Research Article

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Testing and evaluation of cold-start emissions from a gasoline engine in RDE test at two different ambient temperatures

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Abstract: In order to better reflect the actual ecological performance of vehicles in traffic conditions, both the emission standards and the applied emission tests are being developed, for example by considering exhaust emissions for a cold engine start. This article presents the research results on the impact of ambient temperature during the cold start of a gasoline engine in road emission tests. The Real Driving Emissions (RDE) tests apply to passenger cars that meet the Euro 6 emissions norm and they are complementary to their type approval tests. A portable emissions measurement system was used to record the engine and vehicle operating parameters, as well as to measure the exhaust emissions during tests. This allowed for parameters such as engine load, engine speed and vehicle speed to be monitored. The cold start conditions for two different temperatures (8°C and 25°C) were compared in detail. Moreover, the engine operating parameters, exhaust concentration values and road emissions for the 300 s time interval, were compared. The summary of the article presents the share of a passenger car's cold start phase for each exhaust compound in the urban part of the test and in the entire Real Driving Emissions test depending on the ambient temperature.

Keywords: Exhaust emission, Passenger cars, Cold start, Real Driving Emissions, Road test

1 Introduction

Increasingly stringent environmental requirements have resulted in significant changes in the exhaust emissions evaluation from motor vehicles. It was considered that type approval tests carried out in laboratory conditions (on a chassis dynamometer) are not sufficient. Complementary exhaust emissions testing in real traffic conditions has been introduced to amend that. Such real traffic conditions may be characterized by variability of parameters (in an extent as limited by standards) while the values of exhaust emissions cannot be greater than those specified in the relevant regulations. The tests are possible to perform by using Portable Emissions Measurement Systems (PEMS) type mobile research equipment.

According to the Commission Regulation (EU) 2016/646 of 20 April 2016 amending Regulation (EC) No. 692/2008 a new emissions norm Euro 6d-Temp has been established. The requirements of this norm are an extension of the Euro 6 emissions norm regarding road exhaust emissions of nitrogen oxides (NO_x) and the particle number (PN) emissions for passenger cars equipped with gasoline engines, as well as introducing conformity factors (excess emissions) which have been given the value of 1.43 (from 2020). The real driving emissions (RDE) procedure has been introduced in the European Union by Regulation 2017/1151 of 1 July 2017 and updated by Regulation 2017/1154 of 7 July 2017.

For practical purposes, the RDE procedure has been developed in four separate packages [1]. The first package, which was adopted in May 2015, defined the general RDE test procedure. The second package, which was adopted in October 2015, introduced the NO_x Conformity Factor (CF). From September 2020, RDE emissions of new car models need to meet an NTE (Not-To-Exceed) emissions limit and the conformity factor for NO_x emissions equal to 1.43 (an extra 43 percent tolerance in emission value compared to the current NO_x limit of 60 mg/km – in the case of a spark-ignition engine). Package 3 introduced both conformity factor for particle number and RDE cold start emissions,

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while Package 4 has added not only In-Service Conformity RDE testing but also market surveillance.

2 The range of emission studies in real driving conditions

The studies carried out so far indicate that the best reflection of the actual ecological performance of motor vehicles is obtained during the emission tests from these vehicles in real traffic conditions. The following [2, 3]. can be cited as examples. Testing in such conditions enables the calibration of drive units to limit the emission of pollutants in the entire range of engine operation (and not only for the operating points used during dynamometer tests). As a result, more and more advanced exhaust gas aftertreatment systems are being developed [4, 5]. This makes it possible to meet increasingly restrictive legal acts. It is worth noting that the solutions introduced so far are not sufficient and still need to be developed. This is especially noticeable during the cold start phase. This is confirmed not only by the results we have obtained but also other scientists' research.

More and more attention is currently being paid to particulate emissions, especially for nanoparticles, from internal combustion engines also powered by alternative fuels – e.g. natural gas [6, 7]. The article [6] also emphasizes considerable mileage of the vehicle using alternative fuels, which in turn causes an 8-fold increase in emitted particle number for a vehicle with a mileage of 500,000 km compared to the vehicle with mileage of 75,000 km. The authors of publication [7] noted that the ambient temperature has a significant impact on the exhaust emissions from light duty vehicles fueled with gasoline and LPG (liquefied petroleum gas). This issue is particularly visible in urban phase; for both cold and hot start. The authors tested a car equipped with a gasoline engine that meet the Euro 6d standard. However, their research was limited to laboratory testing only. The choice of ambient temperature was slightly different from our research but it can be compared.

