ABSTRACT

AECC, the Association for Emissions Control by Catalyst, conducted a test program to compare the newly developed World-harmonized Light vehicles Test Cycle (WLTC) with the current European regulatory New European Drive Cycle (NEDC) and the cold-start Common Artemis Driving Cycle (CADC).

Vehicle engines and aftertreatment technologies were selected to cover a wide range of future systems. Six European commercially available passenger cars were chosen: three Euro 5 Gasoline Direct Injection cars, two Euro 6 Diesel cars and a Euro 5 non-plug-in gasoline hybrid car. The hybrid car was tested with three different battery state of charge: nominal, minimum charge, and maximum charge.

Investigations on the test temperature were also conducted by comparing emissions at 25°C and at −7°C. Regulated gaseous emissions (HC, CO, NOx) and particulate mass and particles number were measured, together with additional pollutants such as CH$_4$, NO$_2$ and ammonia.

The study isolated cycle-to-cycle effects on emissions for each vehicle by normalizing the test mass in all tests to the draft WLTP (World-harmonized Light vehicles Test procedure) Global Technical Regulation (gtr). Because of the higher inertia used, emissions results obtained on the regulatory NEDC can deviate from type-approval emissions for each tested vehicle.

Comparison of emissions results obtained on NEDC and WLTC tends to show that WLTP may bring more realistic CO$_2$ emissions from the higher vehicle inertia included in the test procedure (closer to real mass of vehicle) but most likely not from its drive cycle pattern, even if it is more transient.

INTRODUCTION

In 2008, GRPE, the Working Party on Pollution and Energy, a subsidiary body of the World Forum for Harmonization of Vehicle Regulations (WP.29) within the United Nations Economic Commission for Europe (UNECE), set up an informal group with the objective to draft a Global Technical Regulation (gtr) for emissions testing of light-duty vehicles, including common methodologies, test cycle and measurement methods: the World-harmonized Light vehicles Test Procedure (WLTP) group [1].

One of the primary motivations for the European Union is to develop a test procedure that would allow for a more realistic measurement of CO$_2$ emissions from vehicles. It would also benefit ambient air quality if the new procedure were able to provide pollutants emissions at vehicle type-approval that are closer to real-world emissions. The later would require key elements such as appropriate transient conditions and maximum speeds together with cold-start [2].

In 2011, a first version of the candidate World-harmonized Light vehicles Test Cycle (WLTC) was evaluated for driveability. Following this first validation phase, the cycle was amended and a “version 5” was established for the purpose of a validation of the whole test procedure (“Validation Phase 2”).
In that context, AECC conducted in an independent lab an extensive test program to compare exhaust emissions performance achieved on the newly developed World-harmonized Light vehicles Test Cycle (WLTC) with the current European regulatory New European Drive Cycle (NEDC) and the cold-start Common Artemis Driving Cycle (CADC) that incorporate more transient operating modes derived from real-world driving and that is used as the basis of emissions factors for modelling of emissions.

**TEST VEHICLES**

Vehicle engines and aftertreatment technologies were selected to cover a wide range of future systems representing the European market. All vehicles were Model Year 2011 or 2012.

**Table 1. Specifications of selected vehicles**

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
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<td>Petrol hybrid</td>
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<td>6</td>
<td>4</td>
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<td>5200</td>
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<td>Emissions control system</td>
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<td>TWC + LNT</td>
<td>TWC</td>
<td>DPF + LNT</td>
<td>DPF + SCR</td>
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<td>2017</td>
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<tr>
<td>Test mass [kg]</td>
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<td>1323</td>
<td>1856</td>
<td>1551</td>
<td>2165</td>
<td>2310</td>
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As shown in Table 1, six European commercially available passenger cars (A to F) were chosen:

- three Euro 5 Gasoline Direct Injection cars
  - a high-power lambda 1 car: A
  - a downsized lambda 1 car: B
  - a lean-burn car: C
- a Euro 5 non-plug-in gasoline hybrid car: D
- and two Euro 6 Diesel cars
  - one equipped with a Lean NOx-Trap and a Diesel Particulate Filter (DPF): E
  - one equipped with a combination of DPF and Selective Catalytic Reduction (SCR) system: F

The hybrid car was tested with three different battery states of charge: nominal, minimum charge, and maximum charge.

