 Volt systems.

In the case of urban driving at 25 km/h, 300 W may contribute 8 g/km to the total CO₂ emission⁷, while on the motorway, at 100 km/h, the value is a quarter of that, due to the shorter time per kilometre. Hence the additional CO₂ from electricity usage will depend strongly on the actual driving. Given typical Dutch driving with modern cars, i.e. 25% urban at 25 km/h, 30% rural at 60 km/h, and 45% motorway at 100 km/h, this will yield 25% at 8 g/km, 30% at 3 g/km, and 45% at 2 g/km. This adds up to an average CO₂ emission of 3.8 g/km if the lights are on all the time.

⁷ Given 300 W yield an additional CO₂ emission of 0.06 g/s, the distance of 1 km at 25 km/h, means a running time of 144 seconds, and 144 s * 0.06 g/s is 8 g.

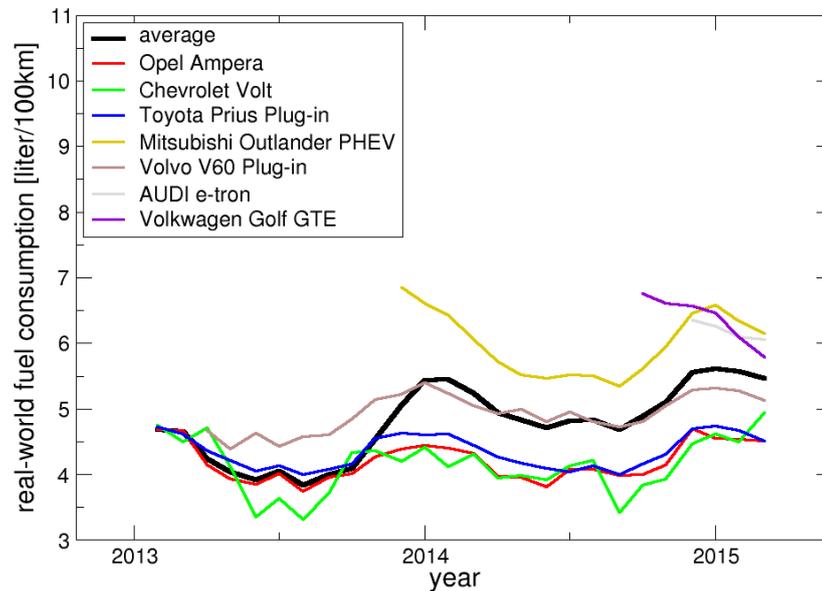


Figure 9 The variation of the month by month average (black line) fuel consumption of plug-in hybrids, based on Travelcard Nederland BV fuel-pass data, typically shows a larger seasonal variation than that of conventional vehicles, except for the Volvo V60, where the variation is similar to the average normal annual variation of conventional cars.

As can be observed in Figure 9 the fuel consumption has a substantial seasonal variation for both diesel and petrol cars. This will be analysed below. However, with new technology even larger seasonal variations can be observed.

An increasingly important aspect of auxiliary usage is the temperature dependence of the performance of battery operated cars like hybrids and plug-ins. In many cases, one sees a larger seasonal variation in fuel consumption for such cars compared to the fuel consumption of normal cars. This is very likely a test effect, since the type approval tests are executed at 20° - 30° Celsius where a battery is more efficient than at lower temperatures which are more representative for average ambient conditions. The notable exception in the Volvo V60 plug-in hybrid electric vehicle, which shows only a small seasonal variation in fuel consumption, in line with conventional vehicles.

3.2 Decomposing energy in terms vehicle state and usage

The total energy in the optimal engine operation and its associated CO₂ emission is the starting point of attributing CO₂ emissions to different aspects, i.e., decomposing the total CO₂ emissions from variation in operation.

Table 1 The complete list of factors as understood to affect the fuel consumption variation and the gap between type-approval and monitoring values.

OEM	road-load test flexibilities	slope, weight, tyre pressure, ...
	chassis dynamometer flexibilities	electric equipment, velocity trace, dynamometer settings, ...
	vehicle preparation flexibilities	battery charging, tyre preparation, decoupling, lubricants, DPF cleansing, ...
	administrative flexibilities	"4%", corrections, weight steps, table values, ...
Vehicle	fuel efficiency technology	stop-start, hybridization, downsizing, plug-in, ...
	market segmenting	cross-overs, new segments, ...
	model options	sport wheels, additional weight, ...
	maintenance state	parasitic braking, DPF clogging, EGR valves, ...
	tyre pressure	lower tyre pressure, limited checks, door-value versus tyre-value, ...
	adaptions and replacements	tyre label of replacement tyres, sport wheels, snow/winter tyres....
Driving & usage	desired velocity	fractions urban/rural/motorway, trip decomposition, modality shifts, ...
	congestion	stop-and-go traffic urban and motorway, ..
	short trips and cold start	annual mileage, total cost, temperature variations, daylight saving time, ...
	luggage	roof racks caravans, equipment, safety material, ...
	passengers	holidays, business and family usages, ...
	electric equipment	air conditioning, power steering, lights, ...
Circumstances	fuel specifications	summer and winter fuels, bio-fuels, ...
	ambient temperature	diurnal variations, annual variation, variation across Europe, ..
	road surface and gradient	tarmac quality, mean-profile depth, slope-velocity balance, road maintenance, ...
	speed limits	motorway, rural, dynamic limits, desired velocity in the absence of speed limit ...
	precipitation	rain, snow, ...
	wind	average wind speed, gustiness, diurnal variation, wind direction, ...

In the previous paragraph the general features on energy usage and CO₂ emissions are explained. In this paragraph the effect of the influencing factors are introduced.

3.2.1 Environmental conditions

3.2.1.1 Weather conditions

The Netherlands has a moderate climate with an average temperature of 11° C. Since it is situated next to the coast, the wind velocities are typically high, especially in the western provinces. For the monitoring period 2004-2014, the average temperature (KNMI, de Bilt) was 10.5°C. For the Dutch monitoring data and temperature effects this data is used. Across Europe there will be some variation in the temperature, but the average ambient temperature is lower than the laboratory test temperature for all countries..

3.2.1.1.1 Temperature

The temperature affects the CO₂ emission in many different ways. The most important difference between type-approval and real-world is probably the air-drag of the vehicle, which decreases with increasing temperature and decreasing air density. Type approval testing is performed at 23° C. Given the fact that the Dutch real-world average ambient temperature is 11° C, this results in a real-world air-drag that is 7% higher, discounting minor humidity effects. With 45% driving on the motorway at 100 km/h, the difference for the total CO₂ emission is about 3 g/km⁸.

⁸ Given the ideal gas law: air density varies inversely proportional with the absolute temperature. A change from (23+273)/(11+273) -1 = 4.3% higher density. Given the fact that air drag of a

Typical variations in the air-pressure, at the same altitude gives a much smaller effect.

The effect cold start consists of two aspects: the temperature and the number of starts per kilometre. The additional CO₂ emissions from a cold start on the NEDC are 100 g for diesel and 140 g for petrol. This results in an 8 to 13 g/km spread over the 11 km of the NEDC test. In the real world, the number of cold starts per kilometre are less. Assuming one cold-start per day on average for eight million Dutch cars, which are not all used on a daily basis, results in 35 km per cold start, which is a longer distance than either the NEDC or the WLTP test, and consequently 2.5 to 4g/km. Detailed studies suggest 1 cold start per 7 kilometre urban driving, one per 15 kilometre rural driving, and no associated cold start for motorways. However, the cold-start temperature is lower as most vehicles are parked on the street at night, which may result in a 25% or more increase in the CO₂contribution per cold start. This would increase the cold-start contribution from 2.5-4 g/km to 3.1-5 g/km. The picture regarding cold-start is therefore mixed: it is higher on the NEDC than on the WLTP, and the WLTP value is close to the real-world value of 4 g/km. The WLTP is more than twice the distance of the NEDC, which halves the effect of the cold start in the beginning. However, the value on the WLTP relies on a shorter distance but a higher conditioning temperature, meaning that the translation is vehicle and emission control specific.

Other effects related to ambient temperature include use of the air conditioning, battery efficiency, heating, and tyre pressure. Tyres come in a wide variety, with a variety in tread. This tread interacts with the different road surfaces. From a comparison of the vehicle velocity from the ECU, based on the rotation of the wheels, and GPS velocity, up to a few percent variation in the one-to-one correspondence in both velocities is seen, indicating a variation in dynamic tyre pressure and tyre radius. Since the dynamic radius is related to indentation and viscoelastic deformation, it is only natural to assume it will affect the rolling resistance along the trip. It is extremely difficult to quantify, as the effect arises from a combination of driving dynamics, road surfaces, ambient conditions, and tyre properties, with a typical ten to twenty minutes delay in the effect. It is expected that ambient temperature, road surface temperature and condition and solar radiation all play an important role.

3.2.1.1.2 *Precipitation*

Rain is likely to affect fuel consumption in an ambiguous way. Most likely, the reduction of velocity and increase in congestion is the largest contribution to the change in fuel consumption for the Netherlands. However, in heavy downpour the effect of a wet road surface may be substantial. Actual figures are not known.

3.2.1.1.3 *Humidity*

The air drag will decrease somewhat as the absolute humidity⁹ increases, since water molecules are lighter than the typical molar weight of air. However, it is only at high temperatures, above 30° C, that the (absolute) water content in air is

passenger car on the motorway is about 500 N, this results in a change 21.5 N, associated with $720 \text{ [g/kWh]}/3600 * 21.5 \text{ [N]} * 1000 \text{ [m]} / 1000 \text{ [kW/W]} = 4.3 \text{ g/km}$.

⁹ At moderate ambient temperatures the amount of water vapour in air is small. Even at its maximal value, 100% relative humidity, before it starts to condense. At higher temperatures the water content in air can be much higher, and its effect is larger.

substantial. Hence, it may affect coast-down testing at high temperatures, but is not likely to contribute significantly to real-world air drag.

3.2.1.1.4 Wind

If the instantaneous fuel consumption is measured in a vehicle, variations in fuel consumption at constant velocity will mainly be due to wind and road slope. A typical wind velocity of 3 m/s will increase or reduce the air drag up to 10% on the motorway. At lower velocities the relative effect is larger, however, the absolute effect is smaller. This is due to the quadratic dependence of air-drag on velocity:

$$\Delta \text{drag} \sim (v_{\text{vehicle}} \pm v_{\text{wind}})^2 - v_{\text{vehicle}}^2 = \pm 2 * v_{\text{wind}} * v_{\text{vehicle}} + v_{\text{wind}}^2$$

For both directions together the terms “+2*v_{wind}*v_{vehicle}” and “-2*v_{wind}*v_{vehicle}” cancel out, and the remaining average wind effect is proportional to the wind speed (v_{wind}²). This is a simplistic first-order approximation. Especially cross winds disturb the air flow around the vehicle and will lead to larger wind effects than the 5 Newton net wind force from the 3 m/s average wind speed at ground level. The net effect of cross winds is estimated about double the net effect of head and tail wind.¹⁰ Hence the wind effect on the drag can be assumed about 50% higher than expected from the simple equation above. Moreover, also in this case, the effect is not proportionate to average wind speed. Higher wind speeds have a disproportionately large effect.

From the recent validation of air-drag determination by wind-tunnel tests, the bandwidth on air-drag in coast-down testing (up and down repeated) is of the order of 4%. Likewise, a test-to-test variation of successive coast downs in the same direction is 3%.¹¹ With the same vehicle, conditioning, and test track, and corrected for variations in temperature air pressure, etc., there remains very little else which can explain this variation. The study of wind fluctuations and wind speeds confirm the magnitude.

3.2.1.2 Road conditions

Rolling resistance increases for rough road textures, undulation and bends. Sharp bends and narrow lanes will lead to more speed variations and lower velocities. Moreover, the amount of energy lost in bends is not negligible, as many of the urban and rural roads are made up of a succession of bends. In the case of urban and rural roads the velocity is below 80 km/h and factors which decrease velocity and simultaneously increase the dynamics will increase the fuel consumption.

3.2.1.2.1 Slope

A 1.0% to 1.2% uphill slope doubles the driving force of the rolling resistance of a typical passenger car by the additional effect of the gravitational force. Hence, minor slopes will already affect the instantaneous fuel consumption. However, in a round trip the effect is limited, as the same slope is also taken downhill. A substantial effect of slopes on CO₂ will only occur if the slope is steep enough to

¹⁰ F. Buckley, 1995, *ABCD – An Improved Coast Down Test and Analysis Method*. This method which removes wind effects from the coastdown result is part of the WLTP phase 1b.

¹¹ Many of the effects on vehicle resistance were established in a large study for the European Commission, reported at several instances, e.g. *The Effect on Road Load due to Variations in Valid Coast Down Tests for Passenger Cars*, P. van Mensch, N.E. Ligterink, and R.F.A. Cuelenaere, TAP 2014, Graz, and UNECE document WLTP-07-05e, Correction algorithms for WLTP chassis dynamometer and coast-down testing. [Ligterink 2014c]

overcome the vehicle's rolling resistance. In that case, the brake has to be applied, and the additional energy required uphill is no longer to the full benefit of the subsequent travel in the opposite direction. For higher velocities, the slope has to be even steeper to have an effect, as the gravitational force must also overcome the vehicle's air drag. On the motorway, the minimal downhill slope which induces braking to maintain a constant velocity is 3% to 4%.

3.2.1.2.2 *Road texture*

Road texture will increase the random deformations of the tyre which do not release the energy again when the contact between the tyre section and the road ends, and thereby the rolling resistance. This effect, even for well-maintained roads, can be as high as 20% additional rolling resistance. On type-approval coast-down tests, it is expected that a hard, smooth surface is used. Such test tracks will be favoured when rolling resistance has a major impact on the CO₂ emissions.

3.2.1.2.3 *Undulation*

Most roads are not flat and even, but vary in height at distance scales of a few metres to hundred metres, making the car move up and down. This will cause the vehicle to vibrate and bounce. Such energy in vertical motion is eventually lost. Dutch roads are of high quality and are usually in a proper maintenance state, as is the case for most of western Europe. It is typically not acceptable that drivers are shaken while driving, and people tend to avoid such roads.

3.2.1.2.4 *Bends*

If wheels do not move in the rolling direction, as is the case for toe-in, but also for bends, the rolling friction increases substantially. Tyres have high friction for safety reasons. When not rolling the reactive horizontal friction force is even larger than the vertical force pressing the surfaces together. Hence, all motions of the wheel, apart from rolling, are associated with forces proportional to the weight of the vehicle. The resulting work from these forces is difficult to determine, but it can be up 0.2% to 0.4% (30 to 50 Newton) of the total average force in urban driving distance. A surprisingly large amount of urban driving contains lateral accelerations: it can be up to half the total time. People tend to drive around bends in a manner to keep the lateral acceleration at a comfortable level, typically below 1.0 m/s². This is one of the causes of velocity variation in urban driving. Depending on driving style, bends may be associated with more or less braking.

3.2.2 Vehicle state

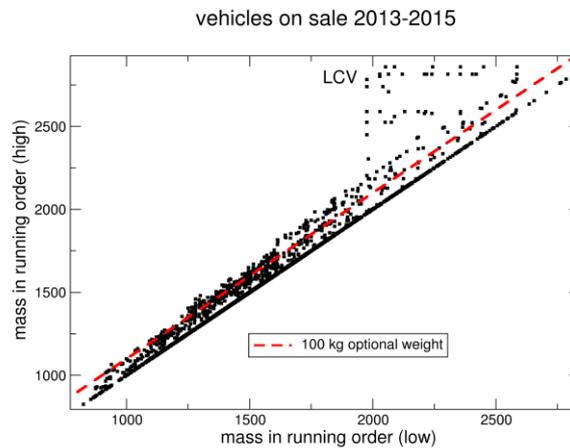


Figure 10 The lower and higher running order weight give an indication of the optional weight margins.

3.2.2.1 Optional weight

The different vehicle models come with optional weight (accessories, spare tyre etc.). The same generic vehicle model is sold with different packages, such that a single vehicle mass cannot be registered. From the 800,000 vehicles sold in the Netherlands between 2013 and 2015, 640,000 have no optional weight in the type approval document, whereas 160,000 do. In particular, the optional weight of LCV's can be as high as 500 kg. For passenger cars, 10% is a normal difference between the low mass and the high mass.

This optional weight is the baseline difference between the type-approval test and the real-world minimal weight. Additional passengers and luggage will increase the weight even further affecting both the rolling resistance and the additional energy lost at braking.

3.2.2.2 Running-in period

Machined components of moving mechanical parts are subject to wear. Initial wear removes the irregularities from the cutting and foundry processes. This is considered 'run-in'. Historically, for a car's initial 3,000 km, care was taken so that the running-in would not lead to damage, which would affect the overall lifespan of the vehicle. However, with improvements in manufacturing processes and manufacturing accuracy, such concerns are less.

A few percent higher fuel consumption is to be expected in the first few hundred kilometres. From 500 km onwards, the changes are limited. This can be determined from fuelling data. From 2004 to 2014, TNO determined the changing fuel consumption in the first hundreds of kilometres on the basis of fuel-pass data of Travelcard Nederland BV, a Dutch tank card company. The odometer setting at the moment of the initial fuelling was typically 650 km. From this moment, the distance and amount of fuel was tracked from the second to the fourth fuelling. The last fuelling was typically at 3,000 km. This way, changes in the average fuel consumption between odometer settings of 660 km to 3,000 km could be tracked.

For this analysis, the data of 55,000 diesel vehicles and 73,000 petrol vehicles were available.

TNO determined the following fuel consumption values, based on the data at consecutive fuelings (Liters, and Odometer_i):

$$FC_2 = \text{Liters}_2 / (\text{Odometer}_2 - \text{Odometer}_1)$$

$$FC_3 = \text{Liters}_3 / (\text{Odometer}_3 - \text{Odometer}_2)$$

$$FC_4 = \text{Liters}_4 / (\text{Odometer}_4 - \text{Odometer}_3)$$

Where Odometer₁ was typically between 500 km and 700 km, and the last Odometer setting was truncated at 3000 km to avoid comparison between different run-in values.

In order to observe changes, the ratios of fuel consumptions are plotted. If the ratio is 1.0, no change occurs. From the data, it can be concluded that between 500 km and 3,000 km the improvement in fuel consumption is at most 1% for diesel cars, and 0.5% for petrol cars.

The spread in the data of +/- 12% is typical for fuel consumption data of consecutive fueling in the same season. An improvement in fuel consumption over time would be shown by ratios FC_3/FC_2 and FC_4/FC_3 being smaller than 1.0. Where the value (FC_3/FC_2) is smaller than 1.0, there is an improvement in fuel consumption between 500 and about 1,750 km. If (FC_4/FC_3) is smaller than 1.0 there is an improvement between 1,750 km and 3,000 km. For diesel, the improvement between 600 km to 3,000 km is about 1%, with an uncertainty in the same range. For petrol vehicles, the improvement in fuel consumption is 0.5%, with an uncertainty of 1%.

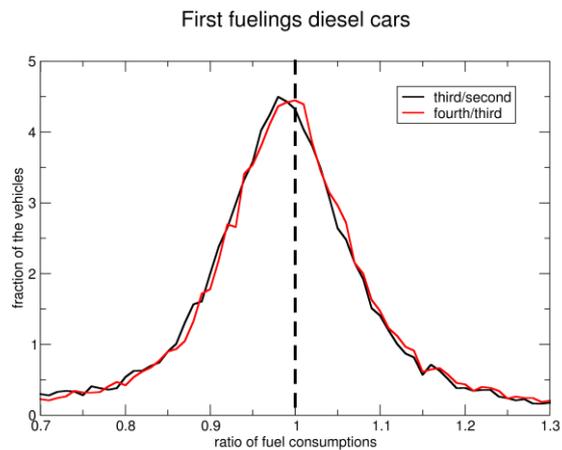


Figure 11 The distribution of the earlier ratio of two fuel consumption determination from consecutive fuelling (black line) seems centred at 0.99, while the later distribution (red line) is centred at 1.00. A very slight improvement in fuel consumption may be concluded from the data in this the graph.

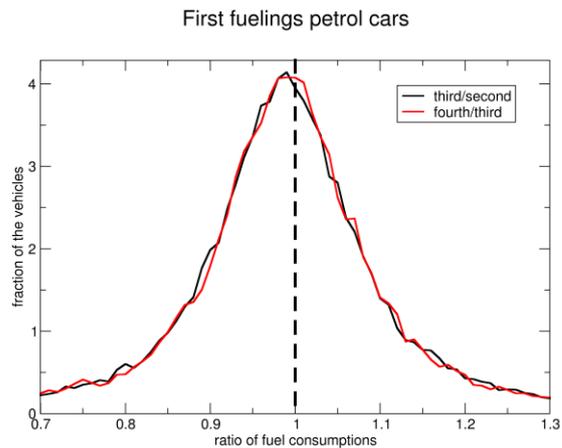


Figure 12 The first ratio differs less the 0.5% from the second ratio and a centre value of 1.0. An improvement in fuel consumption of less than 0.5% is to be expected on the basis of this data.

The main problem with running-in is therefore not a higher fuel consumption in normal use, but the fact that the vehicles from the factory may have a slightly higher fuel consumption on the test. For future Conformity of Production testing, if it is to include CO₂ emissions, this may yield an inappropriate answer. Extrapolating back the effects from 500 km to 3,000 km, where the run-in effect is small, it is to be expected that also in the first kilometres the effects are less than a few percent.

The distribution of fuel consumption between refuelling also shows an intrinsic variation in fuel consumption of about 12%. For a tank of 40 litres that would correspond to about 5 litres. This is partly due to accuracy in filling, as the filling stops automatically when a certain level is reached, but also due to differences in driving styles, and circumstances. The observed fillings occurred typically within a week such that the effect of seasonal variations is limited.

3.2.2.3 Tyres

Tyre design is a balance of safety, noise, rolling resistance and cost price. So far, there has been little incentive to have fuel efficient tyres, so the likely focus is on safety with noise as a boundary criteria in the design.

3.2.2.3.1 Tyre label

The tyre label is determined in an independent test on a drum in the laboratory. The surface of the drum is smooth metal, which would yield a lower rolling resistance than the typical road surface. On the other hand, the drum is curved, increasing the deformation of the tyre somewhat, resulting in a higher rolling resistance. It is generally believed the two effect cancel out, and the drum test yields a proper rolling resistance for the performance of the tyres on the road.

The RRC (Rolling Resistance Coefficient of lateral force given a vertical weight on the axle [kg/ton]) determination in R117 regulation is at 80 km/h. Hence this is an specific velocity. At higher velocity there is normally a small increase in rolling resistance. This effect is difficult to determine, as the air drag is dominant at high velocities. The typical polynomial fits made for the velocity dependence of the rolling resistance is mainly because the increase in rolling resistance occurs above 100 km/h, together with the higher noise levels. The RRC is similar to the tyre part of the constant road load force F_0 at low velocity. Only at high velocities deviations occur, which end up in F_2 , not F_0 .

The velocity-dependence of rolling resistance is not negligible. However, for the vehicle whatever happens at velocities above 100 km/h is dominated by air-drag. It is estimated that there is a 20% increase in rolling resistance above 100 km/h from low velocities which results in approximately 30-40 N increase in rolling resistance compared with 450 N air drag. For all practical purposes the rolling resistance for normal use can be assumed constant. The amount of distance at very high velocities is small, and the effect cannot be establish properly in the margin of the air drag.

The F_1 term in the road load curve is a complicated aspect, which cannot be attributed properly to either rolling resistance, transmission losses, or air drag. It can be removed through a "refit" with only F_0 and F_2 : Given $F = F_0 + F_1 * v + F_2 * v^2$ it is possible to make a least-square error fit with $F_{0_{new}} + F_{2_{new}} * v^2$, by minimizing $F_{0_{new}}$ and $F_{2_{new}}$ in the integral over:

$$\min_{F_{0_{new}}, F_{2_{new}}} \int_0^{v_{max}} (F_0 + F_1 * v + F_2 * v^2 - (F_{0_{new}} + F_{2_{new}} * v^2))^2 dv$$

The simple, general solution is:

$$F_{0_{new}} = F_{0_{old}} + 3 * F_{1_{old}} * v_{max} / 16$$

$$F_{1_{new}} = 0.0 \text{ (set to zero in the fit)}$$

$$F_{2_{new}} = F_{2_{old}} + 15 * F_{1_{old}} / (16 * v_{max})$$

An upper value of $v_{max} = 120$ km/km is appropriate, as it corresponds to the coast-down and NEDC and WLTC velocity ranges.

In this report only F0 and F2 are discussed. In these discussions the effect of F1 is eliminated according to the method above using $v_{\max} = 120$ km/h.

The typical stated rolling resistance of vehicles sold is in the order of 91 N/ton. Fuel efficient tyres perform usually less on safety, for example, on wet road grip. Hence, in the selection of tyres on production models, but also for the aftermarket, the rolling resistance is not very low. These findings are somewhat contradictory to the type-approval road-loads which are reported. In a study for the UNECE, road-loads were collected from different type-approval authorities. The average rolling resistance expressed in F0/M was 105 N/ton. Moreover, it was found that about 12% of the rolling resistance was not related to weight, but likely to driveline losses. This yields an average total rolling resistance of 89 N/ton, slightly lower than the 91 N/ton from the tyre labels.

On the other hand, some type-approval values for the rolling resistance are very low. From the recent testing, values down to 58 N/ton were noted, which is no longer in line with the rolling resistance of the tyres used. Generally, any value for F0/M under 80 N/ton is unrealistically low for normal production vehicles. Within the current IUC test program at TNO, about half of the vehicles reportedly have F0/M lower than 80 N/ton. The average is 83 N/ton.

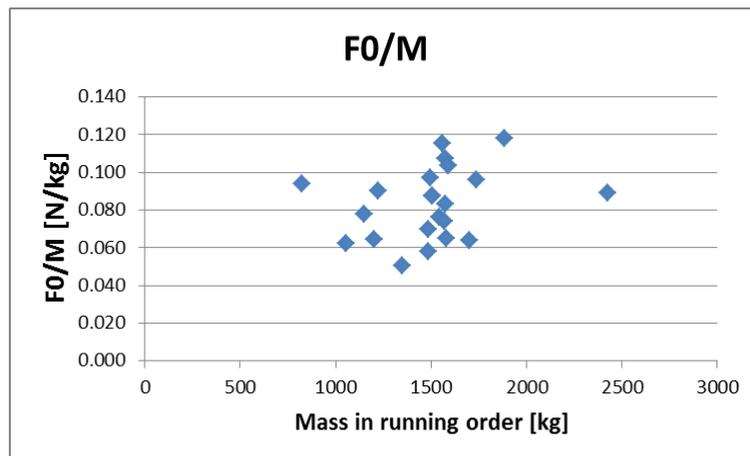


Figure 13 The F0/M from type-approval values of recently tested vehicles. Many results are not in line with the RRC of the tyres sold, ignoring further driveline resistances.

3.2.2.3.2 Tyre pressure

Under-inflation of tyres in normal use is very common. Tyre pressure monitoring should be carried out frequently; typical advice is a monthly check, but in many cases they occur only at the annual check-up. Some minor effects are to be expected from normal under-inflation. However, slow punctures, e.g. nails stuck in the tyre and a significantly reduced tyre pressure, will cause a significant increase in fuel consumption. The in-car TPMS should reduce the latter effects in the future.

There is also a dynamic effect to tyre pressure. While driving the tyres heat up due to the rolling resistance, increasing the tyre pressure by 10% to 30%, depending on the dynamics and circumstances. The average effect is taken into account, but the cause of the variation is unknown, and may lead to significant in the rolling resistance which may be exploited in the coastdown test. There are also differences

due to the fact that the wheel and axle is propelling the vehicle or free running. It is expected that this will contribute to additional fuel consumption at the start, especially in short trips in cold conditions. The number of influencing factors for dynamic tyre pressure is large. It is therefore difficult to quantify the effect.

3.2.2.3.3 *Tyre tread*

A low tread will lower the grip and thereby also lower fuel consumption. This is intricately related to the road surface and tyre pressure, as the tyre profile deformation is a main source of additional rolling resistance.

3.2.2.4 *Wheel alignment*

Toe-in of the front wheels, to improve drivability, will lead to an increase in rolling resistance. It is not known if this flexibility (i.e. removing toe-in) is exploited much on the coast-down test. On the other hand, wheel alignment may change over time. Especially, minor accidents, e.g. hitting a kerb, may bend the suspension and alter the wheel alignment.

There is limited information on misalignment of wheels in passenger cars. For truck trailers, re-alignment has been considered as a method to improve fuel consumption. In the case of minor misalignments, the fuel saving is limited. However, a few trailers have a major misalignment of the wheels which make re-alignment worthwhile.

3.2.2.5 *Lubrication and oil level*

The use of a low-viscosity oil and low oil levels during the type-approval test can reduce the internal friction somewhat. In particular the cold start effects may be reduced. Given the resistance of the driveline after the transmission of about 20-30 N the effect is expected to be in the order of 1 g/km range. The constant, i.e., frictional, engine losses are, however, substantial on the NEDC test, where the effect can be much higher.

3.2.2.6 *Filter loading for diesel vehicles*

The wall-flow particulate filter (DPF), common on Euro-5 and Euro-6 diesel vehicles, has a substantial back-pressure, especially when it is soot loaded. The total exhaust gas flow, combined with the back-pressure, requires a certain power to expel the exhaust gas. For a passenger car, the DPF back-pressure varies between 2 and 10 kPa, depending on the filter loading and the flow. At a temperature of 200° C, and 150 g/km CO₂ at a concentration of 8%, 1.6 m³ exhaust gas is expelled per kilometre. In that case, 3 kJ to 15 kJ energy is dissipated in the DPF, corresponding to 0.5 to 3.0 g/km extra emissions.¹² Clearly, this depends greatly on the air-fuel ratio (λ) and the filter loading. However, the effect is non-negligible and an obvious aspect to take care of during the type-approval test.

In practice, filter loading occurs if a vehicle operates only a limited time at higher velocities. Regeneration of the filter commonly occurs while initiating an accelerating above 80 km/h. At such times the soot is burned away and the back-pressure drops again. Buses, refuse trucks, and taxis are common vehicle

¹²Given 150 g/km CO₂ the CO₂ volume flow is $(150 \text{ g}/1.98 \text{ [g/l]}) \cdot (473 \text{ K}/273 \text{ K}) = 131 \text{ l/km}$. In the case this is 8% of the total flow, which makes the total flow 1.6 m³/km. The pressure drop times the volume flow gives the total work by the exhaust gas through the DPF: $1.6 \times 3000 \text{ to } 1.6 \times 10000 = 3 \text{ kJ to } 15 \text{ kJ}$.

categories which may suffer from engine failures due to too high back-pressure as a result of frequent and/or dominating urban operation, with back pressure values around 20 kPa. It is likely that even after regeneration the back pressure will not come down to the value of a new DPF as some ash remains.

