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TNO-rapport

Correction algorithms for WLTP chassis dynamometer and coast-down testing

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Summary

The flexibilities allowed in the WLTP are necessary to allow efficient testing without having a lot of invalid tests. Nevertheless some of the flexibilities influence the resulting fuel consumption to an extend which makes it worth to consider applying correction functions for deviations against the target values. Such correction functions have several benefits:

+ The repeatability increases
+ In test programs beside type approval tests larger deviations against the target values may be typical. In such cases the application of the correction functions could help to make single tests better comparable and to increase the repeatability.
+ Making use of the flexibilities to reduce the CO_2 test result gives ab better type approval value but does not influence the real world CO_2 emissions. Thus the test result should reflect reality better if the result is corrected for deviations against the target values of the test procedure.
+ The need to optimise the position of the test conditions within the range of flexibilities is reduced to a large extend. Making use of flexibilities ranges from driver training over calibration of test utilities up to optimising the alternator control unit to cycle conditions. Eliminating the need for optimisation of such parameters shall reduce the overall effort for testing without negative effect on real world CO_2 emissions.

- As negative impact the complexity of test evaluation increases and additional signals need to be measured, such as Current flow from and to the battery.

In the summary below the correction methods are described in short. A detailed description of the methods and of test results is given in the main text.

<u>Vehicle specific Willans linear equation</u>: Several of the correction functions need to adapt the measured CO_2 value from the work delivered during the test to the target work which would have been necessary without flexibilities. These corrections need a specific efficiency coefficient in [g/kWh]. This efficiency is not the average engine efficiency but depictures the additional fuel flow due to an additional engine power demand. Thus in this value those parasitic losses which are not affected by changes in engine power are not considered, since these have to be overcome in any case. We call this efficiency coefficient in the following “Willans coefficient”, which can be computed from the chassis dynamometer tests from the four phases of the WLTC by plotting the average CO_2 flow [g/s] over the average power of the phase as shown in Figure 1. The regression line gives the “Vehicle Willans equation” where the inclination coefficient “k” of the equation gives the demanded average Willans coefficient. In the equation the parasitic losses are depictured by the constant “D” in the equation, which gives the CO_2 emissions (or the fuel consumption if FC is plotted instead of CO_2) at zero power output[1].

[1] Typically the regression line of the average engine speed per WLTC phase over average power crosses the zero power line at engine speeds clearly above idling speed. Thus the constant value “D” in the linear equation represents the CO_2 emission value for idling at increased rpm.

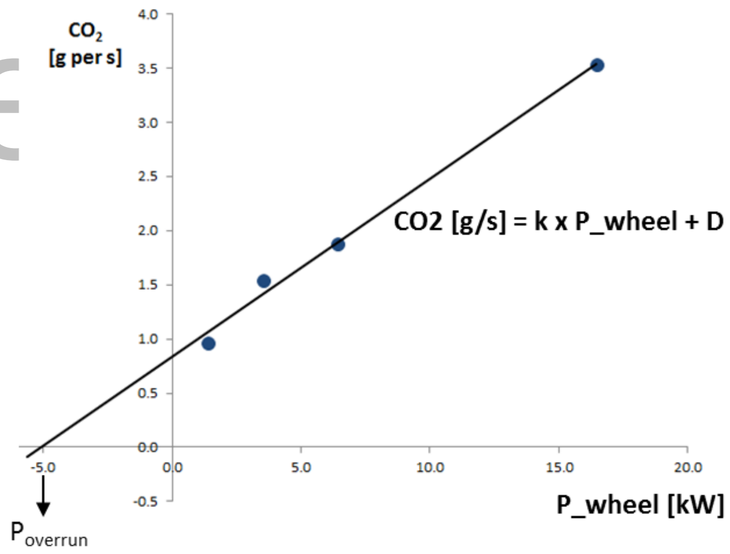

Figure 1: Schematic picture of setting up the Willans linear equation for a LDV from the chassis dyno test

The vehicle Willans equation gives the CO_2 flow as function of the power at the wheel. The Willans coefficient from this equation is suitable to correct all parameters leading to deviations of the work at the wheel (speed deviations, road load settings)[2]. To gain the engine Willans coefficient the vehicle Willans coefficient would have to be transferred to the engine power, which is higher than the wheel power due to the losses in the transmission system in case of positive power output. The losses in the transmission system are not measured in the test Thus this value could be implemented only as generic function for MT and for AT systems. Since this would add reasonable uncertainties to the engine Willans coefficient it seems to be more practical to use directly generic engine Willans coefficients for all corrections which are based on deviations of the engine power over the cycle (i.e. SOC imbalances of the battery).

In the following an overview on potential correction functions are given which partially make use of the vehicle or engine related Willans coefficient.

Imbalance in battery SOC can influence the test result up to approx. 2 g/km in the WLTC. A correction for SOC imbalances is suggested to be based on generic coefficients for the change in fuel flow per change in average power demand over the cycle (“engine Willans coefficient”) combined with a generic average alternator efficiency as already outlined in the draft WLTP. More detailed approaches have been investigated but do not show significant improvements in the reliability of the correction (Leitner, 2014). This gives the following equation for the suggested correction:

$W_{bat} = \int U_{(t)} * I_{(t)} * 0.001 \ dt$ in [kWs] where the Voltage could be the nominal Voltage or the measured one. The Current flow has to be measured at the battery with positive sign for energy flows from the battery.

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[2] All corrections based on the Willans coefficients [g/kWh] can either be based on the change in power to provide the average change in fuel flow [g/s] or by change in work over the cycle to provide the absolute change in fuel consumption over the cycle [g]. Both methods deliver identical results.

$$\Delta CO_{2SOC}\,[g] = \frac{W_{bat}}{\eta} * k_e$$

With k_e .... Engine Willans coefficient [g_{CO2}/kWs], generic values per technology

η .... Generic average efficiency of the alternator including transmission losses to the engine (in the WLTP draft an efficiency of 0.67 is suggested)

The correction shall be done for each WLTC phase separately, if a more accurate base shall be provided for setting up the vehicle specific Willans linear functions from the SOC corrected WLTP results. This is more relevant, if the test is started with low SOC since the vehicle then tends to load the battery from start on, which influences mainly the first test phase. In type approval the defined pre-conditioning and the limits for the SOC imbalance should allow only small influences on the CO_2 emissions par test phase. Thus the SOC correction may be applied to the entire WLTC and not per phase.

Deviation against target road load: Directly after the WLTC a set of 3 coast down tests[3] is performed. The tests with the highest and the shortest coast down time shall be rejected and the remaining test shall be evaluated according to the WLTP regulation[4] to determine the road load coefficients. At the time being it is assumed that the coast down after the WLTC test shall be representative for the road loads applied by the chassis dynamometer during the test. The correction can be done separately or (suggested) be combined with the correction for deviations against the target speed.

A separate correction for the road load would work as follows:

Calculate the actual wheel power for the road load coefficients from the chassis dyno coast down test:

$P_{(t)} = (R_0 + R_1 * v + R_2 * v^2 + m * a) * v$

Calculate the actual wheel power for the road load coefficients from the target value:

$P_{p(t)} = (R_{0w} + R_{1w} * v + R_{2w} * v^2 + m * a) * v$

v............................ velocity driven in the WLTC

R_0, R_1 R_2 .... Road load from the coast down tests at the chassis dyno directly after the WLTC in [N], [N*s/m] and [N*s²/m²]

R_{0w}, R_{1w} R_{2w} .... Target road load coefficients in [N], [N*s/m] and [N*s²/m²]

Then the average power values over the WLTC are computed and consequently the total work at wheels:

$\Delta W_{wheel} = 1.8 \times (P_{p-} P)$ in [kWs]

Then the vehicle based Willans function is applied to correct for the deviation against the work from the WLTC target velocity:

$$\Delta \boldsymbol{CO_{2_p}}\,[\boldsymbol{g}] = \Delta \boldsymbol{W_{wheel}} * \boldsymbol{k_v}$$

With k_v .... Vehicle Willans coefficient [g_{CO2}/kWs] from WLTP

Deviation against target speed: the driven speed profile as well as for the target speed the power at wheels is computed. If combined with the correction for road load deviations, the power for the speed driven in the WLTC is calculated from the

[3] The exact number may need further discussion. Alternatively just one test after WLTC can be made, if we do not expect outliers, see chapter 8.

[4] for the coast down test evaluation on the test track

road load coefficients gained from the coast down after the WLTC test as described above:
$P_{(t)} = (R_0 + R_1*v+R_2*v^2 + m*a) * v$ with v is velocity driven in [m/s]
$P_{w(t)} = (R_{0-w} + R_{1-w}*v_w+R_{2-w}*v_w^2 + m*a_w) * v_w$ with v_w is target velocity of the WLTC
Then the difference in average positive power (alternative the average of the power signals above $P_{overrun}$) is calculated. The deviation against the target cycle work is then:

$$\Delta W_{wheel} = 1.8 \times (P_{w\_pos} - P_{pos}) \text{ in [kWs]}$$

Then the vehicle based Willans function is applied to correct for deviations against the work from the WLTC target velocity

$$\Delta \boldsymbol{CO_{2_v}} \, [\boldsymbol{g}] = \Delta \boldsymbol{W_{wheel}} * \boldsymbol{k_v}$$

With kv................ Vehicle Willans coefficient [gCO2/kWs] from WLTP result after SOC correction

Deviation against target distance: The correction for deviations against target speed covers the time shares in WLTP with positive wheel power (or power above "$P_{overrun}$", as shown in Figure 1). Thus in these times the power is shifted to the power necessary to meet the target velocity. Nevertheless, by braking more or less aggressive than the target decelerations, the distance can be varied by the driver with only small effects on the total WLT fuel consumption [g] since in these phases the engine is most of the time in overrun at zero fuel flow. Thus dividing the entire fuel consumption in the test in [g] after correction for deviations against positive cycle work gives a result without offset from braking behaviour of the driver:

$$\boldsymbol{CO_2}[\boldsymbol{g/km}] = \frac{\boldsymbol{CO_{2_{measured}}} + \Delta \boldsymbol{CO_{2_{SOC}}} + \Delta \boldsymbol{CO_{2_v}}}{\mathbf{23.27}}$$

With $CO2_{measured}$.......... CO_2 test result in the WLTP in [g/test]
23.27 .... WLT target test distance [km]

Deviation against target soak temperature: the WLTP prescribes a soak temperature of 23°C ±3°C. These rather narrow tolerances shall not lead to deviations in the CO_2 emissions measured of more than approx. ± 0.6%. If the oil temperature at test start is measured with reasonable accuracy still a correction of this influence may be reasonable.
Suggested is a linear equation for the small temperature range:

$$\Delta \boldsymbol{CO_{2_t}} = (\mathbf{23} - \mathbf{t}) * \boldsymbol{C_T}$$

With: C_T .... Coefficient for soak temperature correction (average from measurements: CT- = 0.0018/°C)

$$CO_2 \, [\frac{g}{km}] = CO_{2_{measured}} \, [\frac{g}{km}] \times (1 + \Delta CO_2)$$

The order of correction steps is outlined below. Which corrections shall be implemented in type approval needs to be discussed. Main questions are if the effort is balanced with the improvement in accuracy and if the quality of input data is sufficient to apply the correction[5].
1) Perform the WLTP test
Measured values necessary for application of the correction functions: CO_2 [g], distance [km], ΔSOC [kWh], Oil temperature at start [°C], instantaneous velocity [km/h] to compute average P_{wheel} [kW] per phase and a set of 3 coast down tests directly after the WLTC to calculate deviations in road load settings.

[5] the accuracy of the sensor signals should be approx. an order of magnitude higher than the tolerances which shall be corrected (e.g. < ±0.2°C sensor accuracy for a correction of ±3°C; to be discussed.

2) Correct test results for imbalances in battery SOC
3) Set up a vehicle specific Willans function from the SOC-corrected WLTC test data
4) Correct for deviation against target road load settings (can be combined with 5)
5) Correct for deviation against target speed and distance
6) Correct for deviation against target soak temperature
Further options for correction where still open questions exist are:

- Intake air temperature and humidity
- Quality of the test fuel

The following report describes the development of the correction functions and their application on chassis dyno test data.

Rotational inertia correction: Currently 3% of the unladen mass is assumed to be rotating inertia. This is at the lower end of the actual rotating inertia. Weighing the wheels and tyres and using 60% of the weight as rotational inertia yields a more appropriate result for the rotating inertia. Special care must be taken to compensate for the use of other wheels on the chassis dynamometer.

Relative humidity: Humid air is lighter than dry air at the same ambient pressure. This will affect the air drag during coast-down testing. The density of air must be compensated not only for pressure but also for water vapour content.

Rolling resistance coefficients: The rolling resistance coefficient of the tyre may not be a very accurate result, but it is the best available value to correct coast-down tests with different tyres. The rolling resistance must be corrected by the ratio of the class value, as described in the GTR text, and the actual test tyre value.

Tyre pressure during coast-down testing: The preconditioning prior to the coast-down test increases the tyre pressure. However, a large range in the tyre pressures remains. In part it is due to the test execution: intermediate driving, braking, bends, etc. In part it is due to circumstances, like sunlight, precipitation, road surface temperature, etc.. A third cause part is the design of tyres, wheels, and the radiative heat from the engine on the tyres. Some limitations are appropriate on the tyre pressure during coast down testing. For this the tyre pressure must be monitored.

Wind gusts: Wind gusts are common is all weather conditions except completely wind still weather (i.e., < 1.0 m/s wind speed). It is a major source of uncertainty in the coast down test results. In the time scale of “a” and “b” (forward and backward) tests the variation due to wind gusts cannot be controlled. Hence, measurement of the wind in conjunction with the timeline of the test execution should be reported to avoid utilization of this artefact. A proper on-board anemometry, synchronized with the velocity data could yield a robust correction method.

Road surface roughness: The variation in road surface roughness, in particular the mean profile depth (MPD), yielded a significant variation in rolling resistance. As yet it is unclear what would be an appropriate surface roughness representative for Europe. However, it is expected to be in the order of MPD ~ 1.5. Coast down testing on test tracks with MPD of 1.0 or less should be corrected for. VTI made a systematic study of the effect of MPD on rolling resistance. Their formula seems to be the best available means for correcting for testing on smooth road surfaces.

Wheel alignment: The typical toe-in and camber of the wheels, to improve vehicle dynamics, has a negative effect on the rolling resistance. The effect can be significant. If the manufacturer allows for a range of angles of the wheel alignment, the maximal deviation of the wheels from parallel settings should be used in the coast-down test.

Open settings: The grill vanes have a major effect on the air drag. It is difficult to control the settings during testing. The most open settings are most appropriate. Hence the grill-vane control should be disabled and the vanes should be set in the most open setting. Likewise, for all movable body parts with a possible flow through, the most open setting seems most appropriate for the coast down test. Also, open wheel caps are considered the most appropriate choice for the coast-down test.

Inhoudsopgave

1 Introduction

Type-approval testing of passenger cars and light-duty vehicles will have to allow for certain margins. The measurement equipment may have a limited accuracy. The settings of the testing equipment can be stepwise, not allowing for a very precise value setting. Furthermore, one should allow for margins for the operator driving the vehicle in the coast-down test and on the chassis dynamometer. An operator can follow a prescribed velocity profile only with a finite accuracy. Moreover, not all aspects of the vehicle can be specified or controlled during the test, yet they may influence the outcome. For example, the battery state of charge will vary during the test, with an associated energy buffering or discharging. Finally, ambient conditions, such as temperature, wind, and sun cannot be controlled, especially during the coast-down test.

Some corrections, for the variations in the test, are part of the WLTP. This study will extend the corrections to the main test variations expected to affect the test results. Furthermore, the corrections methods recovered here can be used to correct from the test result to the average European situation on the road, such as for wind, temperature, and road surface. There are some restrictions on how much can be corrected for, mainly from the lack of useful and accurate data on the situation at hand.

Recovering the important test variations and the resulting corrections are typically based on physical principles. The consequent corrections are typically robust for extreme cases. Correction methods solely based on test data may yield corrections for situations outside the range of test data which are of the mark. Polynomial fits of arbitrary order typically leads to such non-robust methods. The problem is avoided to the extreme: the methods are designed to be conservative and therefore robust.

The main physical concepts underlying coast-down testing are inertia and friction. Inertia can be divided in weight and rotation inertia. Friction can be divided in tyre friction, driveline friction, and air drag. In the following chapters these physical concepts decomposed to smallest aspects that can be quantified. However, the set-up of the report follows the underlying physical principles.

Perpendicular to the build-up from physical concepts are the variations that affect each of these parts. For example the ambient temperature will affect the air drag through air density and air viscosity. However, it will also affect the tyre temperature and tyre pressure. Moreover, it will affect the lubricant properties through its temperature. Also ambient temperature is not a simple concept as it initially is seen. The air temperature and the road surface temperature are two different things, both affecting the test. Also sunlight can lead to a higher temperature of dark surfaces than the ambient temperature, also a clear sky can yield excessive radiative heat losses of, in particular, metal surfaces, yielding a lower surface temperature than the ambient temperature. In this case the interplay with wind is not even considered. Following this train of thought the testing for variations in conditions will become infinitely complex, and rather academic than practical. In order to avoid this a few essential measurements are suggested to determine the net effect of all these complex processes.

Hence, the pinpoint measurements, suggested in this study, are meant to be handles at which conditions interplay with the test. In essence from all the conditions the properties are recovered and quantified that directly affect the test. If that is not possible, direct measurement of this property is proposed.

For example, the case of the complexity of temperature as explained above and tyre pressure, it is not possible to achieve an accurate tyre pressure, during the coast-down, from the ambient conditions and the warm-up procedure. Since tyre pressure affects to outcome of the coast-down test greatly, it is essential the pressure is properly monitored just before and after the test, minimally, and possibly in between if the test spans several hours.

1.1 Chassis dynamometer testing

The definition of a test cycle, such as the WLTP, grants for test parameters a certain degree of flexibility by specifying a set value and margins for allowed deviations, such as for the driving speed, ambient temperature/humidity, simulated road load, etc.. Some flexibility has to be allowed to perform a test under practical lab conditions. Since several of the parameters to which a flexibility is allowed influence the resulting fuel consumption in the test, the introduction of CO_2 limit values made it attractive for manufacturers to run tests rather at the more advantageous edge of the allowed tolerances to obtain lower CO_2 emission results. This certainly is a useless effort for real world CO_2 emissions of vehicles and just adds burden for manufacturer to design test procedures and to train drivers to obtain the best CO_2 results within the given flexibilities.
In the actual study the influence of parameters which have flexibilities in the chassis dynamometer test procedure have been analysed on their impact on the fuel consumption in the future WLTP test procedure. For parameters with reasonable influence correction algorithms have been elaborated which eliminate effects from deviations against the target settings of the test procedure to a large extent. Main parameters which can be corrected are:

- Imbalances in the State Of Charge of the battery before and after the test (ΔSOC)
- Deviations in oil temperature at test start against the target soak temperature (ΔT)
- Deviations against the target speed of the WLTC (Δv)
- Deviations against the target distance of the cycle (ΔD)
- Deviations against the target road load from the coast down [ΔP]

For each of these effects correction functions are proposed. The correction functions have been applied on chassis dynamometer test data from four passenger cars to test the efficiency of the correction. It was found that the repeatability is increased and that incentives to optimise test runs within the flexibilities seem to be drastically reduced when the correction functions have to be applied in future test procedures.

Additional parameters are analysed in this report but it was found that they have low influence on the results and/or the accuracy of sensors and of possible correction algorithms is not sufficient to increase the accuracy of the test result when the correction is applied. The approach for the work was based on the corrections developed by the EU for the future MAC energy efficiency test procedure (MAC 2011).

1.2 The physical principles of coast down testing

The coast-down test is performed to determine the forces needed to propel the vehicle forward at a certain velocity. This information is needed for the chassis dynamometer test of the emissions in the laboratory.

The simplest way to determine the resistance forces of the vehicle is to let it roll. Newton already noted that due to its weight the vehicle wants to stay in motion, the resistance slows it down. The balance between its weight, and the rate of slowing down gives the resistance:

$$F_{resistance} = M \Delta v / \Delta t$$

Where M is the weight, and Δv and Δt are the change in velocity and the time interval. The heavier the vehicle, the longer it takes to slow down. The higher the resistance $F_{resistance}$ for the faster the vehicle slows down.

The are other methods to determine the resistance of the vehicle, however, quite often they are either interfering with the free and independent operation, or they are determined indirectly from separate measurements. The viable alternative mentioned in the WLTP text is the use of a torquemeter, to determine the amount of power exerted by the engine to retain a constant velocity.

The sources of vehicle resistance are important to determine the soundness of the coast-down test protocol. The total resistance F can be separated in two major parts: the rolling resistance, dominated by the rolling resistance of the tyres, but with other minor contributions like drive-train losses, and the air drag of the vehicle. The rolling resistance is dominant at low velocities and the air drag is dominant at higher velocities. The rolling resistance is more or less proportional with the weight of the vehicles, while the air drag is globally proportional with the frontal surface area and vehicle speed squared. However, the drag coefficient c_D can vary substantially with the actual vehicle shape. The generic form of the resistance is therefore:

$$F_{resistance} = g * RRC * M + ½ \rho v^2 c_D A$$

Where g= 9.81 [m/s^2] the gravity, RRC the rolling resistance coefficient, M the vehicle weight [kg], ρ the air density [kg/m^3], and A the frontal area [m^2].
This generic form of the resistance has no linear dependency to vehicle speed. In practice an extra term linear to speed is needed to explain (fit) the observed coast down results. This extra term can be positive or negative for different vehicles, indicating there's no clear physical principle linked to. In EPA certification data of 2013 10% of the linear term (F1) in the equation below is negative.

$$F_{resistance} = F0 + F1\ v + F2\ v^2$$

where F0, F1, and F2 are determined from testing. The association of F0 and F1 with rolling resistance and F2 with air drag is only generic.