The accuracy of exhaust emission measurements in traffic conditions [8, 9] depends on the engine and vehicle operating conditions (including the speed of other vehicles, road surface, driver's predispositions, and his driving style, and other aspects determining road traffic). These conditions are unpredictable and can have a significant impact on the exhaust emission measurement results. However, according to data contained in publications, the thermal state of the vehicle (the engine) [10], average speed [11] driving dynamics [12] and road topography have the greatest impact on the achieved emission results. This means that

the same vehicle but on different routes (meeting the requirements of the RDE test) will obtain different exhaust emission results. Moreover, such a change is possible already during a change of driver or test date. This makes further research necessary to take account of these minor changes. This applies to both laboratory and road tests.

The publication [13] summarized the legislative changes in the on-road emissions legislation that have been introduced in Europe over the past years. The authors of the publication [14] made an attempt to quantify the on-road emissions of on-road particle number (PN) emissions from a GDI vehicle depending on a catalytic stripper (CS) and a metal-foam gasoline particulate filter (GPF). One of their research aims was to study the PN emissions from a GDI vehicle in different conditions. The use of a catalytic reactor reduced PN emissions during a cold start, but the additional use of GPF significantly intensified this operation. This phenomenon has been observed especially in the rural and motorway part of the test. The analysis of the impact of driving dynamics in the RDE test was discussed in [15]. The authors defined the correlations between the on-road exhaust emission and dynamic parameters (the vehicle velocity and acceleration product, relative positive acceleration and 95th percentile of $V \cdot a_+$). The [16] notes that one rapid acceleration introduces more pollutants into the atmosphere than several accelerations with lower dynamics.

The authors of the paper [17], in turn, have dealt with the assessment of the procedure of emission testing in real traffic conditions. According to the authors, the MAW (Moving Average Window) method is not suitable for the evaluation of exhaust emissions from the cold start phase. The authors performed tests during various heat states of the internal combustion engine. It was found that ambient temperature has an impact on exhaust emissions, but the greatest impact on emissions from this stage of the test has the driving dynamics. Furthermore, in the definition of a cold start, the focus should be on the coolant temperature only. Other views at the issue of cold start had [18]. They created a mathematical model of the influence of the fleet age structure used in Poland on the cold-start emissions which are released into the air shortly after the engine's start. All of the simulations were carried out using the COPERT 5 software.

Concerning the boundary conditions (such as vehicle payload and test mass, ambient and dynamic conditions, vehicle condition and operation), trip and operational requirements, they all are stated in Commission Regulation 2016/427. The following features exist in the RDE regulations:

- Euro 6d-Temp contains the full Euro 6 emission requirements assessed using both lab test cycle and RDE testing adjusted by temporary conformity factors,
- according to the regulation, by way of derogation the lower temperature for moderate conditions shall be greater or equal to 3°C and the lower temperature for extended conditions shall be greater or equal to 2°C between the NTE emission limits coming into effect as defined in section 2.1 and until five years after the dates given in paragraphs 4 and 5 of Article 10 of Regulation (EC) No 715/2007,
- the cold start phase includes the first 5 minutes after the initial start of the combustion engine. If the coolant temperature can be reliably determined, this period ends once the coolant has reached 70°C for the first time but no later than 5 min after the initial engine start,
- if during a specified time period of the RDE test, the ambient conditions are extended, the emissions during this time period shall be divided by a value ext before being evaluated for compliance with the requirements.

The test under real traffic conditions is also characterized by drive cycle requirements, which are summarized in Table 1.

Cold start period is included in the whole RDE test (especially in the urban part of the test) [12]:

- duration of the cold start period is defined from engine start to after the first 5 minutes or coolant temp reaching >70°C,
- max vehicle speed during cold start ≤ 60 km/h,
- the average vehicle speed (including stops) shall be between 15 km/h and 40 km/h,
- total stop time during cold start <90 s,

- idling after ignition <15 s,
- vehicle conditioning for cold start testing: driven for at least 30 min followed by soak duration in the range of 6 to 56 hours.

3 Research aim

The studies consisted of pollutant emissions comparison and determining the relations between results obtained in ambient temperatures of 8°C and 25°C. There was used a passenger car equipped with gasoline engine, which meets the Euro 6d-temp emission standards. The measurements were carried out for the following on-road exhaust emission components:

- carbon monoxide (CO),
- carbon dioxide (CO₂),
- nitrogen oxides (NO_x),
- number of particles (PN).