3.2.2.7 *Parasitic braking*

An average modern passenger car can be pushed forward on a flat surface by a single person of average posture, when the clutch is disengaged. The required force is limited to 140 to 200 N. There are cases however, where it is not possible to push a vehicle forward. Often this is due to parasitic braking. For example, vehicles which are not used frequently may have corroded brake disks, which have substantial resistance. The effect of this on fuel consumption is significant. As an example, the rough estimate of an additional 150 N force for a severe parasitic braking will cost about an extra litre of fuel per 100 km¹³. Likewise, worn and uneven brake pads may touch permanently, adding to the overall rolling resistance. In the in-use compliance testing programme, that TNO executes on behalf of the Dutch Ministry of Infrastructure and the Environment, cars are ensured to have a proper maintenance state. Occasionally, in a few percent of the time, this entails also the removal of parasitic braking. High parasitic braking is not very common, but it does occur occasionally. Small parasitic braking is considered normal.

3.2.2.8 *Fouled injectors*

Occasionally, concerns arise for the combustion efficiency of a car. For diesel vehicles, fouled injectors are often identified as culprits. However, this problem seems more a specific maintenance problem, for example related to poor diesel fuel quality, than a generic issue with engine efficiency and combustion.

3.2.2.9 *Lambda excursions, air-to-fuel ratio in spark ignition engines*

In the 1980's, prior to the introduction of the three-way catalyst, it was argued that its penalty on fuel efficiency would be substantial: values up to a 20% increase were mentioned. In a slightly rich operation the power output is higher and a slightly lean operation improves the efficiency. In fact, the change from pre-three way catalyst vehicles to Euro-1 vehicles with a three-way catalyst was hardly noticeable in terms of a reduction of fuel efficiency, in the test data around 1987-1995. The lambda=1 operation of the vehicle is slightly less fuel efficient, and engine-control excursions away from lambda=1 may improve the fuel efficiency somewhat. With Euro-1 to Euro-3, moments of high power demand occasionally led to rich operation. However, with modern vehicles it is no longer the case. Most petrol vehicles have fixed operations at lambda=1, with a fixed combustion efficiency lower than for diesel vehicles.

3.2.3 *Traffic, speed limits, and congestion*

Apart from the road infrastructure, traffic lights, roundabouts, speed limits, and congestion, most variation in driving behaviour is a personal choice. Generally, one can assume this varies only slightly for a large group over a longer period and it will affect different vehicles alike. Only a few aspects may change over the years, such as the change in traffic congestion with road infrastructure improvements and changes in traffic intensity due to the economic climate. Another aspect are changes in motorway speed limits and drivers' reaction to that change.

¹³ The work of the parasitic braking is in this case: $150 \text{ N} \times 100\,000 \text{ m} = 4.2 \text{ kWh}$. Divided by an engine efficiency of 40% this yields around 10 kWh/km, which is about 1 liter of fuel.

3.2.3.1 Speed limits

Motorway speed limits have a direct impact on average fuel consumption. For example, 30 km/h speed limits in urban areas will increase the fuel consumption when compared to the 50 km/h speed limit. Across Europe, there is a variation in speed limits for urban, rural, and motorway road types.

Table 2 The Dutch CO₂ emission factors on the motorway for different speed limits. Note that above 120 km/h speed limit the average velocity does not increase significantly.

year [g/km]	2015	Motorway speed limits			
	Congestion	80 km/h	100 km/h	120 km/h	130 km/h
Light [<3.5 ton]	251.6	127.8	144.8	158.6	164.4
Medium [3.5-10 ton]	731.6	478.6	478.6	478.6	478.6
Heavy [> 10 ton]	1514.4	748.6	748.6	748.6	748.6

3.2.3.2 Traffic lights and junctions

Every braking event has an associated CO₂ impact. The amount of CO₂ is related to the kinetic energy which is lost by braking. Given a 1,400 kg vehicle in running order, at 50 km/h this energy is 135 kJ, while at 80 km/h this increases by a factor of 2.5 to 346 kJ. The associated CO₂ emission range from 25 g to 67 g.¹⁴ Hence with a few stops per kilometre in urban conditions, and one stop per two kilometres in rural conditions about a third of CO₂ emissions under these conditions are directly related to stopping.

Table 3 The typical coast-down distances at a given velocity. For example, coasting to a stop from driving on the motorway at 120 km/h will add more than 2 kilometres to a trip without fuel consumption. On a trip of 10 kilometres, this amounts to maximal 20% of the distance covered. For a drop of 20 km/h coasting will be around 400 metres of driving without fuel consumption for all velocities.

velocity [km/h]	total distance [m]	segment distance [m]
120	2256	
100	1859	397
80	1424	434
60	963	462
40	508	454
20	145	363
0	-	145

Due to the old-fashioned design of driving cycles, by cut-and-paste of subcycles, and the limited duration of such cycles, including acceleration and deceleration, the focus of driving cycles is more on the transient driving at intermediate velocities, than the longer periods of driving at more constant velocity like they occur in normal driving. Most driving cycles are therefore not properly representative for the driving on the road. A motorist on the motorway may go easily for an hour without a stop:

¹⁴ The kinetic energy of a vehicle is $E = \frac{1}{2} m v^2$ in SI units [J, kg, m/s]. Given the marginal CO₂ emission of 720 g/kWh, the extra emission of a stop is substantial, particular at higher velocities as the kinetic energy increases with the square of the velocity.

this shift the balance from inertial forces to air drag significantly from the driving cycle to real world driving.

It is important to note that with 10 km motorway driving at 120 km/h, still 20% of emissions would be attributed to braking, in the case of one sudden stop from this speed. Hence, due to the higher velocity, braking may still contribute significantly to motorway fuel consumption. This, however, depends strongly on driving style, trip length, congestion and motorway layout.

3.2.3.3 *Congestion*

The effect of congestion on fuel consumption is not simple. It depends on the road type, the actual traffic situations, the vehicle technology, and the driver. In practice, three effects are important: the amount of braking, the engine speed and gear shifts, and the use of engine stop-start while standing still. For example, a congested roundabout, with traffic trickling through, will induce drivers to advance one car length at the time which does not leave a moment to turn the engine off, and where all the kinetic energy of the car is immediately lost in a subsequent stop, and very likely all is carried out in first gear. Hybrids cars are ideal for such situations.

Congestion on the road seems to have a smaller and smaller effect on CO₂ emissions in the Netherlands. It may be surprising, but when decomposed, this effect can be explained. There are two sides of this story. First of all, technology has improved for low engine load. In the past, the urban driving caused by far the largest CO₂ emission in g/km. For modern cars, the CO₂ emissions per km on the motorway are almost in balance with the CO₂ emission in urban driving, due to the focus on the NEDC test in CO₂ reduction of vehicles which lead to improvements, especially for petrol cars, of the efficiency in urban and congestion driving. Hence the actual vehicle usage, with limited urban and congestion usage, as represented by the NEDC test, has a limited effect on its CO₂ emissions. The second effect is a decrease of the free-flow velocity with congestion. This effect is even more pronounced than the increase of driving in congestion. The relation between traffic intensity and vehicle velocity is dominated by a reduction in free-flow velocity in the Netherlands. In the last years the congestion has halved due to an increase of motorway infrastructure and the economic crisis which as reduced traffic demand.

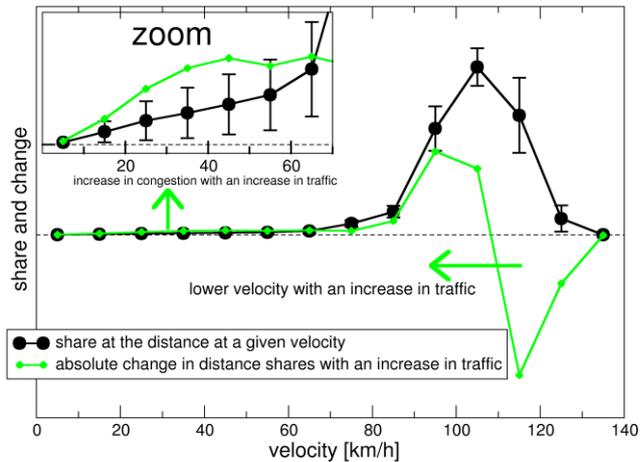


Figure 14 The distribution of velocity on the Dutch motorways, with the share of distance travelled at each velocity, and the change in velocity due to the increase in traffic intensity. The figures are dominated by the free-flow driving at 105 km/h. The upper left side of the figure zooms in on congestion, below 50 km/h, to show the effect of changes in intensity.

Above 100 km/h, higher velocities will cause higher CO₂ emissions. Engine load in this case is already substantial such that engine losses will not interfere greatly with additional CO₂. The additional CO₂ emission is dominated by the air drag increase. Given an air-drag force of 450 N at 100 km/h for a compact car, an extra 1 km/h in average velocity will yield about 9 N extra force and about 2 g/km extra CO₂.¹⁵ For low-powered vehicles the increase in power demand at such velocities may yield some extra CO₂ due to a substantial increase in engine losses above 3000 RPM. For high-powered vehicles, for example with a 6th or 7th gear, the engine losses and associated CO₂ emissions may decrease somewhat, compared to driving in a lower gear.

Using this type of velocity distribution to derive the effect of congestion on CO₂ emissions leads to the analysis two aspects, and the estimation of a third:

1. Air-drag effects: summing the “distance * v²” to achieve the amount of work associated with air drag and the changes therein due to the change in average velocity. This is represented as $\langle v^2 \rangle$ in this study.
2. Engine loss effects: summing the “distance / v” to determine the variation in total engine running time. Note that low velocities contribute significantly to this number: 100 minutes at 100 km/h combined with 5 minutes of standing still reduces the average velocity to 95 km/h. This is represented as $\langle v^{-1} \rangle$ in this study.
3. Braking losses for motorway driving are lower than for urban driving because of more free flow driving, but they are expected to increase from 70 km/h down to 0 km/h. It is thus estimated that 30% of the total power from the engine at the wheels is lost in braking at low velocities.

¹⁵ $450 * (101)^2 / (100)^2 - 450 = 9$ N. The associated work is 9 kJ per kilometre.

The effects can be expressed as “effective velocity”, i.e., taking the square root of $\langle v^2 \rangle$ and the inverse of $\langle v^{-1} \rangle$, for the different contributions, thus estimating the fuel consumption variation with congestion. The average v^2 velocity represents the variation of air-drag. The average $1/v$ velocity represents the relative effect of engine losses. The air-drag velocity has double¹⁶ the opposite effect on the CO₂ as the total driving time, proportional with the inverse velocity, around 100 km/h. Considering the size of the travel-time effect, being about double. The two effects nearly cancel each other out. Travelling shorter reduce the effect of engine losses, but increase the effect of air-drag. For a low-powered car the losses may be larger, but for a compact car the air-drag in total may contribute less.

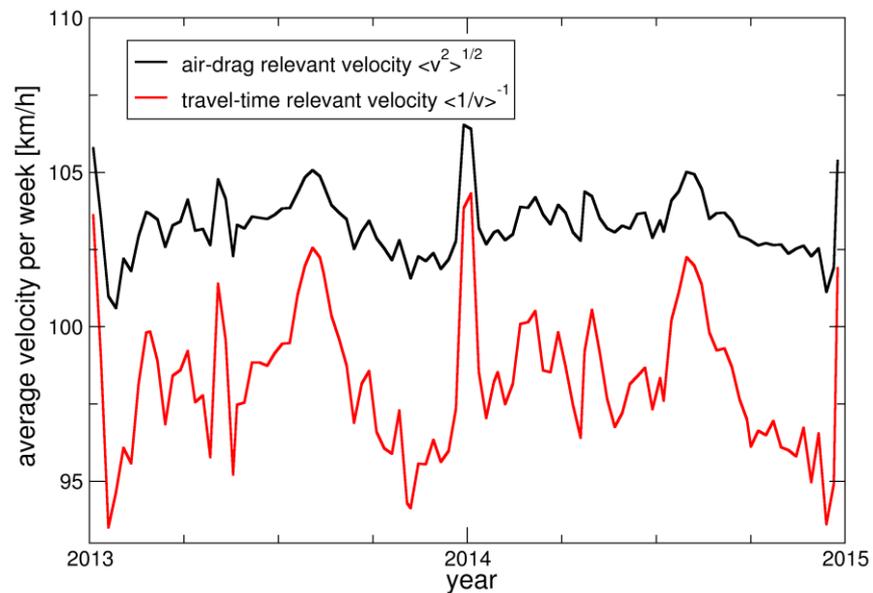


Figure 15 The different contributions to motorway fuel consumption: congestion and air drag, expressed as velocity. Given the average velocity close to 100 km/h the air drag, is 60% of the total work and opposite effect for losses is about 20% of the total emission. In total there is only a minor net effect remaining of the air drag as the variations in travel time are larger than for air drag.

From the velocity data from the motorway induction loops it can therefore be concluded that in 2014-2015 motorway congestion had only a minor effect on the overall fuel consumption, given the average free-flow velocity around 105 km/h. The variations in engine losses are in the order of 5% due to motorway congestion, while the variations in air drag, with the same motorway congestion, are in the order of 2%. Both effects are opposite. Given the larger contribution of air-drag to the overall fuel consumption on the motorway, the two effects cancel out almost completely.

¹⁶ $(v+\Delta v)^2 \sim v^2 + 2 v \Delta v$

3.2.3.4 *Parking, stopping, and idling*

The absolute amounts of CO₂ emitted at low-velocity driving and stopping are only small. However, as limited or no additional distance is covered, the emission in g/km are large to infinite.

3.2.4 *Vehicle usage*

3.2.4.1 *Trip type and length*

The vehicle use for short trips has a negative effect on fuel consumption. Moreover short trips generally have a higher fraction of low velocity urban driving. This is mainly due to the higher fuel consumption of a cold engine, drivetrain, and tyres. On the NEDC, it is a substantial amount: 140 g per start for a petrol car and 90 g per start for a diesel car, for a cold start at 23° C. Hence in the type-approval test, about 10 g/km can be attributed to the cold start. In real world usage the emission increase per cold start effect is more severe as the temperature is lower. However, the number of cold starts as determined from vehicle usages per kilometre is smaller than on the NEDC test. A typical trip length starting with a cold engine is, in real world, likely to be 35 km, based on 8×10^6 cars driving 100×10^9 kilometres annually with one cold start per day, as many older vehicles are not used daily. This number can be estimated in many other ways, but the outcome is similar.

3.2.4.2 *Urban, rural, and motorway driving*

Trip length and trip type affect the fuel consumption of the vehicle. Urban driving is associated with short trips and cold starts, and periods of idling. Hence high urban emissions are not necessarily due to the driving style. With a hot engine, urban driving, alike the urban component of the CADC (Common Artemis Driving Cycle, an often used real-world driving cycle), will cause about 30% higher emissions than the average emissions over the total CADC test, which covers urban, rural and motorway driving. With a quarter of the total distance in urban driving, the effect therefore is in the order of 8%-10%. The cold start adds another few percent effect on the total, with typical trip lengths of 7 km. Drivers who drive solely inside the city have larger effects. However, given the typical variations in the share of urban driving of between 15% to 35% of the total distance travelled across Europe the overall contribution of cold start to the fuel consumption is limited.

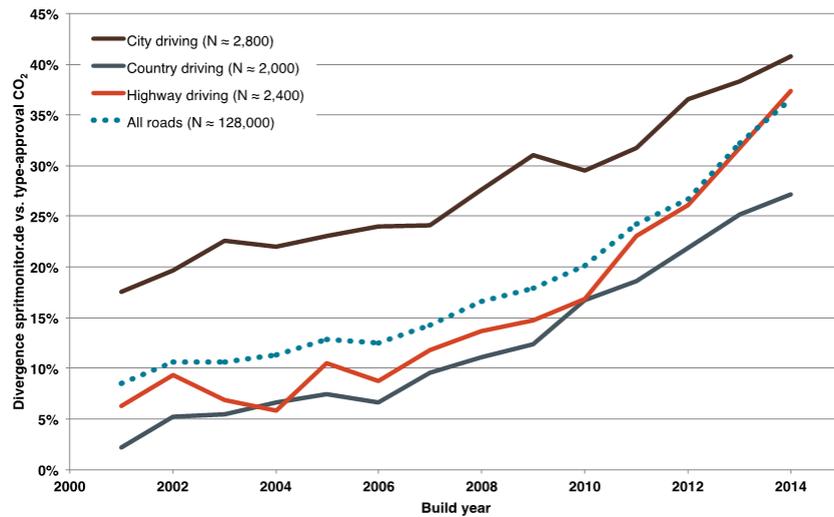


Figure 16 Divergence between spritmonitor.de and type-approval CO₂ values by road type. Data for vehicles predominantly driven on one road type (≥ 75 percent of distance travelled). Number of spritmonitor.de entries per road type in parentheses.

Figure 16 depicts the divergence between real-world and type-approval CO₂ values for different road types over time. Real-world data was collected from Spritmonitor.de, a German website where users can indicate on which type of road their vehicle has been driven between two fuelling events. Vehicles predominantly driven on one single type of road ($\geq 75\%$ of the driving distance) were selected for this comparison. The divergence between real-world and type-approval CO₂ was calculated using the combined fuel consumption value from the NEDC. The results indicate that the divergence has increased for all road types, but that urban driving typically results in higher CO₂ emissions than extra-urban or highway driving. While extra-urban and highway driving exhibited a similar gap increase between 2001 and 2010, the gap appears to have increased faster for highway driving in more recent years.

The result is surprising. The vehicle mass and vehicle power is expected to affect CO₂ emissions on the NEDC in the same manner like in real-world urban driving. Despite the increase in mass and power, a reduction of CO₂ emission on the NEDC should translate one-to-one into urban fuel consumption. One would expect the reductions in the UDC part type-approval test to translate into reductions in CO₂ emissions during real-world urban vehicle usage with only limited increase in the gap for urban usage. The increase in the gap is indeed smaller than the overall effect, but yet substantial. It can only mean two things: either the gap in the UDC part is mainly due to flexibilities, or the technological gains on the UDC part do not translate fully into real-world urban driving. For example, a stop-start system leads to large reductions on the UDC, however, in practice, the stop-start system may not engage in normal situations. Drivers may not, or not timely enough, put the gear in neutral and release the clutch, or the system may not respond due to particular circumstances, such as running auxiliaries like air conditioning.

3.2.4.3 Payload and passengers

In many cases, cars are driven without passengers. Especially commuters are unlikely to carry additional weight through passengers. Holiday periods will lead to additional weight. This seems to show up only marginally in the monitoring data

from Travelcard where holiday periods, Christmas and summer, have higher average fuel consumption. It is however expected that people carry extra weight on top of the type-approval running order weight. For example, a spare tyre is no longer a standard option with a new car, but drivers may buy a spare tyre from the aftermarket, as there is still a space available for a spare tyre.

3.2.4.4 *Lights*

It is surprising that with the ban on traditional household light bulbs, that the standard front light of a passenger car is still a H4 halogen lamp of 55 Watt. If electric equipment, in particular the equipment which is used continuously, such as lights, would be part of the CO₂ type-approval protocol, the power demand would be much lower, with improvements on their efficiency. Additionally, the use of the traditional alternator and the lead-acid battery means that the power demand of each piece of electric equipment must be increased with 40% due to losses in charging and conversion.

3.2.4.5 *Air-conditioning*

The temperature dependency study, to be discussed later in the validation results and shown in Figure 48, shows a limited effect of air-conditioning on the overall fuel consumption. When the temperature increases, so does the power consumption of the air-conditioning. However, this is more than compensated by the positive effect of the higher temperature on losses, air-drag and cold start. This is for the same distance travelled. But, of course, air conditioning use energy, and not using the air conditioning, or a more energy efficient air condition will lower the total fuel consumption. Moreover, air-conditioning used at lower temperatures removes the water vapour from the cabin air. This also requires energy, and it will add to the energy usage in all conditions.

In the Spritmonitor.de data, the air-conditioning use is indicated by drivers in a limited number of cases. This can serve to separate the air-conditioning effect from other temperature effects. For the limited cases of reported air-conditioning use, the effect is already small. Hence, compared to the overall effect for all weather conditions, the total effect of air-conditioning is only a fraction.

Figure 17 shows the impact of air-conditioning on real-world CO₂ emissions based on Spritmonitor.de, which offers users the option of indicating when air conditioning was used between two fuelling events. In addition, Spritmonitor.de users can also indicate the type of tyres (including summer, winter, and all-year tires) used. Two groups of users were identified: users who frequently use air-conditioning ($\geq 75\%$ of the driving distance) while their car is equipped with summer tyres and users who infrequently use air conditioning ($\leq 25\%$ of driving distance) with summer tyres. Summer tyres were thus employed as a proxy for the summer season so as to limit the impact of seasonality on the estimate. Results indicate that air-conditioning has a measurable impact on the gap between real-world and type-approval CO₂ emissions and that the impact has been relatively stable over time. On average, air-conditioning increased the gap by 3 percentage points when compared to vehicles with infrequent use of air-conditioning, in the same summer conditions.

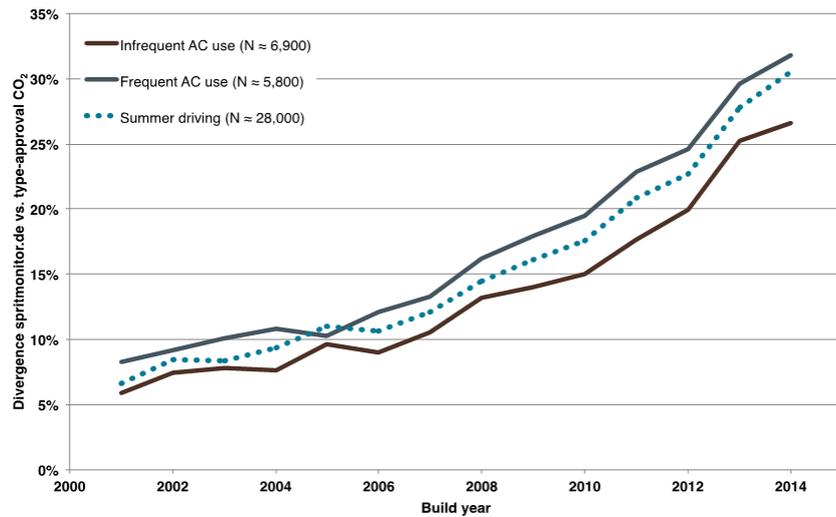


Figure 17 Divergence between spritmonitor.de and type-approval CO₂ values for groups of users with infrequent use of AC (≤ 25 percent of distance travelled) and frequent use of AC (≥ 75 percent of distance travelled) during summer months. Average divergence for summer driving included for comparison. Number of spritmonitor.de entries per group in parentheses.

3.2.4.6 Roof racks and towing

The Netherlands is rich in caravans: about 600,000 caravans are used. However, holiday periods do not show a substantial increase in average fuel consumption, so the effect of caravan towing and roof racks is limited in the monitoring group. On the other hand, assuming 2,000 kilometres holiday driving for 300,000 caravans with twice the CO₂ emission per kilometre for this operation, it would still only cause a small increase in CO₂ emissions (0.06%) for the 101,000,000 kilometres which are driven annually with passenger cars. Also if it is assumed that 1,000,000 roof racks are needed to carry holiday luggage over 4,000 kilometres annually, the effect on the total emissions is small, i.e., less than 1 %.

3.2.4.7 Overnight parking

Cold start is an important contributor to total fuel consumption, in particular for short trips. The temperature at the start affects this result. In most countries cars are parked outside on the road. Hence the night temperature and the radiative losses to the night sky are important factors affecting the morning cold start contribution. This effect is likely an important contributor to the overall temperature effect.

3.2.5 Driving behaviour

The variation in fuel consumption for different drivers with the same vehicle make and model is quite large: i.e., some 30% to 40%. In part, this is due to the vehicle usage and ambient circumstances, and in part due to the driver behaviour. In spritmonitor.de, self-declared driving behaviour is monitored. This driving style explains only part of the full variation.

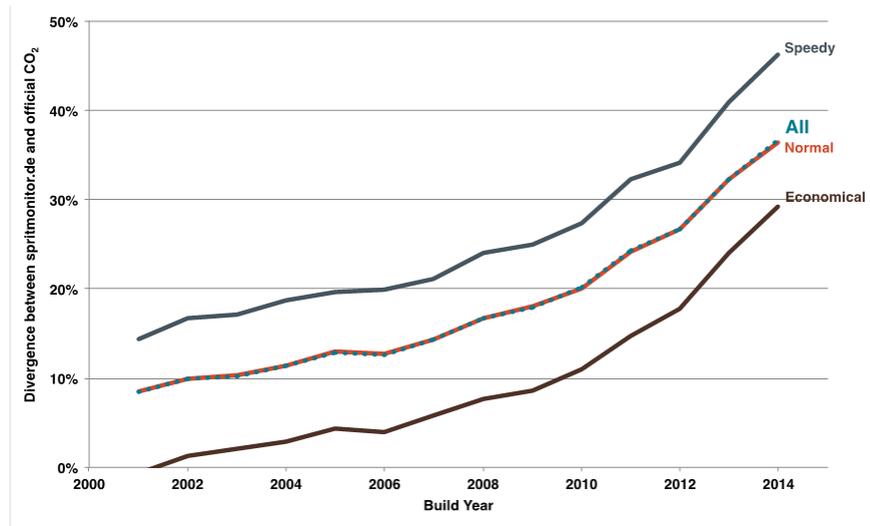


Figure 18 Divergence between spritmonitor.de and type-approval CO₂ values for different driving styles.

Figure 18 presents the impact of driving behaviour on the gap between real-world and official CO₂ values according to Spritmonitor.de, where users can indicate whether they drive in an economical, normal, or speedy fashion. While 57 percent of users rarely use this feature, 43 percent of users provide information on their driving behaviour. The Spritmonitor.de data indicates that driving behaviour has a considerable impact on real-world CO₂ emissions, with speedy driving increasing the gap by 7 percentage points on average, while economical driving reducing the gap by 9 percentage points on average compared to normal driving. It should be noted that, while economical driving reduces the gap, all driving styles exhibit an increase in the gap over time so that even economical driving results in 29 percent higher CO₂ emissions than indicated in type-approval values in 2014.

3.2.5.1 Preferred velocity

The preferred velocity of individual drivers on the motorway has a substantial effect on fuel consumption, as above a velocity of 100 km/h fuel consumption rapidly increases with velocity due to air drag. A study on motorway velocities showed a direct relation between a higher free-flow velocity and lower congestion. Both effects are intertwined because of the traffic intensity on the road. The desired velocity, or free-flow velocity, alone may have a large effect. Because the traffic situations associated with free flow have lower congestion and fewer stops, in average real-world driving the combined effect on fuel consumption is limited because the two factors influence fuel consumption in opposite directions. However, a certain desired free flow velocity on the motorway, e.g., 100 km/h or 120 km/h, may be important for the variation among drivers. Consequently, a large part of the variation in fuel consumption among individual drivers with the vehicle make and model, may be attributed to driver habits regarding driving at a certain velocity on the motorway.

3.2.5.2 Acceleration

Acceleration is often associated with fuel consumption. This association is, however, only partly justified. Especially, if the gear shift velocities are kept fixed, the engine losses are similar during hard and soft acceleration. Energy is converted

to kinetic energy of the vehicle. Only if the vehicle brakes is the energy lost. Instead of braking, the vehicle may coast down using the kinetic energy to overcome rolling resistance. The engine efficiency does vary somewhat with the magnitude of acceleration, but harder accelerations at low velocities will reduce low velocity driving, which also is a contributor to high fuel consumption.

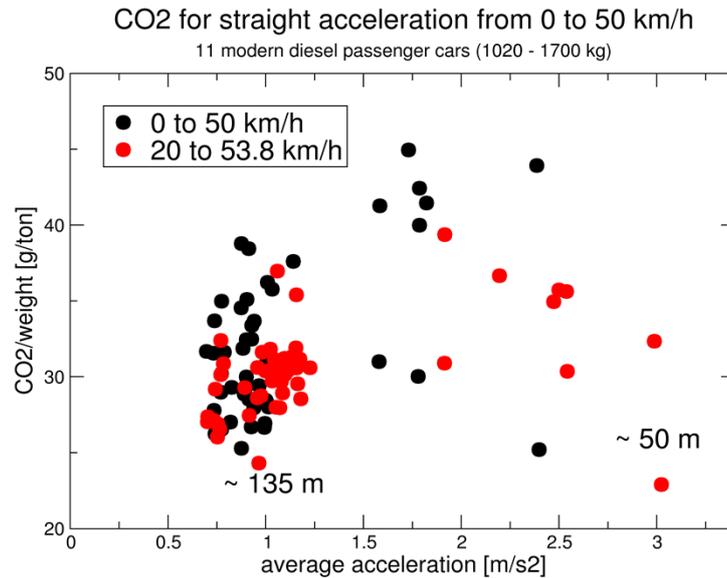


Figure 19 The CO₂ emissions associated with acceleration to increase the kinetic energy by 96.45 kJ/ton. The distances indicated are the acceleration distance needed to achieve the desired velocity.

Figure 19 shows the CO₂ emission per ton for an acceleration from one velocity to the next, associated with a fixed amount of added kinetic energy. The hard and soft acceleration both lead to similar CO₂ emissions.

The magnitude of acceleration has only a limited effect on fuel consumption. The same increase in kinetic energy per ton is associated with an acceleration from 0 km/h to 50 km/h, and with an acceleration from 20 km/h to 53.8 km/h. Both correspond to a kinetic energy increase of 96.45 kJ per ton. With an efficiency of 750 g/kWh it would give 20 g of CO₂ which is close to the best value in Figure 19. The distance travelled of 50 – 135 m would require another 10 to 27 kJ, mainly the result of rolling resistance. This can be another 6 grams of CO₂.¹⁷

3.2.5.3 Overtaking

Overtaking often requires hard acceleration, not necessarily followed by braking. On the motorway, it increases the average velocity and fuel consumption. Generally, overtaking is poorly studied and the effects are unknown.

3.2.5.4 Braking vs coasting

Coasting, or taking the foot off the accelerator and letting the vehicle decelerate slowly, is a very fuel efficient way of driving. No fuel is used in this deceleration in a

¹⁷ 50 m x 200 N = 10 kJ, 720 g/kWh CO₂ x 10 kJ/3600 = 2 g CO₂. For 135 m the results are almost threefold.

modern car: the fuel injection is stopped as the engine is rotated by the wheels. From 50 km/h or 80 km/h several hundreds of metres of driving can be added to a stop at no fuel penalty as shown in table 1.