The commercial offer of genuine Euro 6 diesel cars was still limited at the start of the program; therefore no downsized diesel engine concept could be included in the program.

All vehicles were procured with a minimum mileage. They had actually already driven between 8500 and 25000 km.

**TEST PROTOCOL**

**Test Cycles**

Three test cycles were evaluated at 25°C on a chassis dynamometer: the current European regulatory NEDC (see Figure 1), the new WLTC (see Figure 2) including a cold-start cycle followed by 30-min soak and then a hot-start cycle, and the CADC (see Figure 3) for which emissions were sampled from cold-start on.

![Figure 1. New European Driving Cycle (NEDC)](image)

![Figure 2. World-harmonized Light vehicles Test Cycle (WLTC) version 5](image)

Most of the emissions results analysis in this paper focuses on the cold-start WLTC only, that is to say the 4-phase cycle composed of low-, medium-, high-, and extra-high-speed phases represented in Figure 2, without taking into account
the subsequent hot-start cycle which is not included in the final version of WLTP.

Figure 3. Common Artemis Driving Cycle (CADC)

It should be noted that vehicles A and E were run on a temporary version of WLTC, slightly different from version 5 described in Figure 2. In this temporary version, the main acceleration of the high-speed phase (from 20 to 93 km/h) was somewhat less aggressive. This difference may have had some limited effect on emissions behavior.

Emissions were measured per phases in 3 bags on the cold start NEDC, in 4 bags on the cold start WLTC, in 2 bags on the hot start WLTC (low-speed, and medium-speed only), and in 3 bags on the cold start CADC. Cycle portions for which emissions were sampled in bags are identified in the respective Figures 1, 2, 3. In addition, emissions were measured continuously during each test cycle.

The test cell used in this program was equipped with 3 bags only, but the 4-bag analysis on WLTC was obtained by analyzing emissions from the low-speed phase bag as soon as sampling in this bag was over.

Emissions Measurement

Tailpipe regulated gaseous emissions (THC, CH₄, CO, NOₓ, CO₂) and PM mass and particles number (PN) were measured in bags per phase, according to the Euro 5&6 Regulation for all vehicles, including the Particle Measurement Program (PMP) method. THC, CO, NOₓ, NO, CO₂ and PN were also measured second-by-second.

In addition, NO₂ was measured by subtracting one-second NO emissions measurement from one-second NOx emissions, and then integrating that result over each cycle.

For the PM mass evaluation, particulates were collected on a single filter paper for the whole NEDC and WLTC but on one filter paper per phase on CADC. For WLTC at −7°C, PM were however collected differently to accommodate with the sampling of the extra-high-speed phase during the hot-start cycle only (see Figure 4): a first filter paper was used for all low-speed, medium-speed, and high-speed phases during the cold-start cycle and two filter papers were used for the hot-start low-speed plus medium-speed phases and extra-high-speed phase respectively.

During the 25°C emissions tests, ammonia was also measured. NH₃ was analyzed by two methods in parallel; continuously by FTUV and per phase by ionic chromatography following bubbling though a sulfuric acid solution.

Road Load Determination

The road load determination was carried out in two steps for each of the six passenger cars, according to Annex 4 of the draft WLTP gtr [3]. The aerodynamic force of each car was determined in a wind tunnel, and subsequently frictions of both axles were determined on the chassis dyno that was used for the 25°C emissions tests.

All test cycles were driven with the same vehicle test mass, not respecting the actual Type-Approval procedure for the NEDC cycle, but using the test mass defined in the draft WLTP gtr. This option was chosen rather than using the test mass specified for NEDC in the Euro 5/6 Type-Approval procedure to establish a direct comparison of the effect on vehicles emissions of the different driving patterns.

