

Aspects Regarding the Evolution of the Depollution Norms and Test Cycles in Order to Determine Polluting Emissions

Gheorghe Bancă, Valentin Nişulescu and Gheorghe Frăţilă

Abstract This paperwork presents the evolution of depollution norms from Euro5 to Euro6 presenting at the same time the technologies used in order to meet their requirements and a comparative analysis of the NMVEG (New European Motor Vehicle Emissions Group) and WLTC (World Harmonized Light Vehicles Test Cycle) test cycles respectively, test cycles used in order to establish the level of polluting emissions for homologating the road vehicles equipped with thermal and hybrid engines, as well as for establishing the autonomy of the electric vehicles. It also describes the new WLTC test cycles to be adopted in the EU (European Union) starting with the Euro6c depollution norm.

Keywords Depollution · Emissions · Test cycles · NMVEG · WLTC

Introduction

The climatic changes and the awareness on the damaging effects of the pollutants generated by the internal combustion engines have determined the international organizations to introduce legislative measures concerning the control of polluting emissions generated by road vehicles. Therefore, the American State of California announced the first regulations in 1961, then Japan in 1968, while the EU brought them up in discussion at the beginning of the 1970s, thus resulting “three major international norms” whose stages from the past 3 decades are schematically shown in Fig. 1.

The challenge brought by the international organizations made that the evolution of the limits provided by the norms be updated every 4–5 years, thus preserving and improving the dynamic performances, and the reliability of the thermal engines, concomitant with the evolution of the depollution norms throughout the vehicles lifespan, which forced the automotive manufacturers to come up with new tech-

G. Bancă (✉) · V. Nişulescu · G. Frăţilă
University Politehnica of Bucharest, Bucharest, Romania
e-mail: banca_2004@yahoo.com

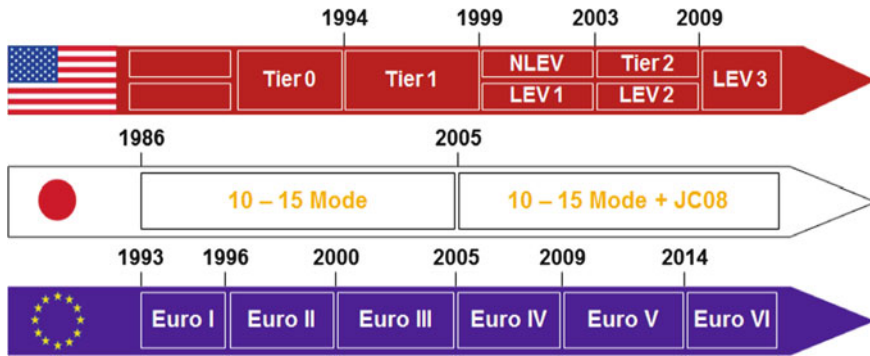


Fig. 1 Stages of the “three major international norms”

nologies in order to meet such limits, increasingly drastic. For the Euro norms, the technical development of the depollution systems faced several stages, each stage being associated to a certain norm from Euro1, Euro2, to Euro6, namely:

- for vehicles with SI engines (Spark-Ignition engines)—Fig. 2;
- for vehicles with CI engines (Compression-Ignition engines)—Fig. 3.

Nowadays, it is difficult to make a comparative analysis of the stringency of the regulations given that the test procedures and cycles are different (NMVEG for UE, JC-08 for Japan and FTP-75 for the USA) (Oprean 2003). In order to eliminate such shortcomings, UNECE (United Nations Economic Commission for Europe) proposed a new polluting emissions testing procedure for the light vehicles, called WLTP (Worldwide harmonized Light vehicles Test Procedure), procedure which shall adopt a new WLTC reference cycles, Fig. 4, to be implemented towards the end of 2017.

