The Effect on Road Load due to Variations in Valid Coast Down Tests for Passenger Cars

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Summary

Real-world CO_2 emissions of passenger cars very often deviate from the Type Approval value. The Type Approval value for CO_2 emissions of passenger cars is based on a chassis dynamometer test in a laboratory. The total vehicle resistance of a vehicle, or 'road load', is simulated on the chassis dynamometer to obtain representative emissions.

The road load of a vehicle is determined by means of a coast down test. As a large number of parameters and external conditions influence the coast down test, the Type Approval procedures for performing the coast down test allow for certain margins within which certain test parameters should lie. These margins can partly explain the difference between the real-world and Type Approval CO_2 emissions.

TNO investigated the effect of variations in test parameters during the execution of a coast down test on the vehicle's road load by performing a series of coast down measurements. This paper reports the most important findings.

Background

Since years, a significant and increasing gap is observed between real-world CO_2 emissions and type-approval CO_2 emissions of passenger cars. As European legislation for CO_2 emissions of passenger cars is based on the type-approval CO_2 emissions, real-world CO_2 emissions that deviate largely from the type-approval CO_2 emissions could result in a decreased effectiveness of CO_2 legislation. One of the aims of the European Commission and also the Dutch government is to decrease the gap between real-world and type-approval CO_2 emissions by improving type approval legislation.

The type-approval CO_2 emissions of passenger cars are determined by means of a chassis dynamometer test in a laboratory. For this test, the resistance of the vehicle, also known as 'road load', is simulated on the chassis dynamometer to obtain representative emissions. The main purpose of the combustion engine is to overcome the resistance force, hence the appropriate value of this resistance force is central for a representative emission measurement on the chassis dynamometer.

The road load of a vehicle in turn is determined by means of a coast down test. A coast down test is performed on an outside test track by coasting the vehicle down from 125 km/h to 15 km/h with the gearbox in neutral position. The magnitude of the deceleration, combined with the total inertia, i.e. the sum of weight inertia and rotational inertia, determines the resistance for each vehicle velocity. To improve the accuracy of the test, the test is performed multiple times in both directions. Speed and time are measured very accurately during the coast down test. Because the weight of the vehicle is known, the so-called resistance curve of the vehicle can be determined.

As a large number of parameters and external conditions influence the coast down test, the type approval procedures for performing the coast down test allow for certain margins within which certain test parameters should lie. These margins relate to the vehicle state and external circumstances and can partly explain the difference between the real-world and type-approval CO_2 emissions

Method for executing the coast down tests

TNO performed a large series of coast down tests, as will be described in next sections. In the tests, the following variations were investigated:

- Vehicle state: fitted tyres, wheel alignment, wheel size and wheel shape, removal of certain fixtures such as antennas, passenger side mirrors, etc.;
- Vehicle usage: tyre pressure, test mass; grill vane settings, etc.;

- External circumstances: temperature, wind speed, wind direction, atmospheric pressure, relative humidity, road surface, road gradient, etc..

To ensure accurate measurements TNO established a fixed procedure for vehicle preparation, vehicle warm-up, execution of the test and post-test checks. Key issues for this procedure are:

- Following the procedure in accordance with the Draft WLTP GTR (August 2013);
- Checking tyre pressure and tyre temperature before, during and after the test;
- Weighing of the vehicle before and after the test;
- Performing a minimum of 12 tests in both directions per test;
- Making sure the starting position and trajectory on test track was similar for each test.

In coast down test results separate effects are all intertwined in a single outcome. To disentangle the effects, and to establish the individual magnitudes, requires a complex statistical analysis, a sufficient amount of coast down data with variations in all relevant variables, and the monitoring of all influences deemed relevant. Multi-regression analysis is performed on the full data set for a the dependencies on a dozen variables. The effects show that different coast down tests can deviate substantial from each other, this can have a large effect on the CO_2 emission of the vehicle. During real world conditions similar variations as during the coast down tests occur.

Results obtained in several measurement programs

TNO investigated the effect of variations in test parameters during the execution of a coast down test on the vehicle's road load by performing a series of coast down measurements during various measurements programs. By this way quantifying the effect of test margins on the type-approval CO_2 emissions, it will be possible to identify legislative improvements needed to let type-approval CO_2 emissions match real-world CO_2 emissions more closely. This paper shortly describes the insights of measurement programs TNO has performed in the last years.