The vehicle test mass used was calculated as indicated in formula (1). It is a surrogate for TMₜₜ (Test Mass High) as defined in the draft WLTP gtr.
\[ TM = WM + 100 \, kg + 0.15 \times (LM - WM - 100) \]  

(1)

Where:
- \( WM \) is the real Weighted Mass of the tested vehicle and replaces the draft gtr-defined \( OM_{lt} \) that is the unladen mass of the vehicle plus the maximum mass of options for the family of vehicles.
- \( LM \) is the Laden Mass.

In essence, the test mass was the vehicle mass plus 100 kg plus 15% of the maximum load after taking out the 100 kg.

The vehicle inertia used in the Euro 5/6 Type-Approval procedure were estimated for each test car and a comparison to the inertia values used in the test program (1) are shown in Figure 5. The inertia introduced by the WLTP procedure corresponded in this case to an increase of 5 to 14% compared to the current Type-Approval values.

**EMISSIONS RESULTS**

Three repeats of each test were conducted so as to obtain the confidence interval (CI) for each result.

\[ CI = \frac{2 \times \sigma}{\sqrt{\text{number of tests}}} \]  

(2)

Where \( \sigma \) is the standard deviation.

Emissions results are reported in the following Figures as the average of the three test repeats (two in the case of vehicle D); the error bars correspond to the confidence intervals as defined in equation (2).

For the gasoline hybrid vehicle (D), only emissions measured in the nominal battery state of charge are reported in Figures 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17.

Figure 6 shows total hydrocarbon emissions measured on NEDC, CADC and the cold-start WLTC. The Diesel Euro 6 indicative limit corresponds to the difference between the regulatory limits of THC+NOx and NOx. HC emissions of all vehicles are below the regulatory limits. Although on a relative basis the HC emissions are multiples higher on the NEDC than on the two other cycles, these differences on an absolute basis are only 10–40 mg/km.

Methane emissions measured on NEDC, CADC, and the cold-start WLTC are shown in Figure 7. The Euro 5 indicative limit for SI engines corresponds to the difference between the THC and NMHC limits. Methane emissions of gasoline and hybrid vehicles are below the indicative Euro 5 limit. Vehicle E (Euro 6 Diesel with LNT) and, to a lesser extent, vehicle C (Euro 5 lean GDI) exhibit the largest CH4 emissions. For vehicle E, methane represents more than 60% of the total hydrocarbon emissions on all three test cycles.

Figure 8 shows CO emissions measured on NEDC, CADC and the cold-start WLTC. Despite some cycle-to-cycle variations, CO emissions measured on NEDC, WLTC, or CADC are generally low (to very low for gasoline and hybrid vehicles) compared to the regulatory limits.

NOx emissions measured on NEDC, CADC and cold-start WLTC are shown in Figure 9. Some NOx emissions results on NEDC are slightly above the regulatory limit. However, as described earlier in Figure 5, vehicles inertia used in this test campaign was higher than the value used at type-approval. This may explain the impact on NOx emissions on NEDC.
Except for vehicle C, NEDC and WLTC are very similar in terms of NOx emissions. Nevertheless, both the Artemis CADC and WLTC highlight some increase in NOx emissions on the lean GDI car (vehicle C) compared to the regulatory NEDC.

The Artemis CADC also highlights the higher NOx emissions in real-world of current diesel cars (vehicles E and F). This is in line with other measurements and is being addressed by the European Commission developing real-driving emissions provision for the second stage of the Euro 6 legislation.

Figure 10 shows NO\textsubscript{2} emissions measured on NEDC, CADC and the cold-start WLTC. Like for NOx, CADC highlights the higher NO\textsubscript{2} emissions observed on current diesel cars when operated in real-world. WLTC tend to give marginally higher NO\textsubscript{2} emissions for diesel cars when compared to NEDC. Again, both the Artemis CADC and WLTC also highlight some increase in NO\textsubscript{2} emissions on the lean GDI car (vehicle C) compared to the regulatory NEDC.