In this report the effects of the conditions which influence the road load determination are analysed. The global diagram of the aspects affecting the road load, or total resistance, are given in Figure 2.

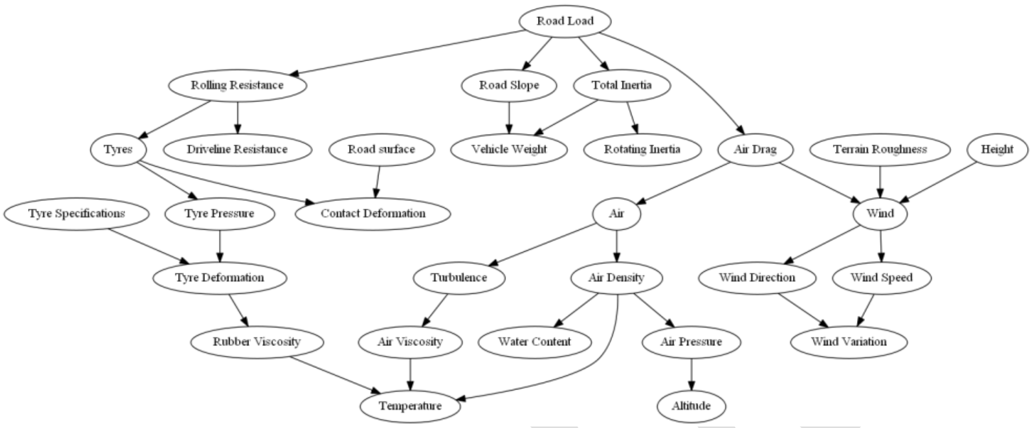

Figure 2 Global separation of conditions which affect the coast-down test results.

2 Correction algorithms for chassis dynamometer tests in WLTP

In the following for different parameters the influence on the CO_2 test result in the WLTP is assessed and options to correct for deviations of the parameter values against the WLTP targets are discussed. For each parameter a recommendation is given, if a correction shall be applied. For the parameters, where a correction is recommended the suggested correction algorithm is provided. The parameters have been identified in the beginning of the project.

1.1 Calculation of the vehicle specific Willans linear equation

Several options to set up the vehicle specific Willans line exist. One may correlate CO_2 and power based on instantaneous test data and separate positive and negative power values, if necessary the data may even be used to set up separate Willans lines per phase of the WLTC. Nevertheless the most stable approach for a type approval procedure seems to be the use of the bag data for CO_2 of the 4 WLTP phases and correlate them to the average power at the wheel in each corresponding phase with an equation of least square deviation.

It is open yet if the target road load values or if the road load coefficients from the coast down after the WLTP shall be used in this equation. The latter would be the logical approach if it shows that the coast down tests directly after the WLTP are representative for the forces at the wheel during the test. To answer this question further discussion with industry is suggested to get a broader view on different test stand behavior.

The SOC correction (see chapter 6) is done on phase per phase level, then the correction shall be applied before setting up the Willans line to eliminate eventually existing unequal imbalances between the phases which typically reduce the R^2 of the regression line.
Figure 3 shows the different options analyzed here to set up the vehicle Willans line from a WLTP tests. Using 1 Hz data is just for illustration and not recommended. Splitting the power range in positive and negative power values before calculating the linear regression gives slightly different Willans coefficients than just using the average power values per WLTP phase (0.188 g/kWs versus 0.192 g/kWs in Figure 3). Since splitting the power values would need to handle the instantaneous test data accurately, it is suggested to apply the simple option based on CO_2 bag data per WLTP phase and the corresponding average power at the wheel per phase.
If the average power shall be computed by the measured vehicle velocity and the road load values as follows:
$P_{(t)} = (R_0 + R_1 \cdot v + R_2 \cdot v^2 + m \cdot a) \cdot v$ [W]
Also phases with negative power are counted into the average power per phase:

$$P_{Phase-i} = \frac{\sum_{1}^{end_i} P_{(t)}}{t}$$

v........................... velocity driven in the WLTC

R_0, R_1 R_2 .... Road load from the coast down tests at the chassis dyno directly after the WLTC[6] in [N], [N*s/m] and [N*s²/m²]

m .... vehicle mass including also the translated rotational inertia of the wheels [kg]

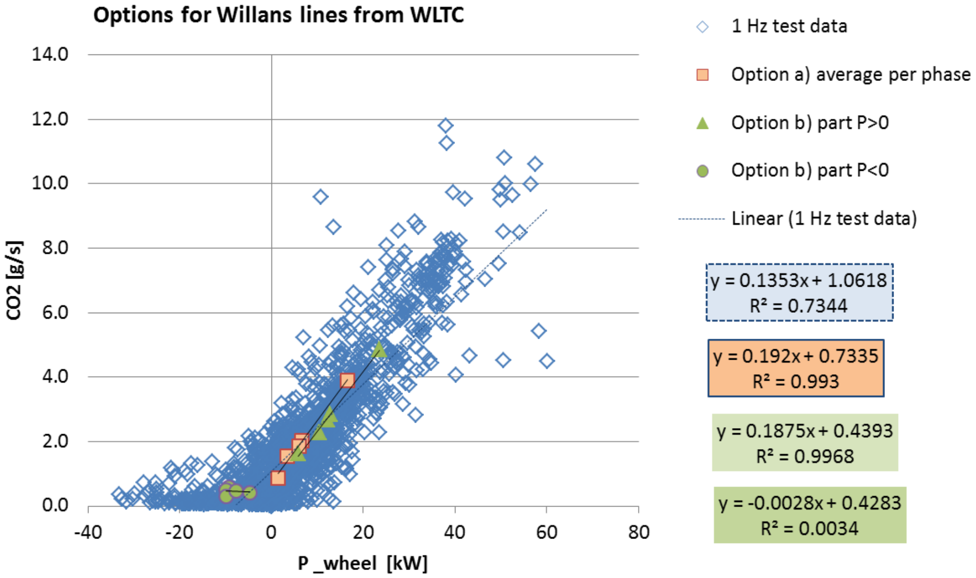

Figure 3: Schematic picture of setting up the Willans linear equation for a LDV from the chassis dyno test, where option a) is suggested as basis for the corrections

The result shall be the Willans linear equation for CO_2 (similarly for FC if demanded):

CO_2 [g/s] = $k_v * P_{wheel} + D$

With: D........................... Constant representing parasitic losses at engine speed that would result from a regression line with engine speed instead of CO_2 on the y-axis [g/s]

k_v .... Vehicle Willans coefficient, giving the change in CO_2 per change of power in the WLTC [g/kWs]

P_{wheel} .... power at the wheel hub (sum of driving resistances) [kW]

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[6] Needs further discussion and analysis, if this coast down test is representative for the WLTC test driven before. As alternative the target road load values shall be applied.

3 Deviation against target speed

Target: Check relevance of deviations against the target speed of the WLTC within the allowed tolerance and develop a method to correct for these deviations.
Method: simulation of effects from generic deviations in the cycle. Development of the correction function based on vehicle Willans coefficient.
Results: reasonable impact (approx. <2%) and reliable correction method seems to be found. Details may need further discussion, such as allowance of “sailing” without correction in these phases and also a combination with correction for deviations in road load simulation (chapter 8) with eventual further simplifications. The check of the accuracy of relevant sensors is open (to be completed)

3.1 Basic approach

Figure 4 shows a simple short part of a cycle with deviations against the target speed which would most likely give lower g/km for CO_2 than the target cycles. The deviation is separated into two different effects
a) Deviations at positive wheel power (or at wheel power above $P_{overrun}$). In the example in Figure 4 a too low speed and as a result a too low power occurs.
b) Deviations at negative wheel power (or at wheel power below $P_{overrun}$), where in Figure 4 a too long distance was driven at zero fuel flow.
In times with deceleration where the engine runs in overrun and additionally the mechanical brakes are active, small changes in velocity do not change the fuel flow which is zero there. Thus correcting such phases by the Willans function would be incorrect since it would correct here towards a “more negative power” and thus would result in a downward correction of CO_2 if the braking was less aggressive than the target. Since both values are zero in reality such a correction would be wrong. It seems to be clear that a correction by distance would be the correct approach for overrun phases, i.e. that exactly the target distance is driven with zero fuel consumption.
Applying the correction based on the vehicle Willans coefficient to the phases with power above overrun would shift the CO_2-level to the power necessary for following the target speed. If the velocity during positive power is in line with the target velocity the distance is automatically corrected to the target distance. Since also the distance in phases with negative power should be in line with the target distance, we can conclude that after correcting the positive power phases with the Willans approach the total cycle distance needs to be set to the target distance in calculating the final g/km value.

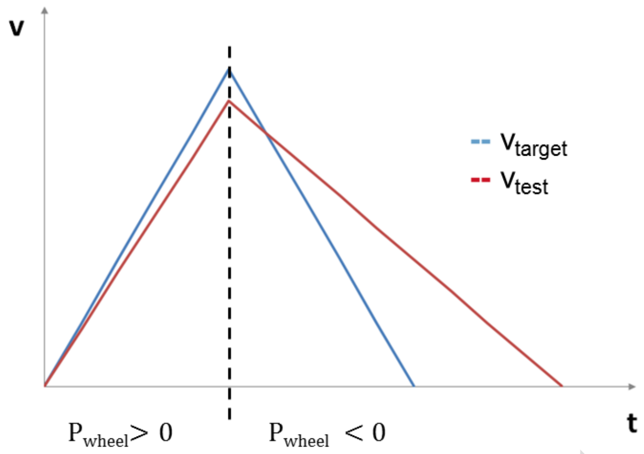

Figure 4: schematic picture of deviations against target speed

The correction method suggested thus is:
Calculation of the actual power for the driven vehicle velocity and for the target velocity in the WLTC:
$P_{(t)} = (R_0 + R_1*v+R_2*v^2 + m*a) * v$
$P_{w(t)} = (R_0 + R_1*v_w+R_2*v_w^2 + m*a_w) * v_w$
With v .... velocity driven in test in [m/s]
v_w .... target velocity of the WLTC in [m/s]
R_0, R_1, R_2.............. road load coefficients[7] in [N], [N*s/m], [N*s²/m²]
From the vehicle specific Willans line the power at zero fuel flow is computed:

$$P_{overrun} = -\frac{D}{k_v}$$

Then the work with power above $P_{overrun}$ is integrated to calculate the power relevant for the fuel flow:
If $P_{(t)} < P_{overrun}$ then $P_{(t)} = 0$
If $P_{w(t)} < P_{overrun}$ then $P_{w(t)} = 0$

$$W_{pos} = \int_1^{1800} P_{(t)} dt \quad \text{and} \quad W_{w-pos} = \int_1^{1800} P_{w(t)} dt$$

Then the difference in the positive cycle work values is calculated[8]:
$\Delta W_{wheel} = (W_{w\_pos} - W_{pos}) \times 0.001$ in [kWs]
Then the vehicle based Willans function is applied to correct for deviations against the average power from the WLTC target velocity

$$\Delta CO_{2_v}\,[g] = \Delta W_{wheel} * k_v$$

With k_v .... Vehicle Willans coefficient [g_{CO2}/kWs] from WLTP result after SOC correction.

<u>Deviation against target distance</u>: The correction for deviations against target speed covers the time shares in WLTP with positive wheel power (or power above "$P_{overrun}$", as shown in Figure 1). Thus in these times the power is shifted to the power necessary to meet the target velocity. Nevertheless, by braking more or less aggressive than the target decelerations, the distance can be varied by the driver

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[7] If the correction is combined with the correction for deviations in the road load the road load coefficients from the coast down test at the chassis dyno shall be applied for $P_{(t)}$ as outlined in the summary.
[8] The steps above can similarly be computed based on average power, as outlined in the summary.

without effect on the total WLT fuel consumption [g] since in these phases the engine is most of the time in overrun at zero fuel flow. Thus dividing the entire fuel consumption in the test in [g] after correction for deviations against positive power due to deviations against target speed gives a result without offset from brake behaviour of the driver:

$$CO_2[g/km] = \frac{CO_{2_{measured}} + \Delta CO_{2_{SOC}} + \Delta CO_{2_v}}{23.27}$$

With $CO2_{measured}$............ CO_2 test result in the WLTP in [g/test]
23.27 .... WLT target test distance [km]

3.2 Assessment of influence on CO_2

Beside analysing the correction effects on real chassis dyno tests also simulation runs have been performed to test possible magnitudes of driver influences since the drivers at TUG are yet not trained to follow CO_2 optimised WLTC velocities. Figure 5 shows the target cycle of the WLTC high speed part and a cycle with deviation (lower velocity with longer braking phases). The fuel consumption and CO_2 emissions were simulated with PHEM for a generic EURO 6 diesel class C car from (Hausberger, 2014). The “low CO_2 velocity gave 1.1% lower CO_2 emissions in this phase of the WLTC. Since no routine for the optimisation of the driven velocity for the WLTC exists at TUG yet, no further variations for the entire WLTC have been performed. A magnitude of 1% deviation in CO_2 test result may be used as a first estimation for further discussion of the potential influence of speed optimised driver behaviour.

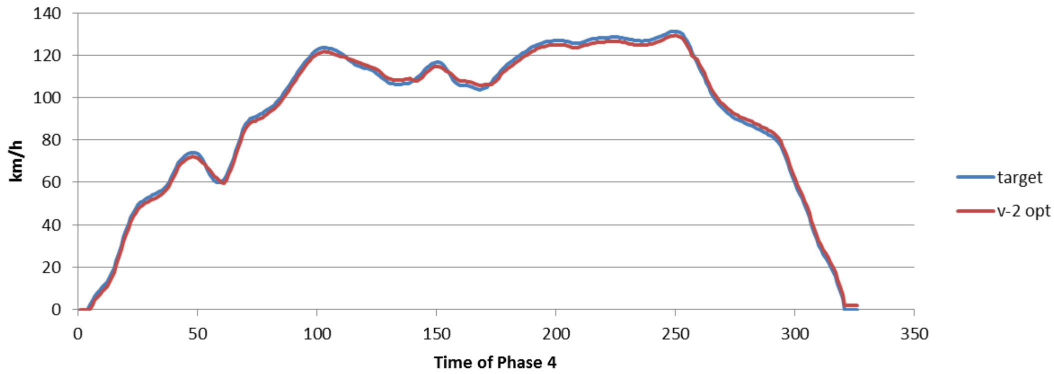


Figure 5: velocity deviation simulated with the tool PHEM for a class C car with diesel engine

Results from the real tests analysed in chapter 1.6 give a maximum influence of the correction for deviations against target speed of 2.1% for all tests where the velocity met the tolerances.

4 Quality of reference fuel

Target: Check relevance of variations in the reference fuel properties on the CO2 emission result and develop options for correction.
Method: Effect on CO_2 emissions computed from energy specific Carbon content of the fuel [kg_C/kWh]. Analysis of relevance still open (no information on variability of C/H ratios found for fuels which meet the given ranges for reference fuels).
Results: impact unknown yet. Correction is possible if C/H ratio and C/O ratio of test fuel known.

4.1 Correction method

The CO_2 emissions in the test cycle depend on the energy specific Carbon content of the test fuel in [kg C/kWh]. If the mechanical work of the engine as well as the engine efficiency over the test cycle is seen as fixed value for a given vehicle, the CO_2 emissions result from the oxidation of the Carbon and have the value

$$\boldsymbol{CO_2[g]} = \frac{\boldsymbol{W_{w-pos}}}{\text{Efficiency}_{Engine}} \times \frac{\mathbf{1}}{\mathbf{3600}} \times \left(\frac{\boldsymbol{kg_C}}{\boldsymbol{kWh}}\right)_{\boldsymbol{fuel}} \times \frac{\mathbf{44}}{\mathbf{12}}$$

With W_{W-pos} positive engine work in [kWs] as outlined before
A correction for fuel properties thus would consequently correct the measured CO_2 value to the energy specific Carbon content of the reference test fuel:

$$\Delta \boldsymbol{CO_{2_f}} = \frac{(\boldsymbol{kg_C/kWh})_{\boldsymbol{reference}}}{(\boldsymbol{kg_C/kWh})_{\boldsymbol{test\ fuel}}}$$

The correction factor could be directly applied to the measured CO_2 value where it is irrelevant if the correction is done at the beginning or at the end of all other corrections.

$$\boldsymbol{CO_2[g/km]} = \boldsymbol{CO_{2_{measured}}} \times \Delta \boldsymbol{CO_{2_f}}$$

The energy specific Carbon content of the fuel mainly depends on the C/H ratio in the fuel. Driving with pure Hydrogen would results in zero CO_2 emissions while pure Carbon would result in the highest specific CO_2 emissions.
The target fuel quality could be set up from the ECE R101 with the H/C ratios mentioned in 5.2.4 (Table 1). The heating value of liquid fuel may be calculated for liquid fuels according to simplified Thermodynamic Enthalpies, e.g. according to Boie, e.g. (IVT, 2013):

$$\boldsymbol{H_u} = \mathbf{9.676} \times \boldsymbol{m\%_C} + \mathbf{26.075} \times \boldsymbol{m\%_H} + \mathbf{1.744} \times \boldsymbol{m\%_N} - \mathbf{3.0} \times \boldsymbol{m\%_O} - \mathbf{0.678} \times \boldsymbol{m\%_{H2O}}$$

With H_u......................... Lower heating value of the fuel [kWh/kg]
$m\%_i$...................... mass fraction of component i in the fuel

Table 1: Possible specification for the reference fuel properties

Fuel	fuel components	mass % C	mass % H	mass % O	mass % total	Hu [kWh/kg]	kg CO_2/ kWh fuel
Source	ECE R101	Calc. from components				calc. Boie	Calc.
Gasoline	$C_1 H_{1.89} O_{0.016}$	0.8483	0.1336	0.0181	1.00	11.64	0.267
Diesel	$C_1 H_{1.86} O_{0.016}$	0.8501	0.1318	0.0181	1.00	11.61	0.268

Neglecting the usually minor effects of Nitrogen and Water content the energy specific CO_2 value of any liquid fuel could be calculated with known mass fractions of C, H and O. The fuel correction factor – i.e. the energy specific CO_2 value of the reference fuel divided by the energy specific CO_2 value of the test fuel as defined above – can be calculated from:

$$\Delta CO_{2_f} = \frac{(kg_C/kWh)_{reference} \times (9.676 \times m\%_C + 26.075 \times m\%_H - 3.0 \times m\%_O)}{m\%_{C_{test\ fuel}}}$$

Although the correction is a simple function, the data relevant for the application of this function seems not to be directly available from the type approval demands on the test fuel for all fuels. Table 2 and Table 3 summarize the actual fuel properties from the WLTP (UN ECE, 2013) for B10 and D7. It seems that for E10 reference fuel the C/H and C/O ratio shall be reported. These ratios would be sufficient to calculate the mass fractions. For B7 and several other fuels the C/H and C/O ratios are not demanded.
The determination of C, H, and N content can be performed by elemental analysis which is based on following principle: combustion of the sample resulting in CO_2, H_2O and a mixture of N_2 and NO_x. NO_x is further reduced by Cu to N_2. The resulting gases are adsorbed, consecutively desorbed and quantitatively determined by a thermal-conductivity detector. Oxygen is not covered but can be indirectly determined (if no other hetero-atoms are present in the sample) as 100% - sum of C, H, N. The costs of such measurement seem not to be high, if one test per charge of test fuel delivered by the supplier is demanded.

Table 2: Example for E10 fuel specification for LDV chassis dyno tests from WLTP, Annex 3

3.6. Gasoline/petrol (nominal 95 RON, E10)

Table A3/6

Gasoline/petrol (nominal 95 RON, E10)

Parameter	*Unit*	*Limits* (1)		*Test method* (2)
		Minimum	*Maximum*	
Research octane number, RON (3)		95.0	98.0	EN ISO 5164
Motor octane number, MON (3)		85.0		EN ISO 5163
Density at 15 °C	kg/m^3	743	756	EN ISO 12185
Vapour pressure	kPa	56.0	60.0	EN 13016-1
Water content	% v/v	max 0.05 Appearance at -7°C: clear and bright		EN 12937
Distillation:				
— evaporated at 70 °C	% v/v	34.0	44.0	EN-ISO 3405
— evaporated at 100 °C	% v/v	54.0	60.0	EN-ISO 3405
— evaporated at 150 °C	% v/v	86.0	90.0	EN-ISO 3405
— final boiling point	°C	170	210	EN-ISO 3405
Residue	% v/v		2.0	EN-ISO 3405
Hydrocarbon analysis:				
— olefins	% v/v	6.0	13.0	
— aromatics	% v/v	25.0	35.0	EN 22854
— benzene	% v/v		1.0	EN 22854 EN 238
— saturates	% v/v	Report		EN 22854
Carbon/hydrogen ratio		Report		
Carbon/oxygen ratio		Report		
Induction period (4)	minutes	480		EN-ISO 7536
Oxygen content (5)	% m/m	3.3	3.7	EN 22854
Solvent washed gum (Existent gum content)	mg/100ml		4	EN-ISO 6246
Sulphur content (6)	mg/kg		10	EN ISO 20846 EN ISO 20884
Copper corrosion			Class 1	EN-ISO 2160
Lead content	mg/l		5	EN 237
Phosphorus content (7)	mg/l		1.3	ASTM D 3231
Ethanol (5)	% v/v	9.0	10.0	EN 22854

(1) The values quoted in the specifications are 'true values'. In establishment of their limit values the terms of ISO 4259 Petroleum products - Determination and application of precision data in relation to methods of test have been applied and in fixing a minimum value, a minimum difference of 2R above zero has been taken into account; in fixing a maximum and minimum value, the minimum difference is 4R (R = reproducibility).
Notwithstanding this measure, which is necessary for technical reasons, the manufacturer of fuels shall nevertheless aim at a zero value where the stipulated maximum value is 2R and at the mean value in the case of quotations of maximum and minimum limits. Should it be necessary to clarify whether a fuel meets the requirements of the specifications, the terms of ISO 4259 shall be applied.

