Correction of test cycle tolerances: evaluating the impact on CO₂ results

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Abstract

The World-wide harmonized Light duty Test Procedure (WLTP) issued as UNECE GTR No. 15 is designed to check the emissions compliance of Light Duty Vehicles (LDVs) around the world and European Commission is planning to introduce the WLTP in the European Type Approval process starting on 1 September 2017. WLTP has greatly reduced the flexibilities that are in the NEDC procedure and has eliminated many loopholes. However a certain degree of flexibility in the test procedure is necessary, otherwise no type approval test would be valid. In order to lower the impact of those flexibilities having influence on CO₂ emissions, a European Task Force dealing with the corrections of WLTP flexibilities was established. The work presented in this paper shows the result of the practical implementation of some corrections, such as imbalances in the state of charge (SOC) of the battery, deviations against the target road load, target speed, target distance, and target soak temperature. These corrections have been applied also to NEDC tests, in order to compare their impact with WLTP corrections. The repeatability “r” (test-to-test variations) and the reproducibility “R” (lab-to-lab variations) of CO₂ results measured in different laboratories, for the same vehicles, are evaluated before and after the normalization. In summary, all corrections steps performed in this study influenced the average CO₂ emissions by approximately 1.3% and 3.8%, for WLTP and NEDC respectively, which in our opinion is an indication of the reduction of flexibilities from NEDC to WLTP. This initial analysis of the impact of the correction on the repeatability and reproducibility of test results shows promising potential, however it must be pointed out also that in several cases the application of this methodology has led to a worsening of either r and/or R. In particular, the correction of the Road

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Load coefficients seems to have practical issues of difficult solutions. Further tests and analyses are needed and expected for a better understanding of this issue and for the improvement of the whole procedure.

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1. Introduction

Increasing gap between the certified CO₂ emissions measured over the New European Driving Cycle (NEDC) and the corresponding real life values identified in many recent studies (Mock et al. (2012); Weiss et al. (2011); Pelkmans and Debal (2006)), was one of the major reasons for development of a World-wide harmonized Light duty Test Cycle (WLTC) and Test Procedure (WLTP).

The objective set by the European Commission is to introduce the WLTP in the European Type Approval (TA) process starting on 1 September 2017 in parallel to the introduction of the Euro 6c emission limit step (Regulation No. 715/2007; Regulation No. 692/2008) and together with the procedure for measuring Real Driving Emissions (Vlachos et al. (2014)).

A test procedure covers everything from the preparation of the test vehicle and measuring equipment to how the test is to be conducted and the results calculated. Some flexibilities, i.e. deviations against the target values defined in the test procedures, are necessary and therefore allowed during the tests (both WLTP and NEDC) in order to get valid test results in a real test environment. However these tolerances lead to test-to-test variations in results, in particular for CO₂ emissions and can to some extent be exploited to reduce the CO₂ test value. After-test corrections can therefore increase the repeatability of the test results and provide CO₂ values that better reflect the target cycle decreasing external influences (i.e. driver, fluctuations in test conditions, etc.). In addition, this normalization gives the valuable opportunity to compare the CO₂ results for the same vehicles tested in different laboratories, i.e. to increase also the reproducibility of results.

In NEDC, no corrections are carried out, giving the opportunity to vehicle manufacturers to artificially lower the CO₂ emissions of their vehicles by, e.g. driving towards the lower tolerance limit in the speed profile, testing with fully charged battery, etc. Being aware of this impact on CO₂ test results, a European Task Force dealing with the corrections of WLTP flexibilities was established and is working on their integration into the European Legislation. The main research in developing correction algorithms for WLTP chassis dynamometer and coast-down testing has been carried out by Graz University of Technology (TUG) and Netherlands Organization for Applied Scientific Research (TNO). The work presented in this paper evaluates practical implementation of the most common tolerance corrections and their potential impact on measured CO₂ emission results.