On CADC, large confidence intervals can be noticed for NOx and NO\textsubscript{2} emissions of the SCR-equipped diesel car (F). NOx emissions are indeed extremely variable within the three CADC test repeats. This is illustrated in Figure 11, showing cumulative NOx emissions of vehicle F when driven on CADC. The larger variations in exhaust NOx emissions occur at the higher vehicle speeds. The reason for this problem has not been fully investigated but one possible explanation could be that the urea dosing strategy of the SCR system is not fully optimized for the type of operation encountered on the motorway section of CADC.

Ammonia emissions measured by the bubbling method are plotted in Figure 12. CADC leads to higher NH\textsubscript{3} emissions than NEDC or WLTC for stoichiometric gasoline (including hybrid) vehicles. NEDC and WLTC are generally similar even though the SCR-equipped vehicle F tends to emit slightly more NH\textsubscript{3} on WLTC. This may be explained by the urea injection calibration not being optimized on all cycles. NH\textsubscript{3} emissions actually peak at the end of the extra-high speed phase of WLTC. Nevertheless, ammonia concentration at the tailpipe does not exceed 20 ppm.

Figure 13 shows emissions results of PM mass on NEDC, CADC, and cold-start WLTC. For most vehicles, PM mass emissions are of the same level on the three drive cycles and PM mass is low for all test vehicles. However vehicle A tends to have higher PM mass than expected; on NEDC, PM mass is higher than the Euro 5b SI limit of 4.5 mg/km.
It can also be noticed that PM mass confidence intervals are relatively large, especially for vehicle E equipped with a DPF. This is a consequence of the very low PM mass measured on each filter paper.

Figure 12. NH₃ emissions at 25°C

Figure 13. PM mass emissions at 25°C

Figure 14. Particles number (PN) emissions at 25°C

Figure 15. CO₂ emissions at 25°C

ANALYSIS OF EMISSIONS PERFORMANCE

Temperature Influence on Particle Number Emissions

CO₂ emissions measured on NEDC, CADC, and the cold-start WLTC are shown in Figure 15. All three cycles are comparable in terms of CO₂ results. The selection of cars chosen provides a wide range of CO₂ emissions on NEDC, going from 126 g/km for the hybrid vehicle D to 220 g/km for the GDI car A. These results include the higher vehicle inertia used in this test program and therefore may not entirely match with type-approval data (not publicly available or measured during the test campaign). However, it can be noticed that when NEDC and WLTC are run with the same vehicle inertia, both cycle provide similar CO₂ results. WLTC even tends to give marginally lower CO₂ emissions. This means that when it comes to measuring more realistic CO₂ emissions, the improvement brought by WLTP can come from the higher vehicle inertia included in the test procedure (closer to real mass of vehicle) but most likely not from the drive cycle pattern even if it is more transient.

As illustrated above in Figure 14, GDI vehicles (A, B, and C) have PN emissions between $3.4 \times 10^{12}$ km and $6.6 \times 10^{12}$ km. This is true for NEDC, CADC and WLTC at 25°C. As shown in Figure 16, PN emissions of these vehicles increase further when cars are operated at −7°C, ranging then from $5 \times 10^{12}$ km to $1.3 \times 10^{13}$ km on NEDC and CADC. The low temperature effect is even more pronounced on the hybrid car (D) for which PN emissions increase by one order of
magnitude between 25 and −7°C, from $4 \times 10^{11}$/km up to $3 \times 10^{12}$/km.

On the other hand, PN emissions from DPF-equipped diesel cars are controlled below $6 \times 10^{11}$/km, even at low temperatures such as −7°C. For car availability reasons and because of test program timing constraints, vehicle E was only run on WLTC at −7°C, not on NEDC.

**Temperature Influence on NOx Emissions**

As illustrated by Figure 17, NOx emissions of all vehicles increased when cars were tested at −7°C. However, the influence is the largest on diesel cars, which can emit 800 to 1000 mg/km of NOx on NEDC and WLTC. This is more than ten times the NEDC Euro 6 limit value of 80 mg/km and highlights that without a regulatory limitation of Diesel NOx emissions at low temperature as is currently being investigated by the European Commission \[5\], NOx emissions at low temperatures may not be controlled.