(2) Equivalent EN/ISO methods will be adopted when issued for properties listed above.

(3) A correction factor of 0.2 for MON and RON shall be subtracted for the calculation of the final result in accordance with EN 228:2008.

(4) The fuel may contain oxidation inhibitors and metal deactivators normally used to stabilise refinery gasoline streams, but detergent/dispersive additives and solvent oils shall not be added.

(5) Ethanol is the only oxygenate that shall be intentionally added to the reference fuel. The Ethanol used shall conform to EN 15376.

(6) The actual sulphur content of the fuel used for the Type 1 test shall be reported.

(7) There shall be no intentional addition of compounds containing phosphorus, iron, manganese, or lead to this reference fuel.

Table 3: Example for B7 fuel specification for LDV chassis dyno tests from WLTP, Annex 3

5.4. E-Diesel (nominal 52 Cetane, B7)

Table A3/16
E-Diesel (nominal 52 Cetane, B7)

Parameter	*Unit*	*Limits* [1]		*Test method*
		Minimum	*Maximum*	
Cetane Index		46.0		EN-ISO 4264
Cetane number [2]		52.0	56.0	EN-ISO 5165
Density at 15 °C	kg/m^3	833.0	837.0	EN-ISO 3675
Distillation:				
— 50 % point	°C	245.0	—	EN-ISO 3405
— 95 % point	°C	345.0	360.0	EN-ISO 3405
— final boiling point	°C	—	370.0	EN-ISO 3405
Flash point	°C	55	—	EN 22719
Cloud point	°C	—	-10	EN 116
Viscosity at 40 °C	mm^2/s	2.30	3.30	EN-ISO 3104
Polycyclic aromatic hydrocarbons	% m/m	2.0	4.0	EN 12916
Sulphur content	mg/kg	—	10.0	EN ISO 20846/ EN ISO 20884
Copper corrosion		—	Class 1	EN-ISO 2160
Conradson carbon residue (10 % DR)	% m/m	—	0.20	EN-ISO10370
Ash content	% m/m	—	0.010	EN-ISO 6245
Total contamination	mg/kg		24	
Water content	mg/kg	—	200	EN-ISO12937
Acid number	mg KOH/g	—	0.10	ASTM D 974
Lubricity (HFRR wear scan diameter at 60 °C)	µm	—	400	EN ISO 12156
Oxidation stability at 110 °C [3]	h	20.0		EN 14112
FAME [4]	% v/v	6.0	7.0	EN 14078

(1) The values quoted in the specifications are 'true values'. In establishment of their limit values the terms of ISO 4259 Petroleum products – Determination and application of precision data in relation to methods of test have been applied and in fixing a minimum value, a minimum difference of 2R above zero has been taken into account; in fixing a maximum and minimum value, the minimum difference is 4R (R = reproducibility).
Notwithstanding this measure, which is necessary for technical reasons, the manufacturer of fuels shall nevertheless aim at a zero value where the stipulated maximum value is 2R and at the mean value in the case of quotations of maximum and minimum limits. Should it be necessary to clarify whether a fuel meets the requirements of the specifications, the terms of ISO 4259 shall be applied.

(2) The range for cetane number is not in accordance with the requirements of a minimum range of 4R. However, in the case of a dispute between fuel supplier and fuel user, the terms of ISO 4259 may be used to resolve such disputes provided replicate measurements, of sufficient number to archive the necessary precision, are made in preference to single determinations.

(3) Even though oxidation stability is controlled, it is likely that shelf life will be limited. Advice shall be sought from the supplier as to storage conditions and life.

(4) FAME content to meet the specification of EN 14214.

To be completed if more info on fuel properties is found

4.2 Analysis of relevance

Analysis of relevance should be based on the possible variability of C/H and C/O ratios found for fuels which meet the ranges for reference fuels given in the WLTP annex 3.
Update planned, if information becomes available.

5 Inlet air temperature and humidity

Target: Check relevance of humidity and temperature of the intake air for the engine. If relevant, correct for combustion efficiency variations with ambient air conditions.
Method: detailed simulation of combustion and measurement for validation.
Results: low impact found for diesel (<0.1%) and higher impact for gasoline (<2%) but relative high uncertainty in the effects and also in the relevant sensor signals (representativeness of T and RH as well as accuracy of RH, see chapter 1.4).
Actual WLTP boundaries analyzed: 5.5 to 12.2 g_{Water}/kg_{air} and 296K ± 5K (temperature tolerances during the test).

5.1 Simulation of the effect

The modelling exercise was done for a modern 2 liter diesel engine with the software AVL Boost. Following conditions have been simulated:

- Constant load at: 2000rpm, BMEP~2bar
- VTG controlled turbocharger
- EGR for following variants:
  a) automatic control deactivated
  b) control to constant air flow (usual engine operation mode)
- Charge air: coolant temperature kept constant

In total 10 different combinations of intake air temperature (+/- 2°C against a base temperature of 27°C) and intake air humidity (25% and 45% RH) have been simulated. Table 4 and Figure 6 show the results for active EGR and VTG controllers, which should depicture real conditions well. As expected the lower humidity results in higher engine efficiency. The simulation shows on average -0.04% BSFC for 25% RH compared to 45% RH. Having the rather inaccurate Humidity sensors in mind which may also be placed in a not completely representative location in the test cell, the results do not suggest that a correction of RH would improve the quality of the test results. The intake air temperature influences the BSFC in the simulation by approx. +/-0.05% when the temperature is changed by +/- 2°C[9]. The results with deactivated EGR and VTG controller showed even lower effects from temperature and RH on the BSFC.

Table 4: results from the engine simulation for a modern 2 litre diesel engine with variation of intake air temperature and humidity at 2000rpm and BMEP~2bar with active EGR and VTG control

Intake air			BSFC	Change to base (1)
[°C]	RH	X [g/kg]	[g/kWh]	
25	25%	4.9	276.18	-0.09%
26	25%	5.2	276.21	-0.08%
27	25%	5.5	276.29	-0.05%
28	25%	5.9	276.4	-0.01%

[9] The increase of intake air temperature reduces the air density and thus gives slightly lower air to fuel ratio which has then slightly negative impact on the efficiency.

29	25%	6.2	276.47	0.02%
Avg. @25% RH		5.5	276.31	-0.04%
25	45%	8.9	276.27	-0.05%
26	45%	9.4	276.36	-0.02%
27	45%	10.0	276.42	0.00%
28	45%	10.6	276.49	0.03%
29	45%	11.3	276.59	0.06%
Avg. @45% RH		10.0	276.426	0.00%
Effect of +1°C intake air				0.03%
Effect of +1% RH intake air (2)				0.002%
Effect of +1g/kg absolute humidity				0.009%

(1) base value set here at 27°C, 45RH[10]

(2) if a correction function for Humidity shall be installed, the correction shall be based rather on absolute water content (x = kg_{H2O}/kg_{air})

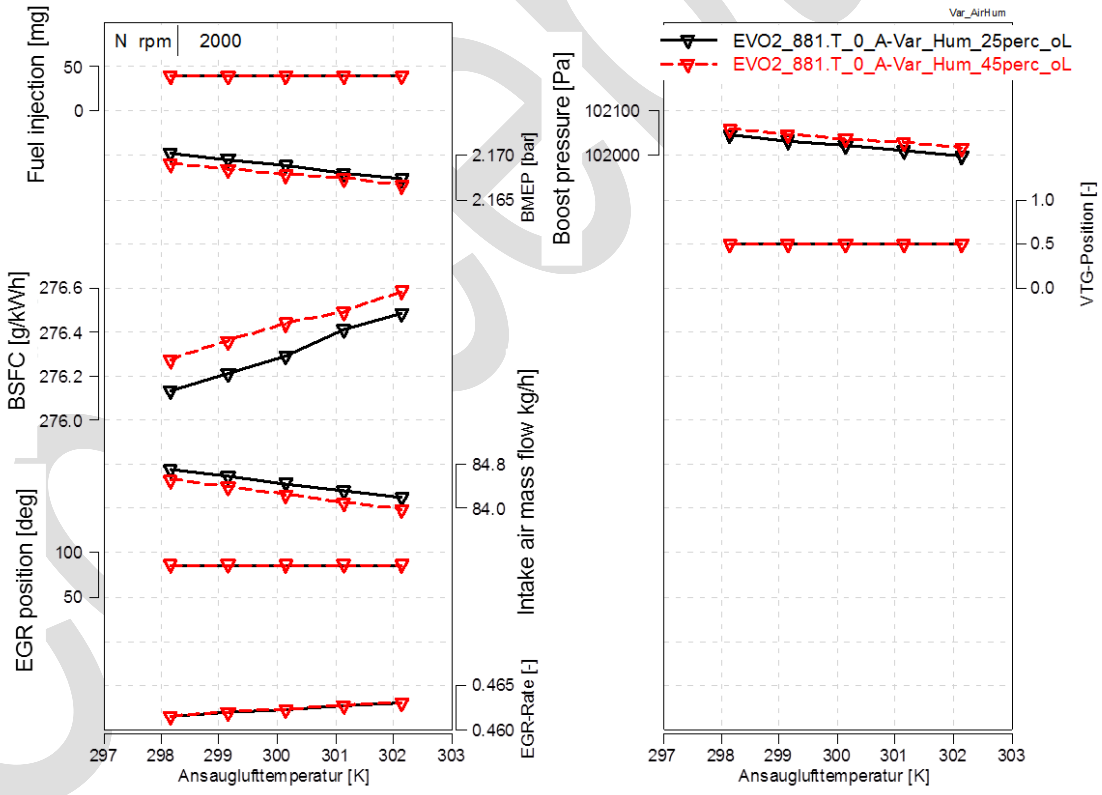


Figure 6: results from the engine simulation for a modern 2 litre diesel engine with variation of intake air temperature and humidity at 2000rpm and BMEP~2bar with active EGR and VTG control

[10] In the first phase of the project the target temperature in the WLTP was not defined. The effect for the actual WLTP target of 23°C ± 2°C however should be similar as for 27°C +/-2°C

5.2 Measurements

After analysing the effects for diesel only minor effects have been expected for gasoline cars too, thus not much emphasis was put to variations of intake air conditions in the vehicle tests. Since no suitable engine simulation model was available for the study measurements at vehicle No 3 have been performed (gasoline EU5). The NEDC was driven with hot start once with standard intake air temperatures and once with high intake air temperature and low humidity. The directly measured CO_2 emissions indicated that the influence of the variation in humidity and temperature is low (-0.5% for the test at 35°C). However, after applying all other corrections, the temperature effect was founded to be rather larger with -1.5% for a change of 10°C and 1.8 g/kg humidity[11]. A separation into humidity and temperature effects is hardly possible due to the few variations tested for humidity. The allowed tolerances (3K and 3.35 g/kg humidity) against the average of the thresholds would have an influence in the range of ±2% on the CO_2 emissions if temperature increases at reduced absolute humidity.
It has to be noticed, that the uncertainty in the findings based on just one tested vehicle are large. Before applying the correction, certainly more tests on gasoline but also diesel cars are necessary.

Table 5: Test results for Veh. No. 3 in the NEDC with hot start at 2 different set points for intake air conditions

			CO_2/km			
Tair [°C]	RH [%]	Humidity [g/kg]	measured	SOC-corrected	SOC+T-start+P+D corrected	Change against 25°C @47%RH
25	47.0%	9.3	129.26	134.89	133.79	0.0%
35	22.0%	7.7	128.00	133.24	131.94	-1.4%
35	21.0%	7.3	128.33	133.47	131.69	-1.6%
25	47.0%	9.3	128.29	134.65	133.81	0.0%
Average 25°C @ 47.0%		9.3	128.78	134.77	133.80	0.0%
Average 35°C @ 21.5%		7.5	128.17	133.36	131.82	-1.5%
Effect per +1°C						-0.15%
Effect per 1 g/kg increase						0.5% (1)

(1) High uncertainty due to insufficient variations tested for humidity

[11] For Otto engines certainly different mechanism have to be considered than for diesel engines. With Lambda=1 control the effect of varying air to fuel ratio has not relevance and the lower air density at higher temperature can reduce the throttling losses. In addition a higher combustion temperature tends to improve the efficiency. Nevertheless, order of magnitude of the effect measured at vehicle No. 3 seems to be quationable.

6 Battery state of charge

Target: Check relevance of imbalances in the battery stage of charge and develop correction functions.
Method: Calculation of imbalanced electric work of the alternator from measured Current flow from and to battery and correct with engine specific Willans function and efficiencies of the alternator.
Results: rather high impact (approx. 3g/km possible) and correction function found with reasonable uncertainties (generic efficiency of alternator and generic engine Willans coefficient). In the actual WLTP the effect is restricted to 0.5% electric energy of the fuel energy for the entire WLTC. With average efficiencies of the alternator and the Willans coefficients given in the WLTP the 0.5% limit corresponds to less than 2g CO_2/km.

6.1 Magnitude of the influence

The imbalance in battery can have a quite high influence on the test result although only auxiliaries are consuming energy which are necessary to run the car. Assuming an average basic electrical load for basic devices of maximum 300W an imbalance of 150 Wh would occur if the energy is taken from the battery only. With an alternator efficiency of 65% and a WIllans coefficient of the engine of 600g CO_2/kWh the effect of such an imbalance would be more than 3 g/km in the WLTC. If the test is started with empty battery and the alternator controller algorithm leads to a battery loading over the cycle the effect can be much higher. Similarly a start with full battery can lead to a discharging at the beginning to provide capacity for eventual following brake energy recuperation, e.g. Figure 7.

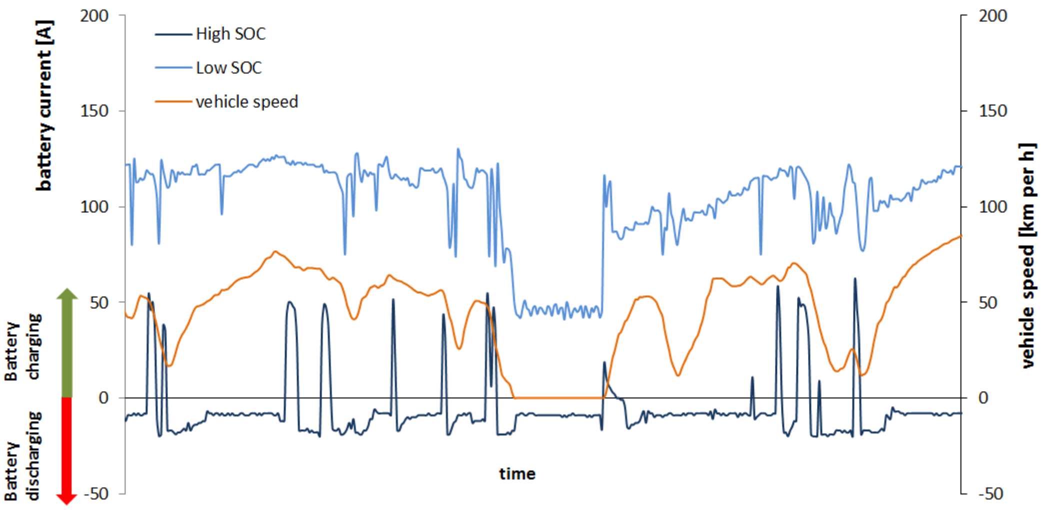


Figure 7: SOC of the battery from a passenger car over a part of the WLTC once started with empty battery and once with full battery

A test started with empty battery lead to more than 20% higher CO_2 emissions per km in the WLTC (chapter 1.6) but such test conditions will hardly occur within the WLTP regulation. When the battery is charged before the preconditioning test cycle, the SOC at the end of the test is expected to be for most vehicles already on a normal level which shall not lead to such large SOC imbalances in the subsequent test.

6.2 Option for correction of SOC imbalances

The correction for SOC imbalances can either be based on the vehicle specific Willans coefficient (k_v in g/kWh) or on generic ones. Since the vehicle based Willans factors are related to the work at the wheel they would have to be converted into engine work based values by division by the transmission efficiency. Since the latter is not known from the chassis dyno test, a generic efficiency would have to be assumed for different transmission systems. As a consequence of high differences which can be found in the efficiencies from different transmission systems (manual and automatic) it seems to be strait forward to use generic engine Willans factors.
This gives the following correction method:
Calculate the imbalance of energy flow from and to the battery:
a) simple option: $W_{bat} = \int U_{(t)} * I_{(t)} * 0.001 \; dt$ in [kWs] with Current flow from the battery counted with positive sign
The Voltage could also be a generic value of nominal Voltage as suggested in the WLTP draft. For higher accuracy we may also consider the charging and discharging losses which lead to the fact that the battery SOC is reduced if the same electric energy is consumed from the battery as was charged before. This would lead to the more detailed approach:
b) more detailed option:
$W_{bat-charge} = \int U_{(t)} * I_{charge(t)} * 0.001 \; dt$ in [kWs] counting only Current to battery
$W_{bat-discharge} = \int U_{(t)} * I_{discharge(t)} * 0.001 \; dt$ in [kWs] counting only Current from battery
$W_{bat} = W_{bat-discharge} - (W_{bat-charge} \times \eta_{bat})$ in [kWs]
With η_{Bat}.............. efficiency of charging and discharging (η_{charge} x $\eta_{discharge}$) For a typical battery systems the η can be assumed with generic values. Draft examples are shown in Table 6.

Table 6: Draft generic combined charge & discharge efficiencies

	Efficiency [%]
Pb	87%
Ni-Mh	90%
Li-Ion	97%

Calculate the CO_2 correction value from the battery imbalance:

$$\Delta CO_{2_{SOC}} \text{ [g]} = \frac{W_{bat}}{\eta_{Alt}} * k_e$$

With k_e Engine Willans coefficient [g_{CO2}/kWs], generic values per engine technology
η_{Alt}.............. Generic average efficiency of the alternator including transmission losses to the engine (in WLTP draft an efficiency of 0.67 is suggested. This value is in line with the results from a simulation with the model PHEM using alternator efficiency maps)

The correction shall be done for each WLTC phase separately, if a more accurate base shall be provided for setting up the vehicle specific Willans linear functions from the SOC corrected WLTP results. This is more relevant, if the test is started with low SOC since the vehicle then tends to load the battery from start on, which influences mainly the first test phase.
An open question concerning the engine Willans coefficient "k_e" is if and how the behaviour of smart alternator controllers shall be considered. Basically modern alternators are loading the battery at engine overrun conditions (brake energy recuperation). Thus a negative battery energy balance can be attributed mainly to a too low activity of the alternator in phases with positive engine work. Similarly a positive SOC balance should result rather from extra alternator activity at phases with positive engine power[12]. If we consider this effect, the correction would have to be done with the coefficient of a Willans line which is established from test phases with positive engine power only. At the moment it is not clarified, if the Willans coefficients given in the WLTP (UN ECE, 2014) have been set up from the average power including negative power values or from the positive power only (needs to be clarified with ACEA).
From the vehicle based Willans coefficients the difference between the regression including also negative power in averaging the power per phase and the regression using only the average positive power is small (some 5% deviation in k_v)

[12] Certainly the amount of brake energy recuperated depends on the alternator power installed.

7 Temperatures from preconditioning and soak

Target: Check relevance of the temperature during soak and preconditioning. If relevant, correct for temperature conditions.
Method: analysis of dependency of friction losses and of fuel consumption as function of oil temperature and measurement at different temperatures at the chassis dynamometer
Results: approx. <0.4% impact on CO_2 emission result for 2°C deviation against the target temperature. Generic correction is possible but would need measurement of oil temperature at test start[13].

1.1.1 Measurements

The influence of variable temperature at test start was found to be a reasonable influencing factor for the resulting fuel consumption. Nevertheless, the rather stringent limitation of +/-3°C of cell ambient temperature and +/-3°C for the lube oil of the vehicle as described in the WLTP draft also limits the effect of deviations against the target temperature as long as the deviations are within the allowed boundaries.
The temperature influences the friction losses but also the combustion efficiency. The combustion efficiency is influenced by the cooler cylinder walls, by different intake air density (see chapter 5) and by the control algorithms applied by the manufacturer for EGR, VTG and injection timing during heat up. The control strategies may vary between makes and models, thus a correction function could either consider only general valid effects or take combustion efficiency matters into consideration as generic average function.
Analysis of existing measurements at engine test stands at TUG for friction losses as function of the oil temperature showed that the friction losses at the engine explain by far not the entire additional fuel consumption at cold starts. Similar tests on the transmission system and at bear rings to get a complete view on friction related losses as function of oil temperature were not available. The idea was, to define generic additional friction losses in the engine and in the transmission as function of the start temperature to compute the additional work the engine needs to deliver per °C deviation against the target start temperature. With the engine Willans coefficients the effect on the fuel consumption could be calculated. This approach was tested as option to exclude eventual effects from differences in engine control at different start temperatures. Figure 8 shows results from an engine test at steady state conditions. In the end the uncertainties in assuming the losses in the transmission proofed to be too high to follow this approach.

[13] Taking the average cell temperature over e.g. last hour of soaking would add reasonable uncertainties since temperature at start depends on temperature course over hours with different weighting of temperature over time.