<u>Road load determination of passenger cars</u>

The Dutch Ministry of Infrastructure and Environment and the European Climate Foundation contracted TNO to determine - among other things - 'real-world' road load data and to compare this data with road load data provided by OEM's. For the measurements six modern, i.e. Euro 5 and Euro 6, passenger cars and two Euro 4 models of the same type were used. Measurements were performed on a test track in the Netherlands and in Belgium.

Real-world road loads are found to be substantially higher than the type approval road loads. At high speeds the road load differences are up to 30%. At low speeds, with very low road load forces, these differences even amount to as much as 70%. The older models have about half such a difference. For all vehicles the results show the same, consistent trend in road load deviation.

Weighting the individual road loads according to the velocities as they appear in the New European Driving Cycle (NEDC) leads to the following results. The weighted real-world road load settings of the two Euro 4 vehicles are on average 19% higher than the settings of the type approval road load curves. The weighted real world road load settings of the 5 Euro 5 and 1 Euro 6 vehicles are on average 37% higher than the settings of the type approval road load curves. This indicates an increasing trend of road load ratios in recent years (Kadijk, 2012).

<u>In-use compliance programme</u>

Several measurements were performed within the in-use compliance program for light-duty vehicles on behalf of the Dutch Ministry of Infrastructure and the Environment. The following paragraphs describe shortly the insights from the measurements.

<u>Check proposed WLTP table values</u>

At the end of 2012 the first WLTP table values of running resistances were proposed. TNO performed measurements with the objective to assess the proposed WLTP table values of vehicle running resistances. Three different light commercial vehicles were taken from Dutch rental fleets, the vehicles differed in shape and mass. Coast down tests were performed at Ford Lommel Proving Ground in Belgium.

It was shown that the proposed WLTP table values of running resistances are more representative than the current NEDC / UNECE R83 table values of running resistances, especially at low and medium speed. In this test program of three vehicles the proposed table values were in one case lower, in a second case nearly equal and in a third case higher than the TNO measured road load curves. This indicates that the proposed WLTP table values need further investigations, especially if these table values will be used as worst case values. A new table was proposed by the Netherlands, and has been accepted by the Working Group in Geneva.

Table values for road load

To limit the test burden, a coast down test for type-approval can be waived. Instead table values can be used. This was already the case in the NEDC test. The NEDC (UNECE R83) table values were low for heavy and large vehicles. For the WLTP TNO has advised the Dutch government for appropriate road-load table values, in line with worldwide certification data from USA, Korea, Germany, and the Netherlands. These values were adopted. From certification data it is clear there is a large spread in road-load values for the same size and weight vehicles. Most data lies within a +/-35%-40% band around the average based on 200 vehicles, and thousands of USA data with size information. The average of all type-approval data as function of the vehicle weight (mass in running order), width and height is determined by the following formula:

$$F_{average}[N] = 0.100 * (1 + 0.00002*v^2) * M[kg] + 0.0121 * width * height * v^2 \; [m^2]$$

Frontal area would have been more appropriate than width and height, however, such data is commonly not available from certification. The formula uses the available information of the vehicles, combined with general physical principles of rolling resistance and air drag. For the NEDC only few LCV's above 1600 kg were actually tested for rolling resistance. See Figure 1.

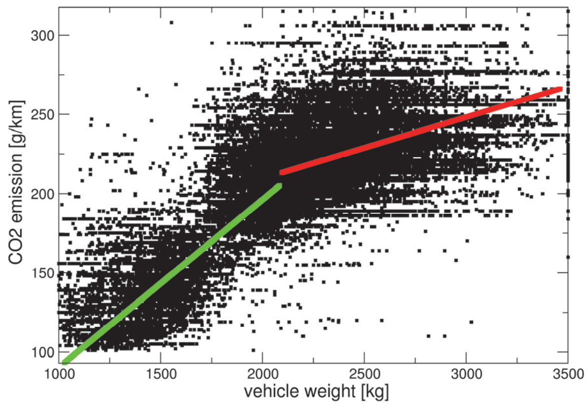

Figure 1: The European monitoring data of LCV's. The low-mass vehicles have a correlation between weight and CO_2 emission. For the weight above 1600 kg the correlation is limited, probably due to the use of NEDC table values.