Such driving is however very uncommon. Most drivers have a symmetric driving style: the magnitude of acceleration is matched by the magnitude of deceleration. Even if a deceleration of 0.2 to 0.5 m/s² (a stop in 500 metres) would be appropriate, a driver who accelerates at 2 m/s² also generally also tends to brake later and decelerate at the same magnitude of -2 m/s² rather than coasting.

3.2.5.5 *Gear shifting*

The number of gears and amount of gear shifting significantly affect fuel consumption. This is related to the engine operating speed. Reducing the engine speed by 10% will reduce the engine losses by 10% or more. For normal vehicle technology and usage, the losses are about 30% of the total fuel consumption. Hence, a 3% reduction can easily be achieved.

This is the reason why a 6th gear significantly lowers fuel consumption. It typically reduces the engine speed on the motorway from 3000 rpm to 2400 rpm, i.e. a 20% reduction. Given a low rated power of 60 kW at 4500 RPM, the available power at 2400 RPM is about 32 kW. Up to 120 km/h 32 kW is sufficient power to have a reduced engine speed with a 6th gear. Above 120 km/h additional high power is needed.

In the driving test there is nowadays attention for eco-driving, which also includes the gear-shift strategy, which a quick up-shift to retain low engine speeds. In practice one sees that complex traffic situations and sportive driving will lead to a later gear shift and higher engine speeds. This adds mainly to the additional fuel consumption in the urban driving. In the chassis dynamometer test gear shifts can be matched with the whole of the driving cycle

With automatic gears the engine speed can be optimised, but on the other hand, there are three reasons this may not yield a net benefit over a manual transmission: First, the additional weight of the automatic transmission. Second, the high drivetrain losses of some automatic transmissions especially at higher velocities. Third, the different modes of operation for automatic transmissions. The sportive mode will increase the fuel consumption for a better driveability.

3.2.5.5.1 *Clutch operation*

Modern cars cut off the fuel consumption if the car is decelerating while the clutch is engaged. Only when the clutch is disengaged and the wheels no longer drive the engine the engine needs to keep itself in motion. In eco-driving the instruction is to keep the clutch engaged as long as possible.

The lower the average velocity, the more the clutch must have been disengaged. Typically below 30 km/h clutch disengagement increases rapidly. If the average engine speed is determined for a given velocity, it is important to exclude the data from the time the clutch is disengaged. In that case, no power is exerted, and the engine speed is substantially lower, affecting the determination of the engine losses, and the effect of gear shifting on it.

3.2.6 *Fuel composition*

The admixture of bio-fuels yields a much larger variation in fuel composition and fuel quality than with refinery fuels. The market fuel may affect the fuel consumption.

3.2.6.1 *Three important fuel characteristics*

The type of fuel and the fuel composition have a large effect on CO₂ emissions. Three main fuel characteristics are of interest for the different parties involved in CO₂ emissions: the density, the carbon content per kilogram, and the caloric content per kilogram. Very little is known of the latter two, as it is not explicitly regulated in the fuel specification, but only indirectly. In particular, the admixture of substantial fractions of biofuels, e.g. FAME in diesel and ethanol in petrol, seems to have increased the variation in fuel composition. The bio-admixtures can be used to bring the refinery base fuel, from crude oil, to specification, which otherwise would not have met the fuel specification.

For national energy statistics, the caloric value per kilogram is relevant. For fuel consumption monitoring, the caloric value (lower heating value) per litre is the relevant property. Interestingly enough, the caloric value, which is essential for the propulsion power of an engine, is not part of the fuel specifications, and certainly not part of the fuel quality monitoring. The consequence is that consumers in fact buy unknown quantities of energy, while paying for litres of fuel at the fuel station. There are strong indications that with the admixture of biofuels the caloric value of market fuels is less fixed than for traditional fossil fuels. A report will be published in the Spring of 2016.

3.2.6.2 *Summer and winter fuels*

Fuels have specifications to ensure proper vehicle operation and safety in all circumstances. Particularly, in cold wintry conditions, diesel fuel should have a low viscosity for cold start operation. On the other hand, in hot summer conditions, the vapour pressure of the fuel should remain low enough to limit the risk of open-air combustion. The variation in summer and winter fuel can be substantial, in particular in regions where the winter temperature is low. Diesel composition is mainly limited by the viscosity at low temperature, while petrol fuel is mainly limited by the partial vapour pressure at high temperatures. The consequences are, however, similar: summer fuels are more dense, with less short chain components compared to the winter fuels. However, with the admixture of biofuels, these traditional differences may have changed. It is no longer clear how the different components and fractions yield the fuel within specification.

Eventually, the heating value is the most important property of fuel, for turning combustion into forward movement. There are some minor effects to be expected from heat capacity of the combustion products and the flame velocity for the intrinsic details of the pressure build-up in the cylinder, generating the force on the piston. Heating value is not part of the fuel specifications, hence, it is not a priori clear if a litre of fuel always provides the same energy.

The variation of the relevant lower heating value from one fuel sample to the next can be in the order of a few percent, especially in case of petrol. A few percent in variation of the lower heating value has a significant effect on the monitoring results. Possibly, it can explain some year-to-year variations in fuel consumption.

3.2.6.3 *Reference fuel*

Fuel used in the chassis dynamometer tests for type approval must meet more narrow specifications than the market fuels available in Europe. However, also for this reference fuel the caloric value is not specified. Given the variation of several percent in heating value, with for similar carbon fractions, it seems likely the type-approval tests are executed with a reference fuel with a heating value at the low end of the carbon content spectrum, and the high end of the caloric content. Possibly some of the more narrow specifications of the reference value limit somewhat the margins in heating value.

4 Scale of contribution of different factors

4.1 Quantification of individual factors

4.1.1 Work

4.1.1.1 Rolling resistance (*R*)

R: About 87% of the rolling resistance is related to tyres and vehicle weight; 13% represents drive line losses, for real-world conditions. As shown in section 3.2.2.3, the rolling resistance expressed as F_0/M in the case of type-approval tests is about 8, in the case of real-world driving on average 11. The rolling resistance can be expressed in the constant part of vehicle road load $R=F_0/M$.

4.1.1.2 Air drag (*A*)

A: the air drag coefficient varies only little between different circumstances, but the air-drag contribution varies substantially. Two effects are dominant:

1. air density, which is higher for real-world circumstances at lower temperature than for the coastdown test, which is normalized to 23°C.
2. normal driving contains more constant driving at higher velocities above 100 km/h, and more distance covered at that velocity than is the case in test cycles, in particular the NEDC test.

Air drag depends on the frontal area and aerodynamic design. It is well known what aerodynamic design lowers the air drag, but such designs are not always deemed saleable by marketing departments. The size of the car; frontal area of width times height, is clearly related to air drag and yields a high air-drag for SUVs and vans.

- *A* is the air drag, proportional with the frontal surface area defined by width times height in metre². The typical value is 130 N per m² at 100 km/h. The typical frontal area is 2.6 m² for a medium passenger car.

Ambient temperature affects air-drag, as at low temperature air-density is lower, which decreases the drag. From 0°C to 30°C the air drag decreases by 11% and the related CO₂ emissions reduce by about 7 g/km.

4.1.1.3 Braking losses (*B*)

B: braking accounts for about 30% of the energy losses in urban driving. This is proportional to the weight of the vehicle. Additional weight more than proportionally increases the braking losses, due to the fact that in that case more braking is needed. With the same deceleration, a heavier vehicle needs to dissipate more energy in the brakes. On the one hand, the additional inertia obviously increases the braking force, while on the other side it reduces the free coastdown deceleration, i.e. the deceleration which requires no additional braking.

Driving more smoothly can therefore reduce the need for braking. The personal driving style affects the energy dissipation by through frequent braking. For example, the driving flexibility in the tests (i.e. bandwidth for the speed profile to be followed) means that about 3% of the NEDC braking losses can be reduced, and 13% of the WLTP braking losses. This does however require a highly skilled operator or a sophisticated driving robot. There are no indications how much this

flexibility is exploited in the type-approval tests, only the net effect of all flexibilities can be determined.

- The amount of braking, expressed as deceleration, will lead to energy loss depending on the total inertia of the vehicle ($B = 1.03 \cdot M$)¹⁸. The power-weighted average deceleration is about $a_{\text{brake}} = 0.1 \text{ m/s}^2$ for average driving. This corresponds to about $1500 \text{ kg} \cdot 0.1 \text{ m/s}^2 = 150 \text{ N}$, similar to the rolling resistance force.¹⁹

4.1.2 Losses

4.1.2.1 Friction (E)

E: frictional engine losses and DPF back-pressure losses are affected by the gear choice, but less so than pumping losses. Frictional losses can be estimated at 1.5% of the rated power at idling engine speeds, with further engine losses as pumping losses. Given the typical power demand of a vehicle in urban driving, this is about 30% of the total power demand in urban driving. The operational temperature is likely to affect these losses the most. Moreover, heating up of catalysts and other temperature dependent vehicle parts are best captured together, as driving behaviour only marginally affects the heat.

- At idling, the pumping and friction losses are approximately equal. Both are set at 1.5% of the rated power. Given an idling engine speed of $\text{RPM} = 1000 \text{ min}^{-1}$, the coefficients P and E are each $0.015 \cdot P_{\text{rated}}[\text{W}]/1000$.

4.1.2.2 Cold start effects (C)

The cold-start effect is captured by two constants: the additional losses (C) in cold start, and the duration (τ) of the cold start. The product of the two must be in the order of 0.45 MJ corresponding to 450 seconds x 1 kW. Given an end temperature of 67° C, the cold start effect is proportionally larger if the temperature at the start is lower.

- The cold start lasts about $\tau = 500 \text{ sec}$ and adds about 0.2 g/s CO₂ from the start of the type-approval cold-start at 23° C due to a temperature difference of 44° C with respect to a warm engine. If the temperature is lower, the effect is expected to be proportionally larger.²⁰

4.1.2.3 Pumping and cooling losses (P)

P: pumping losses increase faster with the engine speed and the turbulent air flow through the engine and the exhaust system. Pumping losses are about 1.5% of the rated power at low engine speeds. In urban driving, at low engine speeds this accounts for additional 20% of the total power demand. For small, downsized engines the losses in motorway driving can increase rapidly, as the throughput must increase to deliver the power demand which can be 20 kW and up, even for constant driving only.

- Given an idling engine speed of $\text{RPM} = 1000 \text{ min}^{-1}$, the coefficients P and E are each $0.015 \cdot P_{\text{rated}}[\text{W}]/1000$.

¹⁸ The mass M is in this case the total vehicle inertia, which includes 3% rotational inertia.

¹⁹ The force associated with braking is $F = M \cdot a$. The power is $P = F \cdot v = M \cdot v \cdot a$.

²⁰ Additional average cold start emissions over time $t[\text{s}]$ are $\text{CO}_2[\text{g/s}] = 0.2 \cdot \exp(-t/500)$.

It should be noted that the baseline is the optimal engine efficiency, the waste heat associated with this engine operation is left outside the considerations.

4.1.2.4 *Electric and auxiliaries usage (X)*

X: auxiliaries are typically not used in the type approval tests. The lights and air-conditioning are off. In real-world driving, the power demand can be large, and it may typically be in the order of 500 Watts, up from the 200 Watts needed to operate a modern engine at its most energy economic condition. These differences are seen at different tests. Some variation is to be expected, but it should be noted that, as the vehicle speed increases, the contribution of auxiliaries to the total CO₂ emission per kilometre decreases.

- The auxiliary losses X are about 300 W, on top of the 200 W minimal electric power usage, corresponding to 0.07 g/s. This is the average value; specific auxiliary use, for example in the case of air-conditioning, is about twice as high.

4.2 **Relation among contributing factors**

Now that the different factors have been individually quantified to first order, this section will determine the relation among them. As stated before, the modelling will be done by grouping effects into suitable terms. These terms are combined in a CO₂ model for a particular trip, vehicle state, and circumstances:

$$\text{CO}_2[\text{g/km}] = Q[\text{CO}_2/\text{kJ}] * (\text{Force}[\text{N}] + \text{Loss}[\text{W}]/\text{velocity}[\text{m/s}])$$

$$\text{Force}[\text{N}] = R + A*v^2 - B*a_{\text{brake}}$$

$$a_{\text{brake}}[\text{m/s}^2] = \min(0, M*a + R + A*v^2)$$

$$\text{Loss}[\text{W}] = \text{friction} + P*\text{RPM}^2 + X$$

$$\text{friction} = (E + C*(340 - T_{\text{soak}})*\exp(-t/\tau))*\text{RPM}$$

This equation includes not only the factors described above, but also the relevant characteristics related to fuel and driving behaviour, which are described below. The optimal efficiency combined with fuel specification is given by Q. The amount of energy lost in braking depends on vehicle resistances and the magnitude of braking. It can only be determined from a combination of vehicle information and driving data, as the null-line; the deceleration below which the brake is applied varies throughout the tests. The velocity trace is further less important, and the average velocity v and the distance-weighted square of the velocity <v²> determine the engine loss and air-drag contributions respectively to the different driving cycles.

4.2.1 *Specific power and piston pressure*

Q incorporates some generic increase of engine losses with vehicle speed and engine speed: 750 g/kWh for diesel and 820 g/kWh for petrol, to arrive at the constant optimal efficiency for high load and moderate engine speeds. These numbers are also used to convert additional losses and auxiliary use to CO₂. They are used to translate freely between energy and CO₂. The effect of the marginal

changes are: a small increase in work will yield a less than proportional increase in CO₂ based on this Q. The efficiency typically increases with the engine load, and a constant Q, based on the end point value yields a robust extrapolation. The engine losses are separate from this marginal effect, as a constant offset in the CO₂ emission, using the same Q.

In principle, the mechanical work starts with the pressure the combustion gas exerts on the piston. The fast expansion will cool the gas somewhat, such that a pseudo-adiabatic pressure curve is followed. For Diesel and Otto cycles, the optimal efficiency is different. Moreover, in a practical case of a continuous motion of the piston during the combustion process and the inlet and outlet of gases, the efficiency is even further reduced.

4.2.1.1 *Fuels and cycle*

Apart from the Diesel and the Otto combustion cycle, some other alternative cycles for improved engine efficiency have been developed. The complexity of a functioning emission after-treatment system seems to restrict the use of such high-end technologies to some extent. The use of CNG instead of petrol, to reduce the CO₂ emissions associated with the fundamental process of converting caloric energy into mechanical work, is gaining popularity slowly. The (direct or tank-to-wheel) CO₂ benefits are substantial, however, the aging of the three-way catalyst may increase the methane slippage more than it would increase the hydrocarbon emissions for petrol.

4.2.2 *Total work and cycle work*

In the Annex 6 of the WLTP text the cycle work is an important concept to translate the CO₂ test result of one vehicle to other vehicles of the same family. This is a theoretical exercise with limited measurement data or validation. It is based on two main assumptions: The first is the assumption of a linear relation between CO₂ and cycle work, i.e., the work at the wheels. The second assumption is that a simple sum of the total force as marginal changes from one vehicle to the next. The second assumption is valid by the fact that the first assumption is correct: in the case of linearity the sum of the parts equals the whole. Any deviation from linearity can be exploited to yield a lower result by testing the optimal vehicle and extrapolating.

Due to the fact that the rest of the CO₂ emission also finds its origin in the vehicle and engine operation it is essential to make a proper sum in which, where certain effects, such as the engine speed, the motoring, etc. are also included explicitly. Only if the total factorisation is made of the total CO₂ emission, however crudely, effects can be attributed, and variations in emissions which are not related to work can be assigned.

4.2.2.1 *Null line*

Only once the vehicle starts braking, the energy is 'lost', i.e. converted to heat in the brakes. The braking occurs if the deceleration is larger than the force of the driving resistance. A deceleration equal to the driving resistance, or coasting, is the null line. In principle there are two null lines: one for the clutch engaged such that also engine resistance is to be overcome, and one for the clutch disengaged similar to the coast-down curve for the road load determination. There are proposals to

enable “sailing” by temporarily disengaging the engine as a possible means to further reduce CO₂ emissions.

The location of the null line depends on the road load or driving resistance. Hence in some way, especially for tame driving, a higher road load in real-world driving reduces the energy dissipated in braking, compared to the optimised road load on the type approval test.

4.3 Transient effects

The relation between forces established in section 4.2 assumes a linear dependency between force and CO₂. Moreover, it is an instantaneous relation that is expected to hold at every time. It does not take into account the effect of transient operation. Generally, transient effects are poorly known. In this study, it is assumed that transient effects have similar contribution when comparing the type approval testing with real world vehicle use and they are therefore not quantified here. This section addresses a few of these transient effects in a qualitative fashion.

4.3.1 *Willans lines: lumping losses and efficiencies*

The Willans line is a simplified assumption of the relation between engine operation and CO₂. The generic approach to converting power demand to CO₂ emission is the Willans line. The Willans line assumes a linear relation between the two, with an offset in CO₂ emission for idling operation with no power output. The offset is related to the internal losses: all the power needed to keep the engine running, overcoming friction, and pumping the gases through the engine and the exhaust system. These effects are incorporated in E and P.

4.3.2 *Inertia and control*

Transient operation is associated with higher fuel consumption. This has a number of underlying causes. Internal inertia is one cause: speeding up an engine requires energy, which is commonly not fully released when slowing the engine down again, because during slowing down this energy is typically not required for operation. Hence in transient operation the fuel consumption per amount of work is higher.

4.3.3 *Turbo*

A turbocharger increases the inlet pressure and the filling of the cylinder. This will increase the mainly engine power, and, to a lesser extent, the engine efficiency. The drawback of turbo is the lag. The pressure build-up occurs only seconds after the engine stabilizes at a higher load. When accelerating from 0 km/h to 70 km/h, combined with a number of gear shifts in between which the engine speed drops, the benefit of a turbo is only limited. A turbo helps to increase power on a smaller engine to achieve the same rated power, possibly at the cost of additional pumping losses.

4.3.4 *Pollutant emission control*

In many cases emission control interferes with fuel efficiency. The rated power is truncated, the air flow is larger, and so is back pressure. Hence, already from physical principles it is clear that some penalty may arise from reducing engine-out pollutant emissions. It should be noted that emission control is typically most effective in the type-approval test, hence the trade-off should hardly be noticeable,

or even the opposite, in the difference between type-approval and real-world fuel consumption.

4.4 Trade-offs

CO₂ emissions are not only related to work and losses, but also to engine operation related to emission control. In order to reduce pollutant emissions, applied emission control will typically somewhat increase the CO₂ emissions. This CO₂ increase is independent of vehicle use. The effects are small and are qualitatively described below.

4.4.1 *NO_x emission reduction*

There is a trade-off between NO_x emissions and CO₂ emissions in the use of EGR. The high NO_x emissions observed in real-world driving have, very likely, a small positive effect on fuel consumption. For Euro-5 diesel vehicles, the CO₂ emissions for 130 km/h speed limits increase less than is expected on the basis of physical principles. Instead the NO_x emissions increase dramatically above 120 km/h. Possibly, with proper RDE regulation of NO_x emissions, diesel vehicles will have somewhat higher CO₂ emissions on the motorway, depending on the after-treatment technology.

4.4.2 *Three-way catalyst*

Before the three-way catalyst was introduced, claims were made in the 1980's that it would lead to a 20% increase in fuel consumption, due to the fact that the engine has to operate at $\lambda=1$ rather than the most fuel efficient operation. In reality the fuel consumption hardly showed an increase on the downward trend. The technological improvements ensured a lower fuel consumption.

4.4.3 *DPF back pressure*

The DPF back pressure is a physical effect which requires additional energy and an associated fuel consumption. On the other hand, the engine can be calibrated differently, as the particulate emission out of the engine is less critical, since the wall-flow filter is an effective means to stop these emissions. The balance between technology, calibration, and vehicle usage is a complex interplay. However, it is expected that the introduction of DPF's on diesel vehicles has led to an increase in CO₂ emissions of a few g/km, and that in real-world conditions the effect is probably slightly larger, due to the larger exhaust gas volume flow and the larger DPF loading.

4.5 Type approval testing

4.5.1 *General procedure*

Only one vehicle is tested for a family of vehicle models. Very often this vehicle has a low mass in the NEDC test. Under WLTP, a very large part of the legislative text is to ensure an appropriate CO₂ value for the different vehicle models available.

The type-approval test consists of two parts: the on-road determination of the vehicle driving resistance with a coastdown test (or equivalent methods), and a chassis dynamometer test.

4.5.1.1 Road load test

The coastdown test has received much attention lately with the advantage of a sloping track in the NEDC protocol. Moreover, test tracks advertise with low rolling resistance. See Figure 20.

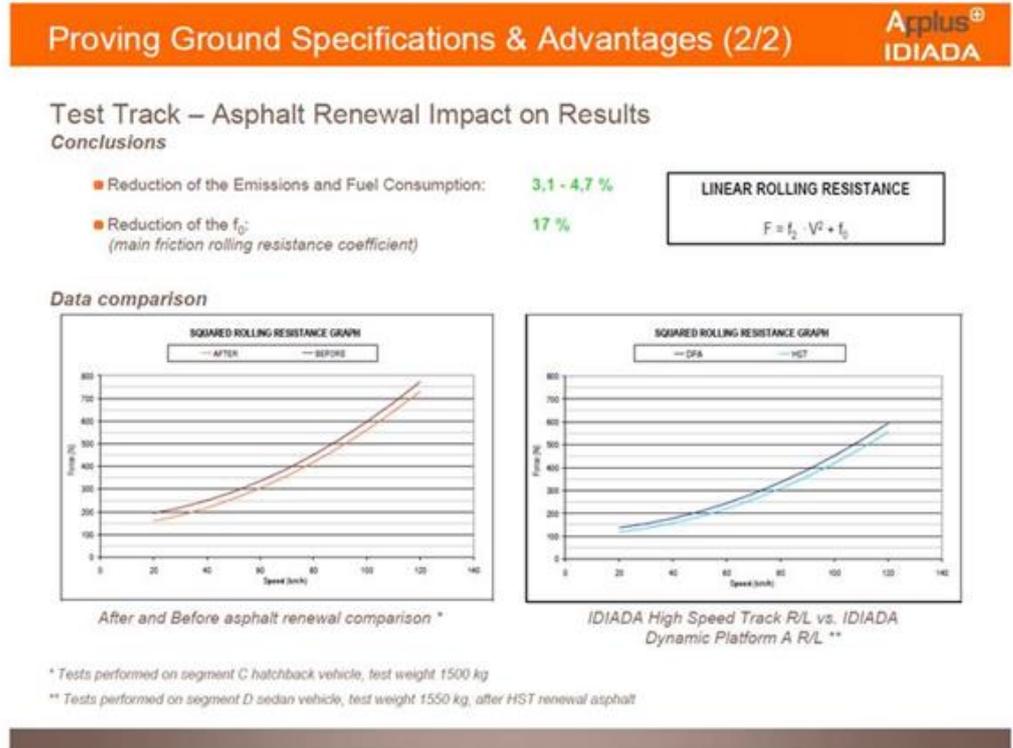


Figure 20 Result of the asphalt renewal on the rolling resistance at one of the test circuits for coastdown testing.

4.5.1.2 Emission test

The driving resistance is used in the laboratory test to represent the resistance on the road. In the laboratory, the vehicle is stationary with rotating wheels.

4.5.1.3 Auxiliary testing

Apart from the standard test, there are additional cold tests, durability tests and, evaporative emissions tests. These are to ensure that new production vehicles, the vehicles perform well also in other conditions than the standard type-approval test.

4.5.1.3.1 Tyre label

Rolling resistance of tyres are tested in the laboratory on a smooth steel drum, free running at 80 km/h. This is described in UNECE regulation R117. The result is expressed in [kg/ton] rolling resistance force for a given vertical force. The actual values do not have to be reported in general, but the energy class is to be reported.

A clear distinction must be made to the tyres installed by the manufacturer and the tyres in the aftermarket installed by the dealer of the customer. For the latter case some data is available, but on the production vehicles there is limited information on the installed tyres.

4.5.1.3.2 Driving behaviour in the tests

Given the NEDC, the WLTC, and the CADC as an example of a real world driving cycle, the physical properties of each of these test cycles are very different. Later the driving characteristics are used in the model, and the effects will be discussed, as an intricate relation exists between the different features.

Table 4 The comparison of typical driving characteristics on different test cycles. For example $\langle v^2 \rangle^{1/2}$ is the relevant velocity for the determination of the total air drag contribution.

	Velocity	$\langle v \rangle$	$\langle v^2 \rangle^{1/2}$	Braking force	Idling time
	km/h	km/h	km/h	[%]	[%]
NEDC	33.3	62.1	68.6	20.9%	20.7%
WLTP	46.5	74.4	81.5	19.4%	13.0%
CADC	60.9	91.6	97.4	11.6%	9.8%

4.5.2 Test cycle flexibilities

In the past, results of independent testing of CO₂ emissions following the NEDC test specification was in line with the declared values of the manufacturers. TNO performed many tests on the CO₂ emissions of run-in passenger cars. Test results obtained by TNO from 1996²¹ to 2004 found independent NEDC CO₂ emissions lower than the official type-approval, as well as independent values that were higher than the type-approval values. The tests were generally executed with type-approval road-load values, meaning that the difference covers effects on the chassis dynamometer test only. The spread in the test results is significant. This is, in part, due to particular test execution, which cannot be deduced anymore from the database. It is however expected that for the greater part this is the natural spread, expected from different tests at the time. With an average of 181 g/km and a variation of +/- 12.7 g/km, it can be assumed the natural variation at the time was 7%.

In the current climate, such variation is unacceptable for the declared value, and the lower value is likely to be the type-approval test: 7% to 10% below a non-optimised test value.

²¹ 1996 was the first year in which manufacturers reported the type-approval CO₂ emission of a vehicle.

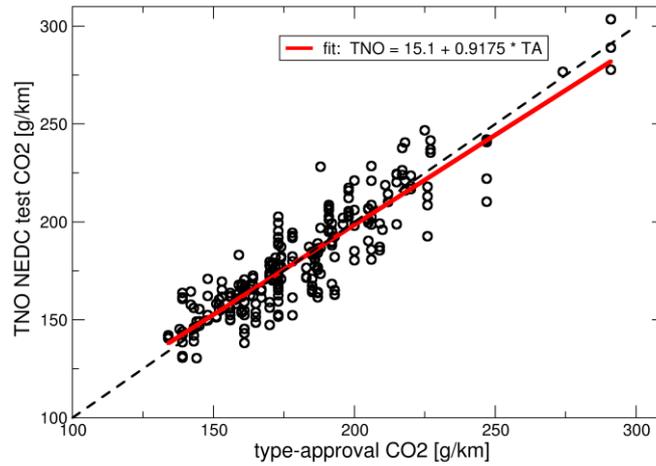


Figure 21 The declared values and the TNO test values on the NEDC tests in the period 1996-2004

Indeed, CO₂ emissions differences of 10% between independent testing and OEM's optimised tests are seen from measurements on the chassis dynamometer. Even larger differences, still using type-approval road load, are not uncommon. These are often technology-specific: amongst others the loading of the DPF, the operation of the automatic transmission and the electric usage and battery state seem to all contribute to a lower official type-approval value. Prior to 2004-2007 there is little reason to assume such flexibilities were exploited. In the more recent period it is the case.

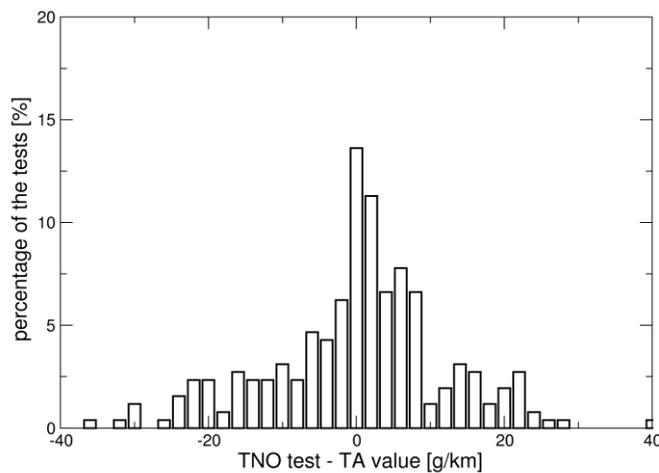


Figure 22 The spread in CO₂ emissions in separate tests from the previous figure.

This optimisation is very difficult to repeat in independent testing. It is therefore unclear how the total effect is achieved. From flexibilities studies only a part of the total effect can be explained. All in all, the state of the vehicle and the execution of the test is an art difficult to match by independent parties. As a result, a deviation of

an additional 5 g/km might be the maximal achievable difference in technology specific cases. Larger deviations are seen on top of the 10% natural bandwidth, which is above the top range above the 7% variation on test execution, which the manufacturer is expected to exploit.

In recent years, the measured value no longer varies symmetrically around the type-approval value. Using the official type-approval weight and road-load, the bandwidth has decreased to 20 g/km full-width.

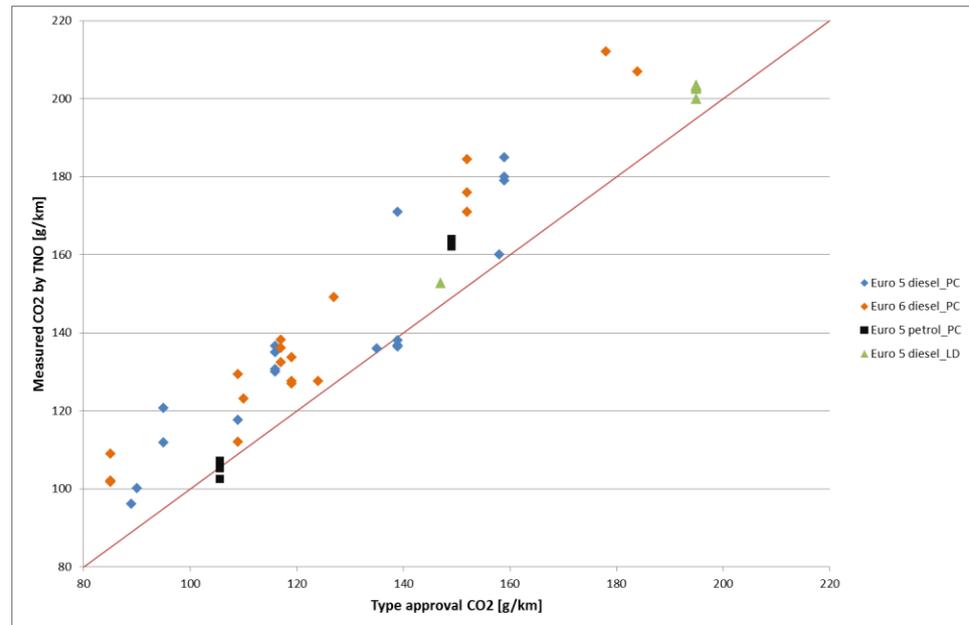


Figure 23 Recent NEDC tests by TNO results typically in higher values than the official type-approval value.