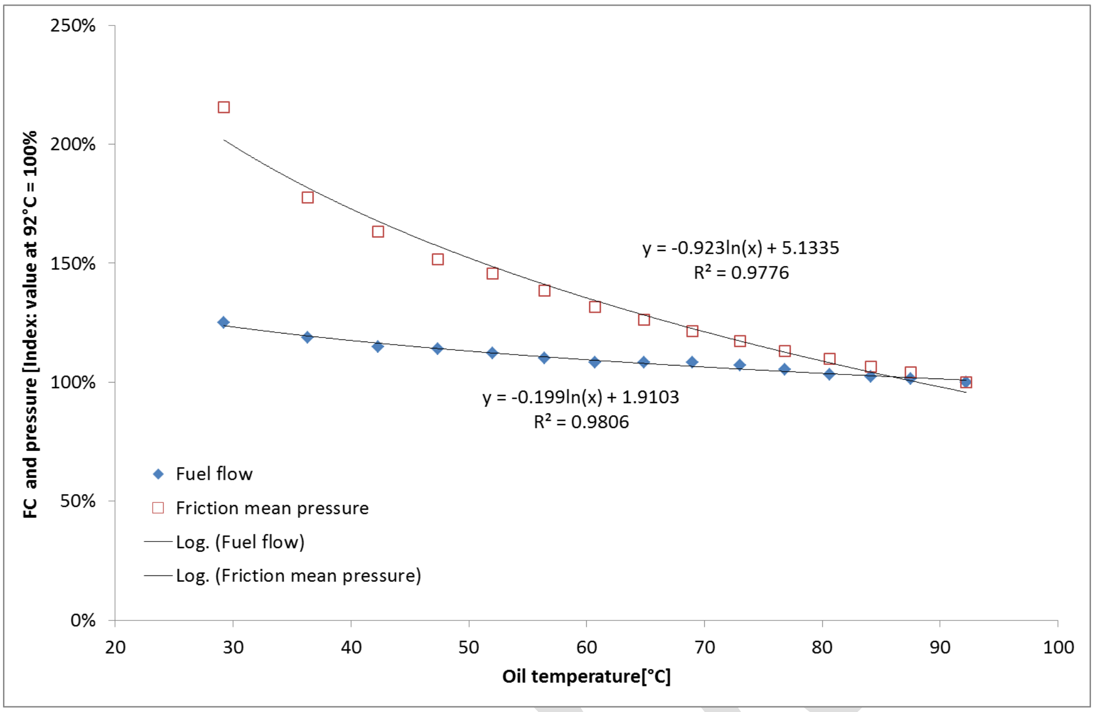


Figure 8: test data of a constant load point for a 2 litre diesel engine at 2 bar and 2000 rpm

As alternative tests have been conducted on the chassis dynamometer at differing soak temperatures and the additional fuel consumption to reach 90°C oil temperature has been computed by comparison with hot start tests. Table 7 shows test results at vehicle No.2.

Table 7: test results in WLTC at different start temperatures with vehicle No1

	Oil temperature at test start	Fuel consumption	Additional consumption against cold start
	[°C]	[l/100km]	[%]
WLTC Cold start	28.6	5.58	6.4
WLTC Cold start	28.6	5.55	5.9
WLTC Cold start	24.7	5.61	7.0
WLTC Cold start	24.5	5.58	6.5
WLTC Cold start	22.4	5.61	7.1
WLTC Cold start	22.7	5.64	7.7
WLTC Cold start	11.7	5.80	10.6
WLTC Warmstart	90.0	5.24	0.0

The results from the engine test in Figure 8 suggest that a correction function cold follow a logarithmic function. Certainly the range of 23°C +/- 2°C could be approximated by a linear equation also without losing accuracy. Figure 9 shows the resulting regression function for vehicle no. 2.

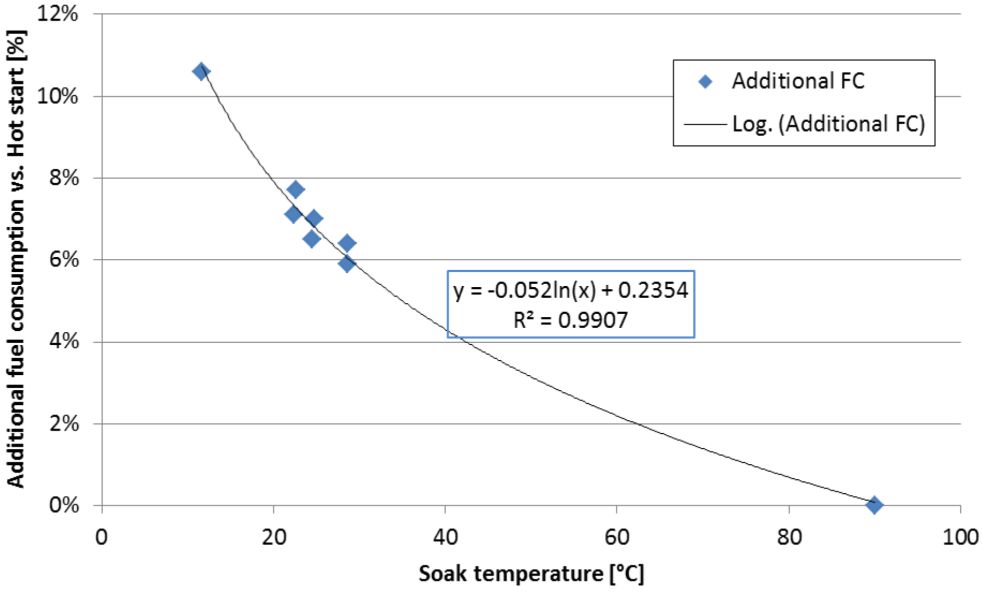


Figure 9: additional fuel consumption against hot start conditions as function of oil temperature for vehicle No. 2 in the WLTC

If just the difference at different start temperatures shall be calculated, the logarithmic equation from Figure 9 results in:

Equation 1: $\Delta FC = -0.052 * ln\left(\frac{t}{t_{ref}}\right)$

t_{ref}................ WLTP target temperature (23°C)

Similar tests have been performed with vehicle no. 3 (gasoline EURO 5), which gave lower effects of the soak temperature.
To base the correction function on a larger data base of vehicles, test data from the ERMES data base was used (http://www.ermes-group.eu/web/), which is also the base data for HBEFA and COPERT emission models. The data base includes for several EURO 5 and EURO 6 cars hot and cold start NEDC tests (no WLTC yet). To convert cold start extra emission influences, the percent extra emissions of the NEDC have been multiplied with 2/3 to compensate the longer duration of the WLTC (1800 sec versus 1200 seconds). Then logarithmic regression curves have been computed to fit the two test values per car (cold start temperature and hot start). The final correction in the range of 23°C ±2°C was then fitted as linear function on top of the results from the logarithmic regression line in this temperature range as shown in Figure 10.

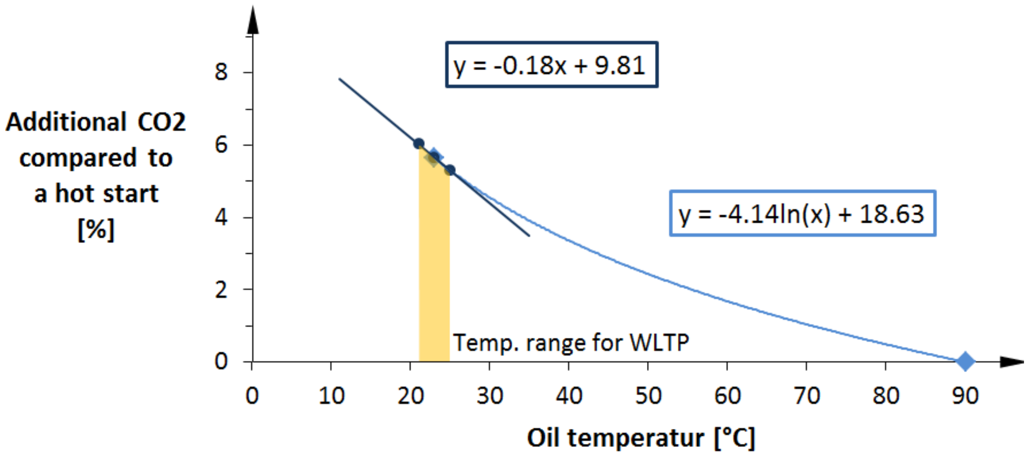


Figure 10: schematic picture of the method to compute the soak temperature influence from hot and cold start tests

Table 8 shows the vehicles which have been used for setting up the correction function.

Table 8: vehicles measured in hot start and cold start from the ERMES data base.

	Capacity	Empty weight	Emission standard	Extra FC at (23°C) versus hot start (90°C)
Gasoline cars	[ccm]	[kg]		[%]
Veh. B1	1339	1343	Euro 5	5.60
Veh. B2	1984	1505	Euro 5	8.86
Veh. B3	1197	1040	Euro 5	4.95
Veh. B4	1390	1142	Euro 5	5.60
Veh. B5	1997	1700	Euro 5	3.88
Veh. B6	1364	1410	Euro 5	3.54
Veh. B7	1368	1170	Euro 5	7.83
Veh. B8	1390	1290	Euro 5	4.93
Average				5.65
Diesel cars				
Veh. D1	1560	1318	Euro 5	6.18
Veh. D2	1995	1565	Euro 5	3.70
Veh. D3	1968	1276	Euro 5	7.08
Veh. D4	1968	1542	Euro 5	6.17
Veh. D5	1995	1580	Euro 5	4.61
Veh. D6	2993	2150	Euro 6	4.25
Veh. D7	2993	1810	Euro 6	5.48
Veh. D8	1598	1204	Euro 5	8.16
Average all				**5.70**

The method described before gives similar corrections for gasoline and for diesel cars. When the method is applied for all cars in Table 8 we get the following suggested correction function.

$\Delta CO_2 = 0{,}0018 * (t - t_{ref})$

With t .... Engine oil temperature at test start °C

t_{ref}................ Target temperature in WLTP (23°C)

The CO_2 test result corrected for the influence of variable soak temperature is then:

$CO_2\,[\frac{g}{km}] = CO_2\, * (1 + \Delta CO_2)$

8 Inaccuracy of road load setting

Target: Check relevance of the inaccuracy of the road load applied at the chassis dyno. If relevant and possible elaborate correction method.
Method: measurement of coast down tests on the chassis dyno directly after the WLTC to establish a method to test the actual values of the road load coefficients. From differences against the target road load again the difference in the work at the wheels over the cycle can be computed and corrected with the vehicle Willans coefficient.
Results: more than 3% impact on CO_2 emission result possible. It is not clear yet, if the road load measured directly after the WLTC is representative for the road load during the WLTC. Clarification may need costly measurements with torque meter rims.

1.1.2 Method

The correction is based on results from coast down tests directly after the WLTC. The conditions and the evaluation of the coast down shall follow the WLTP regulation for coast down tests on the test track. The resulting road load values are then used to compute differences in the work over the cycle against the target road load values. The effect on CO_2 emissions is then calculated from the work difference with the vehicle Willans coefficient.

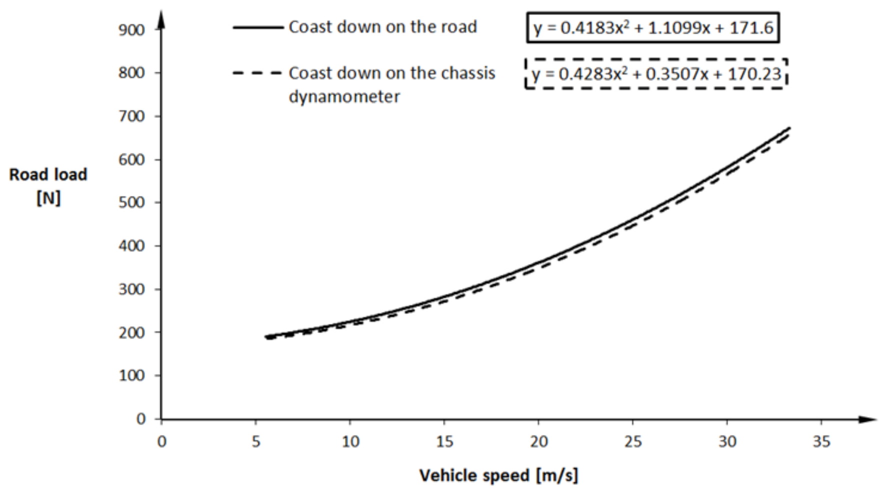


Figure 11: schematic picture of the target coast down and of the coast down result after the WLTC

Supposing that the coast down test is representative for the road load in the WLTC, the correction for the road load would work as follows:
Calculate the actual wheel power for the road load coefficients from the chassis dyno coast down test:

$P_{(t)} = (R_0 + R_1 * v + R_2 * v^2 + m * a) * v$

Calculate the actual wheel power for the road load coefficients from the target value:

$P_{p(t)} = (R_{0w} + R_{1w} * v + R_{2w} * v^2 + m * a) * v$

v............................ velocity driven in the WLTC
m .... vehicle test mass + rotational inertias converted to equivalent translator mass [kg]

R_0, R_1 R_2 .... Road load from the coast down tests at the chassis dyno directly after the WLTC in [N], [N*s/m] and [N*s²/m²]

R_{0w}, R_{1w} R_{2w} .... Target road load coefficients in [N], [N*s/m] and [N*s²/m²]

Then the average power values over the WLTC are computed and consequently the total work at wheels:

$\Delta W_{wheel} = 1.8 \times (P_{p-} P)$ in [kWs]

If the correction for road load deviations is not combined with the correction for vehicle speed deviations (chapter 3), the calculation of the difference in work can be simplified since mass and acceleration are then identical for both road load settings.

$P_{p(t)-} P_{(t)} = R_{0w} - R_0 + (R_{1w}*-R_1) *v + (R_{2w}-R_2) * v^2$

$$\Delta \boldsymbol{W}_{\mathbf{wheel}} \quad = \int_{1}^{1800} (P_{p_{(t)}} - P_{(t)})\mathrm{dt}$$

Then the vehicle based Willans function is applied to correct for the deviation against the work from the WLTC target velocity:

$$\Delta \boldsymbol{CO}_{\boldsymbol{2_p}}\,[\boldsymbol{g}] = \Delta \boldsymbol{W}_{\boldsymbol{wheel}} * \boldsymbol{k_v}$$

With k_v .... Vehicle Willans coefficient [g_{CO2}/kWs] from WLTP

1.1.3 Test results

In the WLTP (UN ECE, 2014) the preconditioning for measuring the “initial chassis dynamometer setting load[14]”, see Annex 4 – Appendix 2, seems to be sufficiently defined, if the criterion given in WLTP chapter 4.2.4.1.3 has to be fulfilled also at the chassis dyno test (minimum 20 minutes at defined velocities). Performing the tests after shorter warm up gives typically high initial losses from the bearings and transmission at the roller bench and from the tires and from the dragged part of the vehicles transmission and bearings. As a result the “adjustment road load” which is the difference between target road load and initial road load would be rather low to meet overall the target road load. If the temperature level from roller and the vehicle is higher in the later WLTC, lower internal losses occur at the roller and from the vehicles tires, bearings etc. As a result for such a scenario the adjusted road load would be lower in the WLTC than in the initial coast down test. Such insufficient preconditioning was found to influence the CO_2 test results by more than 5%. Performing the preconditioning according to the WLTP still gave reasonable deviations in the road load parameters for some tests, resulting in effects on the CO_2 emissions of more than 4 g/km (Figure 12 to Figure 14).

The deviations found for the test vehicles did not follow a common trend:

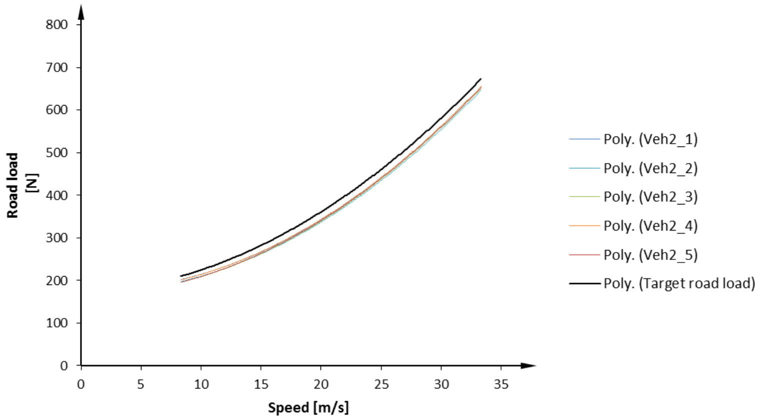
For vehicle No.1 no coast downs after the tests have been performed since the idea for this method came up later in the project.

For test vehicle No. 3 the fitting was very good for all coast down tests that have been performed after NEDC (Figure 13). For vehicle No.2 no coast downs after WLTC have been performed, since the WLTC tests have been measured before the idea for the correction method came up. When applying the road load correction on the NEDC CO_2 values, the correction function consequently shows only small effects (see chapter 1.6).

Higher differences between target road load and coast down results after the WLTC tests were found for vehicle No. 2 and 4 (Figure 13 and Figure 14). The differences

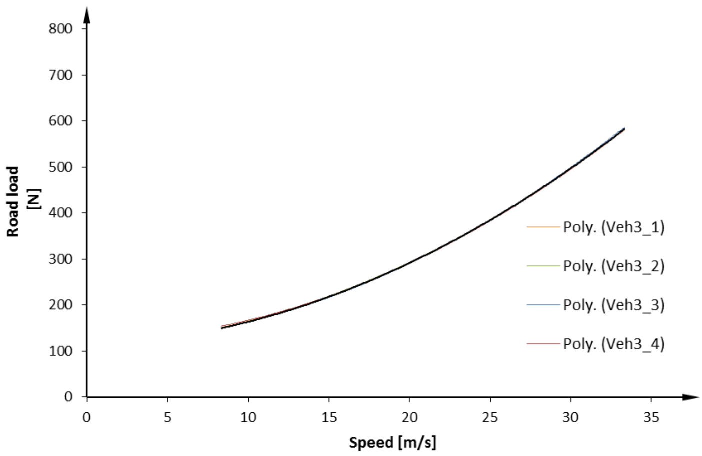
[14] There seems to be a small error: in the equation we read “F_{dj}“ but in the explanation only “F_{di}“ appears.

between the measured road load values against the target values is different for R_0, R_1 and R_2 with no uniform trend between the two vehicles tested.
The explanation for the different effects after NEDC and WLTC seems to be, that after WLTC the state of chassis dyno and vehicle is hotter than after NEDC and thus the internal losses are a bit lower after WLTC. Since the same effect should occur also in preconditioning before the initial loss run, the effects found here may depend on the design of the chassis dynamometer and on details in the procedure for the initial loss run.



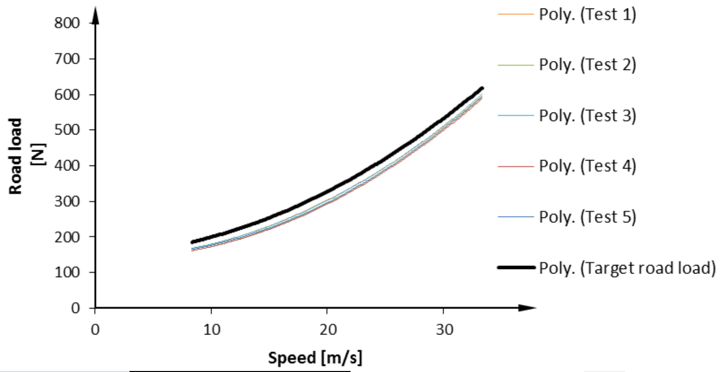
	dev.against target		
velocity [km/h]	20	60	130
target [N]	0%	0%	0%
chassis test 1 [N]	-2.1%	-17.4%	-10.9%
chassis test 2 [N]	-4.5%	-17.4%	-10.9%
chassis test 3 [N]	-5.9%	-17.4%	-10.9%
chassis test 4 [N]	-2.8%	-17.4%	-10.9%
chassis test 5 [N]	-6.2%	-17.4%	-10.9%

Figure 12: Comparison of the coast down tests after the WLTC tests with the target coast down for vehicle No. 2



	dev.against target		
velocity [km/h]	20	60	130
target [N]	0%	0%	0%
chassis test 1 [N]	-1.4%	-0.1%	-0.3%
chassis test 2 [N]	1.0%	0.5%	-0.3%
chassis test 3 [N]	1.0%	-0.5%	0.8%
chassis test 4 [N]	4.8%	0.1%	-0.1%
chassis test 5 [N]	0.0%	0.0%	0.0%

Figure 13: Comparison of the coast down tests after the NEDC tests with the target coast down for vehicle No. 3



	dev.against target		
velocity [km/h]	20	60	130
target [N]	0%	0%	0%
chassis test 1 [N]	-11.5%	-8.5%	-3.3%
chassis test 2 [N]	-12.8%	-11.5%	-3.5%
chassis test 3 [N]	-8.5%	-8.8%	-2.1%
chassis test 4 [N]	-12.0%	-12.2%	-4.0%
chassis test 5 [N]	-9.4%	-10.7%	-3.1%

Figure 14: Comparison of the coast down tests after the WLTC tests with the target coast down for vehicle No. 4

Concerning the selection of the proper coast down test after the WLTC we see similar behaviour for all tested vehicles. The first test after WLTC gives the lowest road load results while the 3rd test gives the highest ones (Figure 15). This indicates a cooling down of vehicle and chassis per coast down. If no errors in single coast down test after WLTC are expected, it would be the best option to make one test and use these results. If outliers may occur, a series of three coast downs is suggested, where the test with the medium coast down time shall be selected for the evaluation.