NEDC-WLTP correlation

The WLTP legislation is under development. Currently an investigation is ongoing regarding the correlation between the NEDC and WLTP with a main focus on CO_2 emissions. During this investigation various chassis dynamometer measurements are performed with NEDC and WLTP road load settings. Both road loads values were provided by OEM's. To gather more information about the determined NEDC and WLTP road loads coast down tests were performed by TNO with a rental vehicle. The testing procedure to determine the WLTP road load differs from the NEDC procedure at various points. During the TNO tests only the test mass and tyre pressure were adjusted, as these were the main difference between the two test procedures. Coast down tests were performed at Ford Lommel Proving Ground in Belgium.

Test results show that the measured WLTP road load is about the same as the provided provisional WLTP road load by the OEM. On the other hand, the measured NEDC road load was only a little lower, while the OEM NEDC road load was significantly lower. Somewhat different circumstances and vehicle conditions partly explain the difference between the NEDC road loads.

Validation test program for "Correction algorithms for WLTP chassis dynamometer and coast down testing"

The most extensive measurement programme performed by TNO is the validation test program for "Correction algorithms for WLTP chassis dynamometer and coast-down testing". The main objective of this project was to develop correction factors for various variables in the coast down test and the chassis dynamometer test. In order to develop correction factors for the coast down test, TNO investigated the effect of variations in test parameters during the execution of a coast down test on the vehicle's road load by performing a series of coast down measurements.

In order to ensure representative test results, TNO selected a vehicle within the 2012-2013 top-five of EU sales lists for the measurements. The vehicle was equipped with a manual gearbox and was in its original condition. Before testing, the vehicle was checked at an official dealer, the wheel alignment was set in the exact middle of the given tolerances and new tyres were fitted.

TNO performed a total of 25 coast down tests, resulting in over 600 runs and 58 hours of data. The tests were performed on three different test tracks in Spain, Belgium and the Netherlands.

TNO used the same equipment for each test to obtain reliable and comparable data. For the measurements a 100Hz GPS Racelogic VBOX 3i v2 data logger was used, combined with an Inertial Measurement Unit (IMU). This equipment has a velocity accuracy of 0.1 km/h and a distance accuracy of 0.05% and thus fulfils the standards prescribed in the type-approval test procedures. Furthermore, a weather station, tyre pressure gauge, temperature gauge and weighing scales were used.

General results of the coast-down testing for WLTP correction algorithms

The typical spread in coast down values, expressed as 1/T, in consecutive "a" tests, and consecutive "b" tests separately were 2.8%. For a large part this is attributed to the variation of the wind during the test. The total variation with the different conditions was much larger. The size of each effect is reported below. It must be noted however, that given a test-by-test variation of 2.8%, a similar error margin can be applied to the results, to be on the safe side. The successive tests will reduce the overall error of the tests, however, 2.8% must be considered "unexplained", i.e., non-reproducible. Very likely, the wind gustiness plays an important role in the variation in the test results.

The coast down test results were corrected with the WLTP correction methods, for weight, temperature, and air pressure. The other effects were studied with the corrected coast down results. The variation in vehicle state was studied extensively for this single vehicle. It is not possible to make generic statements from testing a single vehicle, however, the expected bandwidth can be determined. The validation programme mainly served the purpose to validate the assumption and signal possible effects of a relevant magnitude. An effect of at least 1% on the total resistance, or 1 g/km, was considered relevant. With a handful of effects, an explained deviation between a standard test and an optimized test of up to 20% or more in total road load is not uncommon (Kadijk, 2012).

In the NEDC test the average velocity is low. In the new WLTP type approval test the velocity is somewhat higher, but still lower than the common vehicle usage in the Netherlands. For this reason the rolling resistance has a significant contribution to the total driving resistance. On the NEDC it is about half, on the WLTP it is about a third.

Fitted tyres and wheels

The coast down tests were conducted with eco-tyres which have a higher set pressure of 2.7 bar instead of 2.1 bar. For the pressure of 2.1 bar, the rolling resistance of the eco-tyre would have been 9% higher, however, this is compensated with the 22% reduction in rolling resistance with the pressure, yielding a net reduction of 13% in rolling resistance for the eco-tyre. However, the condition is that the higher pressure of this tyre is allowed on the WLTP test. The car manufacturer's instruction (in the door frame) were considered leading.

The vehicle was also tested with sport tyres (18") which are wider. The rolling resistance of these tyres was 5% lower. The air drag is 1.5% higher, which lies in the margin of error. The test was not corrected for the substantial high rotational inertia of these wheels and tyres. This has an effect of an 1% underestimation of the road load values.