**Diesel NOx Control Technologies**

NOx emissions of Diesel Euro 6 cars can be controlled either by a Lean NOx-Trap (vehicle E) or by Selective Catalytic Reduction (vehicle F). Figures 18, 19 and 20 allow for some comparison of the two technologies on NEDC, cold-start WLTC, and CADC at 25°C respectively.

On NEDC and WLTC, the LNT allows controlling NOx emissions right from the start of the drive cycle, but the NOx conversion efficiency tends to decrease at higher speeds, especially in EUxDC and the extra-high speed phase of WLTC.

On CADC, both technologies efficiency to control NOx are similar in the urban phase. The SCR technology then tends to better control NOx over the rural phase except on one of the test repeat. Relatively important NOx breakthroughs are identified on the motorway phase with both LNT and SCR applications. Again, the European Commission is investigating how to close the gap with their Real-Driving Emissions for Light-Duty Vehicles (RDE-LDV) program.
Cold-Start Influence on Diesel Cars

Version 5 of WLTC, as used in this test campaign, includes the cold-start 4-phase cycle followed by a soak period and a hot-start cycle limited to low and medium-speed phases as described earlier. The influence of cold-start on NOx emissions from diesel cars can be evaluated on these low- and medium-speed phases of WLTC. Figures 21 and 22 show tailpipe NOx emissions measured on diesel vehicles E (LNT) and F (SCR) respectively.

On the two diesel vehicles tested in the program, NOx control was generally more effective on the cold-start WLTC than the hot-start. This may be related to the specific calibration of the emissions control systems or to temperature considerations. However, on vehicle F equipped with the SCR system, NOx emissions by the end of the low- and medium-speed phases are similar in either cold- or hot-start conditions.

Influence of Battery Charging Level of Hybrid Vehicle on Exhaust Emissions

On a non-plug-in hybrid vehicle such as Vehicle D, the energy needed is supplied by the electric motor or the conventional engine. The global energy consumed over a test cycle being theoretically constant, there is a linear relation between the CO₂ emissions from the conventional engine and the integrated RCB (RESS Charge Balance, where RESS stands for Rechargeable Energy Storage System, measured in Ah) of the electric motor as described in equation (3).

\[
\text{Total energy} = \text{energy supplied by conventional engine (proportional to CO}_2\text{ emissions)} + \text{electric energy (proportional to RCB integration)}
\]

All emissions results of Vehicle D reported above refer to the ‘nominal’ state of charge. However, the minimum and maximum states of charge have also been investigated, with two test repeats for each RCB level. Depending on the driver, it is actually possible that such a hybrid vehicle will operate in more extreme conditions than the nominal stage. The minimum battery charge was obtained in driving the vehicle at low speeds to favor the use of the electric motor. On the other hand, the maximum battery charge was obtained in driving at high speeds to favor the use of the conventional gasoline engine.

The charging and discharging of the battery are non-repeatable procedures but allowed reaching different enough battery state of charge at the beginning of the test cycle to influence the CO₂ emissions as shown in Figure 23. It confirms that there was not much difference in CO₂ emissions when hybrid Vehicle D drove either NEDC or WLTC in the same inertia and road load conditions (127.7 vs. 128.7 CO₂ g/km respectively).

As the CADC characterization line is flat compared to NEDC and WLTC, there is apparently for this vehicle no influence of the RCB state of charge on CO₂ emissions during CADC.
This may be explained by the fact that the hybrid vehicle D relies much less on its electrical motor when driving CADC than NEDC or WLTC.

It can be noticed that the RCB interval between minimum and maximum state at −7°C shifts towards lower values than the interval measured at ambient temperature, from [−1.5 − 0.4 Ah] to [−0.4 − 0.8 Ah]. From the slope comparison of NEDC and WLTC at 25°C and at −7°C, it can also be noticed that there seems to be less RCB sensitivity at lower temperatures than in ambient conditions. The reasons for those differences were not investigated though.