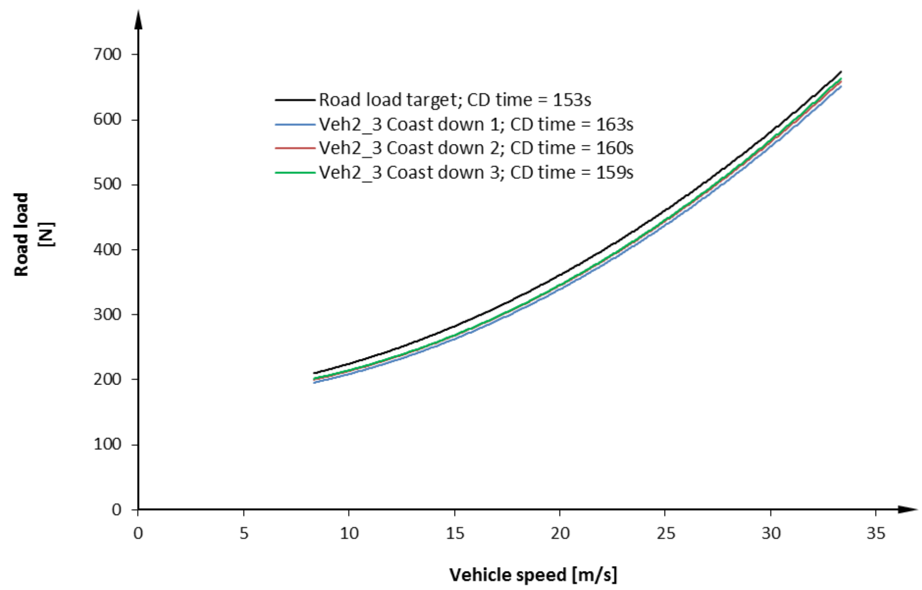


Figure 15: results of 3 consecutive coast down tests after the WLTC for vehicle No. 2 in comparison to the target road load

9 Additional effects on chassis dynamometer

1.2 Electrified vehicles

Main effect to consider is how the battery charging/discharging losses have to be considered in the energy balance.
Similar approach as for SOC imbalances in chapter 6 is possible. More detailed elaboration shall be started after discussion if this option fits into the actual discussion on HEV.

1.3 Gear shifts

Target: Check relevance of deviations against target gear shift points and develop correction function if possible.
Method: simulation with PHEM to obtain influence of gear shift variations.
Results:
The gear shift points influence the vehicles fuel consumption essentially. For the FC investigation of different gear shift points in WLTC various simulations with one petrol and one Diesel engine were performed to test the sensitivity. The investigated vehicles from segment C with their engine power, unloaded and max. permissible mass, transmission type and number of gears are listed in Table 9. This table shows also the test mass for the WLTC, which was calculated according to the WLTP regularities. (WLTP, 2013)

Table 9: Vehicle data used for the sensitivity analysis

Vehicle	Engine power [kW]	Unloaden mass (DIN) [kg]	Max. permissible mass [kg]	WLTC test mass [kg]	Trans-mission type [-]	Number of gears [-]
Diesel segment C	81	1298	1870	1579	manual	6
Petrol segment C	132	1338	1910	1623	manual	6

Simulation of the influence from different gear shift points in WLTC
As mentioned before various simulations for each vehicle with the simulation tool PHEM were done. For a start the FC from both vehicles in WLTC were simulated with standard gear shift points and settings. The standard gear shift points were calculated with the MS-Access-tool containing the actual gear shift rules for the WLTP (provided by Mr. Heinz Steven). To show the influence of different gear shift points following versions in accordance with the WLTP regularity (the gear change must be started and completed within ± 1 s of the prescribed gear shift point, WLTP, 2013) were investigated:

a) Move all gear shift points by - 1 s
b) Move all gear shift points by + 1 s
c) Move all gear shift points by - 1 s @ gear up and +1 s @ gear down
d) Move all gear shift points by + 1 s @ gear up and -1 s @ gear down

In Figure 16 and Figure 17 the gear shift points for the different versions are shown for a part of the WLTC until 100 seconds duration. The velocity is the blue line, the red line represents the original gear shift points. In Figure 16 the dotted green line shows the moved gear shift points by - 1 s and the dashed violet line the moved gear shift points by + 1 s. In Figure 17 the dotted green line shows the gear shift points by version c.) and the dashed violet line the gear shift points by version d.).

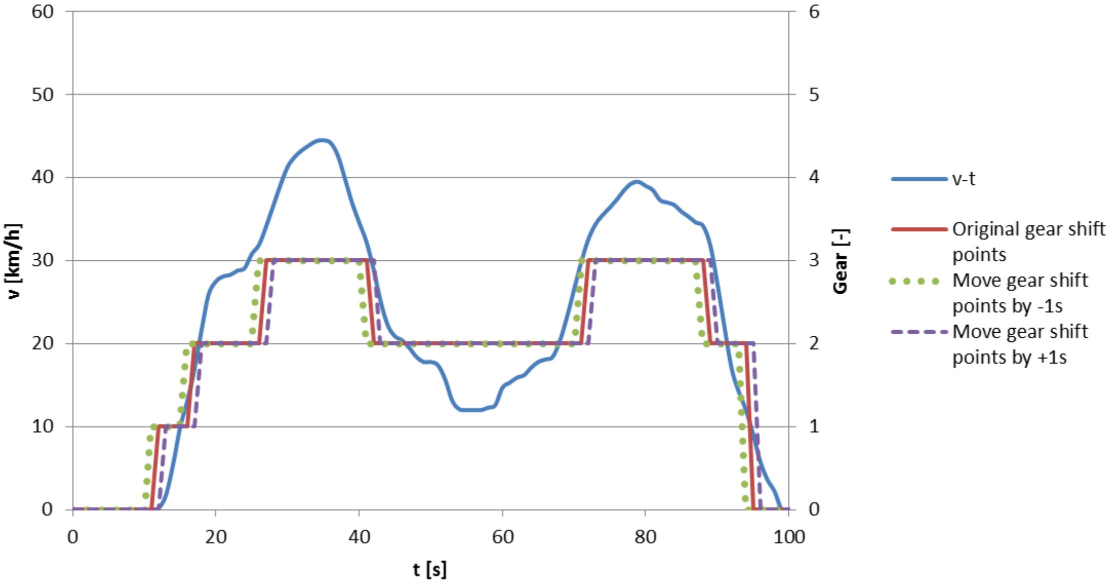


Figure 16: Visualization of different gear shift points, version a.) and version b.)

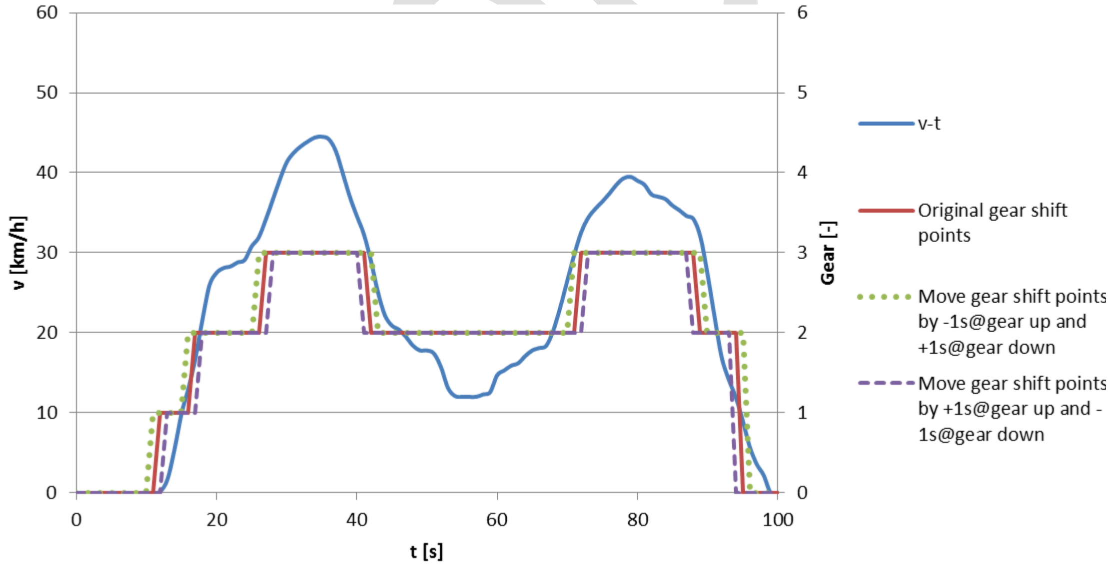


Figure 17: Visualization of different gear shift points, version c.) and version d.)

In Table 10 the FC from the different cases calculated is listed. Case No. 1 and No. 6 give the FC for the petrol and Diesel engine with standard gear shift points and settings. The FC deviations from the other cases (expressed as a percentage) are based on the corresponding basis vehicle.
As expected version c.) gives the lowest FC for both engines with 1.2 % FC reduction for the Diesel vehicle and 1.1 % reduction for the petrol vehicle. With version d.) the FC increase by 1.6 % for the Diesel engine and 1.4 % for the petrol engine. The FC deviations from the other versions are between the mentioned best and worst case values.

Table 10: FC regarding different gear shift points

No.	Vehicle	Cycle	Gear shift points	FC [g/km]	Delta [%]
1	Diesel segment C	WLTC	Not modified	39.07	0.0 %
2			Move by + 1 s	39.57	1.3 %
3			Move by - 1 s	38.69	- 1.0 %
4			Move by - 1 s @ gear up and + 1 s @ gear down	38.58	- 1.2 %
5			Move by + 1 s @ gear up and - 1 s @ gear down	39.68	1.6 %
6	Petrol segment C		Not modified	54.06	0.0 %
7			Move by + 1 s	54.68	1.1 %
8			Move by - 1 s	53.57	- 0.9 %
9			Move by - 1 s @ gear up and + 1 s @ gear down	53.44	- 1.1 %
10			Move by + 1 s @ gear up and - 1 s @ gear down	54.81	1.4 %

Possible correction functions
Corrections could be applied only if the change in gear shifts against the target is known. Deviations could be computed from a measured engine speed signal. A correction function then could be based on generic functions for change in FC over change in rpm. A simple but less accurate option could be based on integration of deviations in gear shift time against the target in total seconds with a generic function for change in FC over integrated time deviation for the gear shift manoeuvres. Further details need to be elaborated if it is clear that an engine speed signal shall be available from type approval tests.
To be completed if reasonable idea comes up.

1.4 Accuracy of relevant sensor signals for correction functions

The correction methods demand accurate input data to improve the accuracy of the CO_2 test result. The accuracy of the input signal needs to be clearly higher than the range in which the signal shall be corrected. E.g. a correction for ±2°C oil temperature at the test start needs an accuracy of the temperature signal <<2°C to achieve an overall improvement.
Table 11 summarizes the actual definitions in the WLTP (UN ECE, 2014) and the demands for applying the correction functions. Certainly the demands can be discussed to find a compromise between effort and accuracy, but following signals seem to need higher accuracy than stated in the WLTP:
Vehicle speed: relevant for correction of deviations against target speed; at 130 km/h 1.3 km/h inaccuracy is allowed according to WLTC. It seems not to be reasonable to correct ±2km/h deviation with such sensor inaccuracy.

Oil temperature of the vehicle: relevant for correction of start temperature. No definition of position and accuracy found in WLTP yet.
Test cell temperature and humidity: if a correction of intake air conditions shall be applied, much higher accuracy than demanded in the WLTP would be necessary.

Table 11: Accuracies defined in WLTP for the input data relevant for the correction functions elaborated before

Signal	Accuracy demanded in WLTP	Accuracy necessary for proper correction function
Vehicle speed and chassis dyno roller speed	± 0.5 km/h or ± 1 per cent, whichever is greater	If a deviation against target velocity within a tolerance of ±2km/h shall be corrected, the accuracy of the speed signal needs to be at least less than 0.5 km/h also at higher velocities if deviations of <2km/h shall be corrected.
Time accuracy:	min. ± 10 ms; time resolution: min. ± 0.01 s	Sufficient
Wheel torque (per torque meter):	± 3 Nm or ± 0.5 per cent of the maximum measured torque, whichever is greater	Signal not used for corrections yet. Torquemeter wheel rims allow accuracies of up to 0.25 per cent (ACEA, 2014). The 0.5% seem to be reasonable.
Chassis dynamometer force	± 10 N or ± 0.1 per cent of full scale, whichever is greater	Signal not used, accuracy seems to be sufficient.
Test cell ambient air temperature	accuracy of ± 1.5 K Measured at vehicle cooling fan outlet	Not sufficient for correction of intake air temperature in a tolerance of ± 5 K. In (MAC, 2014) temperature sensors with accuracy of ≤ ±0.3K+0.005*t are requested, what gives ± 0.5 K. DIN IEC 751 also defines for class B: 0.30+0.005 * t. This could be a reasonable demand also for the WLTP. Position of sensor seems to be suitable.
Test cell absolute humidity (Ha)	accuracy of ±1 g_{H2O}/kg_{air} Measured at vehicle cooling fan outlet.	A total tolerance of 6.7 g_{H2O}/kg_{air} is defined in WLTP, thus more accurate sensors seem to be advantageous. In the actual draft for the MAC test procedure an accuracy of < 0.2 g/kg at +20..30 °C (i.e. ±1% for a range between 35% to 55% RH) is demanded (MAC, 2014). Position of sensor seems to be suitable.
Current transducer	accuracy of	Seems to be sufficient, (MAC,

Signal	Accuracy demanded in WLTP	Accuracy necessary for proper correction function
	0.5 per cent of the measured value (in A) or 0.1 per cent of full scale deflection, whichever is smaller.	2014) refers to the WLTP in this case.
Oil temperature	No definition of accuracy found in WLTP yet	If the soak temperature shall be corrected in the range of +2°C, an accuracy of the sensor according to DIN IEC 751 class A (0.15+0,002 * t) seems to be necessary. In addition a representative location for temperature measurement would be necessary.

1.5 Test vehicle description

In total 4 cars have been measured on the chassis dynamometer of TUG to develop and to validate correction functions for the chassis dynamometer tests. Two of the vehicles are EU6 diesel cars and two are EU5 gasoline cars. Two of the vehicles have been measured completely from the budget of the actual study, for two cars the base vehicle set up was funded by other projects and just the additional test days have been allocated to the actual study. The vehicle parameters are described in the following table. Since in the chapters before detailed test results are shown, makes and models are not stated here since the road load values have been provided by the OEMs under confidentiality agreement.

Table 12: overview on the passenger cars tested

		Vehicle 1	Vehicle 2	Vehicle 3	Vehicle 4
Engine	-	Diesel	Diesel	Otto	Otto
Euro class	-	EU5	EU6	EU5	EU5
Max. power	[kW]	120	130	100	90
Kerb mass (DIN)	[kg]	1600	1700	1500	1650

1.6 Application of the correction methods on chassis dyno tests

Since in chassis dyno tests not just one single parameter can be varied within the small WLTP tolerances, the entire set of corrections need to be applied to validate the effects. Otherwise it may be that a positive effect of one correction is hidden behind deviations of other parameters.
The following chapter shows the measured CO_2 emissions and the results for each single correction step together with the deviation of the relevant parameters against the target values.

Test vehicle No. 2

Figure 18 shows the test results for vehicle No. 2 and the effect of the single corrections discussed in the chapters before. A correction for intake air conditions

was not applied due to the high uncertainties. Also the correction for fuel properties was not applied since all tests have been performed with the same test fuel.
The generic SOC correction method described in the WLTP (charging and discharging efficiencies of the battery not considered) shifts the test results from the two WLTC started with rather empty battery to the level of the tests started after normal preconditioning. To empty the battery before the tests 3 and 5 electric load was activated during soak.
Applying the speed correction and road load correction further reduces the standard deviation between the tests (see also Table 13). The distance correction and the soak temperature correction do not further reduce the deviation between tests. Since for vehicle No. 2 the oil temperature was not measured, the test cell temperature before vehicle start was used as input for the soak temperature correction. Most likely this temperature is not sufficiently accurate to correct cold start effects within the small tolerances.
The road load correction increases the test result for vehicle No. 2 by 2.6 g/km on average. The background and the underlying coast down tests are discussed in chapter 1.1.3.
The correction for speed deviations and road load deviation was applied in the version, where all time slots with positive wheel power is corrected. The option to correct all time slots with the power above overrun (i.e. the intercept point of the Willans line with the power axis at zero CO_2 flow) may lead to better results. This option shall be applied to the data in the next weeks.

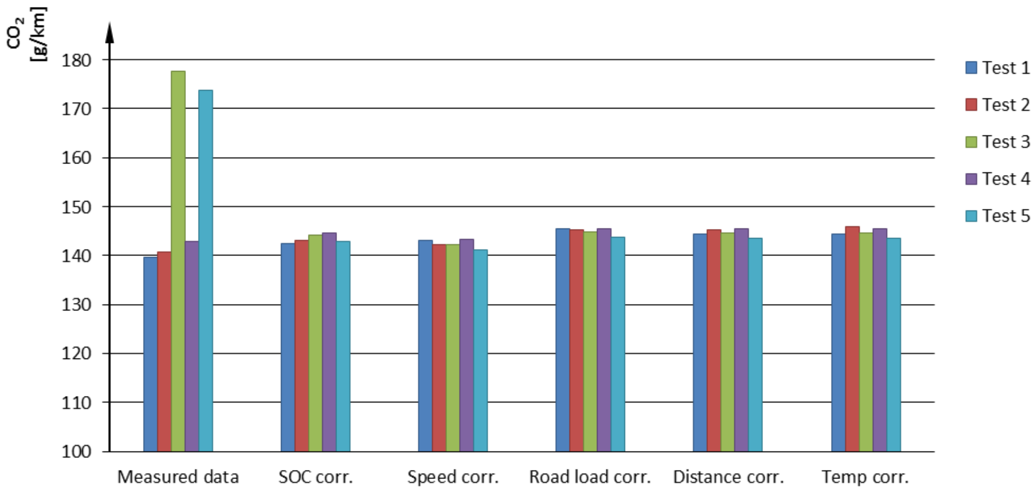


Figure 18: Test results and effects of the correction in the WLTC for diesel vehicle No. 2 (test 3 and 5 were out of WLTP flexibilities, since started with empty battery to test SOC correction effects)

The effects of the single correction steps are summarised in Table 13.

Table 13: Test results and effects of the correction in the WLTC for vehicle No. 2

	Comments	Start-temp.	Measured data	SOC corr.		Speed corr.		Road load corr.		Distance corr.		Soak temp. corr.		Final CO2
			CO2	ΔCO2	CO2	ΔCO2	CO2	ΔCO2	CO2	ΔCO2	CO2	ΔCO2	CO2	CO2
			[g/km]	[g/km]	[g/km]	[g/km]	[g/km]	[g/km]	[g/km]	[g/km]	[g/km]	[g/km]	[g/km]	[g/km]
Test 1	Within WLTP flexibilities	23°C	139.7	2.68	142.4	0.66	143.0	2.34	145.4	-0.90	144.5	0.00	144.5	144.5
Test 2	Within WLTP flexibilities	26°C	140.6	2.47	143.1	-0.93	142.2	3.10	145.3	-0.04	145.2	0.77	146.0	146.0
Test 3	Low SOC	23°C	177.6	-33.52	144.1	-1.93	142.1	2.78	144.9	-0.28	144.6	0.00	144.6	144.6
Test 4	Tyre pressure 2.8 bar	23°C	143.0	1.53	144.5	-1.09	143.4	2.15	145.6	-0.04	145.5	0.00	145.5	145.5
Test 5	Low SOC; tyre pressure 2.8 bar	23°C	173.9	-30.97	142.9	-1.66	141.2	2.59	143.8	-0.22	143.6	0.00	143.6	143.6
	Standard deviation [g/km]		17.03		0.79		0.77		0.63		0.67		0.84	0.84
	Std.dev from tests1,2,4 only		1.38		0.89		0.52		0.12		0.44		0.64	0.64

Test vehicle No. 4

Figure 19 shows the effect of the single steps of the correction functions for vehicle No. 4. The possible correction for fuel properties was not applied since all tests have been performed with the same test fuel and the variations in intake air temperature and humidity also have not been corrected due to the high uncertainty of the influences found. Test 4 and 5 have been started with low charging level of the battery, thus the SOC correction improves the repeatability a lot. The tests 1, 2 and 3 have been started with rather full battery. Here a correction gives slight increasing effects (+1.5 g/km). The correction for deviations in the vehicle velocity further reduces the standard deviation between the tests (see also Table 14). The additional correction for road load settings, distance and soak temperature do not further reduce the standard deviation but shift test result.

The road load correction increases the test result for vehicle No. 4 by 4 g/km on average. The background and the underlying coast down tests are discussed in chapter 1.1.3.

It has to be noted, that the oil temperature was not measured for this vehicle, thus the correction for soak temperature deviations was based on the test cell temperature before test start. This may be an explanation that the temperature correction does not reduce the standard deviation here.

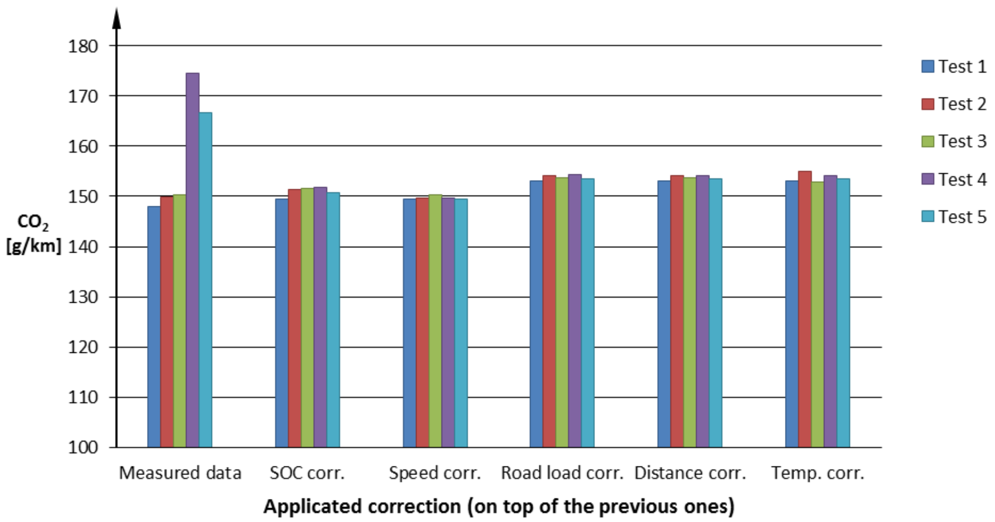


Figure 19: Test results and effects of the correction in the WLTC for gasoline vehicle No. 4 (test 4 and 5 were out of WLTP flexibilities, since started with empty battery to test SOC correction effects)

The effects of the single correction steps are summarised in Table 14.