Deviations evaluated here are: imbalances in the state of charge (SOC) of the battery, deviations against the target road load, target speed, target distance, and target soak temperature. The correction algorithms are explained and their application validated on several vehicles tested at the Joint Research Center (JRC). In addition, the reproducibility of CO₂ results measured in different laboratories, for the same vehicles, is evaluated before and after the normalization. Different drivers with different driving behavior, but still within the given tolerances, can influence the resulting CO₂ emissions and that effect is assessed and normalized.

The paper is organized as follows. In the next section, correction steps and calculation algorithms are described. Information about the vehicles tested and test matrix is provided in section 3. Results are summarized in the section 4 and the conclusions, including an estimate of the final influence of test flexibilities on the measured CO₂ results under the old NEDC and the new WLTP test are presented in section 5.

2. Corrections of test deviations

2.1. SOC correction

The NEDC procedure does not include any balancing/correction of state of charge (SOC) of the vehicle battery between beginning and the end of the test. That usually results in tests that are started with fully charged battery and
ended with depleted or partially depleted battery, and fuel consumption/CO₂ emission not corrected for this effect. In the real life use of the car there is no external charging/recharging of the battery. The WLTP has filled this loophole of the NEDC procedure and the correction of imbalances in SOC of the battery has already been included in GTR No. 15 (UNECE GTR No. 15, 2014).

Battery current is monitored over the whole WLTC cycle and fuel consumption and CO₂ emission results are corrected as needed for the imbalances in the battery SOC. In addition, in the WLTP procedure, the battery is not charged during its soak, as is the common practice for NEDC. Previous results have shown that the imbalance in battery SOC can influence the WLTC test result up to approximately 2 g/km of CO₂ (Ligterink et al. (2014)).

To apply the correction function, the electric power to the battery shall be calculated from the measured current and the nominal voltage value for each phase of the WLTC test:

\[ \Delta E_{el,phase(i)} = U_{REESS} \int_0^{t-end} I(t)_{phase (i)} dt \]  

(1)

where \( \Delta E_{el,phase(i)} \) is the change in the REESS (Rechargeable Electric Energy Storage System) energy content of phase in J; \( U_{REESS} \) is the nominal REESS voltage in V; \( I(t)_{phase (i)} \) is the electric current in phase (i) in A; and \( t-end \) is the time at the end of phase (i) in seconds (s).

The resulting CO₂ emissions difference from the engine for each WLTC phase due to load behavior of the alternator for charging the battery shall be calculated as shown below:

\[ \Delta CO_2,phase(i) = \Delta E_{el,phase(i)} \times \frac{1}{\eta_{alternator}} \times \text{Willans factor} \]  

(2)

Where \( \Delta CO_2,phase(i) \) is the resulting CO₂ emission difference of phase (i) in g; \( \eta_{alternator} \) is the efficiency of the alternator (0.67 for electric power supply system battery alternators); and \( \text{Willans factor} \) is the combustion process specific Willans factor as defined in Table A6 of GTR No.15 (UNECE GTR No. 15, 2014).

2.2. Target road load and speed correction

Due to the fact that actual power at the wheels delivered during the test can be different from the target power, a correction function needs to be developed that will adapt CO₂ result against the target settings. Power at wheels is compared with the target road load coefficients (measure from on-road coast-down, or torque meter method, or wind tunnel) and the correction is carried out. More details can be found elsewhere (Ligterink et al. (2014)).

The actual \( P(a) \) and target \( P(t) \) wheel power are thus calculated using the following formulas:

\[ P(a) = (F_0(a) + F_1(a) * v(a) + F_2(a) * v^2(a) + m(a)) * a(a) * v(a) \]  

(3)

\[ P(t) = (F_0(t) + F_1(t) * v(t) + F_2(t) * v^2(t) + m(t)) * a(t) * v(t) \]  

(4)

where \( F_0(a), F_1(a), F_2(a) \) are the road load coefficients measured from coast down test immediately after the test and \( F_0(t), F_1(t), F_2(t) \) are the target road load coefficients. Subsequently, \( v(a), a(a), m(a) \) represent velocity, acceleration and mass measured during the test and \( v(t), a(t), m(t) \) are the target values. Only positive wheel power (or power above “POVERRUN”) is averaged.