There is on the other hand no linear correlation for pollutant emissions. For example, Figure 24 summarizes hydrocarbon emissions measured on the various test cycles with the three levels of RCB (minimum, nominal, and maximum).

At 25°C and −7°C, there is little to no influence of RCB level on total HC emissions measured on the different test cycles. However, there is a tremendous difference in HC emissions between −7 and 25°C.

NOx emissions are described in Figure 25. It should be noted that all NOx emissions measurements on this vehicle were very low, below 70 mg/km, including in a very transient cycle such as CADC or at low temperature. When the combustion engine operates more often (minimum battery level), NOx emissions tend to be higher, this is especially true at low temperature. There is very little influence on NOx emissions when the battery is charged at maximum level; NOx emissions are then similar to the nominal battery level.

A similar comparison for PN emissions is given in Figure 26. In that case, there is no visible influence of the minimum level of battery charging on PN emissions. When the battery is at its maximum level, lower PN emissions are measured in the low temperature tests though.

CONCLUSIONS

Six commercially-available European vehicles representative of future engines and emissions control technologies were evaluated with regards to their tailpipe emissions on three different drive cycles, the current European regulatory NEDC, the developmental world-harmonized WLTC, and the Artemis suite which is often considered closer to real-world
operation than NEDC and has been used for the development of emissions factors in EU Member States.

The three gasoline direct injection and the hybrid vehicles emitted particle numbers 1 to 2 orders of magnitude higher than DPF-equipped diesels, whatever the drive cycle. The difference was even more pronounced on CADC.

NOx control of the selected Euro 6 Diesel vehicles was generally more effective on the cold-start WLTC than the hot-start. This may be related to the specific calibration of the emissions control systems or to temperature considerations. Nevertheless, NOx emissions over low- and medium-speed phases of WLTC were similar in cold or hot-start condition for the SCR-equipped vehicle.

The hybrid-gasoline non-plug-in vehicle tested showed very good emissions control performance, even under extreme conditions of operation, with a minimum or maximum battery charging level but at low temperature (−7°C), very high PN emissions were measured.

Emissions results obtained on NEDC and WLTC were quite similar. As the new vehicle inertia and road load determination procedure were used for all test cycles rather the existing Type-Approval procedure, this program tends to demonstrate that WLTP may bring more realistic CO₂ emissions from the higher vehicle inertia included in the test procedure (closer to real mass of vehicle) but most likely not from its drive cycle pattern, even if it is more transient.

CADC emissions results highlighted some higher NOx emissions from diesel vehicles and somewhat higher NH₃ emissions from stoichiometric gasoline cars. As high NOx emissions have also been reported for modern diesel cars in real-driving conditions, this tends to confirm that CADC is closer to real-world driving than NEDC or even WLTC. There was little difference for other emissions though, including CO₂.

REFERENCES

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DEFINITIONS/ABBREVIATIONS
AECC - Association for Emissions Control by Catalyst
CADC - Common Artemis Driving Cycle
CI - Confidence Interval
CVT - Continuously Variable Transmission
DPF - Diesel Particulate Filter
ECE-15 - Urban Driving Elementary Cycle (within NEDC)
EUDC - Extra-Urban Driving Cycle (within NEDC)
GDI - Gasoline Direct Injection
GRPE - Working Party on Pollution and Energy
gtr - Global Technical Regulation
LM - Laden Mass
LNT - Lean NOx-Trap
NEDC - New European Drive Cycle
NMHC - Non-Methane HydroCarbon
OM₄ - Unladen mass of vehicle plus mass of all optional equipment available for the vehicle family
PM - Particulate Matter
PMP - Particle Measurement Program
PN - Particles Number
RCB - RESS Charge Balance
RESS - Rechargeable Energy Storage System
SCR - Selective Catalytic Reduction
THC - Total HydroCarbon
TM - Test Mass
TM₄ - Test Mass High
TWC - Three-Way Catalyst
UNECE - United Nations Economic Commission for Europe
WLTC - World-harmonized Light vehicles Test Cycle
WLTP - World-harmonized Light vehicles Test Procedure
WM - Weighed Mass