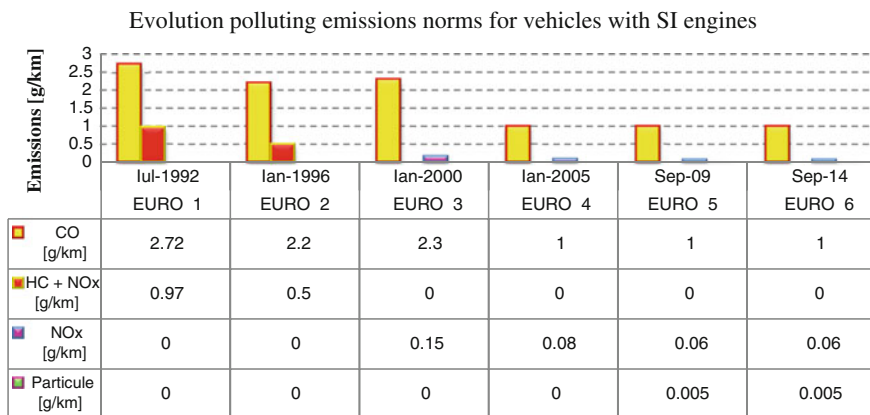


Fig. 2 Evolution of Euro norms for vehicles with SI engines

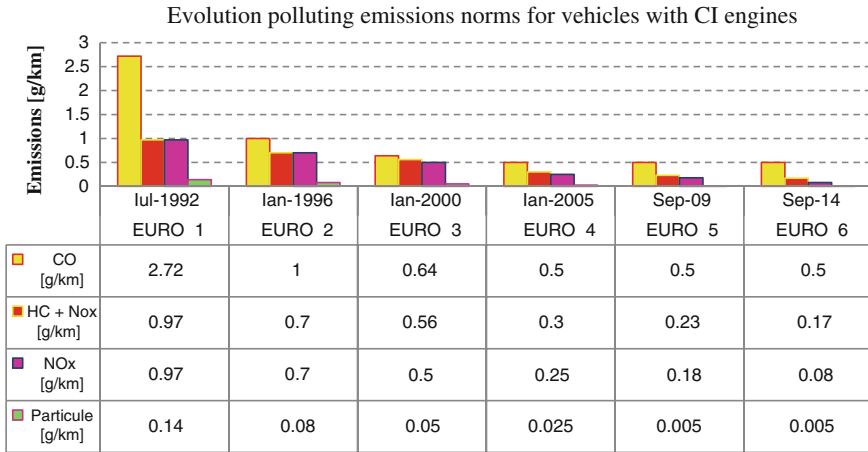


Fig. 3 Evolution of Euro norms for vehicles with CI engines

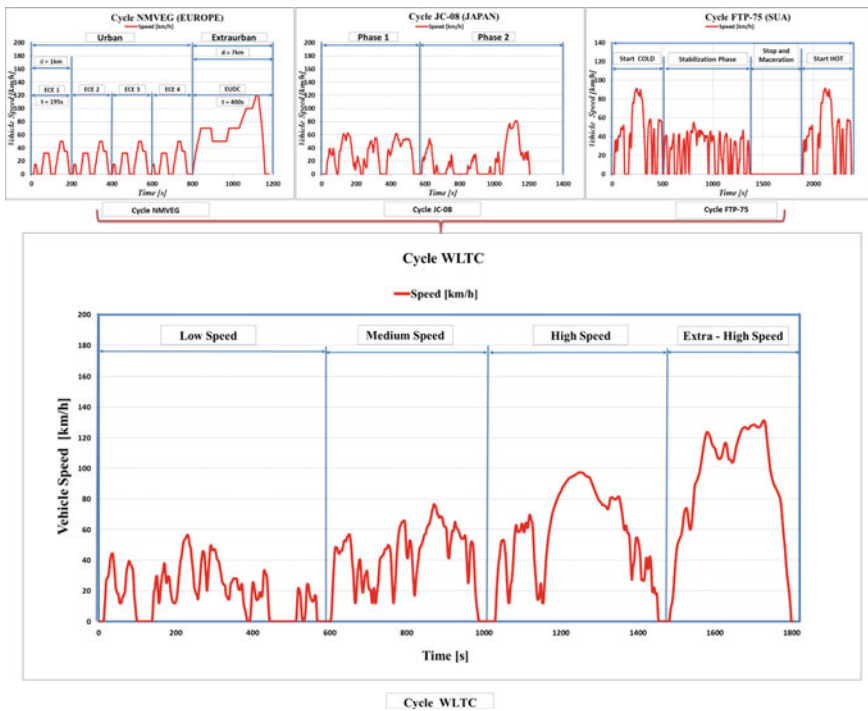


Fig. 4 Types of test cycles for determining the polluting emissions (NMVEG, JC-08, FTP-75 and WLTC)

The WLTC (Worldwide harmonized Light-duty Test Cycle) cycle, Fig. 4, is the cycle dedicated to testing the light vehicles in order to establish the polluting emissions, being proposed to replace the current NMVEG cycle, and it represents the base of the new test procedure, a procedure initially proposed by the UNECE, to be implemented since 2017.

