Comparative studies of harmful exhaust emission from a hybrid vehicle and a vehicle powered by spark ignition engine

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Abstract. To better reflect real-world emissions of harmful exhaust, substances from light-duty vehicles, the WLTP cycle (World Light Test Procedure) was introduced in laboratory tests. This article discusses that test and conditions for its implementation in the context hitherto of the NEDC cycle (New European Driving Cycle). The article presents results of emission tests of two vehicles: one hybrid (electric motor + spark ignition combustion engine) and the other with an internal combustion engine with similar rated powers in the above-mentioned WLTP cycle. Reference is made mainly to the gaseous pollutant road emissions, i.e.: CO, CO₂, THC, NOₓ. A comparison of the above emission with the one obtained for both vehicles in the NEDC cycle was also made.

1. Introduction

The reduction of harmful transport emissions is one of the key challenges of the 21st century. Every year the number of vehicles used on roads is growing. In 2015 there were c.a. 1.1 billion vehicles worldwide. This means that 6.5 individuals per one vehicle. This number is growing continually. According to estimates there will be more than 1.5 billion vehicles by 2025 and almost 2 billion in year 2040 [1].

In the future the greatest increase in the number of vehicles is expected in developing countries, such as China or India. According to the World Energy Council there were 4 vehicles per 1000 persons in 2000 in China, with 40 in 2010 and estimated 310 in year 2035. In 2013 there were 250 million vehicles registered in China [2].

According to the most recent report by Euler Hermes, an insurance company dedicated to transaction insurances and collecting receivables in 2017 the worldwide production of vehicles is expected to exceed 100 million cars annually. Forecasts regarding the industry point to the reinstated average increase of 4 percent [3], [4], [5]. According to data of OICA, an international organisation grouping car producers in 2013 a total of 87.3 million of vehicles had been produced. Projections on the production of vehicles in China are very optimistic. This year some 20 million vehicles are expected to leave factories, whereby China is going to strengthen its global position as the major car producer [3].

Due to the growing number of vehicles in the world it is necessary to introduce more and more restrictive requirements concerning exhaust emission levels.
2. Exhaust emission levels

To determine general rules regarding exhaust emissions from vehicle engines adequate standards have been introduced. The world trend to reduce exhaust emissions generated by road transport assumes a considerable reduction of such emissions, also CO₂ emissions. Figure 1 presents the anticipated reduction of carbon dioxide with regard to the producers’ fleets of light-duty vehicles by 2025 [6], [7].

![Figure 1. Assumptions of reducing carbon dioxide emissions for light vehicle fleet manufacturers in the world in the perspective of 2025 [1]](image)

In Europe the EURO standards are applied. The most recent and prevailing standard is Euro 6 for passenger cars and Euro VI for heavy trucks. Tables nos. 1-4 below present admissible exhaust emission levels from light vehicles under the European standards, depending on the effective date of those standards and the type of the vehicles’ engine.

| Level       | Effective date | CO  | HC  | NMHC | NOₓ | HC+NOₓ | PM   |
|-------------|----------------|-----|-----|------|-----|--------|------|
|             |                |     |     |      |     |        |      |
| Veh. self-ignition engines |                |     |     |      |     |        |      |
| Euro 1      | June 1992      | 2.720| -   | -    | -   | 0.970  | 0.140 |
| Euro 2      | January 1996   | 1.000| -   | -    | -   | 0.700  | 0.080 |
| Euro 3      | January 2000   | 0.640| -   | -    | 0.500| 0.560  | 0.050 |
| Euro 4      | January 2005   | 0.500| -   | -    | 0.250| 0.300  | 0.025 |
| Euro 5      | September 2009 | 0.500| -   | -    | 0.180| 0.230  | 0.005 |
| Euro 6      | September 2014 | 0.500| -   | -    | 0.080| 0.170  | 0.0045|
| Veh. spark-ignition engines |                |     |     |      |     |        |      |
| Euro 1      | July 1992      | 2.720| -   | -    | -   | 0.970  | -    |
| Euro 2      | January 1996   | 2.200| -   | -    | -   | 0.500  | -    |
| Euro 3      | January 2000   | 2.300| 0.200| -    | 0.150| -      | -    |
| Euro 4      | January 2005   | 1.000| 0.100| -    | 0.080| -      | -    |
| Euro 5      | September 2009 | 1.000| 0.100| 0.068| 0.060| -      | 0.005|
| Euro 6      | September 2014 | 1.000| 0.100| 0.068| 0.060| -      | 0.0045*|