It seems that the spread compared with the type-approval values in testing by TNO is still the same, but the type-approval value is the bottom of the bandwidth. TNO's test-by-test repeatability is about 3 g/km. The average deviation between type-approval and TNO testing is 13 g/km with a 10 g/km spread. This confirms optimised testing and the type-approval tests yielding the lowest possible results within the margins of the test..

TNO tests using representative vehicle weight and self-measured road-loads on vehicles obtained from the Dutch fleet show even higher CO₂ emissions than the type-approval value.

4.5.2.1 NEDC test

The NEDC test is considered artificial and soft, given the velocity and the magnitude of the accelerations, compared to real-world driving as represented in the WLTP or the CADC tests. However, a vehicle test must be suitable for all vehicles, including low-powered ones. Moreover, an artificial profile, with constant accelerations and constant velocities, is smoother and has less flexibilities incorporated, i.e. less room for optimising the driven speed profile inside the allowed bandwidth to yield a low CO₂.

4.5.2.1.1 Drawbacks of the NEDC test

Two main drawbacks of the NEDC are:

1. The limited driving at velocities, above 100 km/h, which is contrary to the common usage of vehicles in Europe, with 25%-50% of their mileage driven on the motorway.
2. The fixed velocities and accelerations and the repetitive nature of the cycle, which de-facto results in engine optimisation for only “seven operation points”:
 - a. Constant 15 km/h
 - b. Constant 35 km/h
 - c. Constant 50 km/h
 - d. Constant 70 km/h
 - e. Constant 100 km/h
 - f. Low velocity acceleration of 1.0 m/s²
 - g. High velocity acceleration of 0.8 m/s²

Typically, the gear ratios are chosen such that the different constant velocities lead to similar operation points.

Table 5 The characteristics of the urban (UDC) and the extra urban (EUDC) and the total cycle (NEDC).

Characteristics		UDC	EUDC	NEDC
Distance	km	3.976	6.955	10.931
Total time	s	780	400	1180
Idle (standing) time	s (%)	228 (29%)	39 (10%)	267 (23%)
Average speed (incl. stops)	km/h	18.4	62.6	33.4
Average driving speed (excl. stops)	km/h	25.9	69.4	43.1
Maximum speed	km/h	50	120	120
Average acceleration	m/s ²	0.60	0.35	0.51
Maximum acceleration	m/s ²	1.04	0.83	1.04

4.5.2.2 WLTP test

The WLTC has still rather low-power requirements to allow all vehicles to drive the same test, although the power requirement is somewhat higher than the NEDC.

4.5.2.2.1 Drawbacks of the WLTP test

Due to the more sportive velocity profile, the WLTP test will not stimulate low engine load optimisation in the same manner as the NEDC did. Neither does it sufficiently stimulate aerodynamic improvements by its limited distance at high velocities, which would reduce further fuel consumption for motorway driving at constant velocity. It focuses on rural and transient driving, and it has been smoothed to allow also low-powered vehicles to drive the test, in case they have a high test mass. Load variations on the test are mainly the result of accelerations and decelerations.

When people drive at constant velocities different than on the driving cycle, the average engine load will be lower at velocities below 80 km/h, for which low-load optimisations are beneficial. The efficiency of constant driving at higher velocities

would benefit from a substantially greater weighting in the test, unlike the current situation.

4.5.2.2.2 *Risks of the WLTP*

The WLTP is an improvement compared to the NEDC test being a test closer to real-world vehicle usage. Some of the generic risks anticipated with the current status (phase 1b approved in Spring 2015) of the WLTP regulation are:

1. “options”: The WLTP allows for several options in the test procedure, e.g. both for determining road loads and for executing chassis dynamometer tests. This means the manufacturer can choose the options which generate the largest benefits.
2. “calculations”: As many values are determined through calculations there is a risk of benefits on paper, not checked against underlying measurements.
3. “complexity”: the WLTP procedure with the calculations and options is a complex procedure of which little information is shared at this stage. For example, the gear shifting points are no longer fixed, but based on the engine characteristics so that they can be calibrated to improve the engine load. There is a risk that errors in the calculations may go unnoticed.
4. “optimal is normal”: manufacturers find it no longer acceptable that the road-load values obtained in the test can be higher due to wind. As during normal driving wind is usually present, the gap increases between test conditions and the test vehicle state on one hand, and average conditions and vehicle state on the other, and lead to an increase of the gap if this instruction is not respected.
5. “user instruction”: What is now considered a large improvement over the NEDC, such as a tighter description of the state of the tyres during the coast-down test could be weakened through adaptations of the user instructions. Requiring a higher tyre pressure, with an associated lower rolling resistance, can be added to the instruction manual.
6. “exceptions”: Generic testing is not always standard, there are many exceptions and cases where at the request of the manufacturer there can be deviations from the prescribed test protocol.
7. “aftermarket”: If the production vehicle has features to reduce CO₂ emissions affecting other aspects relevant for consumers, some can easily be removed, added, or altered in the aftermarket sales. Fuel-efficient wheels and tyres may be replaced by “sports wheels” thus reducing the fuel efficiency.

4.6 **How vehicle technology influences CO₂ emissions**

4.6.1 *Reducing engine losses*

Improvements in vehicle technology, for the reduction of fuel consumption, can be classified according to some generic categories. Each of these groups have different benefits in real-world driving with respect to the type-approval improvements. Significant gains are achieved through reducing engine losses. One can be distinguished in three main categories of engine improvements: generic offset, efficiency improvements at low engine load, and overall efficiency improvements.

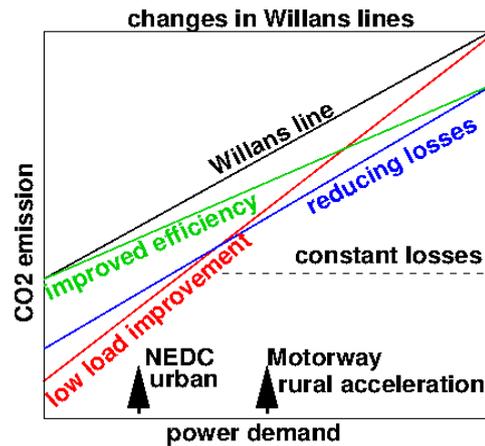


Figure 24 A sketch of the changes in the Willans lines based on the type of fuel efficiency improvements on the engine. Three main groups of measures can be distinguished.

The different groups lead to different fuel efficiency improvements for different vehicle usage. The three main distinctions in usage are:

1. Low-load usage: an average power demand of 2 kW with idling and short and limited peak powers, between gear shifts. (urban driving and congestion)
2. Transient power use: high power peak above 25 kW due to accelerations at intermediate velocities, but limited overall power demand of 5 kW. (rural driving)
3. High constant power use of 15 kW due to high velocity with high peaks during accelerations with higher engine speeds in this case. (motorway)

Compared to average driving, the typical driving cycles over-represent low-load usage and transient power while they under-represent higher constant power use.

Heavy-duty diesel engines running idle give a good indication of the magnitude of the idling losses (Figure 25). Idling losses are more or less the lower bound of the expected losses for an engine, as the rotational friction and the pumping losses are the lowest, and would increase with engine speed.

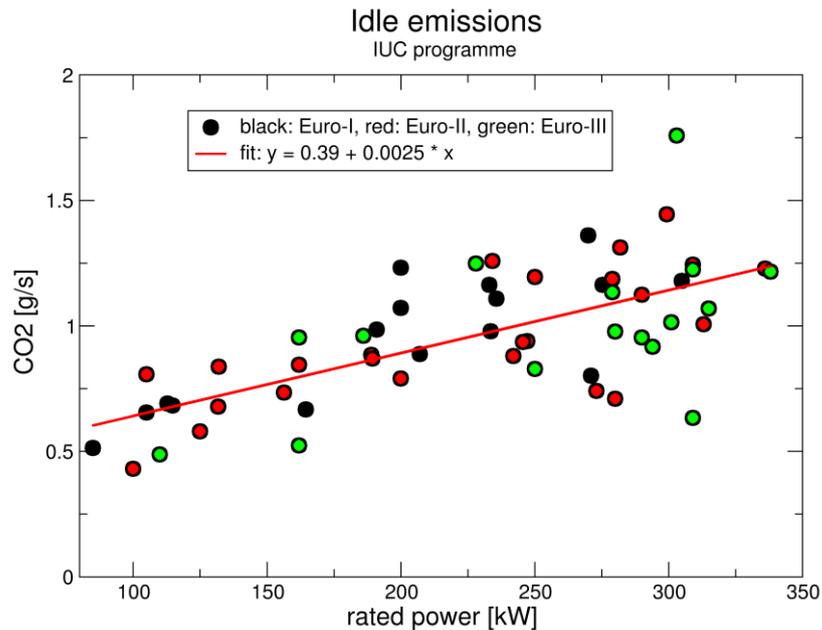


Figure 25 The typical idling losses of a large group of older heavy-duty trucks, without much specific optimisation. In this case, the losses are about 2% of the rated power where the smallest engines have the highest proportional loss.

For a diesel passenger car, an assumption of 0.5 litre per hour of idling fuel consumption seems proper.²² For petrol cars it is somewhat higher, as the petrol engine is less efficient at low load. It may seem a small quantity, but at an average velocity of 50 km/h, the idling loss accounts for one litre out of a 4-6 litre total fuel consumption per 100 km for a small diesel engine.

4.6.2 Engine size and rated power

The engine is designed for the drivability of the vehicle. The average engine power has increased steadily over time. For constant velocities only a small fraction of the engine power is needed, unless the vehicle drives at velocities above 100 km/h.

In many cases, the engine dependence of fuel consumption, used in different studies, is often based on a function of both the rated power and the engine size. These two parameters are strongly correlated. With the increasing engine size the engine is more efficient²³, due to the smaller overhead, less thermal losses and lower engine speed. Thus, an offset exists between the engine power of a large engine and engine power of a small engine. Based on data on vehicles on sale from the second quarter of 2013 to the first quarter of 2015, the properties of all vehicle models can be fitted with a linear relation, as shown in Figure 26.

²²Given a 3% losses of the rated power at idling, and an engine power of 70 kW, yields 1.5 kg CO₂ per hour, or about half a litre of fuel.

²³The efficiency is understood Q⁻¹ as the kWh per CO₂, excluding the engine losses

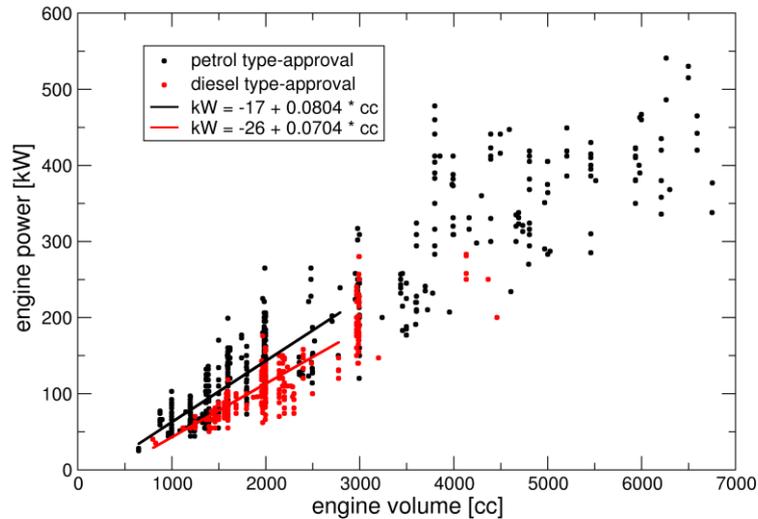


Figure 26 The relation between engine size and rated power. The fixed losses of an engine generate a non-zero offset for small engine sizes. Based on vehicle models on sale 2013-2015. With an average CO₂ type-approval value around 110 g/km, these are typical downsized engines.

In the further analysis, only the engine power will be considered, not engine size. However, the relation between engine power and engine size gives a good indication of the increasing engine efficiency with engine power, as the ratio of the two relates to specific power. For petrol cars a share of 1 kW and for diesel cars 1.5 kW of the engine losses can be seen as a generic offset unrelated to the engine size.

The total operational losses of an engine can be derived from the difference between the UDC and the EUDC part of the type-approval NEDC test. On both tests the engine losses are a significant contribution to the total emissions, and the optimisation is likewise. Moreover, a large amount of data is available for a fleet average result. In both cases, the required engine power is low, and losses play an important part in the total CO₂ emission. If the difference of both tests is taken, the differences in power demand of driving are limited and the focus is on the losses. For the 4 kilometre of the UDC it is associated with 195.7 seconds per kilometre, while for the 7 kilometre of the EUDC it is associated with 57.5 seconds per kilometre. The difference is 138 seconds per kilometre of engine operation. In the case of a stop-start system, the engine is switched off when the vehicle is stationary. In that case the difference is only 86 seconds of engine operation per kilometre. The time of engine operation per kilometre in both these low-load tests is quite different, and mainly associated with the CO₂ emission from running the engine, i.e., the losses.

The difference is substantial. For example, with a 70 kW engine and a loss of 3% of the rated power, the difference in total internal energy usage is 290 kJ of energy usage. This accounts for almost 60 g/km CO₂ emission. In the case of an engine fitted with a stop-start system, this is reduced to 35 g/km. This is the difference

between the UDC and the EUDC CO₂ emission, which is confirmed by the actual differences observed in type-approval data.²⁴

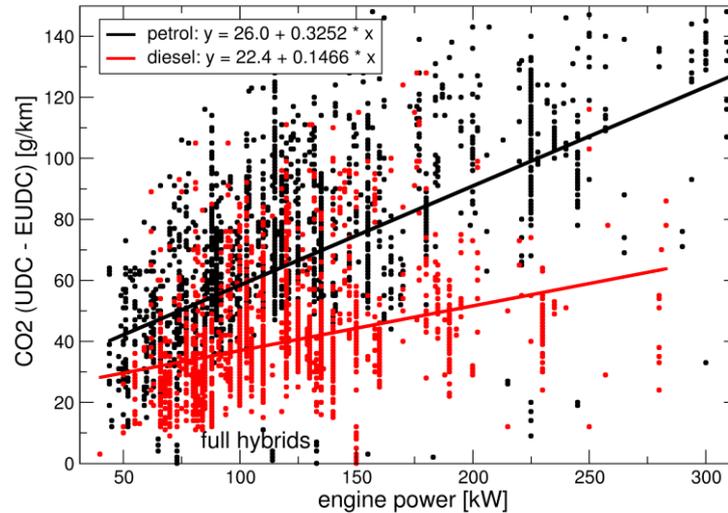


Figure 27 The difference between the UDC and the EUDC CO₂ emission of modern vehicles. Hybrids have similar emission for the UDC and the EUDC, which confirms that the difference of UDC and EUDC are related to the engine losses for conventional vehicles. The work, also braking losses are also similar, on the UDC and the EUDC, which make both subcycles comparable.

4.6.3 Driveline

4.6.3.1 Transmission

Automatic transmissions have improved a lot over the last twenty years. They have evolved from sluggish and heavy oil-filled transmissions in automated manual transmission. On the other side, CVT (Continuous Variable Transmission) allows for a lower engine speed at high constant vehicle speeds, thus lowering the engine losses.

The gear ratio of the highest gear affects the losses on the motorway. It is the main variability in the vehicle technology affecting the losses. A low-powered vehicle will have an engine speed of 3000 RPM or above at 100 km/h, while a high-powered vehicle, in particular those equipped with a sixth or seventh gear, will run at 2500 RPM or lower. The gear ratio can be deduced from the maximum vehicle velocity.. Given a rough and general estimate of 4500 RPM engine speed at rated power at the maximal velocity, the engine speed at 100 km/h can be extrapolated: (See also Figure 29)

$$\text{RPM}_{100 \text{ km/h}} \sim 450000/V_{\text{max}}$$

²⁴3% of 70 kW is 2.1 kW. Over the extra 138 seconds it takes more to drive an UDC kilometer compared to a EUDC kilometer thus it adds to 290 kJ. Given 720 g/kWh, this corresponds to 58 g/km CO₂ emission. If for the 57 seconds of idling the engine is stopped, it removes 41% of the running time with the same reduction in engine losses.

A lower engine speed at 100 km/h, possible with sufficient engine power, reduces losses, partially compensating for the higher fuel consumption typically associated with a larger engine. Looking at the type-approval data, a clear relation between the rated power and the maximal velocity can be deduced.

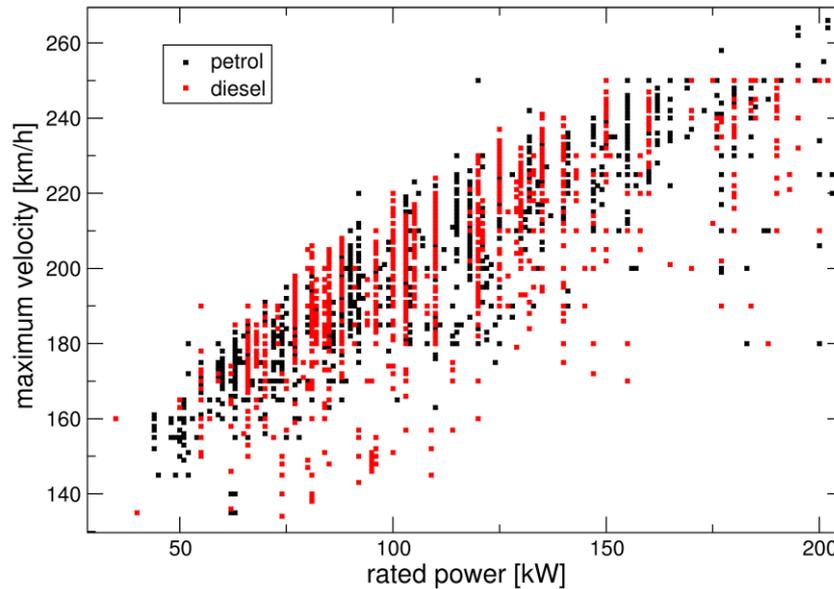


Figure 28 The relation between the maximal velocity and the rated power. From physical principles, the upper bound lies at $V_{max} < (90\,000 * kW)^{1/3}$,²⁵ except for small sports cars which can have a higher maximal velocity. The gear ratio of the highest gear is likely to affect the maximal velocity.

The average RPM with the clutch engaged is more or less constant until the highest gears are reached. This means that up from 60 km/h for both eco driving and type-approval testing the engine speed is around 1800 RPM. At average driving, the engine speed is somewhat higher, such that the highest gear is reached at a slightly higher velocity. The presence of a sixth or even seventh gear alters this relation to some extent.

In Figure 29 the different effects are shown. A high powered vehicle may increase the gear ratio and reduce the engine speed and losses proportional with engine speed on the motorway. This effect can even further be expounded by a 6th or a 7th gear. For low velocity, it is not the technology, but the driving behaviour, and the gear shifts, which determines the engine losses.

²⁵Given 400 N air drag at $v = 100$ km/h for a compact to medium car, the power demand at higher velocities is dominated by the air drag: $P = (v/3.6) * 0.4 (v/100)^3$ kW = $v^3/90000$ kW.

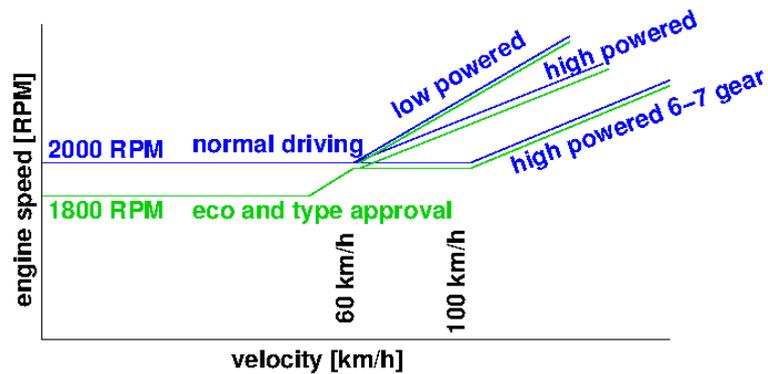


Figure 29 Schematic picture of the typical engine speeds of vehicles. High engine power reduces the gear ratio somewhat. Clutch disengaged with idling engine is excluded.

4.6.3.2 All-wheel drive

Drivetrain losses are small compared to air drag and rolling resistance, however, they are not negligible. In particular, all-wheel drives and vehicles designed to handle forces associated with off-road driving may be responsible for 15-30 N additional force, given the fact that a driven axle and driveline have more resistance than a non-driven axle. As regards the USA certification data from the EPA, this effect is hardly notable among the vehicles, but the resistance and inertia testing at TNO have shown such effects.

4.6.4 Vehicle inertia

4.6.4.1 Engine-speed inertia

High transient driving and erratic gear shifting will cost energy, not only because the engine is not optimised for such an operation, but also because the rotational inertia of the engine and the turbochargers are losing energy from spinning down and up again. It is not expected that these factors operate very differently for various driving conditions. But it explains they explain in part the higher fuel consumption for urban driving.

4.6.4.2 Wheel-speed inertia

A generic 3% of the unloaded vehicle weight is assumed for the inertia of the wheels. This affects the overall coastdown results,²⁶ and also adds to the inertia of the car for acceleration and braking.

4.6.5 Control strategies

4.6.5.1 Automatic transmission

For Euro-4 vehicles it was observed that automatic transmissions led to lower pollutant emissions. This was associated with the limiting driver control over engine operation, as the automatic transmission acts as an intermediate between the driver and the engine actuators, and the control of the engine can make it run in a more efficient mode, which may reduce the emissions as well. Automatic transmissions have improved since then, and they are no longer sluggish and irresponsible. Very likely, the differences with respect to manual transmission have decreased.

²⁶Any additional inertia, also rotating, translates directly into a lower force on the chassis dynamometer test, as the force F is determined from $F = M \cdot a$, where M is the total inertia and a is the deceleration.

Nevertheless, an automatic transmission can be further optimised for the type-approval test. In a type-approval test, the vehicle is aware of the velocity profile, and the transmission can anticipate the need, or lack of need, for additional power or velocity, to keep the engine speed optimal. In real-world driving, the lack of this deterministic optimisation is believed to make the modern automatic transmission more attractive. Typically, changing the mode from default eco to sportive will lead to an increase in fuel consumption on the same test. Very likely, the gap between type-approval and real world has increased also due to this aspect.

4.6.5.2 *Air-flow control*

The airflow through the engine is not without obstruction and this resistance requires work. In a spark ignition engine, the airflow is proportional to the fuel consumption and the power demand. In a compression ignition engine, there is more room to control the airflow, and it may be optimised for the lowest fuel consumption on the NEDC. In other cases, such as real-world operation, the airflow may be different, with a better drivability traded for a higher real-world fuel consumption. This is expected to result only in a minor effect, except in the cases where airflow control is also meant to reduce pollutant emissions, in particular particulates emissions.

4.6.6 *Decoupling of power demand and power supply*

Traditionally, fuel consumption was causally determined and instantaneously coupled to power demand: when the accelerator was pressed, the vehicle accelerated and the fuel consumption was high at the same time. The battery operation has already changed this to some extent: charging required additional engine work, and the charging strategy was independent of the work demand for vehicle propulsion. The battery is the main source for energy buffering and it decouples the power demand from electric auxiliaries from the combustion engine. The electricity demand from the battery has increased with increasing electric equipment, stop-start systems, and ultimately hybrid and plug-in hybrid vehicles. This also makes the emission testing of vehicles more complicated.

4.6.6.1 *Stop-start systems*

Table 4 shows that the NEDC has a very large amount of idling time (25%). With the WLTP, the amount of idling is reduced to 14%. However, in real world, the idling will vary greatly from driver to driver, not only due to traffic situations, but also from habits like the moment of starting the engine/car and engaging the clutch prior to driving.

4.6.6.2 *Hybrid technology*

Hybrid technology behaves very similar to conventional powertrain technology as regards to the difference between type-approval and real-world fuel consumption. The gap is of the same magnitude as with conventional vehicles of the same age and type-approval value. Trying to model hybrid technology as a separate feature in the increasing gap between type-approval and real-world fuel consumption often fails due to the strong correlation with other factors, and the changing fleet characteristics over time. All effects are strongly correlated.

4.6.6.3 *Plug-in hybrid vehicles*

In the Netherlands, the real-world fuel consumption of plug-in hybrid vehicles is 2.5 to 3 times higher than the type-approval one. The determination of the type-

approval value is inappropriate for the use of these high-end vehicles, which drive 25,000 kilometres or more annually. Cheaper petrol cars are bought for limited mileage usage, unlike the high-end cars which are associated with business use.

As plug-in hybrids seem to gradually evolve from fuel-efficient vehicles into powerful vehicles with an extra electric boost, the gap between real-world fuel consumption and type-approval fuel consumption is expected to further increase. Maybe the plug-in vehicles can be considered symbolical for the gap: a high-powered vehicle on the road with a limited electric driveline to perform the type-approval test. The nature of the type-approval test, where 25 km conventional driving on the engine is added to the electric range.

4.6.7 *Cooling and heating for EVs and PHEVs*

Electric and plug-in hybrid vehicles are more affected by ambient temperature, in particular by low ambient temperatures, than conventional vehicles. On one hand this is due to the reduced battery capacity at low temperature, but on the other hand this is due to the heating of the cabin. For a conventional vehicle, the waste heat of the combustion process is usually sufficient to also provide the necessary heat for driver comfort. For a (partly) electrically operating vehicle this is no longer the case. Electric distance on a full battery drops significantly if the temperatures are low. A drop of 20% or more is often reported for vehicle operation in winter conditions.

4.6.8 *Electric equipment*

The amount of electric equipment is substantial in a modern car. Among them, lights are a constant factor in the auxiliary power usage, throughout the year. Other items are only used intermittently, such as window actuators and windscreen wipers.

4.6.9 *Driver assist*

4.6.9.1 *Gear-shift indicator*

Modern vehicles with a manual transmission are equipped with a gear-shift indicator. The indicator is typically non-obtrusive, and its advice can easily be ignored. In particular, the indicator cannot anticipate upcoming driver manoeuvres, or the need for an engaged clutch or two hands on the steering wheel. Most gear shifting is done below 50 km/h, where traffic situations are complex. Hence, it is not surprising that the normal gear used in driving is lower than the optimal gear. The effects of testing vehicles with eco-driving, normal driving, and aggressive driving in real-world testing shows up mainly in the engine speed, more than in velocity and acceleration which are restricted by other traffic on the road.

4.6.9.2 *Driving modes*

Since the year 2000, mechanically controlled engines have been replaced more and more by electronically controlled engines. As a consequence, cars nowadays have more 'computing power' and ample possibilities to adjust injection timing and other fundamental aspects of the engine and vehicle operation. The drivability and the "feel" of the vehicle, in terms of response to the driver's action is no longer a mechanical actuation. Many modern vehicles feature "mode" selection, to make the car more, or less, directly responsive. It is difficult to obtain precise details on the effect on engine operation and CO₂ emissions, but a few random tests indicate the effect on the type-approval test is already large, amounting to approximately 5% to

8% additional CO₂ emission for a sportive engine-control mode applied to the same driving pattern. In the case of real-world driving, it is expected that the effect of mode selection is slightly smaller, as the combination of the default, eco mode is likely to be heavily optimised with the type-approval test. For driving beyond the type-approval test, this optimisation is likely to be less effective.

5 Development of mathematical approach

Defining the list of factors and their generic contribution to the CO₂ emission of a car in previous chapters already revealed parts of the model. To look at specific aspects, such as vehicle segments or applied technology, the generic model of Chapter 3 must be adapted to be able to address CO₂ emissions from different angles. In this chapter, the previously presented model is expanded in different directions. For example, in this chapter regression models are used to fit the monitoring data. The models will be used to fulfil the second goal of this project: to better estimate the real-world fuel consumption and CO₂ emissions of specific vehicles under future LDV CO₂ standards.

Two types of model were developed: an energy-based model (section 5.1) and regression models (section 5.2). The results of the regression models of section 5.2 can be used for forward extrapolation to estimate the expected effects of a changing vehicle fleet. Section 5.3 provides rules of thumb for this purpose.

5.1 Energy-based CO₂ model

5.1.1 Aspects to be covered

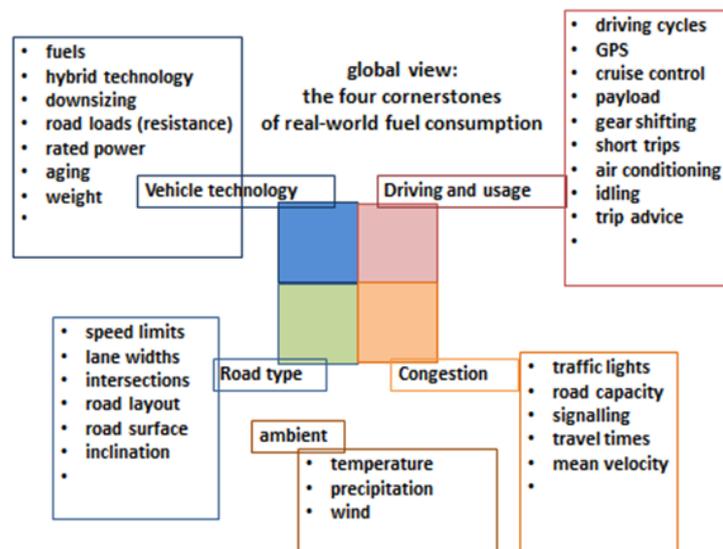


Figure 7 The aspects that must be covered and can be influenced, to yield an accurate real-world fuel consumption prediction of an individual car [Ligterink 2012].

5.1.1.1 Generic properties and characteristics

Relevant and publicly available vehicle properties are only a few. Fuel type, type-approval CO₂ emission, the rated power, the vehicle weight, and the width x height are deemed relevant, being only weakly correlated with each other and available to be included in the mathematical model.

5.1.1.1.2 *CO₂ reduction technologies*

The effects of applied CO₂ reduction technologies are reflected in the type-approval CO₂ emissions. In particular, some technologies will reduce the UDC CO₂ emissions more than the EUDC emissions. The latter are more related with the driving style than the former.