Wheel alignment

Most tests on the vehicle were carried out with the nominal toe-in of the wheels of 0.2^{o}. The wheels are not adjustable in the other directions, like camber and caster. The vehicle was also tested with a toe-in of 0^{o}. This gives a reduction of rolling resistance 6% with respect to the nominal, or midpoint, value. With the normal wheel alignment of 0.2^{o} the vehicle seemed to have the lowest rolling resistance if the trajectory was slightly curved (about 1 -2 metres per 100 metres). Likely, this is related to the wheel alignment.

Removal of certain accessories such as antennas, passenger side mirrors, etc.

In one test sequence the vehicle is tested with kerb-side mirror removed, driver-side mirror folded, antenna and windscreen wiper blades removed, and the wheel caps taped close, to approximate closed wheel. These combination together yielded a reduction of the air drag of 4%.

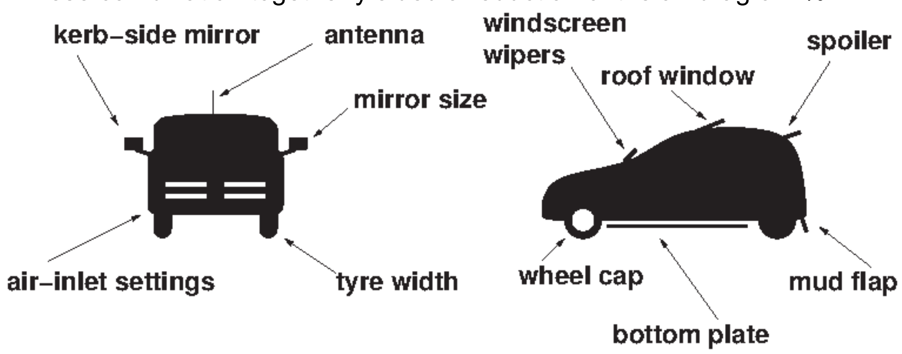

Figure 2: Some of the aspects affecting the air drag on a car.

Tyre pressure

The effect of tyre pressure turned out to be a complex problem. During the testing tyre pressure was monitored and a large variation was found. Rather than relying on the initial tyre pressure only and the variations therein, the tyre pressure monitoring data was used. The standard tyres have a pressure of 2.1 bar. After conditioning the pressure was around 2.3 bar. In case of higher initial pressures, the pressure after conditioning was also higher, albeit slightly less than in the case of the 2.1 bar. The variation of the rolling resistance with the monitor pressure was:

$$F0 = 157\text{ N} + 51\text{ N/bar} \sim 75 * (2.1 + 0.7/\text{bar})$$

Using the conditioning pressure p of 2.1 bar, the correction of the rolling resistance, based on this measurement program, would be:

$$F0_{road\text{-}load} = F0_{test}\,(p_{test}/p_{set})^{0.7}$$

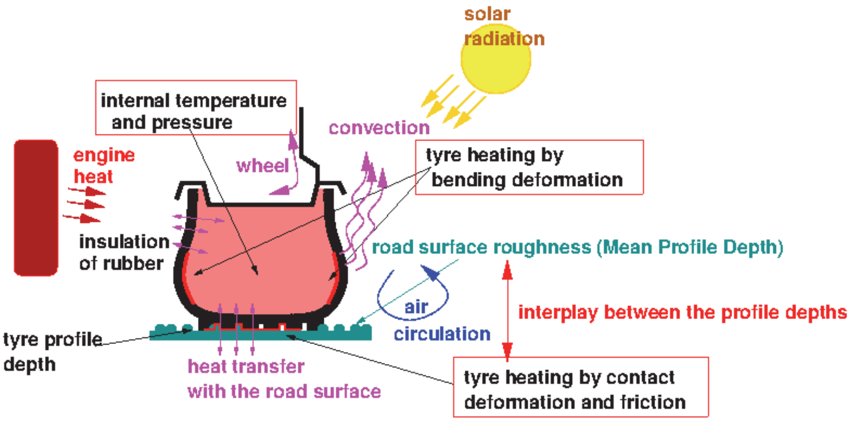

Figure 3: Some of the physical aspects of the complex heat balance of a tyre affecting the tyre pressure.