In the next step measured CO₂ bag results are correlated to the actual/measured power at the wheel for each phase of the test (Formula 3). The Willans equation gives the CO₂ flow as function of the power at the wheel:
\[
CO_2 \left( \frac{g}{\text{km}} \right) = k_v \cdot P_{(t)} + D
\]  

where \( k_v \) is vehicle specific Willans coefficient (g/kWs) and \( D \) is constant representing parasitic losses or CO\(_2\) emissions at zero power at the wheels. The Willans coefficient from this equation can correct parameters leading to deviations of the work at wheel, such as speed deviations and road load deviations.

We note here, and will explain in section 4 (Results and discussion), that this correction, although simple and straightforward in principle, is the most delicate and difficult to perform in practical terms, due to the uncertainties in the determination of the actual road load coefficients.

2.3. Target distance correction

With speed correction described in the previous section, the power (and CO\(_2\) consequently) is normalized to the power necessary to meet the target velocity. However, by braking more or less aggressive than the target decelerations, the distance can be different from the target distance (23.27 km for WLTP and 11.03 km for NEDC). That change does not have the effect on total WLTP fuel consumption and CO\(_2\) emitted since in these phases the engine is most of the time in P OVERRUN and at fuel consumption equal to zero. Still, the CO\(_2\) result (g/km) calculated after the correction for deviations against the positive power (target road load and speed correction) corresponds only to the actual distance travelled and has to be divided by the target value (km):

\[
CO_2(d) \left( \frac{g}{\text{km}} \right) = \frac{CO_2(p-corr) \left( \frac{g}{\text{km}} \right)}{d_t \left( \frac{d}{\text{km}} \right)} \cdot \frac{d_m \left( \frac{d}{\text{km}} \right)}{d_t \left( \frac{d}{\text{km}} \right)}
\]

where \( CO_2(p-corr) \) is the CO\(_2\) result corrected for deviations against the target speed and road load, \( d_m \) is the distance measured during the test, and \( d_t \) is the target distance. Therefore, the final result (\( CO_2(d) \)) is without the offset from different brake behaviour of the driver.

2.4. Target soak temperature correction

For a given driving cycle the effect of cold start in terms of fuel consumption and CO\(_2\) emissions depends on the starting temperature of the engine and the exhaust system. A lower temperature at the start results in higher fuel consumption and subsequently higher CO\(_2\) emission. In the NEDC procedure, the test temperature in the laboratory is set to a range between 20 °C to 30 °C. The WLTP requirement is more precise, with the starting test temperature set to 23 ± 3 °C. Recently published study (Ligterink et al. (2014)) quantified the effect of temperature at start of the test on CO\(_2\) emission level. Approximately 0.2% impact on CO\(_2\) concentration is measured for 1 °C deviation against the target temperature. Therefore, a linear equation for small temperature offsets is suggested:

\[
\Delta CO_2(\%) = 0.18\% \cdot (t_t \left( ^\circ C \right) - t_m \left( ^\circ C \right))
\]

where \( t_t \) and \( t_m \) are target and measured temperatures respectively and 0.18% is the average measured coefficient for soak temperature correction (0.18% change/°C).

Further options for corrections where still open questions exist and are not considered in the present study are:

- Correction to account for the average European temperature (14 °C);
- Intake air temperature and humidity;
- Quality of test fuel; and
- Deviation from designated gearshift points.

3. Test vehicles and procedures

Four vehicles have been tested with the main characteristics listed in Table 1. The influence of normalization was analyzed on two driving cycles: NEDC and WLTP. In addition, reproducibility was measured before and after the
corrections applied on the results reported by different laboratories involved in the study. Six laboratories were involved, but not all of them had results for all vehicles and both driving cycles.