5.1.1.1.3 *Type-approval value*

The type-approval state of the vehicle includes its weight, which for the NEDC is lower than the real world. The WLTP weight is expected to be close to the real-world values. Due to optimised testing and vehicle preparation, the flexibilities in the chassis dynamometer testing alone are in the order of 12 g/km. Under the WLTP, this is expected to decrease to 5 to 8 g/km initially

5.1.1.1.4 *Tyres*

The general figure F0/M is considered the sum of all aspects related to tyres. The NEDC value is set at 80 N/ton, the WLTP value on the limited restriction is expected to be set at 90 N/ton, and an representative average is assumed to be at 110 N/ton. The latter includes road-load testing flexibilities of 4% to 10%, road surface texture, bends, misalignment of wheels after market and winter tyres, under-inflation, etc..

5.1.1.1.5 *Maintenance*

The effect of maintenance on the vehicle's performance is captured mainly through F0/M, i.e., the summed rolling resistance. An otherwise poor performance of the engine is probably not accepted by the driver as it influences drivability and this will usually be repaired. The misalignment of the wheels, for example, due to a bent wheel suspension in a minor accident, will affect the rolling resistance.

5.1.1.1.6 *Usage*

The first and simplest illustration of vehicle usage for different tests and real-world monitoring is to plot the amount of time spent at every velocity. It shows that a large amount of time is spent at a desired velocity close to the speed limit appropriate for that kind of driving, but that lower velocities also occur, due to stops and congestion. In Figure 30 such data is plotted. The time spent at idling and low velocities is large, but this does not mean that most kilometres are driven at low velocities. Given a 25 km/h average urban velocity and 100 km/h average motorway velocity, in a quarter of the time the same distance is covered on the motorway.

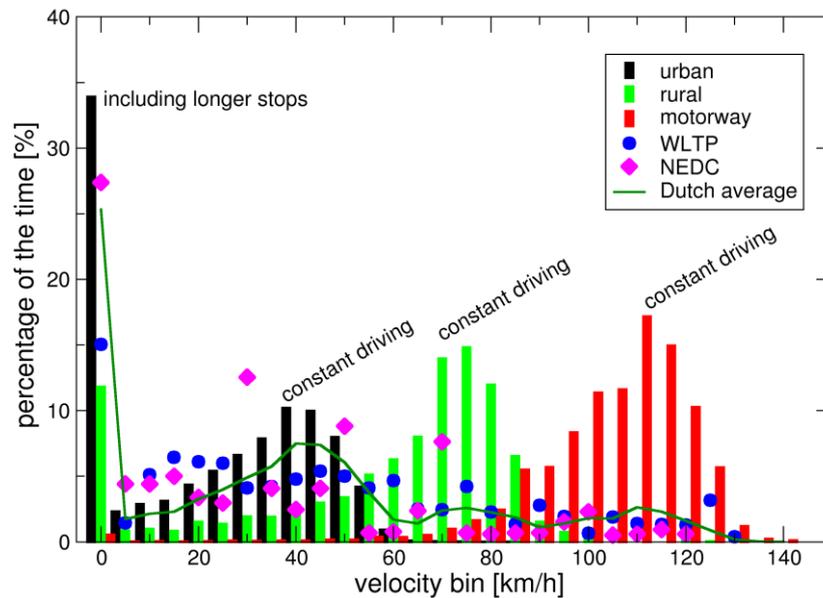


Figure 30 The amount of time spent in average driving at every velocity for a number of cases. The constant driving velocities show up in the real-world data, which are artificially reproduced in the NEDC, but mostly absent in the WLTP.

5.1.1.1.7 Trip

The Dutch average trip length is about 35 km, which reduces the effect of the cold start compared to a test cycle. The average Dutch trip consists of 9 km urban, 11 km rural and 15 km motorway driving. The average velocities are 15 km/h, 50 km/h, and 100 km/h, respectively. With this separation, this velocity may be used for air-drag and engine losses, as the $\langle 1/v \rangle^{-1}$ and $\langle v^2 \rangle^{1/2}$ determination of these velocities are similar to the average velocity $\langle v \rangle$. The amount of average braking forces are 50 N/ton, 40 N/ton, and 15 N/ton for urban, rural and motorway driving respectively, based on a generic vehicle combined with on-road velocity data.

5.1.1.1.8 Ambient

The ambient temperature relevant for the data analysed in this study is 11° C for Dutch and German average real-world driving, compared to 23° C in the NEDC and WLTP test. This will affect the outcome in a number of different ways:

- The air drag is 5% higher under real-world ambient temperature;
- The magnitude of the cold start effect is increased by about 30%.

5.1.1.1.9 Velocity profile

Different cycles have different velocity profiles. Typical driving cycles have a large amount of acceleration and decelerations, however, the velocity signal is rather smooth, with limited short acceleration and deceleration. This has two reasons: the drivability of the chassis dynamometer and the deliberate limitation of power demand, to allow low-powered vehicles to be able to drive the cycle.

Table 6: The relevant characteristics of the main driving cycles, combined with some in-house TNO data collected from on-road monitoring. The deceleration through braking depends on the road load values.

Cycle	Fraction	distance [km]	idling [%]	velocity [km/h]	Deceleration [m/s ²]		<v ² > [km/h]
					low road load	high road load	
NEDC		10.9	25.2	33.4	0.093	0.084	68.6
WLTP		23.3	14.2	46.5	0.116	0.099	81.5
CADC		44.5	12.4	60.9	0.102	0.085	97.4
Dutch urban	40.5%	369.0	25.9	27.8	0.174	0.160	44.4
Dutch rural	21.6%	196.6	9.5	60.3	0.112	0.098	74.1
Dutch motorway	38.0%	345.9	0.5	106.6	0.062	0.045	110.2
Unweighted Dutch total		911.4	19.1	45.8	0.119	0.104	80.8

5.1.1.1.10 Gear shifting

The real-world gear shifting is expected to be less optimal than eco-driving based on the type-approval gear-shift points. For the highest gear, the difference is limited, but in the lower gears, with the clutch engaged, it is expected that the engine speed is 2000 RPM rather than 1800 RPM in the NEDC and 1700 RPM in the WLTP.

5.1.1.1.10.1 Gear shift moments and postponement

Gear shifting in real-world driving is often less favourable than the 2000 rpm average assumed in the test. In complex traffic situations, gear shifting is delayed. Moreover, hard accelerations also are a reason to delay the up-shift of the gear. This is an important contribution to the high fuel consumption experienced in urban situations.

5.1.1.1.10.2 Clutch disengaged

While the clutch is engaged the wheels and the engine are coupled, and the wheel may drive the engine while decelerating. The fuel consumption is zero in that case. When the clutch is disengaged the engine must overcome the internal losses by itself, which requires fuel consumption. If the total power demand is substantial, this effect would be negligible, but in many cases the power demand on a vehicle is small, such that a typical 3% loss of the rated power is a large number compared to the 10%-15% average power demand in urban situations.

5.1.2 Description of the model

The approach used in this project is based on 'translating' CO₂ emissions to energy. Energy is conserved, hence, if a proper assignment can be made, there is an unique decomposition of the total CO₂ emission into distinct parts of the vehicle operation that require energy. In principle, this should correspond to the heating value of the fuel and its carbon content, but in practice the maximal conversion to mechanical work is limited by the thermodynamic cycle and by practical aspects of an engine design. Hence, a more accurate starting point of linking energy to CO₂ takes into account the maximum possible efficiency of conversion. For a large, modern engine this can be as little as 610 g/kWh, but for a passenger car values of 700 to 800 g/kWh²⁷ are more appropriate. This corresponds to a minimum amount

²⁷The typical value used in this report is 720 g/kWh or 0.2 g/km to overcome 1 N driving resistance. The variation with petrol and diesel, and small and large cars will be generic to all CO₂ emissions. Given a CO₂ fuel factor of 74 g/MJ, the optimal engine efficiency varies between 33% and 38%.

of about 47 g/km to overcome a typical 250 N force of driving resistance for normal constant-speed driving. This is the absolute minimum for propelling a normal passenger car with conventional engine technology at constant speed, based on the physical principles of the conservation of energy and entropy for reversible processes.

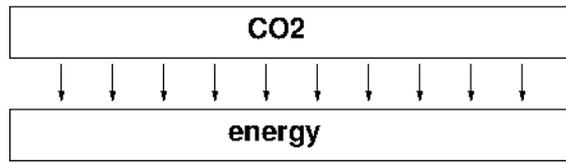


Figure 31 The mathematical model is based on attributing the CO₂ emissions to the energy associated with different aspects of vehicle operation.

The CO₂ should be attributed appropriately to different aspects of the vehicle operation such that the variation in CO₂ emissions can be classified for the effectiveness on type-approval tests and in real world.

In principle, the model developed in this project has not the details of a specific vehicle model, but must be seen as a method of classifying effects and disentangling generic fuel consumption for different vehicle usage patterns and technologies.

After having translated CO₂ into energy, the energy is categorized into the seven main groups described in sections 3.1.1 and 3.1.2, each latching onto different aspects of the vehicle operation.

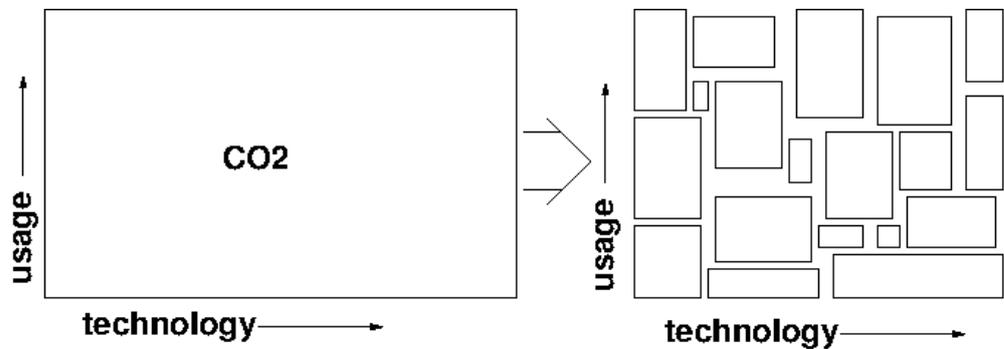


Figure 32 Some technologies reduces CO₂ emissions only in particular cases. For example, stop-start reduces emissions only in the case of idling with the gear in neutral. The assignment of CO₂ emission and its reduction cannot be analysed independently of vehicle usage. A proper factorization must be made.

The equations defined in section 4.2 can be used to determine the CO₂ emission for a particular vehicle usage, gear shifting and velocity profile, at a given velocity v [km/h], acceleration a [m/s²] and engine speed RPM [min⁻¹]. The changes in usage affect the changes in weight [M] and thereby rolling resistance [R] and braking losses [B] and, separately, auxiliary usage [X]. The changes in technology affect the optimal efficiency Q [CO₂/MJ], the losses [E] and [P].

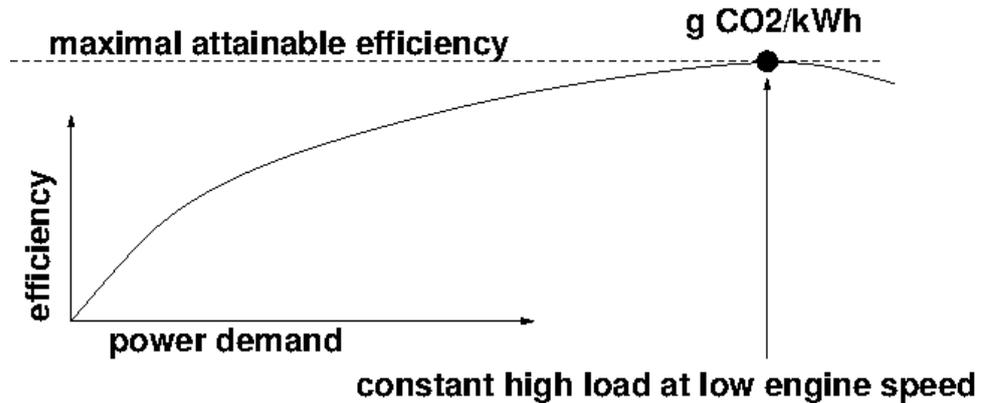


Figure 33 The relation between power and CO₂ emission is based on the lowest possible CO₂ emission for a given power output. The extra CO₂ emissions must be associated with losses. This defines both Q and the additional losses increasing the emissions at non-optimal usage.

One can start for the determination of CO₂ emissions from vehicles with specific usage patterns with the absolute emissions rather than the relative effect. However, that would be a very large effort. Firstly, it would require the replication of the large research effort of all the OEMs in reducing the CO₂ emissions. Secondly, the starting point is very far removed from the determination of the small differences in usage and vehicle state considered here. Instead, determining differences between different cases, require only the marginal effects to be modelled.

Hence, another more practical starting point is considered. It falls within the general approach of Willans lines, commonly used in CO₂ modelling nowadays. This means assuming a linear relation between supplied power and CO₂ emission, which requires two coefficients: the offset, or internal losses, and the slope or marginal dependence. Figure 34 shows an example of the Willans lines approach. Both coefficients, defining a relation between power and the minimal CO₂ emission and the losses, are already laid out in the general setup described above. The offset is often assumed fixed, but as the losses depend both on auxiliary use and engine speed as well, and they are substantial for the common power demand of a passenger car with respect to the rated power, some further details are needed here.

Since not the absolute emissions but the relative emissions are determined, it is important to define the reference point. The choice of offset, or losses, cannot be decoupled from the definition of the slope. In this case, the slope is determined from the optimal engine efficiency. The slope is the tangent line to the optimal efficiency which also crosses the zero-power line, or vertical axis, at the appropriate idling losses, as can be seen in Figure 34.

Originally, Willans lines were reflecting load-CO₂ relations for constant engine speed. Losses increase with engine speed, but also the slope will be steeper, as with the increasing engine load the forces and friction increase. Also, pumping losses increase due to the higher gas throughput.

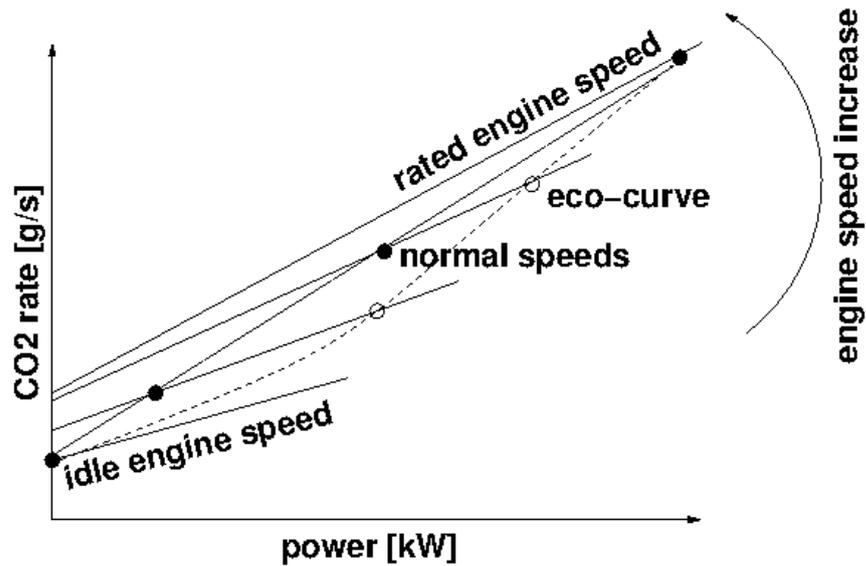


Figure 34 The relation between CO₂ emission and power for given engine speeds. The normal vehicle use, i.e. an increasing engine speed with increasing power, is plotted as an approximate straight line. Eco-driving will lower the engine speed and the associated CO₂ emission.

At a low engine speed, the power output is limited. Hence, engine speed must increase with power demand. In practice, for the normally used engine speeds the maximal torque is near constant, such that the available power is proportional to the engine speed n , with respect to the highest engine speed n_{rated} :

$$P_{available} \sim P_{rated} * (n/n_{rated})$$

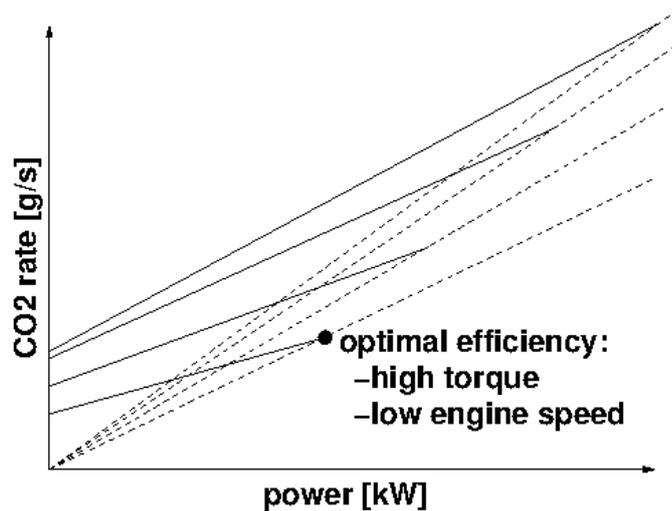


Figure 35 Given the nature of the losses, the optimal efficiency [CO₂/MJ] (dashed lines) is obtained at low engine speed and high engine torque (end points of the solid lines).

A simple yet effective assumption is to base the Willans line, first, on the idle emissions, which are the absolute minimum CO₂ emissions for keeping an engine running, and, second, the maximum efficiency at the optimal operation point. The increase of the losses with engine speed is incorporated in the slope Q . After

subtracting the idle emissions, the slope is obtained from the power output and the extra emission on top of the idle emissions. In most cases, the idle emissions are almost negligible at the optimal load of ~ 50% of the maximal load. This represents the coefficient $Q[\text{CO}_2/\text{MJ}]$ as: at high load CO_2 and engine work are related one-to-one.

Generally, the optimal efficiency is difficult to determine without extensive testing of the vehicle. Idling emissions used to be well-known, but with stop-start systems these became more complex as well. On the other hand, given the fact that these characteristics are captured by means of two coefficients only, their approximate value can be inferred from testing under different conditions. The marginal change in CO_2 emissions for the marginal variation in power demand, for similar vehicle operation and usage, are related to the optimal efficiency Q . For example, executing the same test with a slightly higher rolling resistance or weight is expected to change the CO_2 emission only according to the additional energy demand ΔE through: $\Delta\text{CO}_2 = Q[\text{CO}_2/\text{MJ}] * \Delta E$. The ΔE is determined from the modelling.

Given the optimal efficiency $Q[\text{CO}_2/\text{MJ}]$, to all work done by the combustion pressure on the piston a specific CO_2 emission is separately attributed and assigned. Within the optimal efficiency itself, some effects are grouped. First of all, the thermodynamic cycle efficiency, which differs for the main cycles: Otto-cycle and Diesel-cycle. Secondly, any aspect that can reduce CO_2 per combustion, which may be related to fuel, or utilizes the thermal energy, i.e. waste heat, is to be captured into changes of the optimal energy parameter $Q[\text{CO}_2/\text{MJ}]$. The energy is therefore related to the specific power, or cylinder pressure, per piston stroke.

The optimal efficiency depends on many aspects, such as compression ratio, optimal ignition, valve timing, etc.. For type approval tests and real-world driving it is assumed here that the same efficiency applies. The actual efficiency depends however very much on the vehicle usage and thus the engine load and speed, and variations therein. The optimal efficiency is to be used to establish marginal relations to determine the change in CO_2 emission from a small change in work and usage? This is typically a linear relation: the Willans line.

As mentioned, the approach used is a Willans line approach, assuming a linear relation between power and CO_2 emissions. The slope is constant ($Q[\text{CO}_2 \text{ g/MJ}]$), however, the offset varies with the engine losses and auxiliary usage. In many other cases, a more detailed model is used for simulating engine, driveline and transmission. However, such detailed models lack data on both counts: the large variation in technical aspects of the fleet, and precise data of the vehicle usage and driving behaviour. Even a simple fact as the amount of idling with cars seems poorly known, with very high percentages on test cycles unlike the experiences of most drivers.

Often, effects are lumped together, such that from the results individual effects are no longer quantifiable. Moreover, in test and monitoring programmes, the variation of different aspects at the same time may lead to the wrong attributions of effects. In principle, resulting CO_2 emissions are an intricate interplay of technology, vehicle usage and circumstances, but globally, the incremental change in energy and force will already yield the main attributions by the following approximations:

- $\Delta 1$ MJ energy $\sim \Delta 200$ g CO₂
- $\Delta 1$ N Force = 1 kJ/km $\sim \Delta 0.2$ g/km
- $\Delta 100$ kg $\sim \Delta 10$ N resistance ~ 2 g/km
- $\Delta 100$ W ~ 0.02 g/s CO₂ ~ 3 g/km urban and 0.7 g/km motorway
- stop $\sim 0.05 * v^2$ kJ = $0.01 v^2$ g CO₂ ~ 25 g (from 50 km/h) and 100 g (100 km/h)
- Engine losses (modern, low load) $\sim 3\%$ of rated power: 0.006 g/s per kW
 - 80 kW rated power, urban: 70 g/km, and motorway: 17 g/km
 - Idling 10% of the time contributes 10%, or 7 g/km, to the urban losses
- Air drag force $\sim 0.04 * v^2$ [N] ~ 400 N at 100 km/h ~ 80 g/km
- Auxiliary losses in [g/km] are inversely proportional to the average velocity.

This already gives an indication of the size of contributing effects:

- 1 If substantial distance is travelled at high velocity, air drag is a major contribution;
- 2 If substantial time is travelled at low velocity, the engine losses are a substantial contribution;
- 3 Auxiliaries play mainly a role at low velocity;
- 4 Additional weight plays a small but fixed role, also in braking;
- 5 The number of stops (or decelerations) can greatly affect the total CO₂ emission. Severe decelerations due to traffic lights, for example, are causing a significant amount of CO₂. Gradual deceleration on the other hand, for example by means of coasting down to a halt, limits CO₂ emissions.

This directly points out at a number of issues that arise in typical type approval test cycles, such as the NEDC and the WLTP:

- the limited driving at high velocity;
- the absence of auxiliary usage;
- the large amount of idling;
- the large number of acceleration and decelerations.

As a consequence, in the test cycle, the focus for CO₂ reduction is on vehicle weight and engine losses. And, although these are in principle important aspects, they may eventually only be responsible for half of the real-world CO₂ emission attribution.

5.1.3 Model input of a generic vehicle

In part, the difference in fuel consumption is due to the trip itself. For real-world Dutch driving, a set of monitored trips with random selected drivers is used as a reference. The trips are not necessarily representative concerning their urban/rural/motorway shares, but since this information is available, the data can be reweighted to arrive at different distributions of shares.

For a generic vehicle, the different aspects contributing to the total CO₂ are presented in Table 7. The different weighing of the urban, rural and motorway part give a natural span to the CO₂ emissions. The boldface numbers are included in the total, while the normal typeface give an estimate of the overall variation due to the variations in underlying parameters. The parameter settings used in this analysis are shown the box above,.

Clearly, the deviations in the total CO₂ emissions are much smaller than the variations in the underlying causes. On the NEDC, the engine losses have a very

large contribution. Anything that will bring this number down has a large impact on the type-approval CO₂ emissions, but is less effective in any other situation. The difference between the WLTP and the NEDC, in this case of 8 g/km, is already covered by the weight effect (4 g/km) and the stop-start system (5 g/km).

Table 7 is constructed by determining the running time, assuming engine losses at 3% of the rated power. The stop-start system reduces these engine losses by 8% through the reduction of the time the engine is on. The rolling resistance is proportional to the weight of the vehicle and the distance, and translates therefore directly in g/km. Auxiliary power is constant in time, and has therefore a greater effect when the average velocity is lower. The braking losses decrease if the rolling resistance is higher, as the vehicle decelerates more with a high rolling resistance. Two values for the rolling resistance are used: an optimised NEDC type-approval value and an observed real-world value. The latter does not yet incorporate the colder ambient temperature, the wind, and the increased rolling resistance from road surface and undulation, and precipitation. Here, it is assumed that the rolling resistance does not actually change under the WLTP, except for the added weight, which also affects the losses due to braking. Moreover, it is expected that the optimised gear shifting under the WLTP will reduce the average engine speed by 10%. The effects of gears shifting are taken proportional to engine losses and engine speed. The numerical values based on the results are shown in Table 6.

Table 7: The different aspects of driving and technology which lead to the total CO₂ emission. Only effects directly related to physical aspects are covered.

attributions [g/km]	associated CO2 emissions										NEDC optimized total [g/km]	
	stop-start engine reduction losses	low resistance [80N/ton]	high resistance [110N/ton]	braking (RLlow)	braking (RLhigh)	eco gear shifts	air drag	ambient air	auxiliary effect	weight effect		cold start
NEDC	-8.7	20.8	28.6	24.2	21.8	-4.5	30.2	0.0	9.0	0	9.2	115.9
WLTP	-3.7	20.8	28.6	30.1	25.7	-6.4	42.5	0.0	6.4	3.9	4.3	123.7
CADC	-2.3	20.8	28.6	26.5	22.0	-2.5	60.7	0.0	4.9	3.6	2.2	133.7
Dutch urban	-11.6	20.8	28.6	45.2	41.6	-5.4	12.6	0.5	10.8	5.4	18.6	171.9
Dutch rural	-2.0	20.8	28.6	29.1	25.4	-2.5	35.1	1.4	5.0	4.2	8.7	133.1
Dutch motorway	-0.1	20.8	28.6	16.2	11.6	-1.4	77.7	3.1	2.8	3.1	0.0	141.0
weighted 40/22/38	-5.2	20.8	28.6	30.9	26.9	-3.3	41.8	1.7	6.6	4.3	3.7	146.2
weighted 25/30/45	-3.5	20.8	28.6	27.3	23.3	-2.7	44.0	1.8	5.5	4.0	3.7	138.0
weighted 20/25/55	-2.8	20.8	28.6	25.2	21.1	-2.5	49.6	2.0	4.9	3.8	3.7	138.4

vehicle weight [kg]	Engine Power [kW]	air drag at 100 km/h [N]	additional weight [kg]	Auxiliary power [W]	cold start effect [g/start]
1300	65	320	100	300	100

Putting these effects together, there are three classes, related to the available data, which contribute in a different manner to the gap between type-approval value and real-world CO₂ emissions:

1. Flexibilities related to observed effects linked to physical principles, such as differences in road load and mass, and the use of electric equipment;
2. Flexibilities observed but not simply related to physical principles, but possibly to further optimisation of the test and the vehicle state, such as test optimisation by driving, smooth road surface at coastdown, low wind testing, battery overcharging, increased rotational inertia;
3. Aspects not, or differently, covered in the type-approval tests affecting the gap, such as driving behaviour variation, ambient temperature, limited idling, cold starts, engaging stop-start.

5.1.4 *Flexibilities included in the model*

Flexibilities accounted for in Table 7 are those which were quantified. In addition their effect can also be quantified separately for the different driving styles and trips. The road load differences lead to a variation in force which can be directly linked to a difference in CO₂ emissions. The particular effects are determined for the test in which they occur. In real world some effects may be smaller due to higher vehicle velocities.

Table 8: The estimates of the effects of the flexibilities which can be included in the numerical analyses.

included flexibilities	[g/km]	NEDC	WLTP	CADC
observed road load differences		5.5	3.3	3.3
auxiliary power usage		9.0	6.4	4.9
weight		3.5	-	-
Total		18.0	9.7	8.2

5.1.5 *Flexibilities not included in the model*

The flexibilities not included in Table 7 are those which cannot be properly quantified through physical principles and are attributed to various aspects of the test. They are therefore generic numbers obtained from the available monitoring data.

Table 9: The estimates of the effect of the flexibilities observed, but not possible to quantify properly for the inclusion in the numerical analysis.

excluded flexibilities	g/km]	NEDC	WLTP	CADC
chassis test optimisation		12.0	12.0	12.0
road load test optimisation		2.0	2.0	2.0
road surface		3.0	3.0	3.0
optimised driving		0.8	3.9	-
weight classes		1.8	0.0	0.0
Total		19.6	20.9	17.0

5.1.6 Circumstances

The type-approval test does not fully represent the real world: ambient temperature, wind, the engaging of stop-start systems and so on are all aspects which deviate from the average real-world data which is available to date.

Table 10: The effects of differences between the type-approval test and test conditions and the corresponding real-world conditions.

Effect	[g/km]	NEDC	WLTP	CADC
cold start		-5.4	-0.6	1.5
ambient wind		2.0	3.0	2.0
high velocity driving and engine losses		-3.8	-3.5	-14.1
stop-start system (optimal use)		5.2	0.2	-1.2
Total		-2.0	-0.9	-11.8

5.2 Regression models

5.2.1 Fuel consumption models

Regression models should be based on available vehicle data, and are not supposed to not contain highly correlated variables used in the same model. There are only a number of candidates to do so. In principle, weight and box area (width x height) are related to the physical principles and should be included. The engine efficiency and engine losses can be included in different manners, for example, by means of rated power, engine size, or both the UDC and EUDC CO₂test values. In principle, no constant offset can be used, as the total fuel consumption should be assigned to respective causes. The Travelcard validation is based on a combination with available type-approval data, and a selection the vehicles models sold the last two years. These are 29,000 petrol vehicles and 38,000 diesel vehicles.

Table 11: The average values and their statistical spread for vehicles 2013-2015 used in the models based on Travelcard data.

		Mass [kg]	Area [m ²]	Vmax [km/h]	P [kW]	CO ₂ UDC [g/km]	CO ₂ EUDC [g/km]	CO ₂ NEDC [g/km]
average value	Petrol	1297.5	2.61	186.4	85.9	140.0	101.4	99.0
	Diesel	1393.7	2.65	192.5	82.5	115.8	90.0	115.6
standard deviation	Petrol	237.9	0.186	21.2	22.2	41.5	17.4	17.3
	Diesel	172.8	0.176	14.2	29.3	23.5	14.2	25.3

The correlation between the different parameters remains large, as for example, with weight and rated power. Both increase with the overall vehicle size. Likewise, the type-approval CO₂ emissions increase. This is unavoidable when dealing with monitoring data, and it requires close inspection. However, it would be inappropriate to fit models with 5 or more variables due to the correlation between these variables.

5.2.1.1 Model 1: $RW = constant + UDC + EUDC$

The prediction of the real-world fuel consumption ("RW") based solely on the type approval values and a constant offset is:

Petrol:

$$CO_2^{\text{real-world}} = 46.8 + 0.203 * UDC + 0.760 * EUDC \text{ [g/km]}$$

Diesel:

$$CO_2^{\text{real-world}} = 67.9 + 0.064 * UDC + 0.894 * EUDC \text{ [g/km]}$$

These formulas show that the UDC results have limited relation with the real-world fuel consumption for diesel. For petrol, the fit seems to reflect the split between urban and extra-urban (rural and motorway) driving distance, which may be a coincidence.