With regard to the test procedure, it imposes additional restrictions concerning the tests carried out on the dynamometric benches and of running resistance, ambient temperature, the fuel quality, the gearbox shifting, choosing the tyres model and tyres pressure, charging the storage battery, the total weight of the vehicle (including the optional pieces of equipment, the loading and number of passengers), etc.

The WLTC cycle comprises 4 stages (low speed, medium speed, high speed and very high speed) and depending on the PMR ratio (power-to-mass ratio) of the vehicles—where the rated power is expressed in W, idle running weight in kg, the following test classes were defined and shown in Table 1.

In continuation, Table 2, summarizes the main characteristics of the NMVEG and WLTC cycles.

To determine the characteristics of Table 2 were used the relations:

– total time:

$$T_{total} = t_2 - t_1 + \sum_{i=2}^n (t_i - t_{i-1}) \tag{1}$$

Table 1 Test classes used on the WLTC cycle depending on the PMR ratio

Category	PMR (W/kg)	Speed	Comment
Class 3	PMR > 34	Low, medium, high, very high	If v_max < 135 km/h, the ‘very high’ stage is replaced and the ‘low’ stage is repeated
Class 2	34 ≥ PMR > 22	Low, medium, high	If v_max < 90 km/h, the ‘high’ stage is replaced and the ‘low’ stage is repeated
Class 1	PMR ≤ 22	Low, medium	If v_max ≥ 70 km/h, the ‘low’ stage is repeated after the ‘medium’ stage
			If v_max < 70 km/h, the ‘medium’ stage is replaced and the ‘low’ stage is repeated

Table 2 The main characteristics of the NMVEG and WLTC cycles

Characteristics of the cycles	Unit	NMVEG	WLTC
Total time	s	1180	1800
Total distance run	km	10.993	23.262
Idle time	s	267	242
Average speed (incl. stops)	km/h	33.538	46.4
Average speed (excl. stops)	km/h	43.157	53.8
Maximum speed	km/h	120	131.3
Average acceleration	m/s ²	0.592	0.41
Maximum acceleration	m/s ²	1.042	1.67

- total distance run:

$$d_{total\ run} = (t_2 - t_1) \frac{v_1}{3.6} + \sum_{i=2}^n (t_i - t_{i-1}) \frac{v_i}{3.6} \quad (2)$$

where v_i represents the vehicle's speed in m/s for the time step i ;

- average speed (incl. stops):

$$\dot{v}_{medium\ with\ stop} = 3.6 \frac{d_{total\ parc}}{T_{total}} \quad (3)$$

- average speed (excl. stops):

$$\dot{v}_{medium\ no\ stop} = 3.6 \frac{d_{total\ parc}}{T_{total}} \quad (3')$$

- max speed:

$$v_{max} = \max(v) \quad (4)$$

- average acceleration:

$$a_{medie} = \frac{1}{T_{total}} \sum_{i=1}^n a_i \quad (5)$$

- maximum acceleration:

$$a_{maxi} = \max(a_i) \quad (6)$$

where a_i represents the vehicle's acceleration in m/s^2 for the time step i , if $a_i > 0$.

An important parameter requiring a particular attention when analysing a depollution cycle is the so-called relative positive acceleration or RPA (Relative Positive Acceleration) since it can provide data about how loaded is the respective cycle (http://siar.ro/wp-content/uploads/2015/06/RIA_35.pdf). The formula is given by the relation:

- relative acceleration:

$$RPA = \left(\frac{1}{d_{total\ parcursa}} \right) \sum_{i=1}^n \begin{cases} \frac{a_i v_i}{3.6} & \text{if } (a > 0) \\ 0 & \text{(otherwise)} \end{cases} \quad (7)$$

Experiment

The case study is based on the upstream project study involving on identifying the operational points of the two cycles and the estimation of the polluting emissions for a vehicle equipped with a 1.5 dCI 81 kW Euro6 engine, using the simulation platform AMESim (Advanced Modelling Environment for Simulation of Engineering Systems).

The method of building the AMESim calculation model involves: generating an “ISO Camp” at the engine’s bench, choosing the model architecture—functional/dysfunctional (understanding the physical phenomena, defining the captors and actuators), creating and simplifying the model (formal—linear or nonlinear model), validation based on the initial test at the engine’s bench.