All vehicles were tested over the cold start cycle conditions according to the legislative procedures for type approval. The CO₂ emissions were measured using the Tedlar bags as prescribed by the legislation. Battery current is monitored over the whole cycles (minimum 5 Hz data). For road load correction coast down tests were performed immediately after each test. For speed correction, vehicle speed was monitored with 10 Hz frequency. For target soak temperature correction, temperature of oil was recorded at the beginning of the tests.

4. Results and discussion

This section shows the measured CO₂ emissions and the results of each single correction step performed. Results are broken down by the vehicles tested and laboratories involved in the inter-comparison. In order to keep identity of vehicles anonymous, CO₂ results are shown as a deviation from the mean value calculated over three (in rare cases two) tests obtained.

| Table 1. Overview of passenger cars tested, tests performed and laboratories involved. |
|--------------------------------|--------------------------------|----------------|----------------|
| VEH1 | VEH2 | VEH3 | VEH4 |
| Fuel | Gasoline | Diesel | Gasoline | Gasoline |
| Emission standard | EURO6 | EURO5 | EURO5 | EURO5 |
| Transmission | Manual | Automatic | Automatic | Manual |
| Power (kW) | 100 | 120 | 100 | 120 |
| Test mass (kg) | 1560 | 1520 | 1250 | 1360 |
| Tests performed | NEDC | NEDC | WLTP | WLTP |
| Laboratories involved | LAB1 – LAB6 | LAB1 – LAB6 | LAB1 | LAB1 |

Applying the SOC correction was the crucial step in reducing the standard deviation between the tests in all laboratories, as well as in increasing the reproducibility of the average test results measured in different laboratories. On the contrary, the RL and speed correction in most cases (3 out of 4) increased the standard deviation between the tests. However, it should be noted that this effect is mainly the result of target road load correction and not speed correction. It suggests low repeatability of the road load coefficients from coast downs performed immediately after the tests. Distance correction in 3 out of 4 laboratories further increased deviation between the tests. In contrast, the soak temperature correction (for NEDC all tests were corrected to 25 °C) in most laboratories reduced the standard deviation between the tests.

WLTP tests were performed on the same gasoline vehicle in 3 different laboratories (Figures 2A -2C), and the results were corrected following the same procedure. In summary, correction steps resulted in higher standard deviation between the test results, with the exception of LAB4 where standard deviation dropped from ±2.5 to ±1.7 g/km. In that laboratory every correction step applied leaded to slightly lower variation between measured CO₂ results. However, at the end variation was still high and further correction steps, not analyzed in the present study (such as intake air temperature and humidity, and fuel corrections), might further improve that variation.

Standard deviation between tests measured in LAB1 and LAB6 gradually increased after SOC, RL, and speed corrections, and improved slightly after distance and temperature corrections. However, at the end, variation was two times higher compared to the variability in test results present before any correction.

Comparison of the average test results in these 3 laboratories and the effect of each single correction step is shown in Figure 2D. Significantly lower CO₂ results were measured in LAB6 where WLTP tests were performed on 1-axle chassis dynamometer without applying 1.5% correction (increase) of the vehicle inertia as specified in GTR15. If that correction was applied, the CO₂ results would be higher and more in line with results from other 2 laboratories. Reproducibility of average test results in these 2 laboratories, where tests have been carried out on 2-axle chassis dynamometer, decreased after the correction steps and standard deviation changed from ±0.1 to ±1.0 g/km.
Fig. 1. NEDC test results for vehicle 1 performed in laboratories 2-5 (Figure 1A-1D) along with the effect on average results and reproducibility (Figure 1E).