Instead of the exponent of 0.7, exponents of 1 and 1.5 are often quoted in older literature. Nowadays exponents of 0.5 to 0.7 are common. The result will depend on the tyre type and the initial pressure. Likely, there is a difference between high rim and low rim tyres. The limitations of the test program make it difficult to assess the effects of tyre pressure in its full scale as seen on the road. However, it is an important aspect.

The precondition in the test, by driving at 118 km/h prior to the coast down test, has a limited influence on the final stages of the coast down testing. The total test program takes about an hour. In the last part, the actual driving: acceleration, braking, turns, seem to affect the tyre pressure as well. Moreover, weather conditions, wind, and road surface temperature may have significant contributions. These effects could not be explained, however, a large variation of 14% in tyre pressures for seemingly identical reference tests were observed. The tyre pressure dropped from the high velocity part of the testing to the low velocity part.

The pressure variations during the testing and normal driving remain an interesting topic due to the expected magnitude of the effect. From the Dutch In-Use Compliance program vehicles are driven around for more than an hour. In some cases the quality of the ECU vehicle velocity is good enough (in many cases it is not) to compare against GPS velocity. A few percent variation in the two velocities monitored over the duration of the trip, indicate an increase in tyre radius and tyre pressure especially during urban driving. Surprisingly, the radius is smaller in rural and motorway driving. This independently suggests an effect of varying tyre pressure, which seems mainly associated with dynamics, not velocity.

Test mass

Vehicle mass affects both the inertial energy and the rolling resistance. For all practical purposes rolling resistance is assumed to be proportional with the vehicle weight, such that a higher weight affects mainly the coast down times at higher velocities, where the air-drag interferes with the proportionality of both the inertial and resistance forces with mass. Since mass is such a major aspect in the coast down test, the proper determination of vehicle weight and inertia, appropriate for production vehicles, is paramount. During the testing the weight decreases somewhat, as the successive accelerations and coasting require a lot of fuel.

The rotational inertia from the wheels and tyres are normally assumed to be 3% of the vehicle mass. For the normal wheels and a set of 18” sport wheels from the official dealer, the inertia was determined by simple physical tests. The difference in inertia was four times 4 kg or16 kg in total, which is a substantial amount. For the normal wheel the rotational inertia was 56% of the wheel and tyre weight, for the sport wheel it is 63%. A simple rule would be to use 60% of the weight as rotational inertia. In the same experiment the driveline resistance was also determined. For the driven axle it was 9.9 Newton per wheel, for the other axle 2.3 Newton. This 24.4 Newton in total is only a small, yet significant, part of the 170 Newton rolling resistance.

Grill vane settings

The tests were executed with open grill vanes. Only in one test the grill vanes were closed to study the effect of the air flow through the radiator. The effect on the air drag is about 10%. Not all vehicle models have such grill vanes, and the setting can vary during driving. However, a closed grill is unlikely given the heat from the engine. Hence, an open grill is an appropriate approximation to the worst case, and to the real-world, settings. It is interesting what the potential reduction in air-drag in real-world driving would be.

Temperature

From real-world fuel consumption monitoring, a strong correlation between fuel consumption and ambient temperature is found. The annual variation is about 7%, both for light-duty vehicles and heavy-duty vehicles. In the coast down test the effect is smaller. The lower air density at higher temperatures is expected to be the dominant effect. The tyre viscosity, and its effect on the rolling resistance, is corrected for temperature. Although difficult to understand the effect is recovered in the validation programme.

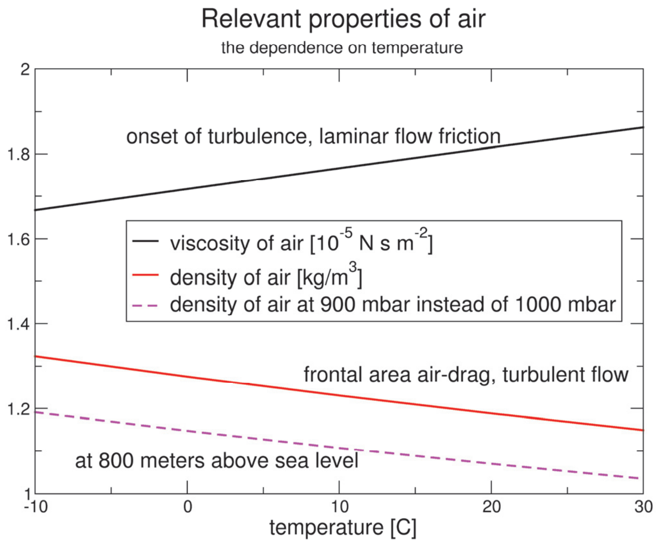

Figure 4: The aspects of air affecting the air drag of the vehicle. The air density is considered the dominant effect. Viscosity and temperature yield otherwise only secondary effects (Hucho, 1998).