As far as the WLTC cycle is concerned, during simulation, just like when testing a vehicle on the roller bench, an important aspect is represented by the calculation of the time when shifting the velocity steps for each vehicle, which is a new aspect as compared against the NMVEG cycle, where the time for shifting the velocity steps is fixed. The purpose is to reflect the practical use and an efficient driving behaviour (low fuel consumption). The indications related to the shifting of the velocity steps per WLTC cycle are based on the balance between the power necessary to overcome resistances to advance in acceleration and the power supplied by the engine in all gears ratio possible, in a specific phase of the driving cycle.

The power necessary is calculated for each second i of the speed profile of the cycle, considering the power required in order to overcome the resistances to advance and provided that the vehicle accelerates using the relation 8:

$$P_{required,i} = \frac{f_0 \cdot v_i + f_1 \cdot (v_i)^2 + f_2 \cdot (v_i)^3 + (k_r \cdot a_i \cdot v_i \cdot m_t)}{3600}, \quad (8)$$

where:

- f_0 the load factor, represents the advanced resistance caused by the contact between the tyre and the rolling track (N);
- f_1 the load parameter, represents the frictions with in the kinematic chain of the transmission depending on speed [N/(km/h)];
- f_2 the load coefficient, represents the stressed caused by the aerodynamic resistance depending on the squared speed [N/(km/h)²];
- $P_{required,i}$ the power necessary in kW at second i ;
- a_i vehicle acceleration at the second i , with $a_i = \frac{v_{i+1} - v_i}{3.6 \cdot (t_{i+1} - t_i)}$ in m/s² and t — —time in s;
- v_i vehicle speed at the second i in km/h;
- m_t the vehicles mass in kg;
- k_r coefficient that considers the inertial resistance values from the running gear during acceleration.

Description of the model: In order to study the influence of the transition from the NMVEG cycle at the WLTC cycle, the realization of the AMESim simulation involve to model a vehicle equipped with a CI engine (compression ignition engine) turbocharged, a clutch, a gearbox, the after-treatment system exhaust (DOC—Diesel Oxidation Catalyst, NOx-Trap and DPF—Diesel Particulate Filter) and the cycles profiles (where the WLTC cycle should be defined in terms of speed and time-based ratio). The model also includes the basic accessories, he starter and the alternator, Fig. 5.

Since, in the event of using the HIL (Hardware in the Loop) model, we are constrained by the calculation time of the model in order to run in real time, we have used the DRVICE01D component (Driver internal combustion engine), a function specific for AMESIM which uses 8 files as inputs (necessary to be known and parameterized):

- the engine torque is calculated from the cartography “torque.data” or “BMEP.data” in inside the model and the engine temperature impact is taken into account by using the water temperature or the oil temperature and the “FMPEP.data” file, after relation 9:

$$T = T_{table} + T_{losses, T_{hot}} - T_{losses, temp} \tag{9}$$

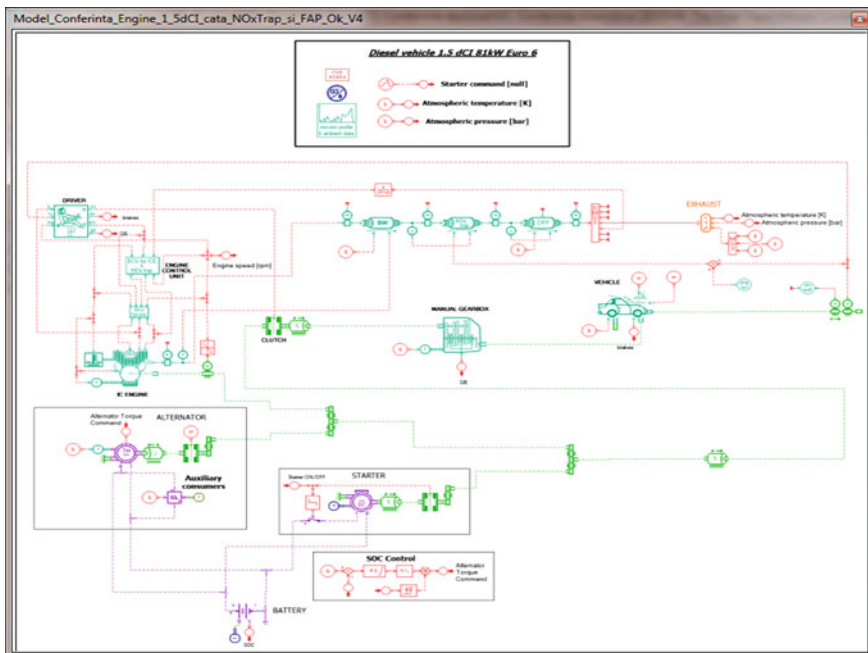


Fig. 5 A drawing of the proposed model

where:

- T means the corrected torque (Nm);
 T_{table} means the torque (Nm) taken from the cartography “torque.data”;
 T_{losses} means the friction torque (Nm) at hot engine temperature T_{hot} taken from the cartography “FMEP.data”;
 T_{hot} means the parameter “hot engine temperature” (°C);
 $T_{losses,temp}$ means the friction torque (Nm) at water temperature or oil temperature taken from the Table 1D “FMEP.data” (temp = T_{water} or temp = T_{oil});
 T_{water} means the temperature of the water coming through the port 7 (°C);
 T_{oil} means the temperature of the oil through the port 8 (°C).

- at the end, a correction is applied on the output torque during the acceleration stages, in order to consider the environment conditions, as follows, relation 10:

$$T_{out,1} = T_{dyn} \cdot \frac{\rho_{air}}{1.205} \quad (10)$$

with:

- $T_{out,1}$ output torque at port 1 (Nm);
 T_{dyn} dynamic engine torque (Nm);
 ρ_{air} air density (kg/m^3).

- for the output torque, the brakes medium effective pressure (BMEP) is calculated using the relation 11:

$$BMEP = \frac{4 \cdot \pi \cdot T_{out,1} \cdot 10^{-2}}{V} \quad (11)$$

where:

- $BMEP$ means the Brakes Medium Effective Pressure (bar);
 $T_{out,1}$ means the torque at the engine shaft (Nm);
 V means the engine’s cylinder capacity (L).

- in the end, the real power is calculated using the relation 12:

$$P = T_{out,1} \cdot \omega \cdot 10^{-3} \quad (12)$$

where:

- P means the real power (kW);
 $T_{out,1}$ means the torque at the engine shaft (Nm);
 ω means the angular speed at the shaft (rad/s).

Results and Explanation

In order to validate the results, compliance with the speed profile on the roller bench is an important criterion in declaring the test as valid or invalid, the accepted tolerance being of ± 2 km/h (or 0.56 m/s) at ± 1 s. Both in Fig. 6 (simulated NMVEG cycle), and in Fig. 7 (simulated WLTC cycle) it could be noticed that this condition is fulfilled, therefore we can further analyse the results.

Considering the dynamics of the WLTC cycle, where the speeds and accelerations are significantly higher to the NMVEG cycle, there was a first comparative analysis between cycles made in Table 3 over the CO₂ emissions, emissions that render the fuel consumption bigger picture. The simulation results show that, although the WLTC cycle is more severe from the point of view of the speed—and loading respectively, the cumulated CO₂ emissions generated by the engine are approximately 103 % higher for the WLTC cycle, fact explained by the longer distance run ~ 23 km, the global emissions of the engine expressed in g/km remained at the same level or even dropped by ~ 2 %.

The logical explanation for which the CO₂ emission on the WLTC cycle are the same as on the NMVEG cycle is given by the fact that, although the engine load is higher on the WLTC cycle, the engine exploitation does make in an optimum operating condition close to the economical pole of the engine, where the range of operational points of the WLTC cycle is higher than the operational points of the NMVEG cycle. This fact is confirmed by the chart in Fig. 8, where the characteristic speed-torque in the WLTC cycle is at the edge of maximum torque