The constant offset in this case is an upper bound of the effects not covered by the approval test. This value is already close to the gap between type-approval and real-world fuel consumption. This is to be expected as the sum of the coefficients for the UDC and EUDC is close to 1 (96.3% and 95.8%).

In principle, it could be interesting to study the effect of hybrid technology separately. However, hybrid technology already exhibit a low UDC value. The fact that the UDC has little predictive value in this model, and also the models below which include the UDC as a separate parameter, already demonstrate the limited significance of the UDC figure for real-world fuel consumption.

5.2.1.2 Model 2: $RW = M + A + UDC + EUDC$

The prediction of the real-world CO_2 based on mass, frontal area (height x width), and the different parts of the type-approval fuel consumption leads to the following results:

Petrol:

$$CO_2^{\text{real-world}} = 0.0121 * M + 23.62 * A + 0.270 * UDC + 0.390 * EUDC \text{ [g/km]}$$

Diesel:

$$CO_2^{\text{real-world}} = 0.0232 * M + 28.93 * A + 0.131 * UDC + 0.197 * EUDC \text{ [g/km]}$$

5.2.1.3 $RW = M + A + P + NEDC$

The prediction of the real-world CO_2 based on mass, area, engine power, and the combined type-approval value leads to the following results:

Petrol:

$$CO_2^{\text{real-world}} = -0.0147 * M + 33.8 * A + 0.292 * P + 0.509 * NEDC \text{ [g/km]}$$

Diesel:

$$\text{CO}_2^{\text{real-world}} = 0.0056 * M + 33.2 * A + 0.127 * P + 0.345 * \text{NEDC} \text{ [g/km]}$$

Clearly, mass and power are strongly related, and with the inclusion of power, the dependency on mass becomes reversed for petrol vehicles. The effect of area has a limited variation between powertrains, but has a considerable overall contribution in the total value of about 80 g/km. Very likely, this is related to the substantially higher real-world driving velocities than in the type-approval tests.

5.2.1.4 Model 3: $RW = M + V_{\text{max}} + \text{NEDC}$

The maximal vehicle velocity combines three aspects of high speed driving: the engine power, the air drag roughly captured by the frontal area (width x height), and the gear ratio of the highest gear. The prediction of the real-world CO₂ based on mass, maximum velocity, and the combined type-approval value leads to the following results:

Petrol:

$$\text{CO}_2^{\text{real-world}} = 0.0623 * M + 0.348 * V_{\text{max}} + 0.683 * \text{NEDC} \text{ [g/km]}$$

Diesel:

$$\text{CO}_2^{\text{real-world}} = 0.0346 * M + 0.256 * V_{\text{max}} + 0.435 * \text{NEDC} \text{ [g/km]}$$

In some sense, this is the most physical model, as the mass is most closely related to the expected dependency with rolling resistance and braking losses included. The low load engine optimisation show up in a low NEDC number, which is more relevant for petrol than for diesel. Also this aspect is replicated in the fit. The use of the V_{max} captures two different aspects: the high velocity driving on the motorway which is underrepresented in the type-approval test and the engine losses.

5.2.2 Model 4: Divergence model

Instead of trying to predict the real-world fuel consumption from the characteristics of the car, one can also focus on the gap itself, i.e., $\Delta\text{CO}_2 = \text{CO}_2^{\text{real-world}} - \text{NEDC}$, and determine which properties are relevant to it. In that case an offset, typically associated with auxiliary losses, not accounted by the type-approval test, has to be included in the model.

The model is described by the following equation:

$$\text{Delta} = \text{constant} + \text{YEAR} + \text{YEAR}^2$$

The simplest model would assume that the gap is only due to aspects not considered in the test cycles. The increase of the gap over time is modelled as a polynomial of the number of years after 2000.

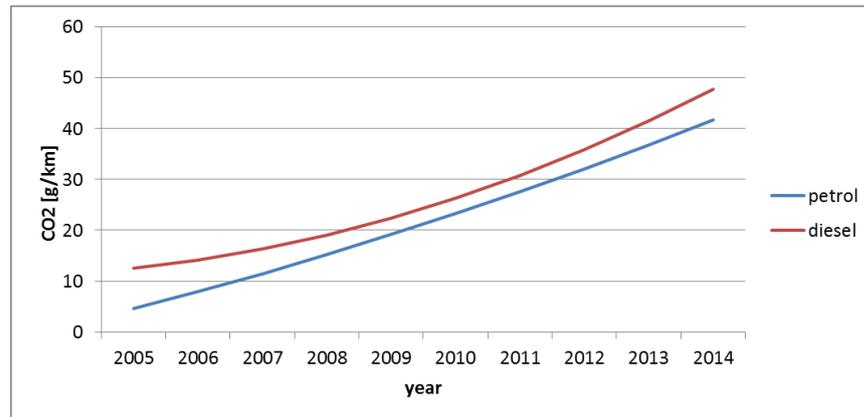


Figure 36: The gap in absolute g/km as result of the polynomial fit of the Travelcard monitoring data.

Petrol:

$$\Delta \text{CO}_2 = -9.3 + 2.279 * (\text{YEAR} - 2000) + 0.09767 * (\text{YEAR} - 2000)^2$$

Diesel:

$$\Delta \text{CO}_2 = 13.2 - 1.560 * (\text{YEAR} - 2000) + 0.2874 * (\text{YEAR} - 2000)^2$$

Both the diesel gap as well as the petrol gap have an increasing slope. However, this may partly be due to year-to-year variations. By analysing each year separately, it is clear that as of 2007-2008 a different trend for the gap is observed, with an ever increasing absolute difference. By attributing this to additional forces or auxiliaries like air-conditioning, it would mean that the difference in total driving resistance force between RW and TA has increased by a fixed 200 N, or by the constant auxiliary power use by about 3 kW. This is however not a sufficient explanation for all the changes that have occurred between 2006 and 2014.

As noted before, the power, the weight, and the size of the vehicles have increased as well over the same period. If these were included in the fit, they would be correlated with the gap as seen before. If some realistic assumptions are made for the real magnitude of the effect of the change in characteristics, the remaining effect can be estimated. The complication lies therein that the effects cannot be decoupled.

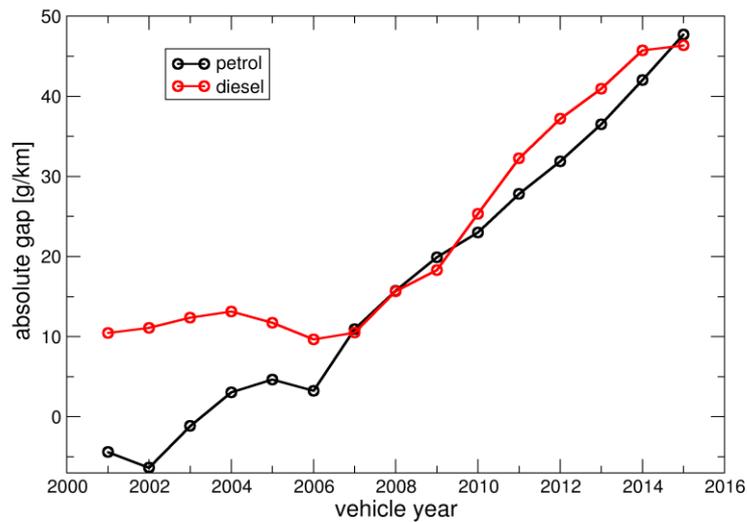


Figure 37 The average values per year for the gap between real-world fuel consumption and the type-approval value. For from 2007-2008 a different trend has set in. Data from Travelcard Nederland BV.

In the analysis of the gap and its underlying causes, it is important that the effects are not implicitly modelling the changes in vehicle characteristics over the years. In the years 2001-2004, prior to tax benefits based on CO₂, large vehicles like SUV's were popular in this market segment of leasing vehicles. Very likely a high type-approval value and the non-optimised test values explains the negative gap for petrol cars of 2001 and 2002. This is not the case for the Sprit monitor data from Germany.

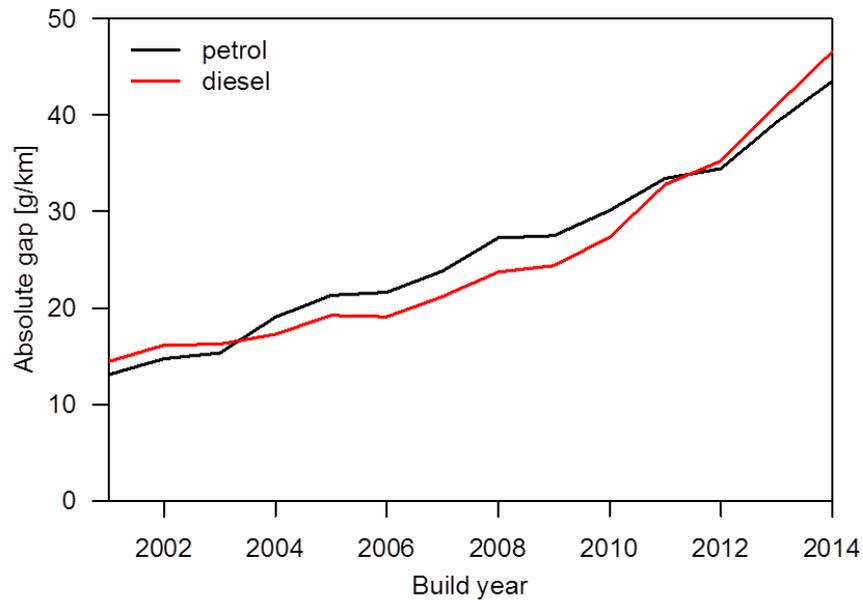


Figure 38 Annual averages of the absolute difference between real-world and type-approval CO₂ emission values based on Spritmonitor.de.

Figure 38 presents the annual averages of the absolute difference between real-world CO₂ emission values from Spritmonitor.de and the corresponding type-approval figures. Petrol and diesel vehicles exhibit relatively similar gaps, which increase from approximately 15 g/km in 2001 to approximately 45 g/km in 2014.

In the validation section, it is shown that in the period from 2006 to 2009 all vehicles are switching to an increase in the difference, independent of the manufacturer.

5.3 Coefficient values expected through physical considerations

Given the different fits, the coefficients vary within a certain range, showing the magnitude of the dependencies. Typically, the size, weight and rated power of vehicles has increased, while the type-approval values have decreased. In particular the changes for diesel vehicles are substantial.

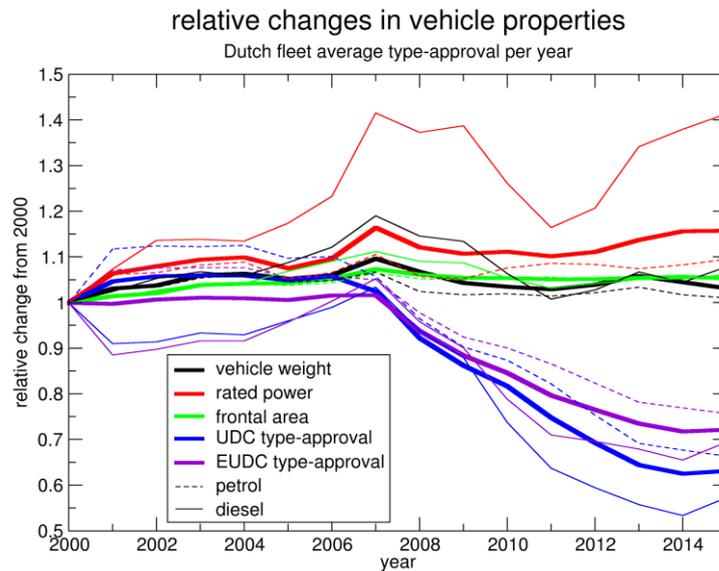


Figure 39 On one hand, the values of typical physical vehicle properties related to fuel consumption have increased, in particular power. On the other hand, the type-approval fuel consumption has gone down. Dutch average fleet data. The bold line is the average.

Their effect on the different type-approval cycles depends very much on the characteristics of the cycles.

5.3.1 Mass effect

The mass effect consists of a number of separate effects: the higher rolling resistance of about 30 N/ton on top of the NEDC road load value and the additional mass in real-world circumstances due e.g. extra luggage and passengers and additional optional mass e.g., like actuators, radio, floor mats, etc.. Together this sums up about about 40 N/ton, which translate into an additional 8 g/km CO₂.

5.3.2 Air drag effect

The air drag effect has two major components. The higher velocity in real world with 45% of the distance driven at 100 km/h, adding a 250 N average force and 50 g/km CO₂. This corresponds to a term of $20 * A$, where A is products of the vehicle's width and height of the vehicle. The latter is probably the reason why SUV's typically have a larger deviation between real-world and type-approval CO₂ emissions, compared to other vehicle with the same type-approval value. Vans are a different story: for these vehicles the road-load is seldom determined for the NEDC, but a beneficial table value from the R83 regulation is used, with limited bearing on the actual road load. In the WLTP vans are expected to be tested more, but this vehicle category will remain special.

5.3.3 Engine losses

The engine losses can be related to engine power, or to the difference between the UDC and the EUDC value. Typically, the engine losses related to idling emissions, are about 3% of the rated power, resulting in losses of 0.21 g/s per kW or 6 mg/s

per kW rated power.²⁸ It is to be expected that for larger engines the losses are slightly smaller. For petrol engines the losses are larger: 8 mg/s per kW rated power. The increasing losses with engine speed are to be incorporated into the slopes expressed in: g/kWh and [g/km]/N.

The simplest rule of thumb for high powered conventional vehicles (200 kW and higher, technology) is that the rated power in [kW] is coincidentally more or less equal to the type-approval emission in [g/km], with a limited decrease over the years. In this case the engine losses dominate the total emissions. Given the time of about 100 seconds per kilometre on the type-approval test, a loss of 3% on a 200 kW engine equates to 0.6MJ, and about 140 g/100s (and 140 g/km) of CO₂. The cycle energy is a minor contribution to the total type-approval CO₂ in the case of high powered vehicle.²⁹ Under the WLTP this situation changes with the increase in average cycle velocity, which leads to a shorter time and a smaller contribution of engine losses over a kilometre. Therefore, with the WLTP the engine power is no longer strongly delimited by manufacturers CO₂ targets in g/km. This may create a new risk for a growing gap between type-approval CO₂ emissions and real-world CO₂ emissions.

5.3.4 *Auxiliary usage*

The additional 300 W at 50 km/h is equivalent to 22 N force and 4 g/km CO₂. This is to be added to the constant part. It is complex to determine this number from detailed studies, but measuring the current from the alternator shows a large variety in power use over time gives a good indication for the 300 Watt additional electric power demand in normal usage.

5.3.5 *Cold start effect*

Cold start accounts for 9-14 g/km additional CO₂ on the NEDC type-approval test, and about 3-5 g/km in real-world driving. Hence this is a reduction in CO₂ emission from type-approval to real-world where the effect is larger.

5.3.6 *Flexibilities*

Optimised testing will ensure the type-approval is typically at the lower end of a 12 g/km bandwidth.

²⁸ With 750 g/kWh / 3600 s/h = 0.21 g/s, given a loss of 3% of the rated power yields 0.03 [kW/kW] * 0.21 g/s = 6 mg/s.

²⁹ Likewise, making cycle work the key ingredient in the new WLTP CO₂ legislation has some drawbacks.

6 Verification of mathematical approach by comparing reported real fuel consumption with estimates based on parameters

6.1 Input data regarding vehicle technology, use and circumstances used for validation

6.1.1 Vehicle fleet

6.1.1.1 Required parameters

Publicly available characteristics of vehicles sold are very limited. The technical data comprises mainly data which have to be provided for type-approval purposes, such as CO₂ emission, weight, rated power, cylinder volume. For example, the torque curve, required for the calculating gear shift points on the WLTP, does not have to be made available in any official capacity yet. The knowledge of hybrid vehicles arises mainly from the fact that the type-approval test procedure is different. Details about hybrid technology cannot be found in any official vehicle fleet data.

The lack of detailed information, and the limitations of the official data, put restrictions on the modelling of average real-world CO₂ emissions for such a fleet in Europe. Often, this additional information is considered by industry to be proprietary and commercially sensitive. Some elements are usually disclosed only to augment certain argumentation.

The limitations of the available data is another drawback. The type-approval empty weight provided may not match either the type-approval test weight or the actual weight of the vehicle sold. It is often difficult to attain the official type-approval weight for reproducing a coastdown test with a production vehicle, without removing seats or other parts. The lack of transparency around type-approval testing occasionally leads to discussions among experts on the appropriate interpretation of a certain mass, and how its value is applied.

A number of parameters are deemed relevant and immutable. These are:

- Type-approval CO₂ value [g/km]
- Vehicle empty weight [kg]
- Rated power [kW]
- Cylinder volume [cc]
- Fuels [petrol, diesel, CNG, LPG, ethanol, electricity]
- Technology [conventional, hybrid (electricity as second fuel), PHEV (charge depleting test)]

6.1.2 Traffic

The Netherlands is filled with traffic control devices, adapting the speed limit on the motorway, the number of lanes, etc.. All these devices are driven by data from induction loops. Hence for the majority of the main roads traffic data is available. The quality varies from time to time, and from location to location.

6.1.3 *Vehicle mileages*

Vehicle mileages, typical trips and number of cold starts are determined in the Netherlands by the National Bureau of Statistics (CBS) from interviews and the recorded odometer settings. The latter data is part of the framework against illegally lowering odometer readings.

6.1.4 *TNO in-use compliance testing*

6.1.4.1 *Road load testing*

Since a few years TNO performs most of its emission testing on road. It has reduced the gap between CO₂ emissions predictions from the test program and the fuel consumption monitoring data. However, the results and differences are not yet fully understood and explained. Therefore, this data is not deemed useful for a detailed comparison.

6.1.4.2 *Chassis dynamometer testing*

From 1988 onwards, TNO, at the request of the Dutch Ministry of Infrastructure and the Environment, has taken vehicles off the road to test their emissions. This is part of the In-Use-Compliance program carried out to determine if emission control systems function properly in vehicles in normal use as well as for determining real-world emission behaviour of vehicles. From about 2,000 of these vehicles also the declared CO₂ emission is known, as supplied by the manufacturer, which allows for the comparison of their independently determined NEDC value and the official type-approval value..

Vehicles in normal use, in the Netherlands, are in reasonably good state, due to the annual vehicle test, which is audited by the road authority. Occasionally, vehicles are not in a proper state and repairs are carried out prior to testing.

6.1.5 *Travelcard*

The data from Travelcard Nederland BV is a large dataset of fuel consumption data. TNO has access to data from the fuel card company of over 300,000 vehicles. The data typically consists of fuelling and odometer data of a couple of years. The large number and homogeneous group of drivers allow for a number of statistical analyses, averaging over the unknown factors related to vehicle use and personal driving styles. However, it has to be acknowledged that these are all company paid fuelling events which may introduce some distortion in the sample.

6.1.6 *Spritmonitor.de*

Spritmonitor.de is a free web service that allows users to track their fuel consumption based on odometer readings and fuelling data. For a detailed discussion of Spritmonitor.de, see Mock et al. (2014). The Spritmonitor.de data is used as an independent validation of the effects. Some of these effects are also observed in Travelcard, and some, such as specific air-conditioning use and the variation of fuel consumption with a predominant road-type use have only been available for the Spritmonitor.de data.

Generically, the Spritmonitor.de data shows the same trend as all data: a linear relation between type-approval fuel consumption and real-world fuel consumption, which shifts upwards and with an increasing slope, towards a constant offset close to 50 g/km for the most recent vehicle models.

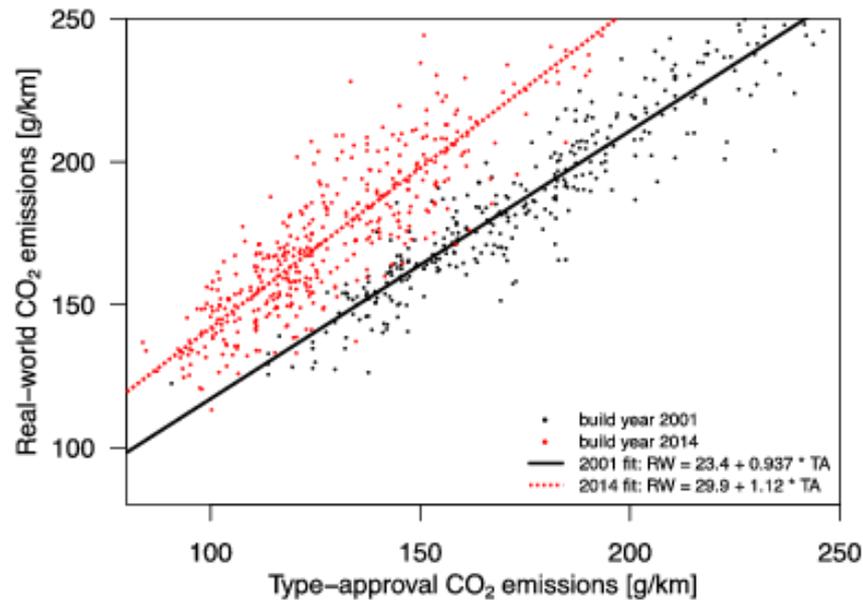


Figure 40: Real-world CO₂ emission values for Spritmonitor.de model variants over type-approval figures for two vehicle build years (2001, 2014). Lines of best fit provide an indication of the relationship.

Figure 40 plots the observed real-world CO₂ emission values from Spritmonitor.de over type-approval values. Comparing observations from 2001 with observations from 2014, type-approval figures decreased to a greater extent than real-world values as evident from the increase in the y-intercept and slope of the best-fit lines.

6.1.7 Consumer tests

6.1.7.1 ADAC Ecotest

The ADAC (www.adac.de) has been performing many emission tests already for some time. These tests are a combination of the NEDC test and the ADAC motorway test, comprising approximately 20 km at 130 km/h. Since 2012, also the WLTP is included. ADAC reports the combined sum results. Based on 1,832 tests, a correlation between their test results and the type approval value can be determined. This correlation is:

$$\text{CO}_2^{\text{real-world}} = 47.5 + 0.812 * \text{CO}_2^{\text{type-approval}}$$

The tests of ADAC are solely chassis dynamometer tests and the road-load values are the type-approval values supplied by the manufacturer. Hence, the result is an intermediate between a monitoring result of real-world CO₂ emission and a TA test result. For example, daytime lights on during testing as well.

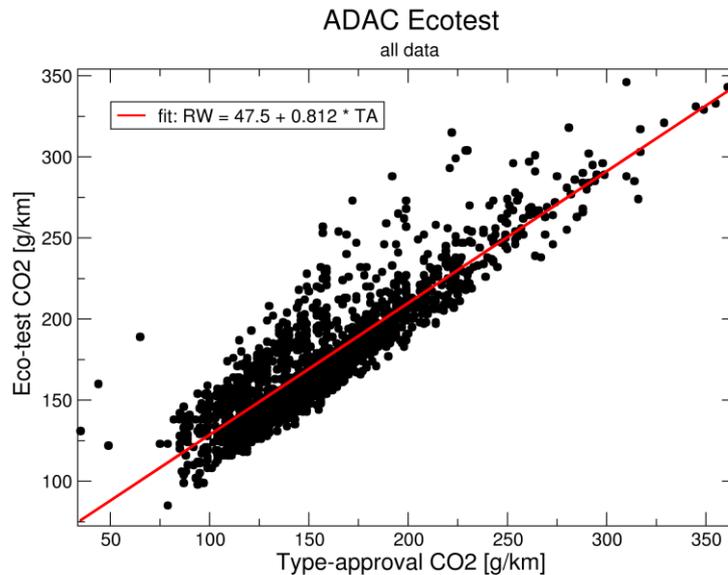


Figure 41: The ADAC ECOtest results compared with the type-approval values. The data in the graph combines the test method beyond 2012, which includes the WLTP test and the results from before using the NEDC.

At 150 g/km type-approval value the gap is 19 g/km, or 13%, at 100 g/km the gap is 29 g/km, or 29%.

6.1.8 *Recording vehicle mileages*

Traditionally, mileages were recorded by the garages at the annual check-up of the vehicles to detect tampering with odometers in second hand sale. Recently, tampering with the odometer has been forbidden by law, the database of recordings of successive mileages is part of the Dutch road authority (RDW), who supplies this data to the National Bureau of Statistics. Hence, for all vehicles in the Netherlands there are accurate recordings of the annual vehicle mileages.

6.1.9 *National Statistics*

The Dutch sales tax and road tax system makes it more expensive to own a car than to drive a car. This is particularly the case for new cars and for diesel cars. This drives up the annual mileages for these cars. Once the car gets older, petrol cars are sold to owners who do lower mileage, while diesel cars are exported in large numbers. Hence, when monitoring the fuel consumption of new cars, it should be noted that new cars drive a large share of the total distance driven by all cars in the Netherlands. In the first five years cars drive about half the total distance of their lifetime. Hence, they are more often in business use, and they are likely to drive more distance on the motorway than the Dutch average.

Larger cities discourage the use of cars for urban driving, through parking fees, restricting city thoroughfare and banning cars from inner-city areas. It is however unclear whether this has led to a shift in the urban, rural, and motorway distribution of average vehicle usage.

6.1.10 *Artemis*

In the past, one large European project was carried out to examine real-driving emissions. This led to the design of the Common Artemis Driving Cycle. Currently, it is the most-used driving cycle for real-world emissions in Europe. Also manufacturers use this cycle to optimise emission technology while developing new vehicles.

The cycle exists in two variants: the 130 km/h version and the 150 km/h version. Moreover, a complex vehicle evaluation exists to determine the appropriate real-world gear-shift points, which typically lie at a higher velocities than the NEDC fixed gear-shift points.

The Artemis cycle is considered to be more sportive than common European driving.

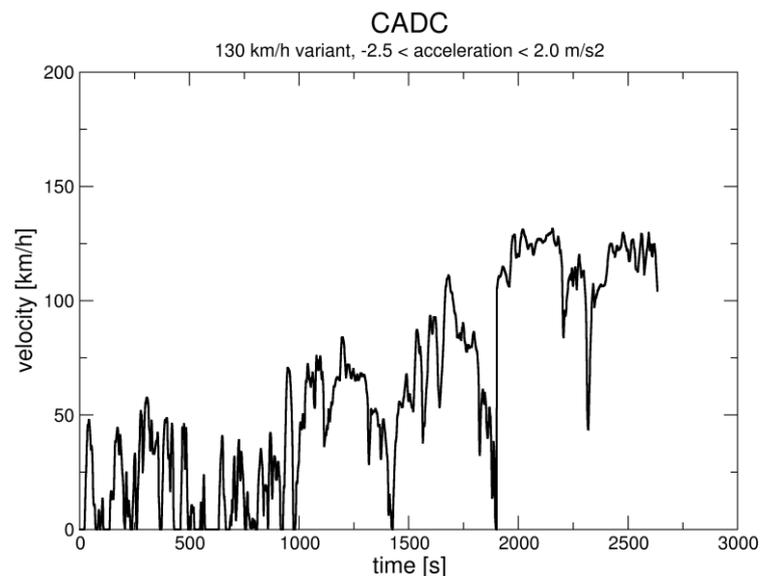


Figure 42 CADC driving cycle (only the parts included in the emission sampling, excluding the intermediate data).

6.1.11 *Spritmonitor data*

6.1.12 *Spritmonitor.de validation results*

Since the regression coefficients presented in sections 5.2.1.1 through 5.2.1.4 are based on Dutch company car data from Travelcard, the regression models were also applied to Spritmonitor.de data to assess their external validity. Since the Spritmonitor.de dataset predominantly consists of cars registered in Germany, applying the regression models to Spritmonitor.de should provide some indication of the applicability of the models outside of the Dutch vehicle market. Vehicles registered on Spritmonitor.de tend to have more powerful engines and higher type-approval CO₂ emissions than Travelcard vehicles (see Table 11 and Table 12). Moreover, Spritmonitor.de diesel vehicles are approximately 130 kg heavier and have a 5% larger width times height than Travelcard diesel cars. These

dissimilarities reflect differences between the new passenger car markets in Germany and the Netherlands: German passenger cars tend to be heavier, larger, and more powerful at the expense of higher type-approval CO₂ emission values (Mock, P., 2014).

Table 12 Summary of vehicle characteristics for Spritmonitor.de data, build years 2013-2014.

	Fuel	Mass [kg]	Area [m ²]	V _{max} [km/h]	Power [kW]	UDC [g/km]	EUDC [g/km]	NEDC [g/km]
Mean	Petrol	1270.1	2.63	-	95.6	163.1	108.9	128.6
	Diesel	1525.7	2.78	-	105.6	151.3	111.2	125.8
SD	Petrol	203.5	0.237	-	28.7	29.4	18.9	22.4
	Diesel	175.1	0.171	-	38.6	28.3	14.5	19.2

The original regression coefficients were first utilized to predict real-world CO₂ emissions for Spritmonitor.de vehicles built in 2013 or 2014. Figure 43 presents the predicted values (regression model output) and observed values (Spritmonitor.de) for individual vehicle model variants and plots them over type-approval values. The model considering mass, frontal area, power, and the combined NEDC type-approval values yields the most accurate predictions and accounts for 59% of the variance in real-world CO₂ values of petrol cars and 52% of the variance for diesel vehicles. Since data on vehicles' maximum velocity was missing from the dataset, the fourth regression model was not assessed. Moreover, the driving behaviour in Germany will be different with less motorway distance, but at a higher vehicle velocity on the motorway.