CO- carbon oxide, HC – non-combusted hydrocarbons, NMHC – non-combusted non-methane hydrocarbons.
NOX – nitrogen oxides, PM – particulate matter
1/ Euro 5a, 2/ Euro 6b/6c (PN 6,0 E11/km), 3/ THC, * for engines with direct injection

2.1. NEDC cycle
The ECE+EUDC test cycle was used for EU type approval testing of emissions and fuel consumption from light duty vehicles [9]. The test is performed on a chassis dynamometer. The entire cycle includes four ECE segments (Figure 2) repeated without interruption, followed by one EUDC segment (Figure 3). Before the test, the vehicle is allowed to soak for at least 6 hours at a test temperature of 20-30°C. Effective from year 2000 that idling period has been eliminated, i.e., engine starts at 0 s and the emission sampling begins at the same time. This modified cold-start procedure is referred to as the New European Driving Cycle (NEDC) [10].

The full test starts with four repetitions of the ECE cycle (Figure 2). The ECE is an urban driving cycle, also known as UDC. It was devised to represent city driving conditions, e.g. in Paris or Rome. It is characterized by low vehicle speed, low engine load, and low exhaust gas temperature [10].

![Figure 2. ECE 15 Cycle](image1)

The EUDC (Extra Urban Driving Cycle) segment has been added after the fourth ECE cycle to account for more aggressive, high speed driving modes. The maximum speed of the EUDC cycle is 120 km/h (Figure 3). An alternative EUDC cycle for low-powered vehicles has also been defined with a maximum speed limited to 90 km/h, (Figure 4) [10].

![Figure 3. EUDC Cycle](image2)

![Figure 4. EUDC Cycle for Low Power Vehicles](image3)

Emissions are sampled during the cycle according to the constant volume sampling (CVS) technique, analysed, and expressed in g/km for each of the pollutants. The following table includes a summary of selected parameters for the ECE 15, EUDC and NEDC cycles [10].

| Characteristics | Unit | ECE 15 | EUDC | NEDC² |
|-----------------|------|--------|------|-------|
| Distance        | km   | 0.9941 | 6.9549 | 10.9314 |
| Total time      | s    | 195    | 400   | 1180   |

![Table 2. Characteristic of ECE 15, EUDC and NEDC test](image4)
| Parameter                                      | Value |
|-----------------------------------------------|-------|
| Idle (standing) time                          | s     |
| Average speed (incl. stops)                   | km/h  |
| Average driving speed (excl. stops)           | km/h  |
| Maximum speed                                 | km/h  |
| Average acceleration                          | m/s²  |
| Maximum acceleration                          | m/s²  |

1 Calculated using central difference method
2 Four repetitions of ECE 15 followed by one EUDC

Type I, II and III Tests. The urban driving cycle - ECE 15, Figure 1 - represents Type I test, as defined by the original ECE 15 emissions procedure. Type II test is a warmed-up idle tailpipe CO test conducted immediately after the fourth cycle of the Type I test. Type III test is for example a two-mode (idle and 50 km/h) chassis dynamometer procedure for crankcase emission determination [10].

2.2. WLTC cycle

The Worldwide Harmonized Light Vehicles Test Cycles (WLTC) are chassis dynamometer tests for the determination of emissions and fuel consumption from light-duty vehicles. The tests have been developed by the UN ECE GRPE (Working Party on Pollution and Energy) group. The WLTC cycles are part of the Worldwide Harmonised Light Vehicles Test Procedures (WLTP), published as UNECE Global technical regulation No. 15 (GTR 15). While the acronyms WLTP and WLTC are sometimes used interchangeably, the WLTP procedures define a number of other procedures—in addition to the WLTC test cycles that are needed to type approve a vehicle [10], [11], [12], [13].