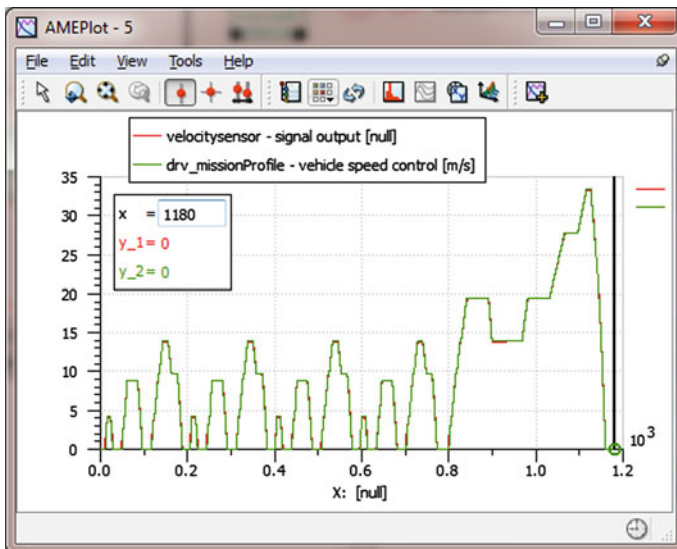


Fig. 6 Speed simulation in NMVEG cycle

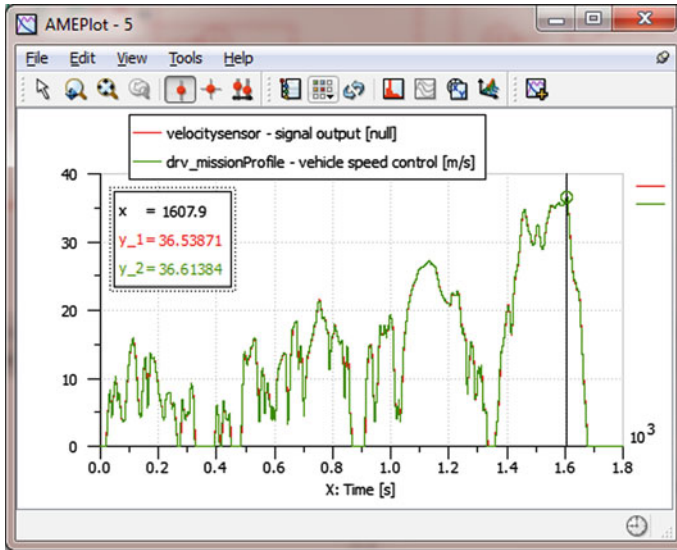


Fig. 7 Speed simulation in WLTC cycle

Table 3 Comparative analysis of CO₂ emissions

CO ₂ emissions by the engine				
Cycle	Unit	NMVEG	WLTC	Variation (NMVG–WLTC) (%)
Norma	g/km	–	–	0
Distance run	km	11.08	22.866	106
Cumulated emissions from the engine	g	1287.37	2610.5	103
Emissions from the engine	g/km	116.19	114.16	–2

generated by the engine, the manufacturer having the freedom to calculate the moment for shifting the velocity steps for each vehicle.

For the particles emissions, Table 4, the shifting to the WLTC cycle faced a growth of the cumulated emissions by relatively up to 433 %, caused by violent accelerations, which lead to a richness >0.6 (richness = 1/lambda)—where the growth of the particles emissions becomes exponential, and a relative growth of 160 % of the global emissions, however, the limits of the Euro6c norm is met due to the DPF (Diesel Particulate Filter) technology, whose efficiency reached up to 99 %. Although the norm limits are met, increasing the loading speed by 160 % leads to triggering more frequent regenerations, reason for which special attention should be given when calibrating the Diesel engines and recalculating the Ki (regenerative coefficient), or re-dimensioning the DPF.

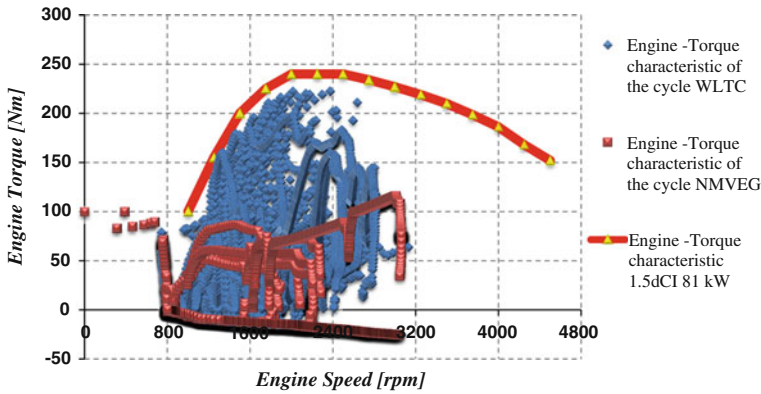


Fig. 8 Engine torque characteristic—operational points

Table 4 Comparative analysis of particles emissions

Mechanical particles emissions				
Cycle	Unit	NMVEG	WLTC	Variation (NMVG–WLTC) (%)
Norma	g/km	0.005	0.005	0
Distance run	km	11.08	22.866	106
Cumulated emissions from the engine	mg	923	4923.96	433
Emissions from the engine	g/km	0.0833	0.21534	159
Cumulated exhaust emissions	mg	9.23	49.24	433
Exhaust emissions (with FaP)	g/km	0.00083	0.00215	159
FaP efficiency	%	0.99	0.99	0