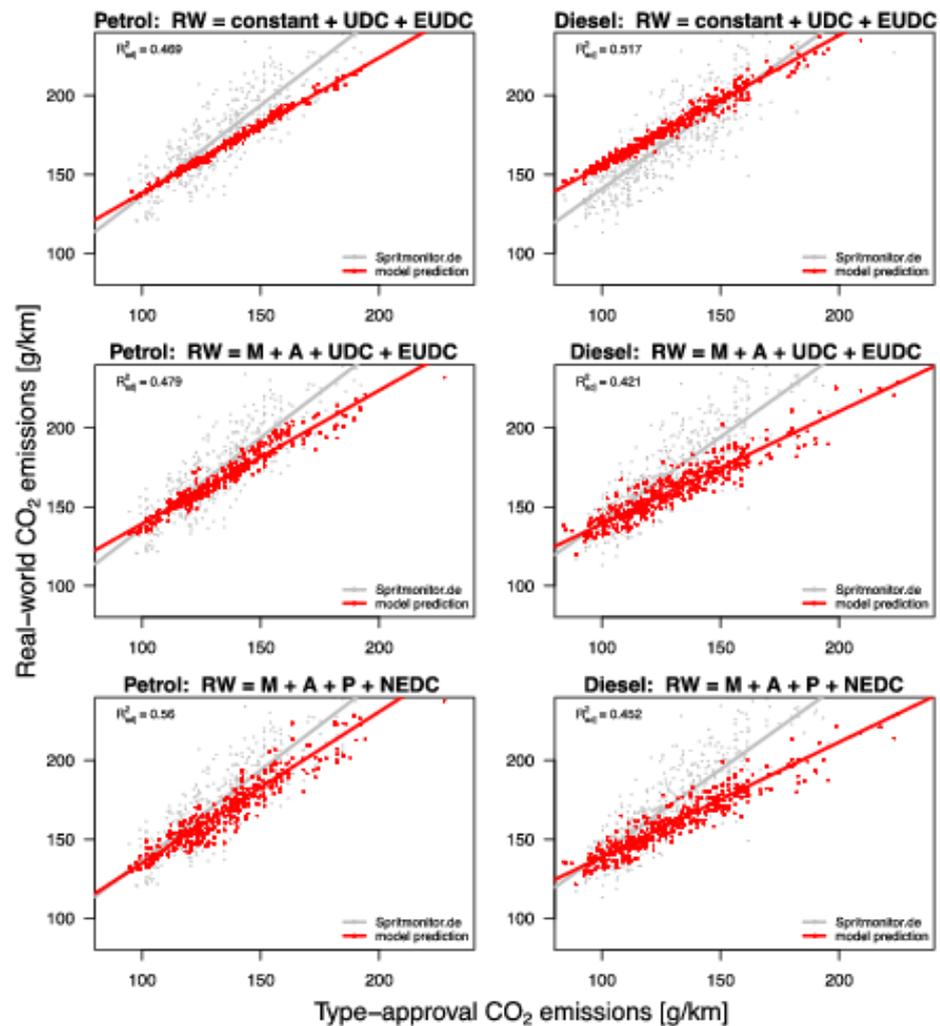


Figure 43 Comparison of Spritmonitor.de observations (build years 2013-2014) and model predictions based on original regression coefficients (number of petrol vehicles \approx 6,000, number of diesel vehicles \approx 7,000). Data points represent individual model variants registered on Spritmonitor.de while lines of best fit give an indication of the trend in the data. Adjusted coefficients of determination are presented in top-left corner of each regression model.

While the foregoing validation results were used to determine the original regression coefficients, these coefficients were recalculated based on Spritmonitor.de data to investigate whether the relationship between the regressors and real-world CO₂ values is different for Spritmonitor.de than for Travelcard. Table 13 presents the coefficients and summary statistics for the regression models. All regressors were found to be significant at a level of 5%. Comparing regression coefficients from this analysis with coefficients presented in sections 5.2.1.1 through 5.2.1.4, Spritmonitor.de data seems to suggest that mass is more influential for German cars, as witnessed by considerably higher regression coefficients in the Spritmonitor.de analysis. In contrast, the vehicles' box area has less impact on real-world CO₂ emissions in Spritmonitor.de data, at times even reaching negative regression coefficients.

Table 13 Regression coefficients and summary statistics for regression analysis with Spritmonitor.de data. Asterisks indicate level of significance (***: p-value \leq 0.001, **: p-value \leq 0.01, *: p-value \leq 0.05).

Regression coefficients (and standard error)						
Regressor	Petrol			Diesel		
	9.6.1	9.6.2	9.6.3	9.6.1	9.6.2	9.6.3
UDC	0.423*** (0.0238)	0.274*** (0.0254)		0.126*** (0.0203)	0.0469* (0.0197)	
EUDC	0.789*** (0.0464)	0.679*** (0.0523)		1.12*** (0.0315)	0.811*** (0.0344)	
Mass		0.0597*** (0.00222)	0.0198*** (0.00247)		0.0530*** (0.00172)	0.019*** (0.00204)
Area		-9.41*** (1.15)	14.8*** (1.14)		-3.32*** (0.816)	11.2*** (0.833)
Power			0.306*** (0.0107)			0.305*** (0.0109)
NEDC			0.601*** (0.0196)			0.609*** (0.0157)
Intercept	14.2*** (2.13)			25.1*** (1.36)		
Summary statistics						
	Petrol			Diesel		
	9.6.1	9.6.2	9.6.3	9.6.1	9.6.2	9.6.3
SER	20.3	19.2	18.1	19.3	18.2	17.5
R²_{adj}	0.570	0.616	0.661	0.620	0.662	0.690
N	6141	6141	6141	7343	7343	7343

In addition to predicting real-world CO₂ emissions of vehicles built in 2013 and 2014, the original regression models were also applied to time-series data from Spritmonitor.de. Figure 44 presents the annual averages of predicted and observed real-world CO₂ emissions. The regressors in the models account for approximately 60% to 65% of the variance in observed real-world CO₂ emissions of petrol vehicles, but are far worse at predicting real-world emissions of diesel vehicles.

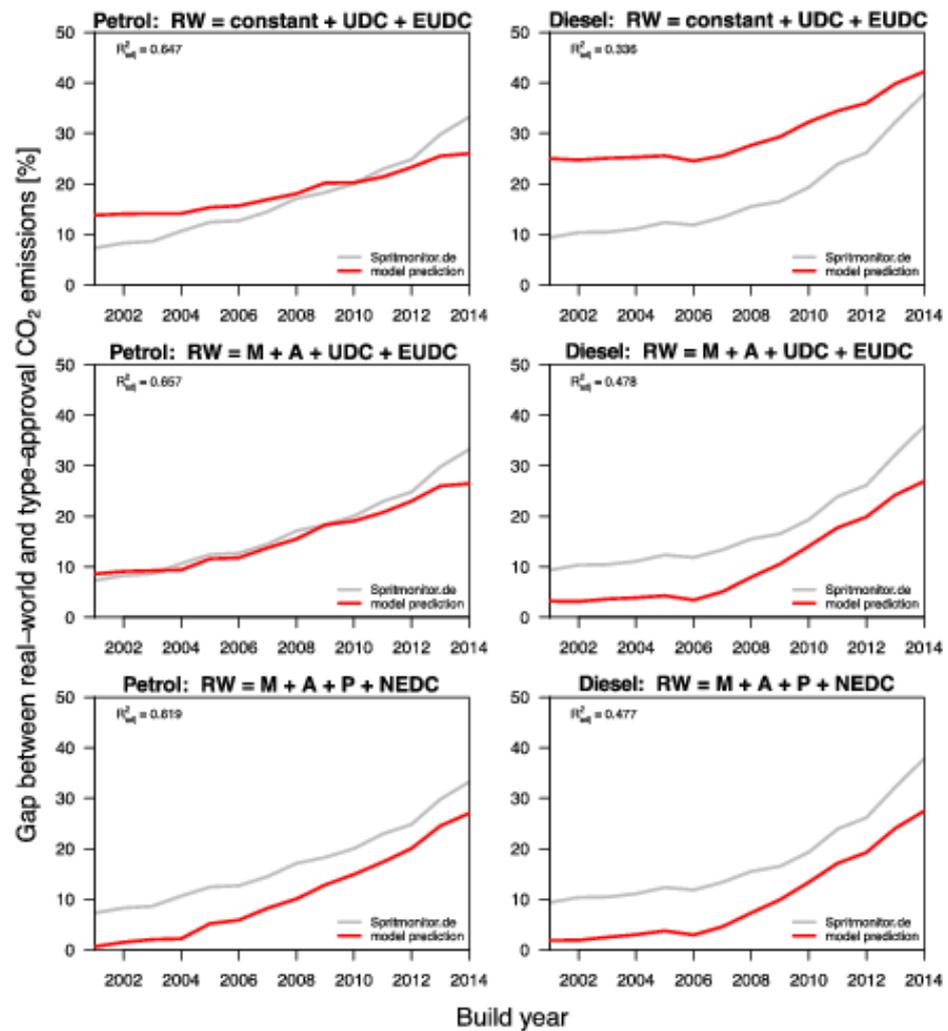


Figure 44 Comparison of annual estimates of the gap based on Spritmonitor.de observations (build years 2001-2014) and model results using Travelcard BV regression coefficients (number of petrol cars \approx 56,000, number of diesel cars \approx 62,000). Adjusted coefficients of determination are presented in top-left corner of each regression model.

6.1.13 Leaseplan validation results

In addition to Spritmonitor.de data, real-world CO₂ emissions data from Leaseplan were employed to assess the regression models. Real-world fuel consumption data for approximately 200,000 German company vehicles were made available by LeasePlan, a leasing and fleet management company of Dutch origin. Out of this dataset, 24 common model variants, representing more than 21,000 individual vehicles, were selected for the analysis. Since the LeasePlan dataset primarily consists of diesel vehicles, this data could not be used for petrol vehicles. Vehicles in the LeasePlan dataset are approximately 190 kg heavier than diesel vehicles in the Travelcard dataset (see Table 14). Similarly, vehicles in the LeasePlan subset are larger (+ 0.09 m² box area), faster (+ 16.5 km/h maximum velocity), and more powerful (+ 24.2 kW engine power), at the expense of type-approval CO₂ emissions, which are 7.8 g/km higher on average.

Table 14 Summary of vehicle characteristics for LeasePlan data from the 2013-2014 fleet.

	Fuel	Mass [kg]	Area [m ²]	V _{max} [km/h]	Power [kW]	UDC [g/km]	EUDC [g/km]	NEDC [g/km]
Mean	Diesel	1580.5	2.74	209.0	106.8	151.4	109.5	123.4
SD	Diesel	117.4	0.133	13.3	22.0	12.0	10.0	10.5

The four regression models presented in sections 5.2.1.1 through 5.2.1.4 were applied to the LeasePlan data using the original regression coefficients. While the first model captures a portion of the variance in observed real-world CO₂ emissions ($R^2_{adj} = 41.2\%$), the other regression models have negative or near zero coefficients of determination. In general, the original regression models underestimate real-world CO₂ emissions compared to LeasePlan observations. When model coefficients are calculated from the LeasePlan data, the coefficients of determination increase to approximately 50%. Comparing the regression coefficients between the original models and the values in Figure 45 illustrates that type-approval CO₂ values and mass are significantly higher when the regression coefficients are estimated from LeasePlan data, while the impact of box area regressor decreases.

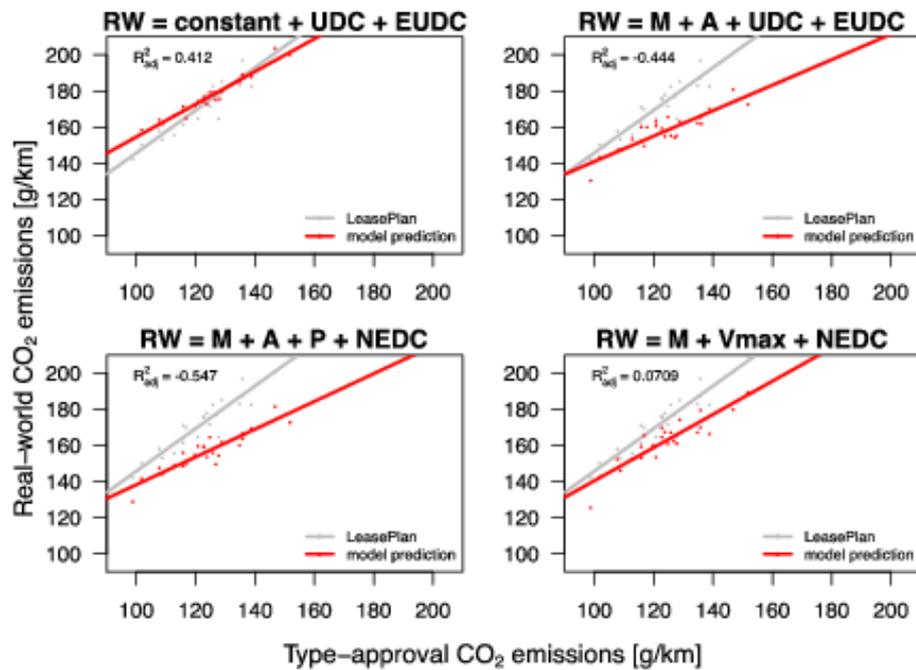


Figure 45 Comparison of LeasePlan observations (years 2013-2014) and predicted values for 24 vehicle model variants using Travelcard regression coefficients (number of diesel cars ≈ 21,000). Data points represent model variants from LeasePlan while lines of best fit give an indication of the trend in the data. Adjusted coefficients of determination for each regression model are presented in the top-left corners.

Table 15 Regression coefficients and summary statistics for regression analysis with LeasePlan data.

Regression coefficients (and standard error)				
Regressor	Diesel			
	9.6.1	9.6.2	9.6.3	9.6.4
UDC	0.290*** (0.0134)	0.221*** (0.0127)		
EUDC	0.910*** (0.0161)	0.708*** (0.0177)		
Mass		0.0474*** (0.00109)	0.0307*** (0.00129)	0.0204*** (0.00137)
Area		-4.64*** (0.456)	3.86*** (0.533)	
Power			0.121*** (0.00639)	
NEDC			0.819*** (0.0142)	0.851*** (0.013)
V _{max}				0.172*** (0.00748)
Intercept	29.6*** (1.16)			
Summary Statistics				
Regressor	Diesel			
	9.6.1	9.6.2	9.6.3	9.6.4
SER	13.4	13.0	12.9	12.9
R ² _{adj}	0.452	0.483	0.489	0.493
N	21229	21229	21229	21229

6.2 Observations regarding monitoring data

6.2.1 Comparison of the model fits

There are some unexpected differences between the different model fits. The type-approval data appears more appropriate for the prediction of real-world fuel consumption of Spritmonitor and Leaseplan than it is for Travelcard. The fit coefficients for the NEDC are larger, hence the type-approval and real-world fuel consumption correlate better. However, it is considered very relevant, the UDC has limited relevance for diesel vehicles in all cases. The Travelcard vehicles are slightly smaller and lighter, but rather lower powered. This may in part explain the difference in the model fits.

The different fit parameters cover similar aspects as they are all related to fuel consumption. Hence, it is the distinguishing features of a given parameter which causes a strong correlation. The complexity lies in the fact that vehicle properties and also vehicle usage differ between the different sets. In particular, it is most likely that the differences between German and Dutch data are best explained by the limited rural driving in the Netherlands, due to the high density of motorways in The Netherlands. Moreover the higher motorway velocities in Germany may also affect this result. For a majority of the Dutch people the nearest motorway is less than 10 kilometres away. This may explain the limited relevance of the UDC figure from type-approval test result for Travelcard data. Apart from that, the gap exists for

all datasets, and the strong dependence on vehicle characteristics is in line with the growing gap related to the increase in size, mass, and power, and a decrease in type-approval values. That is, a fuel efficient fleet, like in the Netherlands, will also be ahead on the growing gap.

6.2.2 *Conjectures and hypotheses for the gap*

6.2.2.1 *UDC is irrelevant for real-world fuel consumption*

The urban part of the type-approval test cycle, the UDC, reflects very low engine load and has a large amount of idling. Consequently, the emissions are high and mainly related to the engine losses. In the combined type-approval value it accounts for 36% of the average (4 out of 11 kilometres). On the other hand, the urban test has the highest CO₂ emission gap with real world (37%) versus 28% for the extra-urban part. If the urban part was discounted in the type-approval and only emissions reductions on the EUDC are used, the EUDC-real-world gap would reduce by 4%.

Moreover, the model fit of real-world data also shows the minor correlation of the urban part on the outcome. Hence, the reductions on the UDC show only a minimal effect on real-world fuel consumption. Consequently, the CO₂ reductions on the UDC test contribute implicitly to the increasing gap.

6.2.2.2 *The real-world velocity is higher*

Indeed, the strong and consistent dependence of the gap on frontal area is a strong indication that the velocity has a significant effect. This is confirmed by the typical fraction of the distance travelled and the average velocity on the motorway. Assuming a 500 N air drag force at 100 km/h, an increase in the $(\langle v^2 \rangle)^{1/2}$ from 60 km/h to 100 km/h would mean an increase in average air drag of 180 N. This corresponds to 36 g/km difference, which is substantial. This is for a large extent compensated in the test by lower engine losses per kilometre at this higher velocity, given the 40% reduction of engine operation time, from 60 to 36 seconds.

Moreover, the air drag is underestimated on the type-approval test, through the absence of wind, the higher temperature, and the overall idealized conditions and vehicle preparation. However, with a limited air drag contribution on the test of 320 N, a reduction of 10% in air drag from idealized air drag determination would result in a 32 N force reduction, associated with an additional 6 g/km reduction.

This difference in velocity explains a large but fixed gap, between the NEDC and real-world fuel consumption. In essence this gap has always been there, but was partly masked by higher fuel consumption on the NEDC test like the UDC and the cold start. The CO₂ reduction due to technological improvements on the overshoot on these parts with limited real-world consequences bring the gap due to velocity differences to light.

6.2.3 *Test flexibilities are exploited more*

The sudden drop in type-approval values mainly since 2008 were not accompanied by large physical changes of the vehicles. It could indicate a change in the approach to testing or new technology deployed. Slightly later, a change in diesel vehicle characteristics, i.e., small diesel engine available from Euro-5, was correlated with a further drop in type-approval CO₂ emission. The spread in type-

approval values and test results seems to indicate a 10 to 12% flexibility in the test execution on the chassis dynamometer and another 5% for the road-load test. This is separate from the vehicle weight, test-track slope, and tyre selection and preparation. At the same time, these effects are estimated at 20% of the rolling resistance based on independent road load testing. Air-drag is mainly affected by wind and ambient temperature.

The further selection and preparation of the vehicle on both the road load test and the chassis dynamometer test, i.e., though tyre preparation, weight reduction, battery charging, DPF blow-out, etc., are aspects which lie at the boundary of acceptable optimisation of the test results.

6.2.4 *Increasing engine power is causing higher real-world fuel consumption*

The increase in engine power seems to be one of the driving forces for the increase in fuel consumption. The drivability of the vehicle, and possibly a different driving style may also affect the fuel consumption. This seems to be separated from the low load operation on the test. Plug-in vehicles are a good example of this split in engine operation in relation to vehicle use: A low power use on the test, typically with electric support, and a high-power use on the road, especially during motorway driving. It does not yet explain the gap because of the limited fraction in the total fleet.

The losses used to be proportional to the engine size. To a large extent, the type-approval data does still show this. But the increase in power, and the reduction in type-approval emissions, particular on the UDC part, seems to indicate that the engine power and the losses are more and more decoupled, for example through turbo and adjustable vanes. Hence, the answer lies probably in specific, type-approval optimisation of the engine for low engine load operation.

6.2.5 *Technological features designed solely for the type-approval test*

Stop-start systems, battery sizes in plug-in hybrids and many other aspects seem to be designed mainly for low type-approval CO₂ emission. In real-world conditions they play only a minor, or a different, role. These factors can be grouped together under very low load optimisation, where engine losses completely dominate the total emissions. This somehow anticipates the driving cycle and vehicle operation on the test. Other aspects, such as VVT (Variable Valve Timing) do also have some low load benefit, but are not solely designed to reduce emissions when idling and during the UDC part.

6.2.6 *Trends 2001-2014*

In the period 2004 to 2014, the Travelcard gap between type-approval and real-world fuel consumption has increased from 8-15% to more than 40%. Also in absolute terms the increase is substantial. Where in 2004, the additional CO₂ in real-world driving was 15 g/km, in 2014 the value is close to 50 g/km.

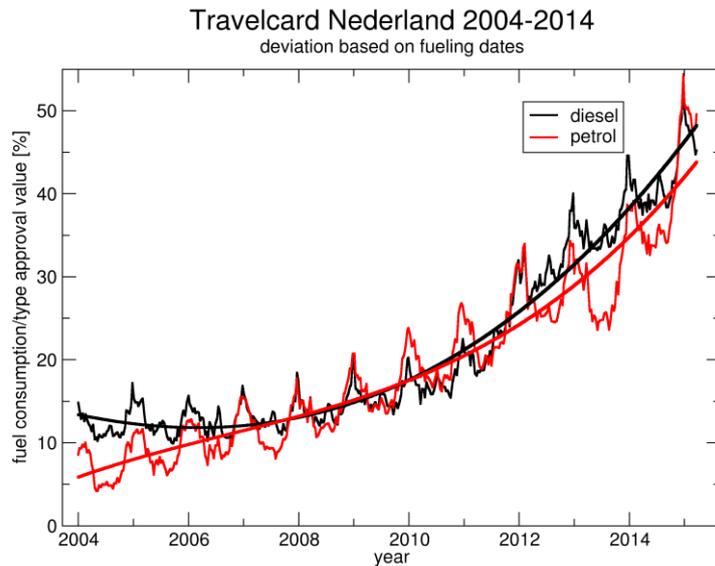


Figure 46 The additional fuel consumption of modern cars expressed in terms of their type-approval value.

The use of such a time series allows the separation of different aspects. For example, seasonal influences are very clearly depicted in Figure 46. However, such effects cannot be determined before the underlying increase in fuel consumption is singled out. If the fuel consumption is expressed for each vehicle with respect to the average fuel consumption, the seasonal variation is even more clear, as shown in Figure 47. For petrol vehicles, the seasonal variation is about 10%, excluding the peaks from the holiday seasons. For diesel vehicles, the variation is marginally smaller. In the period 2012 to 2013, a higher winter fuel consumption is seen followed by a lower fuel consumption in the summer. Clearly, in this period some uncommon effects were captured. As cars are typically only leased for 2-4 years, effects that span longer periods are not detectable in this data.

The major correlation is with temperature. As described before, many aspects depend on temperature: air drag, cold start, etc.. These can all be related back to the ambient temperature. If the temperature is correlated against the seasonal variations in fuel consumption, a strong correlation exists. On simple physical grounds, such as air-density and warm-up times assuming magnitudes proportional to the relative change with respect to the absolute temperature, a variation with temperature is to be expected in the range of $\Delta FC/FC \sim \Delta T/284$ or 0.35% per degree given the average temperature in the period 2004 to 2014 of 10.5° C,. The effects found are somewhat larger. See Figure 48. For petrol, 1° C difference in temperature accounts for 0.4% change in fuel consumption, for diesel the effect is a change of 0.5%.

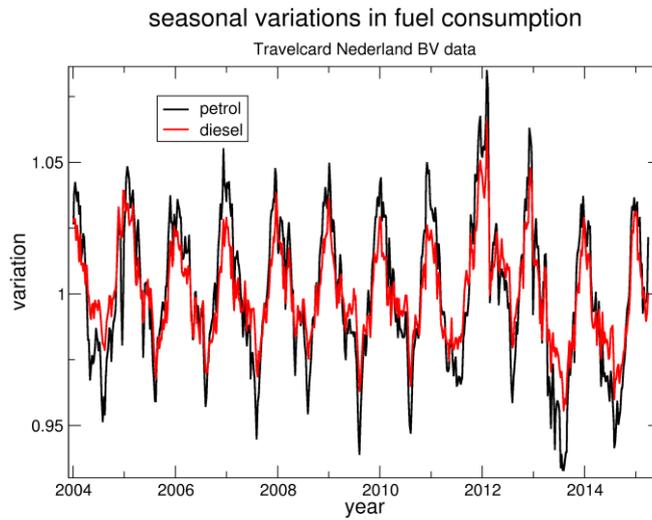


Figure 47 The seasonal effects, separated from the trends with the changing fleet and technology.

Due to laboratory temperature of 25° C and an ambient temperature of 10.5° C, the expected additional real-world fuel consumption is 6% and 8% for petrol and diesel respectively. This temperature effect lumps together several effects. The air drag dependency on air density is one, the cold start contribution is another. But there is a long list of aspects of vehicle operation and fuel consumption related to temperature including the fact that the lower annual mileages of petrol car would yield a higher cold start effect, but, on the other hand, a smaller motorway air-density effect.

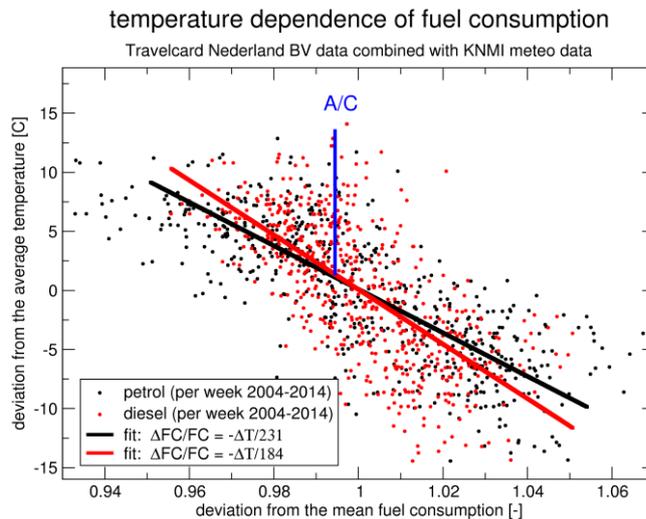


Figure 48 The anti-correlation between temperature and fuel consumption. Some reduced efficiency gain above 15° C average daily temperature may be related to air-conditioning use.

Surprisingly, the effect of air-conditioning, which may be expected at temperatures above 20° daily-average, seems difficult to be difficult to identify in the data. Very

likely, the minor data cluster in Figure 48, at $y = 0.99$ and $x = 10^\circ \text{C}$ above average is related to air-conditioning usage, limiting the positive effect of high temperature to 1% to 2% for a limited time average day temperatures above 20°C occur. Hence the effect is fully compensated by the reduction of air-drag from lower air density.

6.2.7 Other annual variations

With the temperature effect singled out, one can investigate the residual effects, which are smaller and by far not as consistent as that between fuel consumption and ambient temperature.

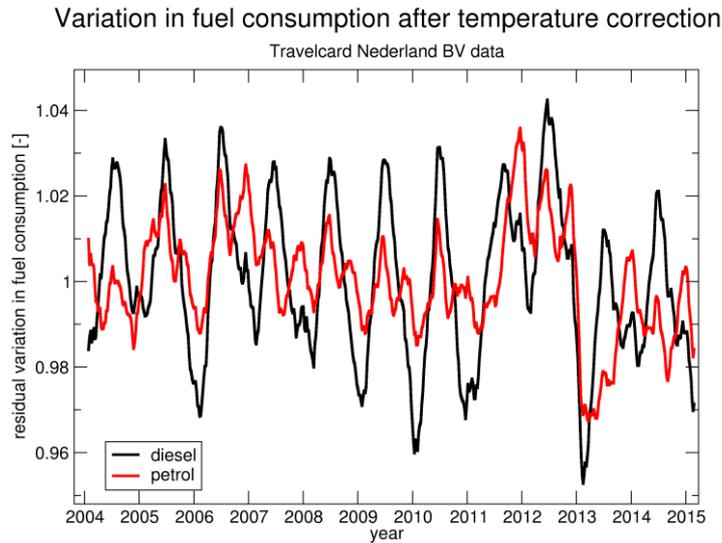


Figure 49 The residual variation in fuel consumption, once the direct temperature effect, by using the fit in Figure 48 with the week-average temperatures is removed. Diesel still seems to have an annual variation. Petrol appears as a variation of double periodicity.

Some seasonal variations are not directly linked to temperature. For example, the switch from summer to winter fuel and vice versa. The remaining effects are in the order of 1 to 2%, averaging over the annual variations for the period 2004-2014. Some further minor effects appear. Other annual variations do not keep trend with the seasons. In the case of diesel, the minimum is in February and the maximum in June.

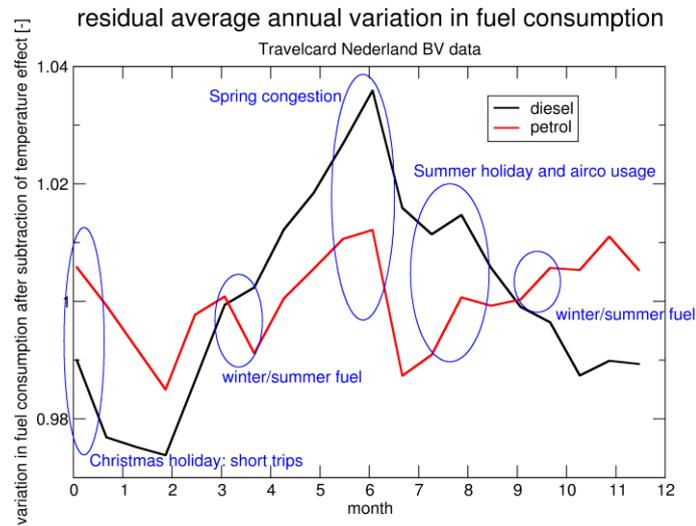


Figure 50 The annual variation unexplained by the temperature effect, by averaging over all the years 2004 to 2014.

In particular petrol cars seem to show an offset for the summer period with respect to diesel. Very likely this is related to the caloric value of winter petrol. The additional fuel consumption recorded in the Christmas holidays is likely be the result of short trips.

6.2.7.1 Weather

Apart from the major effect of ambient temperature on air drag and the severity of cold start effects, precipitation will affect the rolling resistance and tyre temperature and pressure if, in case the road surface is covered by water or snow. Typically, the vehicle velocity is lower in such cases, but at moderate velocities precipitation is likely to lead to an increase in fuel consumption.

Given a very simple assumption of 2 mm of water on the road, the displacement of the water by four wheels each 20 cm wide at a velocity of 20 m/s (72 km/h) is 1.6 m³ water displaced per kilometre with a force of 320 N, associated with 64 g/km CO₂.³⁰ The numbers may differ in reality, but the order of magnitude indicates a substantial effect. A person driving through a puddle will note the force on the wheels dependent on the vehicle velocity.

6.2.7.2 Holiday periods

Holiday periods are typically associated with more variation in trips: long trips to the holiday destination and short day trips, more weight in the vehicle due to passengers and luggage. It is also likely to be associated with the use of air-conditioning and other auxiliaries, and the use of roof racks, pulling of trailers and caravans. Hence one would expect a much higher fuel consumption in this case. This is, however, not visible in the fuel consumption data already for these holiday

³⁰Four wheels of 20 cm wide over 1 kilometre driven produce an area of 800 m². With the thickness of 2 mm, the total volume is 0.002*800 = 1.6.m³. Driving this water away with the same velocity as the car, yields a total kinetic energy of 1/2 * 1600 * 20² = 0.32 MJ. This a rough estimate, but shows the magnitude of the effect.

periods. Only a minor effect in the typical holiday months July and August is visible, even after correcting for the positive effect of the higher temperatures.

6.2.8 *Manufacturers*

The evidence of a growing gap between real-world and type-approval CO₂ exists for all manufacturers. When split by manufacturer, it shows that some followed this trend in 2006 and some manufacturers show an absolute increase only from 2009.