Table 14: Test results and effects of the correction in the WLTC for vehicle No. 4

		Start temp.	Measured data	SOC corr.		Speed corr.		Road load corr.		Distance corr.		Temp. corr.	Final CO2
Vehicle 4	Comments		CO2	ΔCO2	CO2	ΔCO2	CO2	ΔCO2	CO2	ΔCO2	CO2	ΔCO2	CO2
Test No.			[g/km]	[g/km]	[g/km]	[g/km]	[g/km]	[g/km]	[g/km]	[g/km]	[g/km]	[g/km]	[g/km]
Test 1	Within WLTP flexibilities	23°C	147.94	1.49	149.43	0.12	149.55	3.60	153.15	-0.16	152.98	0.00	152.98
Test 2	Within WLTP flexibilities	26°C	149.84	1.53	151.37	-1.71	149.66	4.44	154.10	0.13	154.23	0.81	155.04
Test 3	Within WLTP flexibilities	20°C	150.30	1.32	151.62	-1.28	150.34	3.30	153.64	-0.01	153.63	-0.81	152.82
Test 4	Low SOC	23°C	174.62	-22.92	151.71	-2.05	149.66	4.68	154.34	-0.19	154.14	0.00	154.14
Test 5	Low SOC; tyre pressure 2.8 bar	23°C	166.78	-16.07	150.70	-1.26	149.44	4.05	153.49	0.03	153.52	0.00	153.52
	Standard deviation [g/km]		10.78		0.84		0.32		0.43		0.45		0.81
	Std.dev from tests1,2,3 only		1.02		0.98		0.35		0.39		0.51		1.01

Figure 20: road load polygons gained after the single WLTC tests in comparison to the target road load values for vehicle No. 4

Test vehicle No. 2

For test vehicle No. 2 exploitable test series are available only for the NEDC. For WLTC tests the basic data for some corrections was not yet measured since the ideas for the corrections were developed at the time of testing vehicle 1 and vehicle 2.

For vehicle 2 the SOC correction increases the test result on average by 5.4 g/km (Figure 21 and Table 15). The vehicle was connected to a battery charger during the soak time as usual in the NEDC tests at TUG. Applying the corrections does not reduce the standard deviation significantly. It has to be noted however, that all the tests were driven with exactly the same settings of all relevant parameters and with the same driver behaviour. Thus the repeatability was already good in the base data.

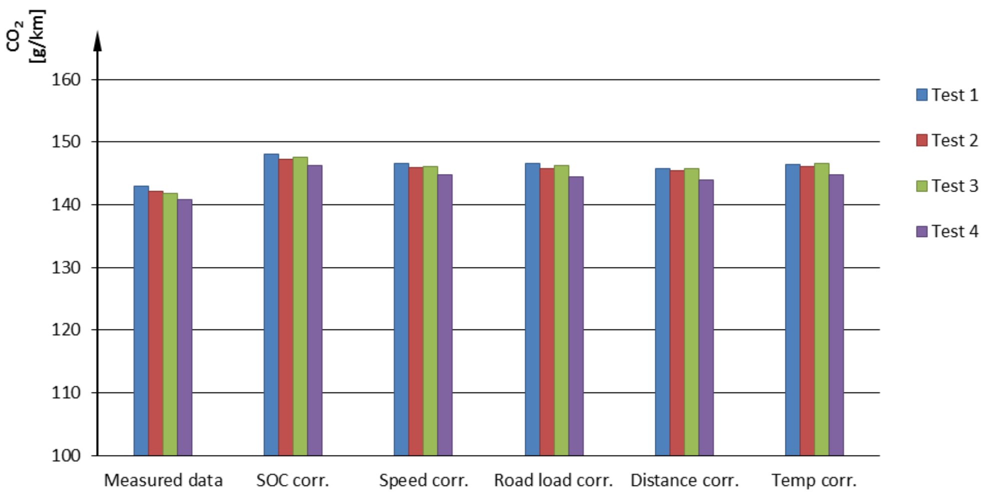


Figure 21: Test results and effects of the correction in the NEDC for gasoline vehicle No. 2

Table 15: Test results and effects of the correction in the WLTC for vehicle No. 2

	Comments	Start temp.	Measured data	SOC corr.		Speed corr.		Road load corr.		Distance corr.		Temp corr.		Final CO2
		t	CO2	ΔCO2	CO2	ΔCO2	CO2	ΔCO2	CO2	ΔCO2	CO2	ΔCO2	CO2	CO2
		[°C]	[g/km]	[g/km]	[g/km]	[g/km]	[g/km]	[g/km]	[g/km]	[g/km]	[g/km]	[g/km]	[g/km]	[g/km]
Test 1	Within flexibilities	24.7°C	143.0	5.16	148.1	-1.54	146.6	0.08	146.6	-0.90	145.7	0.68	146.4	146.4
Test 2	Within flexibilities	24.7°C	142.1	5.12	147.2	-1.29	145.9	-0.16	145.8	-0.37	145.4	0.68	146.1	146.1
Test 3	Within flexibilities	25°C	141.8	5.85	147.6	-1.52	146.1	0.08	146.2	-0.37	145.8	0.80	146.6	146.6
Test 4	Within flexibilities	25°C	140.8	5.38	146.2	-1.50	144.7	-0.24	144.5	-0.50	144.0	0.79	144.8	144.8
	Standard deviation [g/km]		0.76		0.70		0.69		0.82		0.75		0.73	0.73

10 WLTP coast-down test procedure

The coast down testing for road load determination consists of four major parts:

1. Vehicle and tyre preparation
2. Conditioning
3. Coast down testing
4. Data analysis

The WLTP legislative text is based on the NEDC text. The approach is similar, although some major conceptual changes are introduced. An important one is a switch from coast-down time to coast-down power in the evaluation. The approach is still a mixture of time and power (i.e., the reciprocal of time), however, the central theme is that the difference in force in the “a” and “b” run, as the result from wind and test-track slope, are properly added to yield a limited net force.
Many other changes in the text are related to stricter conditions and a more precise formulation of the procedure. In particular, tyres to be used are specified, in terms of tyre label, wear, and pressure. Also the weight of the vehicle is typically higher, matching better the typical production vehicle weights.

10.1 Corrections included in the WLTP

In the WLTP a number of corrections are already included for arriving at a standardized road load:

10.1.1 Wind correction

Based on the a and b test together, there is a small remaining force, resulting from a larger increase of the air drag against the wind, than a reduction of the air drag with the wind from behind. The correction is based on the vector addition of both tests, combined with the assumption that the air drag is of the generic form:

$$\text{Force [N]} = F2 * v^2$$

The combination of the quadratic form, and the factor “F2” yields a correction for wind of the same form:

$$F_{wind} = F2 * v_{wind}^2$$

To be subtracted from the observed force.

10.1.2 Air density

The correction for the air density, also relies on assigning air drag solely to F2 and the use of the ideal gas law:

Density ~ Pressure/Temperature

Only negligible errors are made by using the ideal gas law. No systematic study to assignment of air drag to F2 is found. Furthermore, the onset of turbulence is considered a major influence. For example, it is taken into account in the design of edge curvatures of the A-stile. The onset of turbulence is affected by the temperature through viscosity. These effects do not find their way in the correction procedure. It is considered too complex. No impact of air density on F1 is assumed in the WLTP, as the nature of F1 is not fully known.

10.1.3 Tyre viscosity

The temperature of the tyre, reducing the hysteresis loop and viscous losses in the tyre is included in a correction. In this correction the ambient temperature is used. Tyres, however, heat up, and this may depend on solar radiation, road surface temperature, blue sky, precipitation, etc. None of the underlying effects are taking into account in the correction. However, in the test program the magnitude of the correction is found to be correct. Hence, it can be accepted as an appropriate correction with temperature, however, not based on a sound theoretical model. Furthermore, as in air drag, also here the separation between rolling resistance and air drag is an assumption, globally correct, but the F1 term in the road load seems to carry both air-drag and rolling resistance effects. In the legislative text F0 and F1 are assigned to rolling resistance, F2 to air drag.

10.1.4 Test mass correction

The correction for a different test mass is based on the assumption that rolling resistance acts like friction: the forward force is proportional to the vertical force, or weight. In first order, this is an correct assumption, based on different measurements, and on the different underlying physical phenomena with constitute together the total rolling resistance. Hence the correction for test mass variations is proportional with the rolling resistance:

$$F0 = F0_{test} * (TM_{reference}/TM_{test})$$

10.1.5 The meaning of F1 term

The WLTP relies of the road load coefficients F0, F1, and F2 to apply the corrections. The air-drag is associated with F2, and air drag correction like the air density are applied to F2. The terms F0 and F1 are associated with rolling resistance. This is an a priori assumption. In particular F1 has a dubious status, which may combine both rolling resistance and air drag effects. It is quite common that F1 is negative. For example the EPA certification data of 2013 has 10% of the road load values below zero.

It may very well be that in the transition to turbulent flow, and flow separation at the tail of the vehicle, the air drag initially increases before the eventual drop in air drag associated with developed turbulent flow. In that case F1 may indicate something of this transition.

The velocity dependence of rolling resistance is also changing, this affects the meaning of F1 and F2, which can incorporate some rolling resistance. Traditionally, a linear increase with velocity existed. However, with modern tyres, the rolling resistance remains nearly constant up to high velocities, with an increase above 100-120 km/h. This would suggest a velocity dependence more properly part of F2 than F1.

Since F0, F1, and F2 are the result of fitting coast-down data, the effects are not separated. The assignment of F2 to air-drag only can lead to a minor overestimation of the correction in the order of 10%. It is only the assignment of F1 to rolling resistance only that corrections at higher velocities can be reduced due to the opposite sign in F1, or rolling resistance velocities effects residing in F2 instead of F1.

11 Coast-down test

Coast down testing are performed to determine the resistance of the vehicle to motion. It requires a certain amount of power to keep a vehicle in motion at a constant velocity. In the absence of acceleration or deceleration, this is the friction force of the vehicle: internally, the contact of the tyres, and the air drag constitute this force. Especially at higher velocities, the engine is used mainly to overcome this resistance. In the laboratory, on the chassis dynamometer test, this resistance, determined in the coast-down test, is reproduced to ensure the same engine load as on the road is associated with the laboratory test.

The force balance in Newtons [N] of a vehicle is given by:

$$(M + m_r) * a = F_{driveline} + F_{rolling} + F_{air\text{-}drag} \sim F0 + F1 * v + F2 * * v^2$$

Where:

- M: the weight of the vehicle [kg]
- m_r: the rotational inertia of the vehicle (I_{moment}/R^2) [kg]
- a: the acceleration (a = dv/dt) [m/s^2]
- F_x : the respective forces [N]
- v: the velocity [km/h]
- F0, F1, F2: the road-load coefficients [N, N/(km/h), $N/(km/h)^2$]

Typically, F0 is associated with driveline and rolling resistance and F2 with air-drag. The rolling resistance is dominant over the driveline, during the coast-down test when the clutch is disengaged. The coefficient F1 can be positive or negative, depending on the details at intermediate velocities. However, these coefficient, and the association is an approximation. Rolling resistance is known to increase at high velocities. Furthermore, the generic formula, such as the Streibeck formula, shows also an increase in resistance torque in driveline bearings with an increase in rotational velocity, from a baseline value at low speeds.

The air-drag is often approximated by:

$$F_{air\text{-}drag} \sim ½ * C_w * rho_{air} * v^2 * A_{frontal}$$

Where rho_{air} is the air density [kg/m^3], v^2 the square of the velocity [km/h], $A_{frontal}$[m^2] the frontal area of the vehicle, and C_w the aerodynamic drag coefficient, associated with the shape of the vehicle. This is typically in the range of $C_w \sim 0.25\text{-}0.5$. Note, this formula is based on a turbulent flow around the vehicle, and is better suited for high velocities than low velocities.

Tyres have rolling resistance coefficients (RRC [-]), which, combined with the vertical force on the wheel, yield the resistance force. Tyre labels are based on these coefficients, and therefore seem to suggest the rolling resistance is proportional to the weight of the vehicle. This is a good first order approximation:

$$F_{rolling} \sim RRC * M * g$$

Where M is the weight of the vehicle, and g = 9.81 m/s^2 the gravitational constant converting weight to force.

Since the type-approval test consists of two parts: the coast-down test and the chassis dynamometer there are a number of issues concerning the use of the coast-down results on the chassis dynamometer. Traditionally, there has been a lot of lenience in the NEDC test procedure for the limitations of the chassis dynamometer. However, this does not take away that fundamentally the vehicle should have the same coast-down test results on the chassis dynamometer as on the road. See Figure 22. This involves three aspects:

1. The same vehicle, as much as possible. This includes the same weight and wheels.
2. Correct inertia settings, or weight of the vehicle (with the inclusion of the rotating inertia of a stationary axle on the chassis dynamometer)
3. The same power, or rolling resistance. This can be a limited number of settings, for example power at 80 km/hr, or the three values F0, F1, and F2, or, preferably, the power settings at all the different velocities reported in the coast-down test.

The rotating inertia is a complicating factor in the test. If all axles are rotating there would be no problem. It is the stationary axle which creates a mismatch between the two coast-down tests. A fixed 1.5% (e.g. 21 kg for a 1400 kg vehicle) of the vehicle weight is assumed, which is an appropriate average value, but may deviate substantially is some cases.

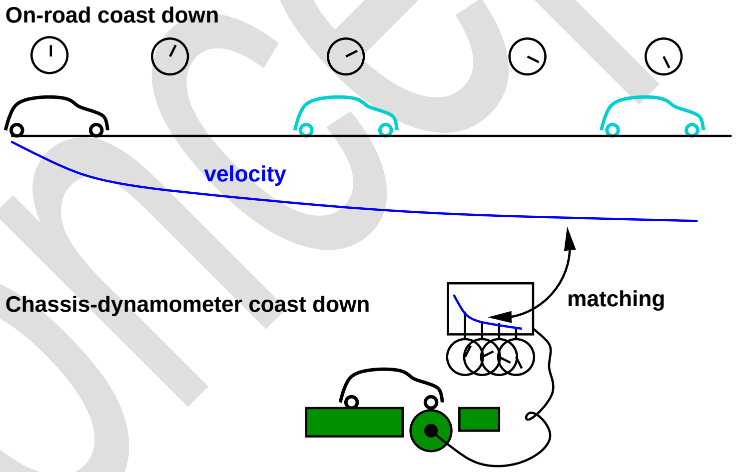


Figure 22 The best guarantee the road-load settings are appropriate, if the coast-down test is repeated on the chassis dynamometer, with the same total inertia. The coast-down test on the chassis dynamometer should follow the WLTP test immediately.

There are several alternative ways of matching the coast-down test and the chassis dynamometer settings. Also values are reported which excludes the tyre rolling resistance. These different approaches allow for flexibilities in the settings. Eventually, the coast-down test on the chassis dynamometer test will tell if all these settings add up to the appropriate net result.

The same roll-out times on the road and on the chassis dynamometer should be achieved only in the case of the same vehicle inertia. Roll-out times are inversely proportional with the inertia. Hence, in the case of a different inertia for both test, it should be corrected for:

$$T_{chassis\text{-}dynamometer}/T_{coast\text{-}down} = (M+m_r)_{coast\text{-}down}/(M+m_r)_{chassis\text{-}dynamometer}$$

This is the correction applied to the coast-down. The carry-over to the chassis dynamometer is not fully covered

11.1 Vehicle preparation

The vehicle must be in proper running order for a coast-down test. This include removing parasitic braking, setting wheel alignment, setting the tyre pressure. These items are very important for the eventual road-load values. Other preparation includes the setting of vanes of the inlet, removal of optional fixtures such as antenna's, and the setting of fixtures. Also cleaning the car may have a little effect of the air flow friction.

The wheel alignment is found to affect the rolling resistance substantially. For the tested vehicle changing the toe-in from 0.2^o to 0.0^o reduced the rolling resistance by 6%. It is difficult to generalize this results. Instead it would be appropriate to test the vehicle with the maximal value, away from upright and parallel wheels, in the range prescribed by the manufacturer.

```
The alignment of the wheels: toe-in and camber, should be set
to the maximal deviation from the parallel positions in the
range of angles defined by the manufacturer.
```

11.2 Vehicle conditioning

The vehicle is prepared for coast down by driving at a high velocity for at least 20 minutes. The result is warming up of the components of the vehicle. The lubricants will be warmer, but also the tyres will be warmer and the pressure increases. Furthermore, the engine block will be warm and radiates heat throughout the test. Eventually, it is very difficult to control these heat transfer throughout the test. Testing on a colder test track surface, or testing in sunny conditions, will all affect the loss of heat and thereby the tyre temperature. The only way to standardize the test is to measure the tyre pressure sufficiently often throughout the test, and correct for the tyre pressure.

```
The tyre pressure during the test is increased due the
precondition. This pressure increase must be appropriate for
the preconditioning driving. The during the test moderate
driving, limited braking and limited exposure of the tyres to
heat must be maintained.
```

The lubricant oil of the driveline in motion during coast down can also be affected by specific heat transfer conditions, however, this effect is considered secondary to the effect of the actual tyre pressure during the test.

11.3 Coast-down test

During the test, fuel is consumed, which decreases the weight of the vehicle. If the test is cut in four parts, and ten repetitions of each are needed, the fuel consumption of such a test may already be as high as 5-10 liters for a passenger car, which may lead to not completely negligible weight differences on a 1200 kg vehicle. However, no correction of the test result or adaptation of the WLTP procedure is proposed, as the impact is much smaller than the observed test to test variations in coast-down times.

Two major aspect affect the outcome of the individual coast-down tests: First, the local wind conditions, both in the time and along the track, which can be 3 kilometer long. Second, the tyre pressure, which will fluctuate with the internal temperature. The tyre pressure can be 10% or more higher during the test than at the conditioning. The amount of heat dissipated in a tyre, at high velocities, can be close to 1000 Watt. At lower velocities, the amount of heat is less; proportional with the velocity. The internal heat is not simply lost. Hence high temperature and the resulting high tyre pressures will affect the outcome of the test. The generated heat per tyre is approximately:

$$\text{Heat [W]} = 2.725 * \text{RRC} * M_{tyre}[\text{kg}] * v[\text{km/h}] \sim 4\text{-}8 * v[\text{km/h}]$$

Where M_{tyre} is the weight on the tyre.

Most kinetic energy dissipated in the tyre rolling resistance is converted to heat, only a small amount is dissipated as noise, or transferred as vibration to the vehicle.

Tyres are heated through three main processes: First, the viscoelastic deformation of the tyre, converting work into heat. Most of the rolling resistance is converted in this manner. Second, the contact of the tyre profile with the road surface, causing local deformation of the tyre. Third, the friction of the tyre on the road. A large amount of energy can be converted to heat in this manner, which however require slip of the tyre over the surface. This is common for bends, but not so much so in the forward motion, i.e., rolling of the tyre. Furthermore, the tyre can be heated or cooled by the surroundings. This comprises mainly of contact road surface, air convection, solar radiation, radiation from the engine block and heat transfer from brakes.

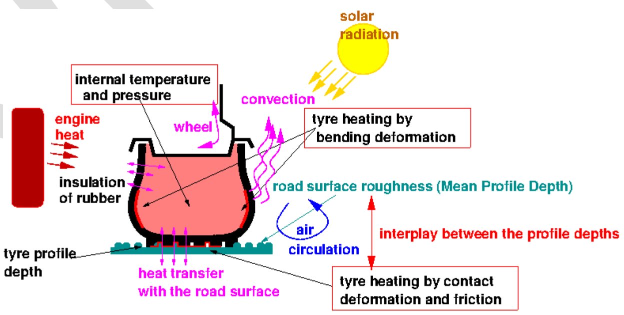


Figure 23 The heat generation and heat transfer of a tyre is a complex process with many unknowns.

Rubber has a low heat conductance, such that 1000 Watt heat transfer across the rubber may yield a temperature difference of 60-80 degrees Celsius. The associated pressure increase is 20%. This is confirmed by measurements. The outer surface of the tyre maybe lukewarm, but this is not a proper indication of the temperature and pressure inside the tyre.

A vehicle turning up and down a straight test track will have a different intermediate velocity profile between coast-down test than a vehicle on an oval test track, where in the bends not only high velocities may achieved, but also the friction from the lateral force can be substantial. Furthermore, the low velocity coast-down tests, may or may not have in between accelerations to high velocity. Hence it almost impossible to prescribe the driving which leads to the tyre pressure. Instead these pressures must be monitored at regular intervals.

`Tyre pressures should be monitored during the coast-down testing. Tyre pressures should remain in a normal range, for the prescribed precondition, with a maximal bandwidth of 6%.`

---

12 Ambient conditions

12.1 Weather

One important aspect of weather is the air density, which yields the air drag, especially at higher vehicle velocities and turbulence. This is affected by the altitude, the atmospheric pressure, the humidity, and the temperature. Another aspect is the humidity. The presence of water vapor in the air affects the composition and such the air density and the air viscosity.

12.1.1 Temperature

Temperature affects both the air density and the air viscosity, in an opposite manner. See Figure 24. Both affect the air drag of the vehicle. The density in a rather straightforward manner when the velocity is high, but viscosity will play a complex role, both in the flow friction on surfaces by laminar flow and by the onset of turbulence, for example, at the A-style in the case of side wind, and the flow separation at the rear of the vehicle.