The analysis of NO_x (Nitrogen Oxides), Table 5, shows an important degradation of the cumulated emissions, of approximately 350 % in relatively, degradation caused particularly by the higher temperatures (over 2000 K) in the combustion room, because of the higher charge in the WLTC cycle. In this particular case, although the simulation was made with an engine whose DT (Technical Definition) complied with the Euro6b norm (Cata + NO_x-Trap and DPF), we could notice that the norm provisions were met for the NMVEG cycle, but not for the WLTC cycle, therefore, a re-optimization of the calibration as well as of the NO_x-Trap re-dimensioning might be considered.

For HC emissions (unburned hydrocarbons)—Table 6 and CO emissions (Carbon Monoxide)—Table 7, the norm is complied with. We even notice an improvement of the HC emissions by approximately 20 %, and the same level of CO emissions in the WLTC cycle, according to ISO standards, this fact being explained by a quicker heating of the catalyser given the high loads throughout the WLTC cycle.

Table 5 Comparative analysis of NO_x emissions

NO _x emissions				
Cycle	Unit	NMVEG	WLTC	Variation (NMVG–WLTC) (%)
Norma	g/km	0.08	0.08	0
Distance run	km	11.08	22.866	106
Cumulated emissions from the engine	mg	1478.949	6675.71	351
Emissions from the engine	g/km	0.13348	0.29195	119
Cumulated exhaust emissions	mg	650.7376	2937.31	351
Exhaust emissions	g/km	0.05873	0.12846	119

Table 6 Synthesis of HC emissions

HC emissions				
Cycle	Unit	NMVEG	WLTC	Variation (NMVG–WLTC) (%)
Norma	g/km	0.05	0.05	0
Distance run	km	11.08	22.866	106
Cumulated emissions from the engine	mg	5100.186	8506.36	67
Emissions from the engine	g/km	0.46031	0.37201	–19
Cumulated exhaust emissions	mg	408.0149	680.509	67
Exhaust emissions	g/km	0.03682	0.02976	–19

Table 7 Synthesis of CO emissions

CO emissions				
Cycle	Unit	NMVEG	WLTC	Variation (NMVG–WLTC) (%)
Norma	g/km	0.5	0.5	0
Distance run	km	11.08	22.866	106
Cumulated emissions from the engine	mg	30416.34	63575.2	109
Emissions from the engine	g/km	2.74516	2.78034	1
Cumulated exhaust emissions	mg	3649.961	7629.02	109
Exhaust emissions	g/km	0.32942	0.33364	1

Conclusions

The evolution of the depollution norm from Euro5 to Euro6 involves reduction of the NO_x polluting emissions limits (0.18–0.08 g/km) only for the vehicles equipped with CI engines, however, the stringency of the Euro6c norm is given by the new type of WLTP test procedure and the new type of WLTC cycle adopted;

As far as the are CO₂ emission, for the studied engine, although the WLTC cycle shows a higher constraining from the loading point of view, the global CO₂ emissions expressed in g/km remained at the same level, with even a slight decrease;

The engine speed torque characteristic for the WLTC cycle is at limit between of the maximum torque delivered by the engine, thus rendering the engine to operate on optimum operating points close to economical pole of the engine, where the engine efficiency is optimum;

Although the norm limits are met for the particles emissions, increasing the loading speed leads to triggering more frequent regenerations, reason for which special attention should be given when recalculating the Ki factor (regenerative coefficient).

Considering the simulation results, there might be considered a re-optimization of the calibration from the MAP (Mise au point) point of view, as well as a NO_x-Trap re-dimensioning in order to comply with the Euro6c norm in relation to the emissions of nitric oxides.

With regard to the HC/CO emissions, the WLTC cycle shows zero non-conformity risks, with “iso” CO emissions, being favourable for reducing the HC emissions given of a high load on cycle, which leads to the quick heating of the catalyser.

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