The WLTP replaces the European NEDC based procedure for type approval testing of light-duty vehicles, with the transition from NEDC to WLTP occurring over 2017-2019 [10], [11], [12], [13].

The WLTP procedures include several WLTC test cycles applicable to vehicle categories of different power-to-mass (PMR) ratio, Table 3. The PMR parameter is defined as the ratio of rated power (W) / curb mass (kg). The curb mass (or kerb mass) means the “unladen mass” as defined in ECE R83. The cycle definitions may also depend on the maximum speed (v_max), which is the maximum speed of the vehicle as declared by the manufacturer (ECE R68) and not any use restriction or safety-based limitation. Cycle modifications are allowed to accommodate drivability problems for vehicles with power to mass ratios close to the borderlines or with maximum speeds limited to values below the maximum speed required by the cycle [10], [11], [12], [13], [15].

| Category   | PMR, W/kg | v_max, km/h | Speed Phase Sequence                      |
|------------|-----------|-------------|------------------------------------------|
| Class 3b   | PMR > 34  | v_max ≥ 120 | Low 3 + Medium 3-2 + High 3-2 + Extra High 3 |
|            | v_max < 120|             | Low 3 + Medium 3-1 + High 3-1 + Extra High 3 |
| Class 3a   | PMR > 22  |             | Low 2 + Medium 2 + High 2 + Extra High 2  |
| Class 1    | PMR ≤ 22  |             | Low 1 + Medium 1 + Low 1                  |

Class 3 Cycle

With the highest power-to-mass ratio, Class 3 is representative of vehicles driven in Europe and Japan. Class 3 vehicles are divided into 2 subclasses according to their maximum speed: Class 3a with v_max < 120 km/h and Class 3b with v_max ≥ 120 km/h. Selected parameters of the Class 3 cycles are given in Table 4, and the vehicle speed for Class 3b is shown in Figure 5 (in this representation, Class 3a trace would look very similar) [10], [11], [12], [13].
Table 4. WLTC Class 3 cycle: selected parameters [10], [11], [12], [13]

| Phase       | Duration | Stop Duration | Distance | p_stop | v_max | v_ave w/o stops | v_ave w/ stops | a_min | a_max |
|-------------|----------|---------------|----------|--------|-------|-----------------|----------------|-------|-------|
| Class 3b (v_max ≥ 120 km/h) |           |               |          |        |       |                 |                 |       |       |
| Low 3       | 589      | 156           | 3095     | 26.5%  | 56.5  | 25.7            | 18.9           | -1.47 | 1.47  |
| Medium 3-2  | 433      | 48            | 4756     | 11.1%  | 76.6  | 44.5            | 39.5           | -1.49 | 1.57  |
| High 3-2    | 455      | 31            | 7162     | 6.8%   | 97.4  | 60.8            | 56.7           | -1.49 | 1.58  |
| Extra-High 3| 323      | 7             | 8254     | 2.2%   | 131.3 | 94.0            | 92.0           | -1.21 | 1.03  |
| Total       | 1800     | 242           | 23266    |        |       |                 |                 |       |       |

Class 3a (v_max < 120 km/h)

| Phase       | Duration | Stop Duration | Distance | p_stop | v_max | v_ave w/o stops | v_ave w/ stops | a_min | a_max |
|-------------|----------|---------------|----------|--------|-------|-----------------|----------------|-------|-------|
| Low 3       | 589      | 156           | 3095     | 26.5%  | 56.5  | 25.7            | 18.9           | -1.47 | 1.47  |
| Medium 3-1  | 433      | 48            | 4721     | 11.1%  | 76.6  | 44.1            | 39.3           | -1.47 | 1.28  |
| High 3-1    | 455      | 31            | 7124     | 6.8%   | 97.4  | 60.5            | 56.4           | -1.49 | 1.58  |
| Extra-High 3| 323      | 7             | 8254     | 2.2%   | 131.3 | 94.0            | 92.0           | -1.21 | 1.03  |
| Total       | 1800     | 242           | 23194    |        |       |                 |                 |       |       |

Figure 5. WLTC cycle for Class 3b vehicles [10], [11], [12], [13]