Fig. 2. WLTP test results for vehicle 1 performed in laboratories 1, 4, and 6 (Figure 2A-2C) along with the effect on average results and reproducibility (Figure 2D).
4.1. Vehicle 2 results

Figure 3 shows the NEDC test results for diesel vehicle 2 obtained in four laboratories. It should be noted that LAB6 reported only 2 valid NEDC tests and for that laboratory statistical analysis is irrelevant. Correction steps performed resulted in higher repeatability only for LAB5. In that laboratory every correction step resulted in lower deviation and average standard deviation dropped from ±1.0 to ±0.6 g/km. In all other laboratories deviation between the results was higher after the corrections and this appears largely due to the RL correction step. Only distance and soak temperature correction steps slightly improved the results and reproducibility.

In addition, repeatability of the results did not change after corrections and standard deviation slightly increased from ±1.0 to ±1.1 g/km. Only the SOC correction improved the repeatability. There is no clear evidence why LAB5 had higher results compared to the other three laboratories.

On the same diesel vehicle WLTP tests were performed in 3 different laboratories and the results were corrected and shown in Figures 4A-4C. The most successful application of correction steps was found for LAB6 test results. In that laboratory every correction step resulted in lower variation between CO₂, and standard deviation dropped from ±0.9 to ±0.2 g/km. For LAB1 SOC correction is the only step that increased repeatability of test results, while for the LAB4 increase in repeatability can be attributed to speed and RL correction, and soak temperature correction steps.

Comparison of the average test results in these 3 laboratories and the effect of each single correction step is shown in Figure 4D. Significantly lower CO₂ results were again measured in LAB6. However, this time WLTP tests were performed on 2-axle chassis dynamometer and there was no clear evidence why the results were lower compared to the other two laboratories. In addition, for that laboratory, each correction step resulted in lower CO₂ result and overall reproducibility as well. Reproducibility of the average test results in two remaining laboratories improved with SOC, speed, and RL corrections (standard deviation after corrections ±0.1 g/km), but then again worsen with distance and temperature corrections.

In summary, for vehicle 2 correction steps applied did not improve the reproducibility of either NEDC or WLTP test results, while the repeatability of WLTP tests increased after corrections in 2 out of 3 laboratories tested.
Fig. 4. WLTP test results for vehicle 2 performed in laboratories 1, 4, and 6 (Figure 4A-4C) along with the effect on average results and reproducibility from different laboratories (Figure 4D).

Fig. 5. WLTP test results and effects of the correction steps on individual tests performed on vehicle 3 and 4.
4.2. Vehicle 3 and 4 results

Figures 5A and 5B show the WLTP test results for vehicles 3 and 4 and the effects of single corrections discussed in the previous sections. For both vehicles tested overall repeatability increased after corrections and standard deviation dropped from ±0.9 to ±0.4 g/km for vehicle 3 and from ±0.8 to ±0.5 g/km for vehicle 4. The SOC correction method slightly increased the variation in test results, while RL and speed corrections were the crucial steps in reducing the standard deviation between the tests for both vehicles. However, it is quite striking the impact of RL and speed corrections on test 2 of vehicle 4, showing a variability that is difficult to fully understand and requires a more specific analysis.

5. Summary of the effects and conclusions

From the results presented in the previous chapters, both on NEDC and WLTP, it is difficult to have clear and final conclusions about the importance of different correction steps and their influence on the final CO₂ results. Variation in results might come from the vehicle itself and its (in)stability during the testing, but also from the laboratory and precision of measuring equipment.

Therefore, in order to get overall conclusions, we have calculated the average influence of each correction step expressed in % of initial/measured CO₂ result for all four vehicles tested and separated by the driving cycle (Table 2). In addition, the influence of correction steps on each phase of the cycle is also presented.