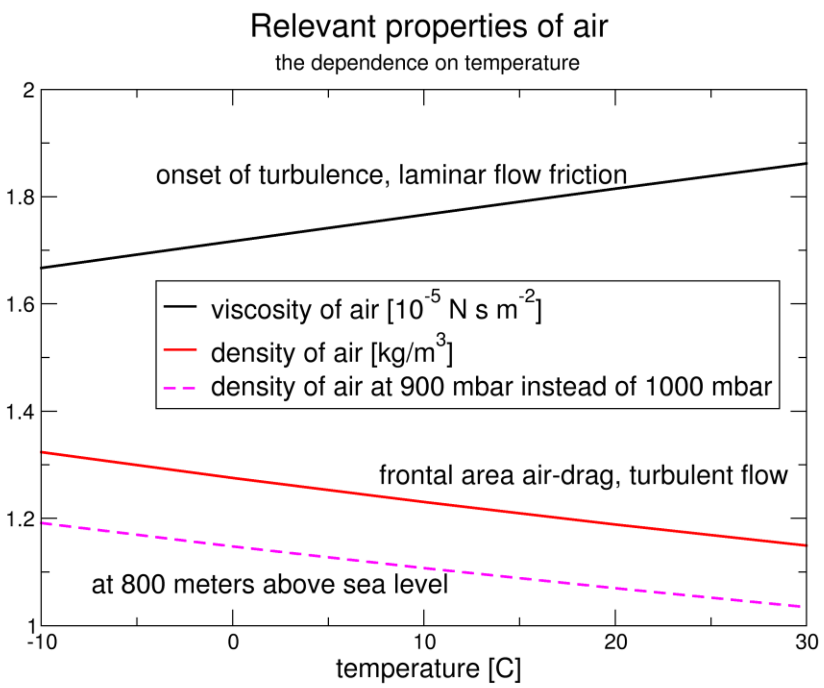


Figure 24 the viscosity and density of air as function of temperature. Density is also affected by altitude, viscosity is not.

12.1.2 Air pressure

The air-pressure is mainly affected by the altitude, as the column of air decreases with altitude. A square meter column of 100 meter contains typically 129 kg air at 0^o Celsius, which exerts a pressure of 1265 Pa below. This is 1.25% of the total atmospheric pressure. Hence 800 meters altitude will decrease the air pressure and air density by about 10%. The situation is slightly more complex as the temperature also decreases, due to adiabatic relation between the air in the column, which results in a lower temperature at higher altitudes. On the other hand, as the density decreases with the altitude, also the column weight decreases.

The air pressure itself may fluctuate with the weather, times of stable high pressure will be alternated by times of low pressure fronts. The normalized sea-level air pressure is 101.325 kPa. The maximal range of air pressure variation is between -14% and +7%. However, typical fluctuations in the air pressure are -2% and 2% around the standard air pressure.

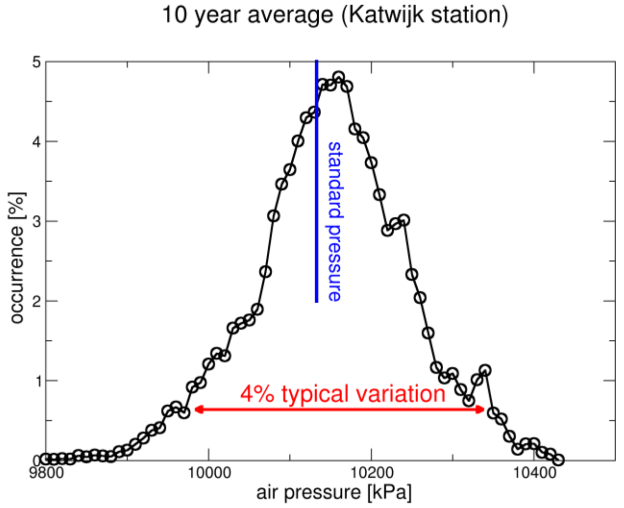


Figure 25 The average over 2000-2010 of the air pressure at the location of the test track. The variations are limited and evenly distributed.

The normal air pressure used in the WLTP text is 100 kPa. At sea level it is at the edge of the distribution in Figure 25, however, at an altitude of about 110 m, the average air pressure is around 100 kPa. The latter value is used as reference in the WLTP text. This value is appropriate for European conditions.

12.1.3 Air composition

At high temperatures, the water vapor content of air may be substantial: 4.1% at 30^o Celsius, and 7.3% at 40^o Celsius. This will lower the air density slightly, as water vapour has 37.7% lower density as air. Hence, the maximal net effect of high humidity is 1.5% at 30^o, and 2.6% at 40^o Celsius. This is for 100% relative humidity. In that case mist may form, which increases the density again. The latter is unfavorable for the air drag. The variation of the viscosity with the water vapor content is expected to be maximal in the order of 2%, based on the mixing rule of Wilke, where the viscosity of water vapor is lower than of air, and an increase in relative humidity decreases the viscosity. Since the viscosity, i.e., the wall friction for laminar flow, is only a minor part in the total air drag, the impact of humidity on viscosity can be neglected.

For the relation between the relative humidity and the absolute water vapour content in air the approximation on Antoine is often used.

$$P_{vapour}[bar] = 157000 * 10^{-1730.63/(233.46+T[C])}$$

See Figure 26.

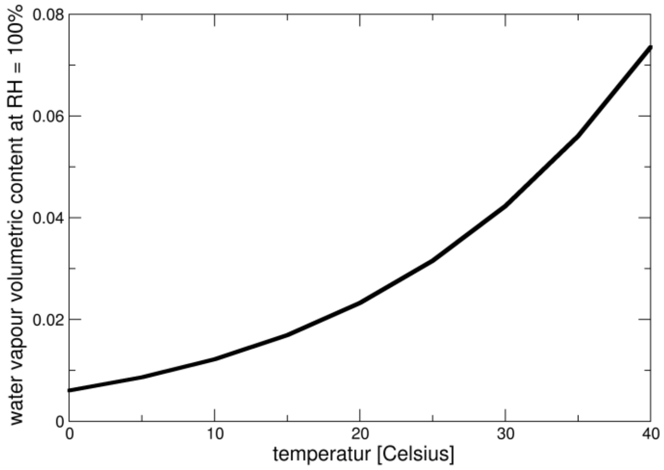


Figure 26 The absolute molar water content of saturated air for different temperatures.

The water vapour content can be used to adjust the air density with relative humidity and temperature:

$$P_{vapour}/P_{ambient}$$

The fraction of water vapour is multiplied with the ratio of densities to arrive at the density ratios:

$$\rho/\rho_0 = 1 - 0.37 * P_{vapour}/P_{ambient}$$

The air-drag must be compensated for the deviation of the air density. The air density is proportional with pressure p and inversely proportional with temperature T, such that the observed air drag is compensated with factor (100/p)*(T/300). Furthermore, the air drag must be compensated for the presence of water vapour through a factor: 1+0.37*Pvapour/Pambient, assuming the standard condition is dry air.

12.2 Wind

Wind is one of the most dominant uncontrollable aspects, which affects the coast-down results. For European on-road conditions the effect for a single direction is about 10%. For a round trip: both directions, the net effect is much smaller. It is estimated in the order of a few percent. This depends very much on the vehicle velocity and shape.

12.2.1 Wind speed

For meteorological data, the wind speed is measured at 10 metres, or 30 feet, above the ground level. The wind velocity at 10 metres is higher, and more constant than at 0.5-1.5 metres height, which is relevant for the air drag of vehicles. Measurements at 0.7 metres height show a large variation in wind speeds and wind direction compared with the meteorological station nearby at 10 metres high.

The relation between wind speeds at different altitudes is not fixed, but dependent on the meteorological conditions. Stable conditions, with a small temperature gradient will yield typically a sharper decline of wind speeds with altitude than unstable conditions. From the theory of boundary layers, such generic results can be inferred.

12.2.2 Wind direction
Side wind always adds to the driving resistance of the vehicle. The wind parallel to the vehicle direction has both positive and negative effects. These effects are largely both opposite, such that by adding the forces of both the “a” and “b” runs together, only a smaller negative net force remains. Hence small variations in the wind between the “a” and “b” run will introduce a large uncertainty in the outcome of the coast-down. In many circumstances it is the largest source of uncertainty during testing.

12.2.3 Wind gustiness
Variations in wind velocity and wind direction exists at every time-scale, due to the turbulent nature of wind. Unhindered by the terrain surface the air-flow follows the isobars to the pressure field, due to the Coriolis force. The friction of wind with the earth will turn the wind direction more towards the low pressure. Hence the surface roughness and the high-altitude wind have an intricate interplay at ground level.

The wind velocity during the test must be measured and reported for regular intervals together with the timing of the test execution. Large time intervals in the test execution should not be correlated with wind gusts.

12.2.4 Wind velocity profile
The WLTP text prescribes wind measurements at 0.7 metres. This is the appropriate height for vehicles during coast down. However, measurements at this height are severely affected by the local conditions, such as obstacles nearby and overall terrain roughness. Furthermore, the wind velocity profile is dependent on the height above the ground and the weather conditions. All in all it is a complex problem to determine the precise effect of the wind, at the level and position of the vehicle.

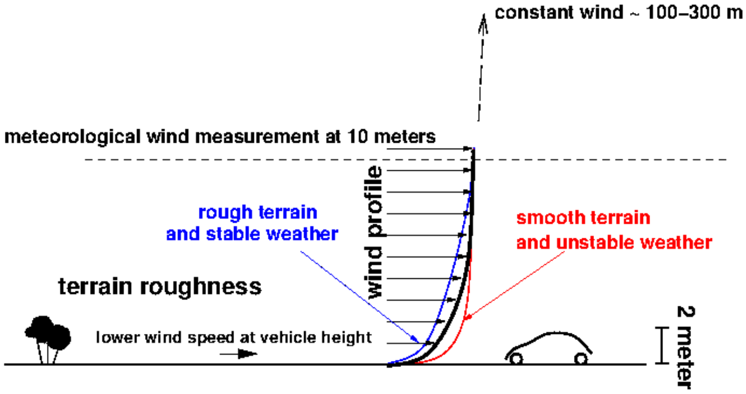


Figure 27 The wind velocity depends on the height above the terrain. This velocity profile is affected by many meteorological aspects and condistions.

Wind, its direction and its velocity profile, are all affecting the coast down results. Probably so, in more complex manners that can be determined with the current knowledge. The air streams around the vehicle and the locations of slip and turbulence are difficult to control in detail. The presence of wind may lead to a separation from the ground, and force the air flow overhead, rather than around and below the vehicle. It is speculation.

12.2.5 On-board anemometry

Ford motor company in the USA uses an on-board anemometry to correct air drag for wind, in order to improve the accuracy of the coast-down results. However, this equipment is bulky and the approach is academic and complex. It should be scaled down for generic use to correct for wind, similar to the stationary wind correction. Moreover, such method should not legitimize correcting at high wind speeds where the air streams around the vehicle are quite dissimilar from the those for the case of a moving vehicle at low wind conditions.

12.3 Test track

12.3.1 Road surface

Road surfaces in Europe are designed to ensure enough grip during braking on a wet surface. A second criteria is the limited amount of tyre noise. The fuel consumption, or rolling resistance, has limited consideration in the road surface evaluation. However, the actual road surface may affect the rolling resistance significantly. The tyre label are determined on a smooth drum, the actual rolling resistance on the road is typically higher. Variations of the rolling resistance with road surface can be 20% or higher.

The mean profile depth (MPD) is the most significant quantity , defining the road texture, which will affect the rolling resistance. The interplay with tyre profile and tyre pressure can be significant, but is, as yet unknown. Testing on different test tracks has led to an estimation of the difference between the best case and worst case rolling resistance surface of 24%, for high tyre profiles and low tyre pressures, typical for the WLTP test protocol.

12.3.2 Road gradient

The NEDC procedure averaged the up and down test times. This introduced an advantage to sloping test tracks. The gradient force, opposite for both directions, will yield to longer times downhill, than the time decrease uphill. The average time of uphill and downhill is longer than the average time of a horizontal track. With the allowance of 0.5% slope, the gravitational force on a 1200 kg vehicle is 59 N. With typically rolling resistances of 80-150 N the gravitational effect is substantial, and the estimate of the rolling resistance can be 10% lower, averaged over the work on the test.

In the WLTP the averaging is shifted from time T, to power (the reciprocal of time: 1/T). Still this is not completely in accordance with the physical principles, which associate gravitation with a conservative force, i.e., the same magnitude but opposite for opposite directions. For example, assume a total inertia of 1200 kg, a road load of 50 + 0.05 v^2, a gravitational force of 60 N, and a coast down from 85 to 75 km/h. The two time constants are:

$$T_{down} = 38.87 \text{ sec and } T_{up} = 27.96 \text{ sec}$$

(See the appendix for the details of such calculations.) The average time is 35.70 sec, compared to test on a flat track at 32.52. This results in a 10% lower road load at 80 km/h. Using the reciprocal times $0.5*(1/T_{up}+1/T_{down})$ = 32.52 sec, and this differs only with the result of the flat test in the fifth decimal place (0.011%). This small difference is the result of power approach (WLTP) versus force approach (physically correct), and related to the distance travelled and the associated time. Generally, the unit of 1/T is appropriate to compensate for road gradient, but it is not exact. The largest deviations between both approaches are found at the lowest velocities. However, this will remain in the order of 1/1000. Hence, averaging over forces would be exact, but averaging over power (or 1/T) is a good proxy, within the limits of the allowed gradients and speed ranges. The error from a finite interval, e.g. 85-km/h 75 km/h, to recover the road-load at the mid-value is in the same order.

The method of averaging over different a and b tests, and the successive tests, is not completely in line with the spirit that “1/T” is the relevant quantity in the road-load determination. Immediate conversion to the 1/T [sec^{-1}] unit and the statistical evaluation in this new variable avoids confusion.

12.3.3 Road undulation

Test tracks are typically flat with very limited undulation. With higher tyre pressure the vibrations of the vehicle increases. Whether this will yield a higher of lower rolling resistance will depend on the vehicle dampers and suspension. The road undulation, or large scale variations, is expressed in the IRI (International Roughness Index). The IRI is related to the absorbed energy in vehicle vibration. A large IRI will increase the driving resistance of the vehicle. It is believed to be outside the scope of coast-down testing. However, in the translation to European on-road conditions it may have a place. The coast-down testing is expected to be optimal, compared to normal European roads, in both the IRI and the MPD.

```
The road surface of the test track must have a texture,
expressed in the mean profile depth, comparable to normal
European tarmac roads. If the mean profile depth of the test
```

track is substantially lower, an appropriate correction of the rolling resistance must be applied. If the mean profile depth (MPD)is below 1.0, the best available method is the correction based on the different findings of VTI in Sweden. If MPD < 1.0 of the test track, the rolling resistance is to be corrected:

$$F0 = F0_{test} (1 + 0.20 (1.0 - MPD))$$

$$F1 = F1_{test} (1 + 0.20 (1.0 - MPD))$$

13 Inertia

A coast down test is a balance between the inertial force, keeping the vehicle in motion, and the resistance slowing the vehicle down. If the inertia is higher it takes longer for the vehicle to slow down. Hence an accurate determination of the inertia is important to translate coast-down times to forces.

In the case the coast-down is repeated on the chassis dynamometer, it will yield to first order the appropriate settings of the chassis dynamometer. However, there are a few limitations:

- The vehicle weight should be identical to the dynamometer inertia settings if all axles are rotating
- The vehicle weight should be compensated for the rotational inertia of axles that are stationary on the chassis dynamometer test. The inertia settings must therefore be higher

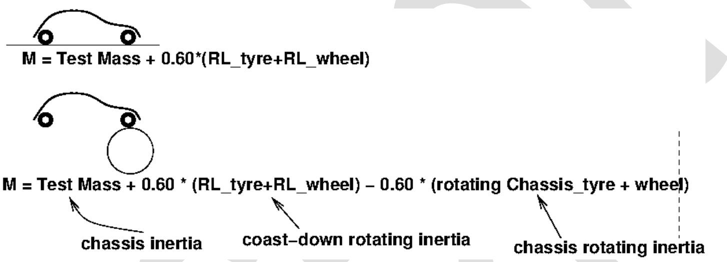


Figure 28 The appropriate translation of the rotating inertia on the road to the chassis dynamometer: account for the different wheels and tyres in both tests. In this case 60% of the weight of the wheels is used as rotating inertia.

Vehicle weight is very well specified in the test procedure, rotational inertia is not. The general approximation is 3% of the vehicle weight for all rotational inertia. Whether the actual rotational inertia is higher or lower, will affect the results in a complex manner. Different values, from different wheels, for coast-down and chassis dynamometer tests will yield the largest deviations. During the coast down test, higher rotational inertia unaccounted for, yield lower road loads. During the chassis dynamometer test, lower rotational inertia of the rotating axle, compared to the coast-down test will yield lower forces during the emission test and will typically result in lower emissions.

13.1 Vehicle weight

Vehicle weight has two opposite effects in the coast down test. First, the resulting force from the coast-down times depends on the total inertia. The more heavy the vehicles, with the same force, yields longer coast-down times. Second, the increase in weight will lead to an increase in rolling resistance. As a rule-of-thumb the rolling resistance is considered proportional to the vehicle weight. Deviations from the generic rule are dependent on both the tyre type and tyre pressure. The net result, however, is a longer coast-down time, and thus lower dynamometer settings for the emissions test. The current mass provisions in the WLTP gtr are sufficiently tight to prevent for exploiting this flexibility.

13.1.1 Weight balance

The balance of the weight between front and rear, and left and right, is expected to be of some influence. Most generic formulas for coast down do not take into account the effect of imbalance. Adding 50 kilograms to the front, which is subtracted from the rear will yield the same rolling resistance based on the tyre label:

$$F = RRC * (M_{front\text{-}left} + M_{front\text{-}right} + M_{rear\text{-}left} + M_{rear\text{-}right}) = RRC * M_{vehicle}$$

Only a minor influence is expected in coast-down, unlike for other aspects. It is ignored in the analysis.

13.2 Rotating inertia

Rotating inertia is the additional kinetic energy stored in the rotation of parts. This is kinetic energy on top of the forward motion of the center-of-mass of the rotating part. Rotating inertia can be from parts of the driveline, but also the wheels and tyres add to the rotating inertia. An axle, at the same rotational velocity as the wheels, may be heavy, but the radius is small, such that its contribution to the rotating inertia is small. For a solid disk or bar the rotating inertia is:

$$m_r = 0.5 * m_{disk} * (R_{disk}/R_{wheel})^2$$

For a ring the rotating inertia is:

$$m_r = m_{ring} * (R_{ring}/R_{wheel})^2$$

The formula is the same, apart from the form factor xi in front: ξ_{disk} = ½, ξ_{ring} = 1. For an axle of 20 kg and an outer radius of 5 cm, the associated rotating inertia is less than a kilogram. For wheels the radii ratio (R_{part}/R_{wheel}) is one, and the radial mass distribution is somewhere in between that of a disk and a ring, such that the associated rotating inertia is:

$$m_r = \xi * m_{wheel} \sim 0.6 * m_{wheel}$$

The form factor xi can vary with the type and shape of the wheels and tyre. However, it is expected that xi lies between 0.60 and 0.75, even for extreme designs. Hence, from weighing the wheels and tyres, a good indication of the rotating inertia can be obtained. Typical wheel and tyre weights encountered for passenger cars are in the order of 8 kg for the wheel and 8 kg for the tyre. The total weight is therefore 64 kg, with an expected rotating inertia of 45 kg. This is 3% of a vehicle of 1500 kg. Hence, the rotating inertia seems to be underestimated somewhat, as cars with 64 kg wheels and tyres are typically smaller, and, in particular, since the other rotating parts such as the axle, brakes, differential, etc. are not included.

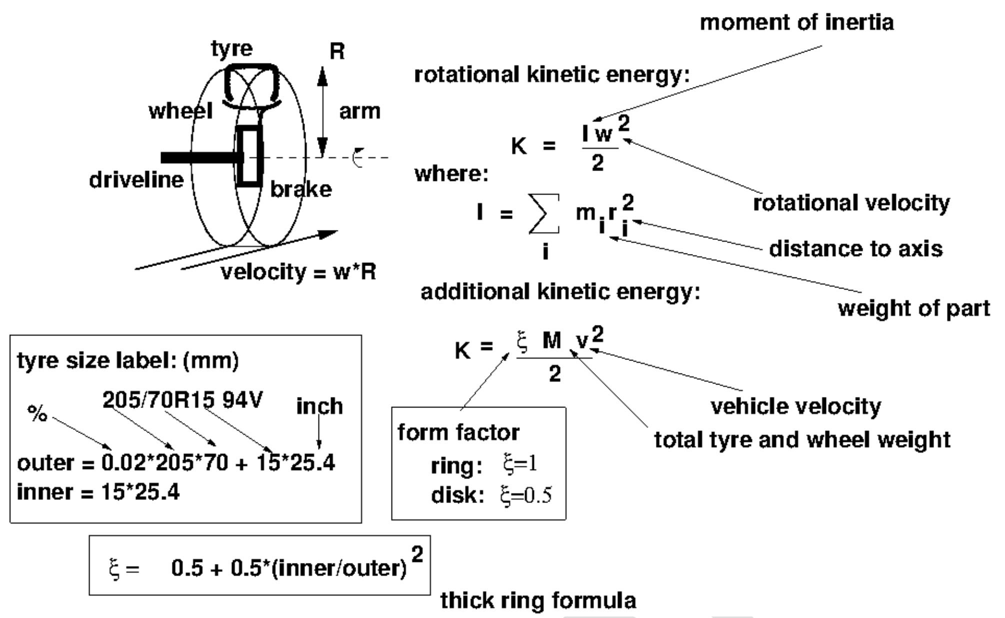


Figure 29 Summary of the physical principles and approximations for determining the rotating inertia.

The tests carried out on two sets of tyres and wheels yield slightly smaller values. The rotating inertia varied between ξ = 55% and ξ = 65% of the weight. The small rim tyre yielded the largest form factor ξ.