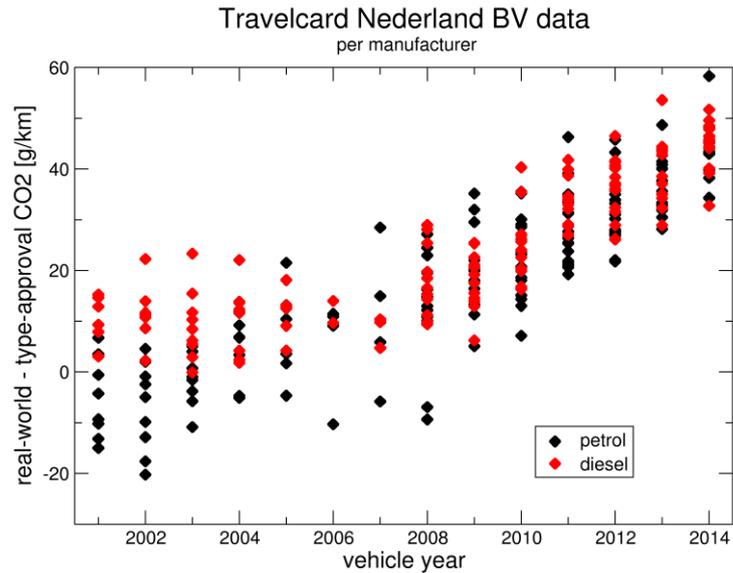


Figure 51 The absolute gap between type-approval and real-world CO₂ emission per manufacturer (not manufacturer group, combinations with at least 150 vehicles per data point). As of 2009, all manufacturers follow the same trend upwards.

For Spritmonitor.de, the results are slightly different, however, the same trend can be observed.

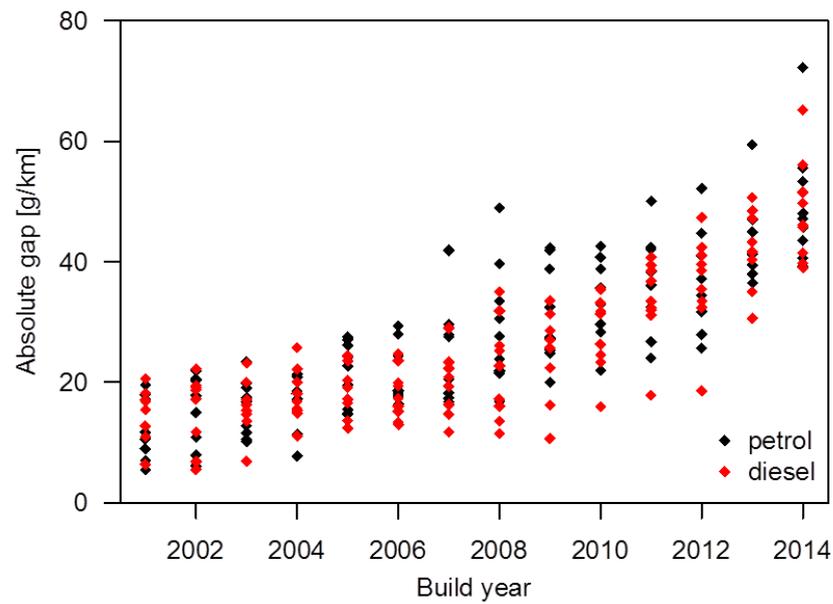


Figure 52 Absolute difference between real-world and type-approval CO₂ emission values based on Spritmonitor.de for a number of manufacturers. Each data point represents a manufacturer-fuel combination.

Figure 52 presents the absolute difference between real-world and type-approval CO₂ emissions according to Spritmonitor.de for a number of manufacturers. The graph shows a relatively uniform clustering of values around 15 g/km between 2001 and 2007, followed by a rapid increase in the mean and variance of the absolute gap between 2008 and 2012. In the most recent years, the observed variance decreased as manufacturers uniformly moved past an absolute gap of 35 g/km.

7 Other jurisdictions - Real-world CO₂ emissions of passenger cars in the U.S. and other jurisdictions

7.1 The 'gap' for the U.S. vehicle fleet

In order to arrive at a better understanding of the divergence between type-approval and 'real-world' CO₂ emission levels of new vehicles in the U.S., an analysis of available statistics was carried out. The U.S. Environmental Protection Agency (EPA), in cooperation with the U.S. Department of Energy (DOE), maintains the website fuelconomy.gov to allow consumers to inform themselves about the fuel efficiency and emissions of current and historic vehicle models. In addition, the website offers the possibility for users to register and provide their own real-world fuel efficiency experience for a particular vehicle model (a section called 'MyMPG'). In that sense it is similar to European websites, such as Spritmonitor.de or honestjohn.co.uk, except that fuelconomy.gov is hosted by government agencies. For the time period 2000 to 2015, the website includes about 80,000 registered vehicles. The raw data for these vehicles was obtained from Oak Ridge National Laboratory. For entering fuel efficiency data, fuelconomy.gov offers three different options:

- 1 users can enter the fuel consumption rate (in miles per gallon) directly;
- 2 users can set-up a list of individual fuelling events and the mileage travelled between fuelling events, and;
- 3 users can report odometer readings and the respective amount of fuel purchased between each odometer reading.

Before analyzing the data, the individual user entries were filtered to ensure that only plausible entries were included in the final dataset. The real-world MPG (miles per gallon) figures were converted into CO₂ emission equivalents and linked to the official (type-approval) CO₂ data for each vehicle model. The final dataset includes data for about 35,000 vehicles.

Figure 53 summarizes the divergence between official and real-world CO₂ emissions, both for the unadjusted test value and the adjusted label value for the U.S. new vehicles' fleet. For the U.S., it is important to distinguish between 'unadjusted' test results and 'adjusted' label values. The unadjusted test results are communicated by vehicle manufacturers to the authorities and are the basis for the vehicle CO₂ regulation in the U.S.. Similar to the EU, the real-world figures reported by vehicle drivers are – on average – about 40 percent higher than suggested by the official test results. However, the increase of the gap in recent years is smaller than in the EU. Between model year 2000 and 2015, the gap approximately doubled in the U.S., from about 20 percent to 40 percent, while over the same time period a fivefold increase in the EU was observed, going from about 8 percent in 2001 (equals model year 2000) to about 40 percent in 2014 (equals model year 2015).

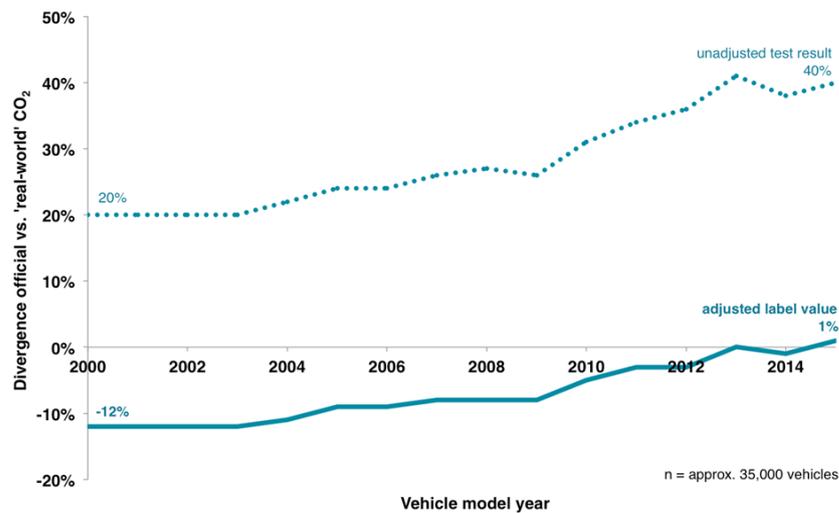


Figure 53 Divergence official versus 'real-world' CO₂ emissions for the U.S. new vehicle fleet (ICCT analysis based on fueleconomy.gov data).

Looking at the adjusted label CO₂ data, the picture is very different. These are the figures reported to vehicle buyers in the U.S., taking the unadjusted chassis dynamometer test results and applying a real-world adjustment factor. While there can also be seen an increase in the gap for these adjusted label values, they nowadays very accurately reflect the on-road driving experience of average customers. Note that the increase in the gap is only 13 percent for the adjusted label values, compared with 20 percent for the unadjusted test values. This is because the label adjustment formula increases the percentage adjustment as CO₂ emissions go down, resulting in larger average adjustments as vehicles become more efficient. Based on the fueleconomy.gov data it can be concluded that the real-world CO₂ emission level of new vehicles in the U.S. is only about 1 percent higher than suggested by the data provided to consumers on the vehicle labels.

7.2 The U.S. vehicle emissions testing and compliance program

Before the Clean Air Act (CAA) was passed in 1970, the vehicle compliance program in the U.S. was very similar to the current EU program and only covered prototypes for new vehicle certification. The CAA changed that, adding authority for the Environmental Protection Agency (EPA) to ensure that all vehicles coming of the assembly lines meet the respective standards. It also authorized the EPA to hold manufacturers responsible for vehicles meeting standards throughout their useful lives, provided that customers properly maintain them. Lastly, the CAA required manufacturers to warrant individual emissions control components on vehicles to protect consumers. Over the years, the EPA compliance program has thereby grown and evolved from one that focused mainly on verifying that prototype and new production vehicles comply with standards to one that places strong emphasis on in-use testing and durability to ensure that emissions standards are met over the useful life of a vehicle.

Figure 54 provides a graphical overview of the U.S. compliance program. Vehicles that have similar design and emission characteristics (e.g., similar engine displacement, cylinder number, arrangement of cylinders, and combustion

chambers) form a 'test group'. Manufacturers select a prototype vehicle for testing that is representative of the production line vehicle. Out of its test group, the tested vehicle is expected to deliver the highest emission levels and the highest increase in emissions over time or, in the case of CO₂, the focus is put on the highest selling vehicle configuration, including the highest selling tyres.

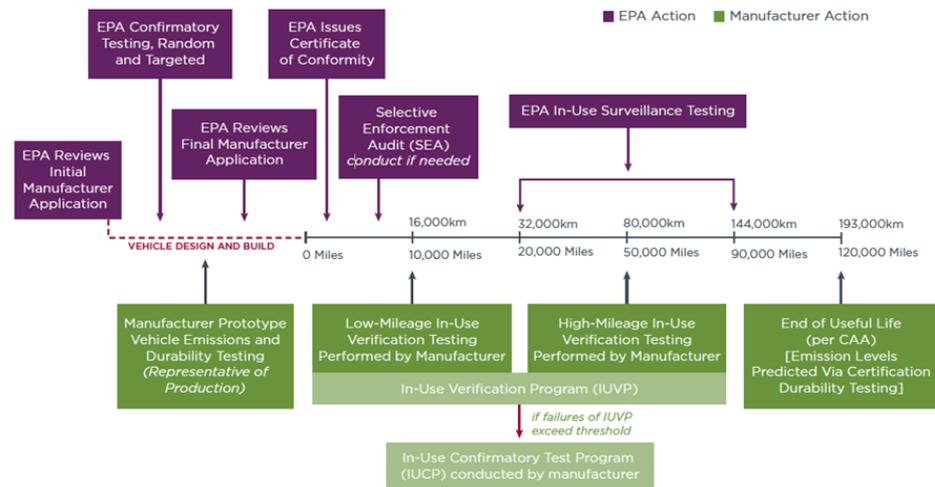


Figure 54 Compliance program for light-duty vehicles

The vehicle is tested by the manufacturer on a laboratory chassis dynamometer. The Federal Test Procedure (FTP) and the Highway Fuel Economy Test (HWFET) is used to measure CO₂ emissions. The manufacturer then submits the results to EPA, where the manufacturer's test data is reviewed and eventually additional confirmatory tests are carried out to validate the results before issuing a Certificate of Conformity.

The vehicle testing program also extends to in-production and in-use. The in-production test program is called Selective Enforcement Audit (SEA) and enables EPA to test vehicles that are drawn from the production line to test compliance with the Certificate of Conformity. This process helps to assess early on whether the prototype vehicle's specifications are in accordance with vehicles that are produced and delivered to customers. The in-use vehicle testing program is called In-Use Verification Program (IUVP) and requires manufacturers to conduct laboratory tests of in-use vehicles drawn directly from the road. The test is conducted at low mileage (16,000 km) and high mileage (80,000 km). If 50 percent of the vehicles of a test group fail to meet emissions limits, the In-Use Confirmatory Program (IUCP) is initiated. Under the IUCP, more vehicles are selected and tested according to the confirmatory test. This process can lead to recalls and fines in case of failure. In addition to the tests mentioned previously, EPA has the right to carry out In-Use Surveillance Tests that focus on randomly-selected vehicles on the road. These tests can also be targeted at specific vehicles that are considered to require more testing. The chosen vehicles are recruited from their respective owners and it is ensured that they were properly maintained before testing their emission levels.

7.3 Comparing the EU and U.S. vehicle emissions testing schemes

Putting the EU and U.S. vehicle testing schemes side by side (Figure 55), it can be seen that the fundamental difference is not so much the actual vehicle testing itself, but the strong focus on independent conformity testing in the U.S. In the EU, on the other hand, this element of independent re-testing is largely absent from the respective regulations.

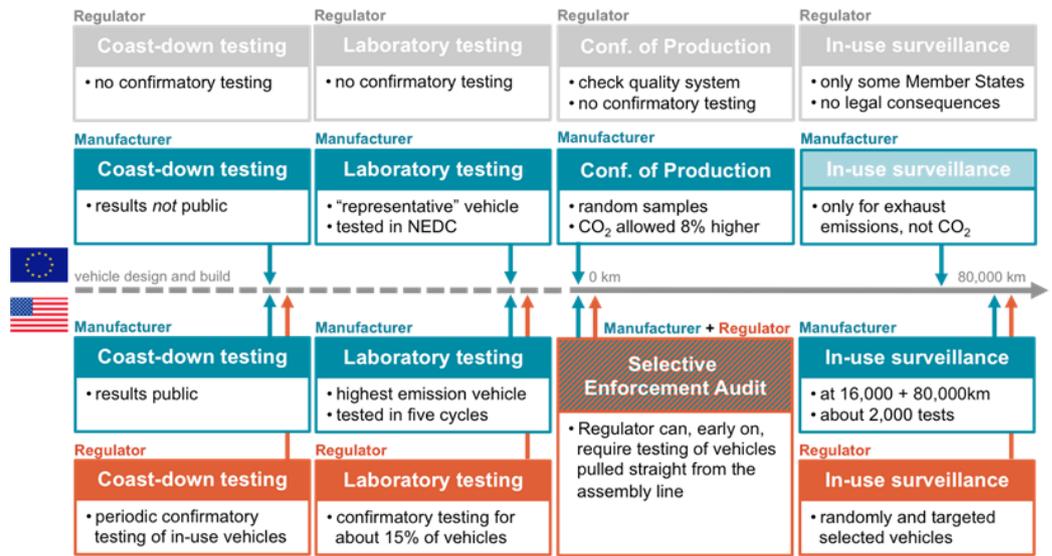


Figure 55 Overview of the EU and US vehicle emission test schemes (ICCT).

As can be seen from the figure, a persistent difference between the two regional schemes is the reliance of the European regulations on vehicle manufacturers when it comes to vehicle testing. In the EU, generally the manufacturer carries out its own vehicle tests, witnessed by a technical service company or – in some cases – the technical service company carries out the testing on behalf of the manufacturer. Independent confirmatory tests by the regulator (i.e. European Commission and/or EU member states) are not foreseen in the current EU system. In comparison, while most of the testing burden in the U.S. is on the vehicle manufacturer, the regulator (EPA) carries out – or at least has the legal and technical capacity to carry out – confirmatory tests for all the various steps:

- Before the actual vehicle emissions test in the laboratory, the manufacturer carries out **coast-down tests** on a specially designed test track to determine the road load coefficients that will then be used to simulate aerodynamic and rolling resistance of the vehicle on the chassis dynamometer in the laboratory. Both in the EU and in the U.S., vehicle manufacturers have to follow technical guidelines while carrying out these tests. For the U.S., EPA recently refined and clarified the procedures to be used when determining road load coefficients. For the EU, it is reported that the current road load determination procedure allows for a number of flexibilities that can be exploited to arrive at road load coefficients that are not representative of normal vehicles on the road anymore. It is impossible to carry out systematic comparisons between road load coefficients determined by vehicle manufacturers and those determined for the same vehicles by independent laboratories, as the type-approval road load coefficients are not publically

accessible in the EU - unlike in the U.S., where the road load coefficients for every vehicle model on sale can be accessed by anyone online .

Furthermore, in the U.S., EPA periodically carries out confirmatory coast down testing on in-use vehicles and in the past has forced vehicle manufacturers to correct misleading road load coefficients and even levied civil penalties in one case. In comparison, in the EU, once a vehicle manufacturer carried out a coast down test that has been witnessed by a technical service company, the results are neither published nor are they subject to confirmatory testing by any of the EU or Member State agencies.

- For the vehicle **testing in the laboratory**, using a chassis dynamometer, in the EU a ‘representative’ vehicle configuration (or – for exhaust emissions – the configuration with the highest emission level) is chosen. In the U.S., for exhaust emissions the configuration with the highest emission level is selected, while for CO₂ emission testing the highest selling vehicle configuration, including the highest selling tyres, is selected. The laboratory testing is carried out by the vehicle manufacturer, in the EU with a representative from a technical service company witnessing the type-approval laboratory test. While in the EU the vehicle is tested using the NEDC test protocol, in the U.S. the vehicle is tested on the FTP and highway cycles for CO₂ and in addition on the US06, SC03 and 20°F (-7°C) FTP tests for exhaust emissions. This U.S. 5-cycle approach thus covers a large spectrum of driving and ambient conditions. As reported by other sources, the NEDC laboratory testing procedure offers a number of flexibilities that can be exploited to achieve lower type-approval CO₂ emissions (Kadijk, et al., 2012). A major difference between the laboratory testing procedures in the EU and the U.S. is again with respect to the confirmatory testing. While independent re-tests by the authorities are not foreseen in the EU, in the U.S. EPA selects about 15 percent of vehicle models for carrying out confirmatory tests at EPA’s testing laboratories.
- For CO₂ and Corporate Average Fuel Economy (CAFE) compliance, manufacturers are required to test enough vehicle configurations to cover at least 90 percent of their actual production, using the same requirements for the highest selling tyres within each configuration. Although this means extra testing for manufacturers after the model year has been completed, it prevents manufacturers from only testing the configurations with the best fuel economy.
- To ensure **conformity of production** in the EU vehicle manufacturers are required to carry out emission tests on random samples taken from the assembly line. For CO₂, the emission level tested is allowed to be up to 8 percent higher than the type-approval level. From the authorities side, the respective type-approval agency checks whether there is an internal quality audit program in place within the manufacturer’s production facilities. Independent confirmatory tests are not foreseen in the EU. In the U.S., the Selective Enforcement Audit (SEA) program allows EPA to require testing of vehicles pulled straight of the assembly line, at the manufacturer’s expense, without prior notice.
- **In-use surveillance** exists in the EU only for pollutant emissions from the tailpipe, with the manufacturer being obliged to test – in the laboratory – every two years a sample of 3-20 vehicles per model family. None of the EU agencies carries out in-use surveillance testing. Some EU Member States have their own testing programs, but without any legal consequences for

manufacturers, if any deviations between test results and type-approval data is found. In the U.S., the regulator requires the manufacturer to carry out laboratory testing for 1-5 vehicles per model family every year, for low- and high-mileage. If significant deviations are found, more testing is required and in the worst case a recall of vehicles on the market can be initiated by the authorities. In addition to the manufacturer's testing, EPA also carries out its own in-use surveillance testing, with a randomly and targeted selected vehicle sample.

7.4 Policy implications

Implementing the World harmonized Light vehicles Test Procedure (WLTP) in the EU is expected to help reduce the gap between type-approval and real-world CO₂ emission figures. However, comparing the vehicle testing schemes in the EU and U.S., it can be concluded that the EU is currently missing an independent and effective vehicle conformity-testing scheme.

One element of such a scheme would be to release the vehicle road load test results of manufacturers into the public domain and to have the respective agencies carry out independent road load conformity tests. This is not only in place in the U.S., as explained above, but also in other jurisdictions, such as South Korea, where there is mandatory verification of road load coefficients by the government. Only if the manufacturer's road load results are within a certain tolerance band compared to the South Korean government's conformity test results can they be used as input for laboratory chassis dynamometer testing. Otherwise the road load coefficients determined by the government laboratories will be used .

Another element of an EU conformity-testing scheme would be re-testing on production vehicles to see if the CO₂ emission levels of these vehicles are in line with the manufacturer's test results for the pre-series vehicle that was tested for type-approval. As explained above, this is already standard practice in the U.S. for many years, with a combination of randomly and targeted vehicles selected for in-use testing by the authorities. Similarly, in South Korea vehicle conformity testing is standard practice, with 20-30 top selling vehicle models per year being re-tested by the government's vehicle testing facilities. Important in this context is also to ensure that the re-tested vehicles are representative of the vehicle fleet, as can be seen from the regulatory practice in the U.S.

Another striking difference between the EU and the U.S. is the use of a real-world adjustment factor for communicating fuel consumption and CO₂ emissions to customers in the U.S. As it was shown above, the values used for labelling and advertisement of new vehicles in the U.S. match very closely the real-world experience of an average customer. This is very different in the EU, where it should be considered to implement a similar real-world adjustment factor for better informing consumers' vehicle purchase choice.

8 Implementation of WLTP

The WLTP has a higher average velocity and higher driving dynamics, mainly at intermediate velocities, than the NEDC. As noted before, real-world driving contains more constant speed driving, with intermediate moments of higher dynamics, at changing velocity. A few stops and accelerations on the motorway will increase the fuel consumption significantly.

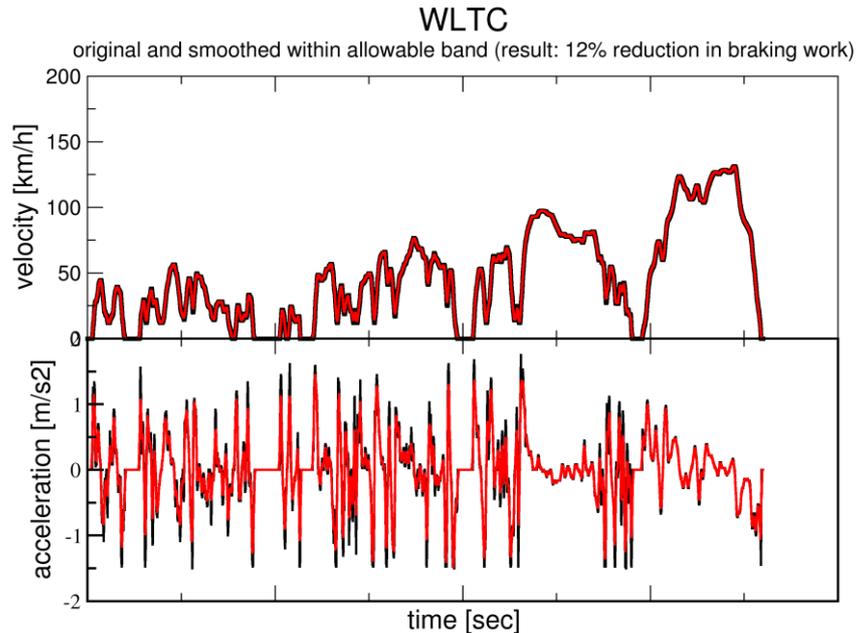


Figure 56 The WLTP velocity and acceleration allows in principle for smooth driving, lower acceleration and more brakeless deceleration which will substantially reduce the braking energy.

Hence the shift from NEDC to WLTP will increase the engine load and reduce the effect of engine losses. Based on the speed profile only, the absolute numbers can be similar for a vehicle optimised on the NEDC. This can be achieved via different means. For example a small and light vehicle will have limited losses and make this transition naturally. However, also a high powered vehicle with stop-start can achieve a similar performance, but the lower engine losses on the WLTP are compensated by a limited reduction through the stop-start system. Hence in both cases the NEDC and WLTP values are expected to be within a typical bandwidth of 10 g/km from each other.

The suggestion that test mass and tyre prescription alone will be responsible for large changes in type-approval CO₂ values from NEDC to WLTP cannot be established from the physical work associated with a weight increase of about 5%-10% and an increase in rolling resistance.

So far, the use of flexibilities in the NEDC is not completely understood. Probably about half the effect can be assigned to particular known aspects. Flexibilities are also expected under WLTP. Only independent testing on arbitrary samples can improve this situation. In a complex matter of type-approval testing the lack of openness is detrimental for realistic results.

JRC has tested vehicles on the NEDC, WLTP and in real-world driving. These data concern a medium size diesel car and a large petrol car. The diesel car was equipped with a powerful engine and a stop-start system which resulted in a low NEDC type-approval value.

Table 16 The measurements of JRC and the expected difference on the basis of the changes in vehicle characteristics. These differences explain the differences in CO₂ emissions.

Diesel	NEDC	WLTP	PEMS
CO ₂ [g/km]	132	161	153
additional force [N]		123	123
additional weight [kg]		53	228
expected difference [g/km]		27	33
observed difference [g/km]		29	21
Petrol	NEDC	WLTP	PEMS
CO ₂ [g/km]	219	214	218
additional force [N]		19	19
additional weight [kg]		231	406
expected difference [g/km]		13	20
observed difference [g/km]		-5	-1

The diesel vehicle has a stop-start system, and both cars are high powered, which explains the overestimation of the difference under NEDC based on actual power demand. On the NEDC a substantial part of the CO₂ is associated with engine losses for both fuels but for petrol the most which are in turn associated with the rated power. This CO₂ emission effect of engine losses is limited under WLTP and real-world driving, yielding a lower CO₂ emission. In the case of stop-start the corresponding CO₂ at the type-approval can be 10 g/km less on the NEDC, bringing the values again in line. In that case the expected differences based on the work, from force and weight, are similar to the observed differences, because the engine losses play a smaller part altogether.

9 Conclusions

The gap between type-approval CO₂ emission and real-world CO₂ emission is the result of many small effects. Most of them drive the real-world fuel consumption up, as the type-approval test is an optimised and idealised world, but a few aspects are overrepresented in the type-approval test with respect to the real-world driving. The cold-start and the fraction of idling are two important aspects.

Manufacturers certainly have a role in the gap between type-approval and real-world fuel consumption. The test flexibilities are exploited. However, given the natural variation in test results, and the underlying variation, e.g. in road loads, it is expected that with the attention for CO₂ emissions, the type-approval tests have been optimised. However, this would explain about half to two-third the total flexibility observed [Kadijk 2012b].

One conclusion of this study is, simply said, that the small difference between the type-approval value and the real-world fuel consumption in the past is more accidental than based on the representativeness of the type-approval test for the real-world fuel consumption. Therefore, it is not necessarily surprising that with changing technologies for reducing CO₂ emissions on the type-approval test the effects on real-world emissions is limited. Basically, the high CO₂ emissions, and fuel consumption on the NEDC test are related with: low velocity and low engine load, a large amount of idling, and the cold start. In real-world, the effect of these are less, but compensated by driving at constant high velocities, lower temperatures, higher rolling resistance, use of auxiliaries, and a higher vehicle weight.

The reductions on the type-approval test are achieved by mainly aspects which are related to these extra emissions on the type-approval test: stop-start systems, reducing engine losses, and cold-start engine strategies. Moreover, reducing test weight, a low rolling resistance, optimised test execution, and minimizing alternator use (exploiting flexibilities), are additional gains on the type-approval test which are not reflected in the real-world fuel consumption reduction.

The usual suspects for the increasing gap: improper exploitation of test flexibilities, the use of air condition, and the specially prepared vehicle and tyres may affect the gap somewhat but do not explain the majority of the gap for the average fleet. For air-conditioning a small effect is established from two independent data sources. The variation in tyres fitted to test vehicles, production vehicles, and available in the aftermarket is substantial, but this effect is limited in the total fuel consumption.

The WLTP is meant to limit this gap, and it may do so for current vehicles optimised on the NEDC. Three effects are important: the higher vehicle velocities on the WLTP test, the higher vehicle weight on the test, and the more appropriate tyre prescription and conditioning. This accounts for less than half of the total gap. Moreover, the retention of this improvement with the WLTP requires continuing attention. The natural variation in the test outcome is about 10%. The type-approval values will remain at the low end of this bandwidth with the existing NEDC-based CO₂ targets. On the other hand, the low load associated with constant driving and

the cold start are limited in the WLTP with respect to the NEDC, which lowers the CO₂ emission on the WLTP.

One main cause for the gap is the additional real-world fuel consumption related to high velocities which is mostly unaffected by the type-approval CO₂ reductions. For example, small vehicles, with reduced weight and engine size do not have a lower fuel consumption with this usage, but they do have a lower type-approval fuel consumption. The low ambient temperatures adds to this effect due to the increased air-drag with lower temperatures. This cause, combined with the optimised testing, the exclusion of auxiliaries in the test, and differences weight and tyres explains most of the gap. The precise nature and magnitude of the effect depends very much on the real world usage. The fraction of the urban distance and of the motorway distance determine most of the net effect and it is strongly affected by the vehicle and engine characteristics.

The CO₂ attributions made in Table 7 based on the equations in Section 4.2 is central to this study. The net result in CO₂ emissions for the different tests and usage cases vary only slightly, while the underlying CO₂ attributions to work, losses, cold start, technology, and variations in road loads in the different cases vary greatly. Basically, the CO₂ emission on the NEDC is dominated by losses and cold start which covers for many vehicle configurations almost half of the total CO₂ emissions, while in other cases these contributions are much smaller, and the engine size is less relevant.

Roughly, the difference between type-approval and the real-world fuel consumption can be attributed to four elements of similar magnitude: 1) different ambient conditions and vehicle usage and weight, 2) excluded factors from the type-approval test, 3) optimised testing within the test bandwidth, 4) NEDC test specific vehicle technology. The last two items have increased from 2007 onward and they are at the basis of the divergence. The seemingly large increase in the gap is partly due to the rather accidental initial cancellation, around the year 2000, of opposite effects between type-approval and real-world fuel consumption.

The main conclusion from this study is that a test protocol alone cannot ensure a proper representation of the real-world fuel consumption due to the numerous interacting factors and their very large variability. The monitoring of vehicles in real-world usage would help to streamline the relation between type-approval and real-world fuel consumption. Vehicle state, vehicle usage, auxiliaries usage, and ambient conditions are all known to affect fuel consumption beyond the test flexibilities. Monitoring these factors on randomly selected vehicles would facilitate a better understanding and assessment of the reasons behind the gap. Consequently, on the basis of such information, measures can be decided to reduce and limit the divergence.

10 Literature

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11 Signature

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