Class 2 Cycle

Class 2 is representative of vehicles driven in India and of low power vehicles driven in Japan and Europe. Selected parameters of the Class 2 cycle are given in Table 5, and the vehicle speed is shown in Figure 6 [10], [11], [12], [13].
Table 5. WLTC Class 2 cycle: selected parameters [10], [11], [12], [13]

| Phase     | Duration | Stop Duration | Distance | p_stop | v_max | v_ave w/o stops | v_ave w/ stops | a_min | a_max |
|-----------|----------|---------------|----------|--------|-------|-----------------|---------------|-------|-------|
| Low 2     | 589      | 155           | 3101     | 26.3%  | 51.4  | 25.7            | 19.0          | -0.94 | 0.90  |
| Medium 2  | 433      | 48            | 4737     | 11.1%  | 74.7  | 44.3            | 39.4          | -0.93 | 0.96  |
| High 2    | 455      | 30            | 6792     | 6.6%   | 85.2  | 57.5            | 53.7          | -1.11 | 0.85  |
| Extra-High 2 | 323  | 7             | 8019     | 2.2%   | 123.1 | 91.4            | 89.4          | -1.06 | 0.65  |
| Total     | 1800     | 240           | 22649    |        |       |                 |               |       |       |

Figure 6. WLTC cycle for Class 2 vehicles [10], [11], [12], [13]

Class 1 Cycle
With the lowest power-to-mass ratio, Class 1 is representative of vehicles driven in India. Selected parameters of the Class 1 cycle are given in Table 6, and the vehicle speed is shown in Figure 7 [10], [11], [12], [13].

Table 6. WLTC Class 1 cycle: selected parameters [10], [11], [12], [13]

| Phase     | Duration | Stop Duration | Distance | p_stop | v_max | v_ave w/o stops | v_ave w/ stops | a_min | a_max |
|-----------|----------|---------------|----------|--------|-------|-----------------|---------------|-------|-------|
| Low 1     | 589      | 154           | 3330     | 26.1%  | 49.1  | 27.6            | 20.4          | -1.00 | 0.76  |
| Medium 1  | 433      | 48            | 4767     | 11.1%  | 64.4  | 44.6            | 39.6          | -0.53 | 0.63  |
| Low 1     | 589      | 154           | 3330     | 26.1%  | 49.1  | 27.6            | 20.4          | -1.00 | 0.76  |
| Total     | 1611     | 356           | 11428    |        |       |                 |               |       |       |
3. Own studies

Homologation tests conducted in laboratory conditions in the chassis dynamometer aim to determine the average exhaust emissions and fuel consumption in newly produced vehicles. So far, the NEDC cycle was found too “easy” to reflect the actual road conditions. For this reason, works on a new WLTP study procedure had been started.

Comparing WLTC with NEDC it is apparent that many changes have been introduced. Above all the impact of the additional equipment and different engine configuration versions have been taken into account as well as the type of gear box used in the vehicle (change of the gear ratio in case of a manual gear box is calculated). But that is not all. The distance and the duration of the cycle were extended. Now it is extended by 10 minutes (WLTC – 30 minutes, NEDC – 20 minutes) and longer by 12 km (WLTC – 23 km, NEDC – 11 km). The duration of stopovers was decreased. Thorough tests have proved that in actual traffic conditions the duration of a vehicle stopover is shorter than as assumed earlier. For this reason, it was reduced from 25% in NEDC to 13% in WLTP cycle [16], [17].

A significant change is the introduction of differences in the cycle depending on the vehicle output and mass ratio in the tested vehicle. Three categories have been distinguished. However, it should be noted that in a greater number of cases as regards vehicles sold in Europe the third category – above 34 kW/ton shall apply [16].

To verify whether the introduction of a new more complex cycle has impact on the value of road emission and fuel consumption, tests were carried out in laboratory conditions in a chassis dynamometer in the Motor Transport Institute. The first tested vehicle was equipped with a diesel spark-ignition engine compliant with Euro 6 exhaustion emission standard, with an automatic gear box.

The next tested vehicle was a hybrid vehicle. It was equipped with a serial – parallel hybrid system. In such system the diesel engine is mechanically connected with the wheels, which are also driven by an electrical engine. An electrical engine may be powered by a generator united with the diesel engine or by batteries.