13.2.1 Tyre inertia

A more complicated approach than "*adding 60% of the tyre and wheel weight as rotating inertia*" can be applied. Naturally, separating the wheel and tyre weights and resulting rotating inertia is the first choice. The tyre is the largest contribution to the rotating inertia due to the larger average radius, despite the tyre typically being somewhat lighter than the wheel.

13.2.2 Wheel inertia

Wheel inertia includes the flange and the rim. This is the part taken off the vehicle, e.g., while replacing the tyre. The brake, with some rotating parts, are not part of the wheel. They have considerable weight, however, the radius is much smaller than the wheel, so the impact on rotating inertia is limited. On the other hand, all rotating parts contribute to the rotation inertia. Neglecting brakes and driveline means neglected part of the rotating inertia. Hence, an estimate of rotating inertia based on the tyre and wheel weight should be on the high side of only these parts, to compensate for additional rotating inertia.

13.2.3 Driveline inertia

In the testing very little difference was found in the inertia between the front axle attached to engine via the differential and the rear, free running wheels. This confirms the limited contribution of the driveline to the total inertia. The weight is substantial, the rotating velocity is similar to the wheels after the transmission. Hence the smaller radii, compared to the radius of the tyre is the determining factor leading to the minimal contribution of the driveline to the total rotating inertia. Only in terms of driveline contributions to the rotating resistance the difference was significant.

The rotating inertia at the coast down test and the chassis dynamometer test are to be determined by weighing the wheels and tyres. 60% of the weight of all tyres and wheels is the rotating inertia to be used. Different weights between the coast down test and chassis dynamometer test due to special tyres or wheels to be used, e.g., to avoid slip on the drum of the dynamometer must be compensated by adjusting the chassis dynamometer settings.

14 Rolling resistance

14.1 Tyre

The tyre is the major source of rolling resistance of the vehicle. The balance between comfort, safety, and fuel economy is a complex one. In a simple approach the vertical indentation z of the tyre is such that the contact area and tyre pressure combine to withstand the force on the tyre from the vehicle weight:

$$z = L^2/(8R)$$

where L is the length of the contact, and R the outer radius of the tyre. Given a tyre pressure p and a tyre width w:

$$p*L*w = g*M/4$$

For a typical weight on a single tyre of 400 kg and a tyre pressure of 2.2 bar, the area (L*w) is 180 cm^2.

This formula is adjusted for rim stiffness of the tyre, which is independent of the tyre pressure. However, major part of the tyre stiffness: the relation between pressure and indentation, is the result of tyre pressure. It means that the indentation z of the tyre depends on the square of the tyre pressure, in a simplistic manner:

$$z = (g*M)^2/(128\ w^2\ p^2\ R)$$

The indentation z is a measure of the energy absorbed in the tyre. Part of this energy is converted to heat, part is elastic as the tyre will resume its original shape as the indented part is rotated away from the contact with the road.

The relation is complex, yet empirical investigations suggest the relation between absorbed energy and tyre properties is grossly linear:

$$W \sim g*M/(w\ p\ R^{1/2})$$

This forms the basis of existing corrections on the rolling resistance, e.g. mass correction, and it may serve to augment the method to include pressure related corrections. The linear relation suggests energy loss due to flexural deformation of the tyre. In the case of compression only the deformation, and losses, expected to be proportional to the indentation z, and p^{-2}. On the other hand, “rubber compression” only suggests a substantial tyre stiffness and a limited pressure dependence.

It is clear that the correction for the variation in tyre pressure is not identical for all tyre types. A large variation exists, also in the literature. A simple relation, combined with a limited range of pressure variation, is the best recipe for a robust approach.

14.1.1 Tyre indentation

The tyre indentation is associated with compression and flexural deformation of the tyre. The tyre wall bends outwards between wheel and road. The rubber is elastic by nature. Hence, greater part of the elastic energy is released. A minor part is not. This phenomenon is called hysteresis: the difference in force between compression and release. Typically, 10%-20% of the energy is absorbed as heat. It depends on many aspects, as rubber composition, i.e., the amount of carbon, the type and magnitude of the stresses, and the rate and speed of deformation.

14.1.2 Tyre contact deformation

Tyre profile and road surface roughness have a complex interaction. It's resulting contact deformation is a second source of rolling resistance, next to the tyre indentation under the vehicle weight. Unlike the indentation, the majority of the energy in the contact deformation can be expected to be lost in vibration, noise and heat. Contact deformation is not a global, or coherent, deformation, such that the release does yield a useful force. Given the tread restriction in the WLTP, to 80% or more of the original tread, the contact deformation can be expected to be significant. A smooth road surface may limit the effect somewhat. The combination of the low tyre pressure and large tyre tread in the WLTP test can lead to a major effect on the road load of the road surface roughness. The complex interplay of the three aspects is not simply disentangled. Instead some requirement on the road surface of the test track, as already exists for tyre noise testing, may be appropriate.

14.1.3 Tyre pressure during the coast down testing

Eventually, tyre pressure is the significant controllable factor in rolling resistance. The set pressure with a tyre at rest and at ambient conditions is only one of the aspects which determine the rolling resistance in a particular coast-down test. From testing it has become clear that tyre pressure may vary greatly between seemingly similar tests. It is influenced by external circumstances, such a sunlight and precipitation. However, it is also affected by the test execution. For example, intermediate driving at different velocities, e.g., in the bends of an oval test circuit between coast downs on the straight tracks, causes systematic deviations of more than 0.1 bar in tyre pressures.

The rolling resistance, measured according R 117, of the tyre used from the prescribed tyre class must be corrected back to the class value from the table:

$$F0_{corrected} = F0_{test} * RRC_{class}/RRC_{test}$$

14.2 Drive line resistance

Driveline resistance is the result of friction in the bearings and the differential. Quite often a 5% or 10% of the total work of the engine does not reach the wheels, but is lost in the driveline. The transmission, or gear-box, will take a major part of the loss. The bearings and differential are the smaller part of the driveline loss, however, it is the part that remains in the coast-down test as the transmission is disengaged.

Bearings are well-examined, but lubricants are a high-tech product, where temperature and velocity dependence of the viscous friction is tuned by specific non-Newtonian fluid properties. Generally a bearing will have an offset friction at low speed to ensure the absence of metal-metal contact and high wear, but the friction will increase somewhat as the rotational velocity increases. The complexity lies in part with the lubricant film thickness which may vary with speed and temperature.

It must however be noted that the mechanical design, including bearing are made to match the maximal forces encountered. The coast-down test and vehicle test mass are at the lower end of the force spectrum of normal usage. The resulting proportionally higher friction may partly be compensated by thinner, less viscous, lubricants, which might be less suitable for normal vehicle operation where the high forces may be encountered.

The driveline resistance of the test vehicle was estimated at 9.9 Newton per wheel at the driven axle, and 2.3 Newton per wheel at the free-running axle. In total 14% of the total rolling resistance of the vehicle, which is not a negligible fraction. With four-wheel drive, assuming the friction is the same of every driven axle, the additional driveline resistance is 60% higher: up to 23%, from 14%, of the total rolling resistance

14.2.1 Lubricants
Lubricants are an art in itself. The non-Newtonian fluid with specific temperature dependence is to ensure proper operation under a wide range of conditions. The relative velocity of the lubricated parts generate a lubricant film. Hence with low velocity the film thickness can be small. Furthermore, the friction can increase the temperature will also affect the rheological properties. No detailed assumptions are made, however, the frictional torque of rotating parts will have a major constant part and a small velocity dependent term. The size of the velocity dependent term will depend on the design.

14.2.2 Cogging
Apart from constant friction of the rotating parts with film lubrication, chain wheels and differentials can have energy losses due to cogging. Cogging is for example the variable force and motion with the contact between chain wheels. With lower rotational velocities this type of losses will be significant, as it will lead to velocity variations in the driveline. So far, the increase in rolling resistance at very low velocities in not included in the coast-down test, and part of the dynamometer test. Hence the effect on coast-down testing can be ignored.

15 Air-drag

At velocities above 40-60 km/h the air drag will dominate the total driving resistance of the vehicle. The generic assumption for air-drag is a quadratic dependence of the force on the velocity:

$$F = \tfrac{1}{2} c_D A \rho v^2$$

Where A is the frontal area, v the vehicle velocity, ρ the density, and c_D the drag coefficient, varying between for a modern passenger car between $c_D \sim 0.25$ and $c_D \sim 0.4$.
The major part of the road load, especially at higher velocities, is determined by this relation. However, the drag coefficient c_D is the result of tweaking vehicle shape to limit the obstruction of the air flow around the vehicle. Deviations from the v^2 dependence are observed and related to flow separation and the onset of turbulence. At high velocity the flow is fully developed and the relation above is guiding up to velocities reaching the speed of sound. In the lower velocities the complications arise. However, these complications have limited impact as the contribution of the air drag to the total road load is also limited.

15.1 Vehicle model variations

There exists a large amount of anecdotal information of the reduction of air drag during the coast down test. This includes the taping of splits at the bonnet and head lights, the removal of mirrors, etc.. Within the legal text there is a limited number of possibilities to actually make such adaptions. Some adaptions are only natural choices, others are at the boundary, and only a few adaption tested were considered beyond the freedom within the interpretation of the text. The removal of the kerb-side mirror is in the latter group.

15.1.1 Wheels

The open or closed structure of the wheel will affect the air drag of the vehicle. A completely closed wheel hub may have an higher drag than a slightly op wheel hub, but all in all, the more open the wheel hub, the higher the air drag is expected to be. The total power, $P_{\text{through flow}}$ [W] dissipated in flow through any part of the vehicle is:

$$P_{\text{through flow}} = \Delta P * Q$$

Where ΔP [Pa] is the pressure drop, and Q is the total volumetric flow per second [m^3/s]. For a large range of settings the pressure drop changes little with the actual setting, but the flow increases with the open setting. Hence it is appropriate to use the most open setting in the coast down test, for parts of the vehicle which have a through flow.

The aerodynamic drag is closest to worst case with the maximal flow through the vehicle body parts. Hence, the most open settings and design should be used during coast-down testing. In particular, grill vanes should be fully open to allow for the maximal flow through the radiator.

15.1.2 Tyres

The width of the tyre affects the air drag of the vehicle. The fact that the tyres rotate in between the moving vehicle and the stationary road, complicates the air stream around the vehicle. However, in the case of an option of different tyres, the widest tyres should be selected.

```
With the freedom to choose different tyres, on the basis of
their rolling resistance, the widest tyre with the smallest
rim must be chosen on the basis on aerodynamic drag.
```

15.1.3 Fixtures

Fixtures come in a wide variety. Many should be considered part of the vehicle model. Different bumpers or door handles are not expected on the same vehicle model. Some fixtures, however, are optional. The antenna for the radio is an example, but the kerb-side mirror could, in the past, be considered a border case for an optional fixture. The combination of closed wheel hubs, and the removal of the kerb-side mirror and the antenna, gave an effect of 4% reduction of the air drag.

15.1.4 Settings

The settings of the movable, or changeable, parts of the vehicles were already mentioned in the case of the wheels where the open wheel or hub is likely to have more air drag associated with it. Other settings affecting the air drag are those affecting the flow though and around the vehicle. Windows can be kept close, but the grill, for cooling the engine via the radiator, should be kept open. A substantial effect of 10% on the total air drag is found between open en closed grill vanes, or slats. Likewise, it is expected that the worst case setting are those with the largest through flow, i.e., the most open structure.

16 Literature

Literature used:

1. *Dubbel, Handbook of mechanical engineering* (eds. W. Beitz and K.-H. Küttner), Springer 1994
2. *American Institute of Physics Handbook*, McGraw-Hill 1972.
3. *Aerodynamics of road vehicles*, W.-H. Hucho, SAE publications 1998.
4. *Bosch Automotive Handbook*, Wiley 2010.
5. Perry and Chilton, *Chemical Engineers' Handbook*, McGraw-Hill 1972.
6. ACEA: *White book on CO2 declaration procedure HDV*; ACEA Workinggroup-CO2HDV; January 2014
7. MAC: Hausberger S., Vermeulen R. et.al: *Draft technical annex for a test procedure on air conditioning systems from LDV*; Version 2.6. (28-02-2014)
8. IVT: Thermodynamic Scrip ; Institute for Internal Combustion Engines and Thermodynamics TU-Graz; 2013
9. Rexeis M., Hausberger S., Kühlwein J., Luz R.: U*pdate of Emission Factors for EURO 5 and EURO 6 vehicles for the HBEFA Version 3.2*. Final report No. I-31/*2013/ Rex EM-I 2011/20/679 from 06.12.2013.*
10. *UN ECE: Proposal for a new UN Global Technical Regulation on Worldwide harmonized Light vehicle test Procedures* (WLTP); ECE/TRANS/WP.29/GRPE/2013/13; Draft from 17th September 2013;
11. Rune Karlsson, Ulf Hammarström, Harry Sörensen, and Olle Eriksson, *Road surface influence on rolling resistance coastdown measurements for a car and an HGV*, VTI 2011.
12. Ulf Hammarström, Rune Karlsson, and Harry Sörensen ,ECRPD *Road surface effects on rolling resistance: coastdown measurements with uncertainty analysis in focus*, VTI, 2009.

17 Ondertekening

Delft, <datum>

Placeholder

<naam afdelingshoofd>
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A Abbreviations

A......................Cross sectional area [m²]
a......................Acceleration [m/s²]
AT....................Automatic transmission
BSFC...............Brake specific fuel consumption [g/kWh]
C_D, C_w ……… Air drag coefficient [-]
C_x.....................Concentration of a component x in the exhaust gas [ppm]
DIN..................Deutsches Institut für Normung
EGR.................Exhaust gas recirculation
FC....................Fuel Consumption
F0, F1, F2……. Road load polynomial fit in [N], [N/[km/h]], [N/[km/h]^2]
LDV.................Light Duty Vehicle
m_{ref}...................Kurb weight of the vehicle [kg]
m_{low}..................Test mass low in WLTP [kg]
m_{high}.................Test mass high in WLTP [kg]
M……………… Generic test mass
m_r …………….. Rotational inertia expressed as additional weight [kg]
MT....................Manual transmission
NEDC...............New European Driving Cycle
PHEM Passenger car and Heavy duty Emission Model (vehicle longitudinal and emission model from TUG)
P_{wheel} ....Power at the wheel of a vehicle, i.e. sum of driving resistances [W]
R_0, R_1, R_2.........Road load from air and rolling resistance in [N], [Ns/m], [Ns²/m²]
RRC…………. Rolling Resistance Coefficient of tyres [-] (ratio of forces)
RH……………. Relative Humidity [%]
p.......................Pressure [bar]
Pe....................Effective power of the engine [W] or [kW] as specified
P_{rated}.................Rated engine power [[W] or [kW] as specified
SOC.................State of charge of the battery [kWh] or [kWs] as specified
t........................Temperature [°C] or time [sec]
T.......................Temperature [°K]
T……………… Coast down time [sec]
v.......................Vehicle velocity [km/h] or [m/s] as specified
W......................Work over the cycle, usually in this document given in [kWs]
WLTC..............Worldwide harmonized Light duty Test Cycle
WLTP...............Worldwide harmonized Light vehicles Test Procedures
ρ.......................density [kg/m³]
ΔFC..................Extra fuel consumption (unit as stated in equation)
ξ………………...Form factor [%] relation between weight and rotational inertia

B Coast down formulas

B.1 Coast down curve

Given the force balance:

$$M\,a = F0 + F1 * v + F2 * v^2$$

The coast down can be recovered from integrating this differential equation:

$$t = \text{int} -M/(F0 + F1 * v + F2 * v^2)\ dv$$

which is:

$$t(v) = -2M*\arctan[(2F2*v+F1)/D]/D$$

or, inversely:

$$v(t) = -1/2 *(D*\tan[D*t/(2M)] + F1)/F2$$

where the determinant is $D = (4*F0*F2-F1^2)^{1/2}$. The coast down times follow from t(v). For example, the coast down time between 85 and 75 km/h is: $T = t(v_{end} = 75)-t(v_{start} = 85)$. The coast-down distance is much more complex, as it is the integral over v(t), between implicit boundaries v_{start} and v_{end}.

B.2 F1 = 0 approximation

The comparison of different road loads parameters: F0, F1, and F2 is less straightforward than expected, due to the correlation of the coefficients, and the mixed contributions, in particular to F1. An approximation where F1 is set to zero gives a better comparison between the different F0's and the different F2's. This transformation can be carried out by considering the least-square approximation of the different road loads between v=0 and v_{max}:

$$F0_{new} = F0_{old} + 3*F1_{old}*v_{max}/16$$

$$F1_{new} = 0.0$$

$$F2_{new} = F2_{old} + 15*F1_{old}/(16*v_{max})$$

In this approximation it is possible to determine the coast down distances from integrating v(t):

$$\text{distance}(v) = M*\ln[1+F2*v^2/F0]/(7.2*F2)$$

The distance is related to the force through the change in kinetic energy:

$$F = M*(v_{start}^2 - v_{end}^2)/(25.92*\text{distance})$$

Where M is the total vehicle inertia including the rotational inertia. This approximation is used in the example regarding road slope.

C Standard conditions

Commonly, standard conditions are defined by the scientific community to compare results from different experiments. The conditions used in the WLTP text are the STP conditions. However, common ambient standard conditions are usually the NTP conditions, at higher pressure and temperature, which is closer to the average mondial values.

Table 16 the standard conditions

Condition	Temperature	Pressure	Humidity
STP	0^{o} C [273.15 K]	100000 Pa	Not specified
NTP	15^{o} C [288.15 K]	101325 Pa	0% RH
WLTP coast down	16.85^{o} C [300 K]	100000 Pa	Not specified

Furthermore, the gravity is set at g = 9.81 m/s^2 and the gas constant at R = 8.31 J mol^{-1} K^{-1}.

D Validation test program

In order to establish the correctness of the existing and proposed corrections an extensive test program has been executed. One common vehicle has been tested on three different circuits, with two types of wheels and three types of tyre for those wheels. The tests have all been executed according the protocol described in the WLTP 1a text. Apart from different wheels, also different weights and tyre pressures were used. The tests are described in a separate report. In this appendix to the main report only the main observations are repeated.

In total 58 hours of test data was collected. The typical spread in coast down values, expressed at 1/T, in consecutive “a” tests, and consecutive “b” tests 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 reduced 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 this variation in the test results.

Hence the analysis consisted of three phases:

1. Multi-regression analysis on all the data per velocity range. From this analysis the appropriateness (functional form and magnitude) of the existing WLTP corrections were determined.
2. Multi-regression analysis on all the data with the functional form a + b*v + $c*v^2$. From this the magnitude of the effects were determined.
3. Multi-regression analysis on all the data, for the functional form, with the corrections for wind, temperature, air pressure, road gradient, vehicle weight, from the the magnitude of the remaining effects were determined.

As much as possible all the data was included in the analysis. For example, the effect of tyre pressure is based on all the data, allowing for offsets for the alternative tyres (sport and eco):

$$F0 = F0_{base} + \Delta F0_{pressure\text{-}dependence} * \Delta p + \Delta F0_{sport} + \Delta F0_{eco}$$

In this manner all the data is fitted with four tyre coefficients: the base value, the dependence on pressure, and offsets for the two alternative tyres.

The statistical noise is significant for the separate effects within the range of the WLTP test protocol. Physical arguments should augment the measurement program in order to arrive at proper conclusions and correction algorithms.

D.1 WLTP corrections

The corrections described in the WLTP text are validated. Overall the corrections are appropriate as the same results were found within the bandwidth of the accuracy:

- Test mass correction in the WLTP is somewhat smaller than is seen in the test. The rolling resistance increased more than proportional with the increase in test mass. This is probably due to the low tyre pressure prescribed in the vehicle door label.
- The stationary wind correction is correct, it reduces the difference between the “a” and “b” test significantly, in cases of wind above 2.5 m/s.
- The temperature correction of the tyres (rubber viscoelasticity) deemed correct by the measurement program, despite the complexity of heat transfer around the tyre.
- The need for an air pressure correction is confirmed by the test program. This air pressure correction is appropriate.
- The new approach to average the reciprocal of the cost-down time ensures the limited contribution of the road slope to the road load results.

The coast-down 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.
Initially, for each velocity, the analysis was performed separately. The appropriate velocity dependencies arose in this analysis: constant terms for rolling resistance, and quadratic terms for air drag, and combination of constant and a linear term for wind.

In the second stage, the appropriate velocity dependency was inserted for each of the elements in the test matrix, and the effect was quantified. This yields the most significant magnitude of each of the variation.

D.2 Consistent effects as observed

In the data, apart from the already existing effects corrected for in the WLTP text, other effects can be recognized.

D.2.1 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%.

D.2.2 Grill vanes

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 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.

D.2.3 Aerodynamic options

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%.

D.2.4 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 of 2.1 bar, the correction of the rolling resistance, based on this measurement program, would be:

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

Instead of the exponent of 0.7, exponents of 1 and 1.5 are often quoted. The result will depend on the tyre type, and the initial pressure.

D.2.5 Different tyres and wheels

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, the latter 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.

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 same pressure, 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.

D.2.6 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 yield lower air drag, in the order of the expected result of around a percent.

D.2.7 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.

D.2.8 Road slope

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 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 the result of gravity, vehicle mass, and slope. In this manner only part of the vehicle mass is recovered.

D.2.9 Curved trajectories

The accuracy of the GPS allowed for the study of a curved trajectory rather than straight. Given the substantial effect of alignment of the wheels, the curved track can affect the rolling resistance positively. Indeed, given typical deviations of 0.5-1.0 meters from the original endpoint over 100 meters, the larger deviations give a slightly smaller rolling resistance. There is insufficient data to see a different effect in the case of 0^{o} alignment.

D.2.10 Wind

The test track in The Netherlands was a few kilometers from the North-Sea coast, with substantial wind. The meteorological station at the height of 10 meters has an average wind velocities (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 an 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.