Table 2. Average influence of each single correction step on the CO₂ results from both driving cycles expressed in percentage of measured CO₂

| Test cycle | Phase | Corrections |
|------------|-------|-------------|
|            |       | SOC | Speed+RL | Distance | Temperature |
| WLTP       | Low   | 1.12| 3.58     | 0.44     | 0.12        |
|            | Medium | 0.36| 3.87     | 0.21     | 0.11        |
|            | High   | 0.30| 1.06     | 0.16     | 0.12        |
|            | Extra-high | 0.22| 0.63     | 0.18     | 0.12        |
|            | TotalAVERAGE | 0.44| 0.57     | 0.19     | 0.11        |
|            | TotalMAX/MIN | 0.89/0.01| 1.44/0.01| 0.34/0.00| 0.16/0.00 |
|            | UDC    | 3.26| 0.37     | 1.50     | 0.46        |
|            | EUDC   | 1.06| 0.85     | 0.37     | 0.46        |
|            | TotalAVERAGE | 2.11| 0.47     | 0.79     | 0.46        |
|            | TotalMAX/MIN | 5.76/0.20| 1.78/0.10| 1.71/0.13| 0.67/0.34 |

From the results presented, influence of SOC imbalance was lower for WLTP tests compared to the NEDC tests. This is the result of the procedural loophole present in the NEDC procedure that has been eliminated in WLTP. For both driving cycles this correction step had the biggest influence when the engine is still cold, i.e. during the low speed phase of the WLTP (1.1%) and UDC phase of the NEDC (3.3%). When averaged over the whole cycle that influence decreases and becomes ~ 0.4% for WLTP and ~ 2.1 % for the NEDC.

Speed and RL corrections had on average ~ 0.5% ÷ 0.6% influence on the total results from both driving cycles, with low and medium WLTP phase being the most sensitive to this type of correction (3.6% ÷3.9%). As mentioned earlier, the correction of speed and RL (in particular this latter) has shown some weaknesses in adjusting the repeatability and reproducibility of tests. This seems related to different laboratory protocols for performing the coast down checks after the tests and time passed between the tests and RL checks. In addition, for target RL correction there are still open questions present whether the coast downs after the tests can be representative for the RLs applied by the chassis dynamometer during the test. RLs measured during the coast downs after the tests when vehicle is warmer, especially after the WLTP, might not be representative and used for corrections of cold start phases, e.g. Low and Medium phase of the WLTP. On the other hand, if the time passed between the tests and coast downs is sufficiently long the temperatures of the tires and bearings will decrease over the time and lead to different
RL values during the CD check that the one experienced by the vehicle during the test. Therefore, instead of correcting these deviations it should be also explored the solution of a more precise procedure for the chassis dynamometer road load reproduction before the WLTP test without ex-post correction. To achieve this, a precise definition of the time intervals allowed between the vehicle warm-up and the first coast down as well as the time intervals between each consecutive coast down should be defined.

The distance correction was higher for the NEDC tests compared to the WLTP tests. It was expected that drivers might have more difficulties to follow the new and more demanding WLTP cycle than the old NEDC. On the other hand, the values shown in Table 3 reflect the absolute numbers calculated. The average NEDC value for total distance correction is actually -0.8%. That result indicates more aggressive braking compared to the target deceleration and subsequently shorter distance driven than the target. This driving behavior does not have influence on the total measured fuel consumption and CO₂ emission, since during these periods engine is most of the time in overrun at zero fuel flow. However, for these cases when driven distance is shorter that the target one, corrected test results can be lower as seen in the present study.

Last correction applied; soak temperature correction, had lower influence on WLTP results (~ 0.1%) compared to the NEDC results (~ 0.5%). That result was expected given the more flexible NEDC test procedure (20-30 °C) compared to the rather stringent WLTP soak temperature requirements (23±3 °C).

In summary, all corrections steps performed in this study influenced the average CO₂ emissions by approximately 1.3% and 3.8%, for WLTP and NEDC respectively. This initial analysis of the impact of the correction on the repeatability and reproducibility of test results shows promising potential, however in several cases the application of this methodology has led to a worsening of either r and/or R. In particular, the correction of the Road Load coefficients seems to have practical issues of difficult solution. Further tests and analyses are needed and expected for a better understanding of this issue and for the improvement of the whole procedure.

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