Wind speed and wind direction

The test track in The Netherlands was a few kilometres from the North-Sea coast, with substantial wind. The meteorological station at the height of 10 meters has an average wind velocity (measured over the last 10 minutes of the hour and over the whole hour in the period 2001-2010) of 4.6 m/s with a standard deviations over an hour and ten minutes of 2.7 m/s and 2.8 m/s respectively. The same data also recorded the maximal wind speed (i.e., gusts) during an hour. The average gust speed is 7.8 m/s. Hence the wind gusts are typically 2.0 m/s higher than the hourly and ten-minute average. For all average velocities, except the lowest velocities, smaller than 1.0 m/s, this is the case.

Hence, it can be concluded that wind gusts occur at small time scales of seconds, as there is hardly a distinction between hourly and ten-minutes averages. Furthermore, at this location wind gusts are substantially higher than the average wind speed.

Comparing the meteorological station with the wind meters at the track side, at a height of 0.7 meters above the terrain, the hourly wind measurement at 10 meters height are 1.5-2.0 m/s higher. In particular at low wind speeds the difference is in the top of the range, while at higher wind speeds the difference is at the bottom of this range. Likewise, the wind gusts at 0.7 meters are still substantially higher than the average wind speeds, with more than 1.0 m/s difference.

Hence the wind gusts at track level of 1.0 m/s can explain very well the variations in the coast down results, from test to test. The test-to-test variation is 2.8%. With a wind speed difference of 1.0 m/s, i.e., 3.6 km/hr, the 5% variation in the apparent velocity at 72 km/h matches well with 3% variation in coast-down times.

Atmospheric pressure

A few hundred metres above sea-level the atmospheric pressure is already lower. This variation is much larger than the variation due to the weather. Since hundred metres or higher is not uncommon for driving in Europe, it should be considered a major effect in the difference between official road-load values and actual air-drag, which is proportional with air density and air pressure. The lower air pressure at high altitudes also has a beneficial effect for low air drag.

Relative humidity

The effect of relative humidity yields a consistent effect over all the tests, despite the limited temperatures, between 10^{o} C and 25^{o} C. The higher relative humidity yields lower air drag, in the order of the expected result of around a percent.

Road surface

The road surface has a significant contribution to the rolling resistance. Once all other corrections were applied to the reference trip, the different tracks showed up as a systematic deviation between the coast-down tests at the different tracks. The effect is up to 20%.

VTI (Hammarström, 2009 and Karlsson, 2011) is one of the few parties with a comprehensive measurement programme of road-load dependencies on the road surface. They show significant effects. There is limited data available on the road surface texture of the different test tracks, however, the commonly-used test track can be assumed to have a smooth road surface compared with the average European road.

Road gradient

From the GPS data the road slope could be determined. This yields a correction on the coast down time. In the WLTP the solution is the use of the average of both directions. However, it is possible to correct for each direction separately. In this case the vehicle weight can be recovered, as the additional force is the result of gravity, vehicle mass, and slope. In this manner only part of the vehicle mass is recovered.

The WLTP test procedure, averaging the reciprocal of the coast down times 1/T of the “a” and the “b” test, rather than averaging the time T itself as done in the NEDC is a major improvement. It removes the advantages of a sloped track over a flat track, which can be as high as 6% in road load forces.

Conclusions

Many small effects together yield a significant contribution to the measured road load. With the current interest in low CO_2 type-approval values, the margins are likely to be utilized to the maximum. The major part of the difference between the type-approval road loads and the independent measurements on production vehicles is not understood and quantified.

Apart from its relevance for the testing procedure and minimizing the margins in testing, the test programmes are also relevant for real-world CO_2 emissions. Different drivers, with different driving behaviour, different vehicle states, and different vehicle usage have large variation in fuel consumption. This can be up to 40% between lowest and highest fuel consumption with the same vehicle model, in normal circumstances over a longer period. (Ligterink 2012)

Acknowledgment

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