The tests were repeated several times to verify the results and the possibility of averaging. In the first part of the tests a series of repetitions was performed in both driving cycles (NEDC and WLTC Class 3) in cold-start. Figure 8 represents averaged results for a vehicle with a conventional drive system and Figure 10 shows the same for a hybrid-system vehicle. It is noticeable that emissions for most harmful substances are lower in WLTC. The same is true for fuel consumption.

In the second part of the studies tests were performed in warm engine start-up in the tested vehicles. As previously, also here a series of tests had been performed based on which average values of exhaust emissions and fuel consumption were determined (Figure 9 – vehicle with a conventional drive system, Figure 11 – hybrid vehicle).
Figure 8. Average results of exhaust emissions and fuel consumption in the tested vehicle with a spark-ignition engine in WLTC and NEDC – cold start-up procedure

Figure 9. Average results of exhaust emissions and fuel consumption in the tested vehicle with a spark-ignition engine in WLTC and NEDC – warm start-up procedure

Figure 10. Average results of exhaust emissions and fuel consumption in the tested hybrid vehicle in WLTC and NEDC – cold start-up procedure

Figure 11. Average results of exhaust emissions and fuel consumption in the tested hybrid vehicle in WLTC and NEDC – warm start-up procedure

4. Results of comparative studies
The completed studies allowed for comparing road emissions in the said vehicles with different drive systems. The first vehicle was equipped with engine with spark ignition. The second one was equipped with a series – parallel hybrid system. The hybrid vehicle was powered with spark ignition engine provided by a generator. The main shaft unit transferring power to the wheels via CVT was an electric motor. Table 5 below presents chosen technical parameters of both vehicles. Attention should be given to the fact that the difference in the weight of both vehicles was taken into account by selecting relevant load parameters of the chassis dynamometer.

|                      | Vehicle with a petrol-fuelled engine | Hybrid vehicle |
|----------------------|--------------------------------------|----------------|
| Engine displacement  | 1798 cm³                             | 1798 cm³       |
| Max. rating power    | 108 kW @ 6400 rpm                    | 90 kW @ 5200 rpm|
| Max. torque          | 180 Nm @ 4000 rpm                    | 142 Nm @ 3600 rpm|
| Compression ratio    | 11                                   | 13             |
| Type of fuel injection| Multi-point (MPI)                    | Multi-point (MPI) |
| Gear box             | CVT                                  | e-CVT          |
The studies prove that the use of hybrid vehicles is reasonable in terms of both emission as well as fuel consumption. Both compared to cold engine start-up in NEDC (Figure 12) and warm engine start-up (Figure 14) the hybrid vehicle demonstrates lower emission levels and fuel consumption. A similar trend is observed in WLTC also in cold start-up (Figure 13) and in warm start-up (Figure 15).

5. Conclusions
The studies conducted on the chassis dynamometer of the Motor Transport Institute confirm the validity of changes in the procedures of vehicle homologation. The introduction of the new WLTC cycle allows for more precise determination of exhaust emissions in respective phases of the mentioned cycle and thus more accurate average values.

The studies of two vehicles in WLTC cycle, which is more similar to the actual cycles, have proved that average emission from the tested vehicle was in effect lower than in NEDC applied thus far. Despite a definitely greater complexity of WTLC the average emission was lower than that generated in NEDC.

The studies also allowed for a comparison between two vehicles. The first vehicle was powered conventionally (a spark-ignition engine) and the other was equipped with a hybrid engine. It appears that both in NEDC and WLTC the hybrid-powered vehicle characterised with a much lower exhaust emission. On average the emission of carbon dioxide was lower by 30%, similar as fuel consumption. Another example is the emission of nitrogen oxides. In this case such emission to a large extent depends on whether the engine was warmed up or not prior to the tests. In the first case the
reduction of road emission of the said component was lower by more than 50%, whereas if the engine was cold – it was lower on average by approx. 35%.

The results of tests clearly prove that hybrid vehicles in daily use may help reduce exhaust emissions considerably and in consequence improve air quality, especially in towns and cities. For this reason, it is reasonable to promote the discussed alternative drive systems in vehicles.

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