Twenty-four hours before a test in real traffic conditions (before the engine start), the vehicle has been conditioned at ambient temperature. Therefore, the engine oil and engine coolant temperatures were the same as the ambient temperature, which was the requirement of cold start emissions test (including an appropriate ambient temperature).

4 Research methodology

4.1 Research object

During the tests, a passenger car with a curb weight of approximately 1450 kg, fitted with a turbocharged spark-ignition engine with direct injection and displacement vol-

Table 1: Drive cycle requirements for a valid RDE test

Driving portion	Urban	Rural	Motorway
Vehicle speed (V)	$V \leq 60$ km/h	$60 < V \leq 90$ km/h	$90 \text{ km/h} < V$
Minimum distance	16 km	16 km	16 km
Distance share	29–44%	23–43%	23–43%
Total trip duration		90–120 minutes	
Average speed	$15 < V < 40$ km/h	–	–
Total stop time ($V < 1$ km/h)	6–30% Urban time	–	–
Stop time	≤ 300 s	–	–
$V > 100$ km/h	–	–	≥ 5 min
$V > 145$ km/h	–	–	<3%

Table 2: Properties of unleaded gasoline fuel EuroSuper 95 (petrol E5)

Parameter	Unit	Value (min/max)
Octane	RON (MON)	95/– (85/–)
Reid Vapor Pressure	kPa	60/90
Density at 15°C	kg/m ³	720/775
Distillation at 100°C	% vol	46/71
Distillation at 150°C	% vol	75/–
Final Boiling Point	°C	–/210
Aromatics	% vol	–/35
Olefins	% vol	–/18
Benzene	% vol	–/1.0
Oxygen	% mass	–/2.7
Sulfur	mg/kg	–/10

Table 3: Properties of oil

Parameter	Unit	Typical value
SAE viscosity class	–	5W-30
Kinematic viscosity (at 100°C)	mm ² /s	9.8
Viscosity index	–	163
Pour point	°C	–30
Total Base Number	Mg KOH/g	9.5
Sulphated ash	% vol	0.9
Evaporative loss according to Noack	% mass	8.2

ume of 1.6 dm³, a maximum power of approximately 130 kW and meeting the Euro 6d-Temp emissions norm (vehicle approved according to the WLTP procedure). The exhaust aftertreatment system was typical for SIDI engines, *i.e.* a three-way catalytic converter with a particulate filter. The choice of such a research object was dictated by the fulfillment of RDE emission tests requirements. Additionally, more than 70% of new vehicles equipped with a gasoline engine and meeting the Euro 6d-Temp norm is fitted with such drive units. Due to the tests being carried out within the same week, the fuel and engine oil used in both cases were the same. They fulfilled the properties given in the Tables 2 and 3.

4.2 Exhaust emission measurements

Emission measurements were carried out under real driving conditions; this approach requires the installation of the gas sampling apparatus on the vehicle in such a way

Figure 1: Diagram of the measurement system used for testing (a) and mobile exhaust gas analyzer with marked flue gas flow (b) for the measurement of gaseous compounds and particulates; T – ambient temperature, H – air humidity

that ensures its normal operation. Therefore, a gas sampling system was prepared, which together with the system measuring the flow rate of the exhaust gas also performed partial sampling of the flue gas for the analyzers to enable making the measurement (Figure 1 shows the wiring schematic of the measuring equipment).

4.3 Test route

The test route has been selected in accordance with RDE requirements and divided into three sections: urban, rural and motorway (Figure 2). The driving distance and shares of the individual test sections have been chosen so that they meet the requirements described in the Commission Regulations EU 2016/646. The total distance of the test route was approximately 90 km. The test was repeated twice for two different ambient temperatures (8°C and 25°C).

Figure 2: Vehicle velocity of individual route tests

5 Analysis of recorded parameters

The first stage of the research was to validate the performance of road tests, which are specified in Regulations 2016/646, 692/2008 and 2017/1154, mainly in relation to the length of individual section of the test and their shares in the entire RDE test, the test duration, the share of vehicle parking duration in the urban portion and driving dynamics in individual sections of the RDE test. All parameters were verified by appropriate procedures and no deviations from the required values were found. However, the most important was to check the validity of the cold start emission parameters and the boundary conditions (parameters that were discussed in the introduction of this study). Therefore, the analysis of vehicle velocity after the cold start has been made – the requirement is for the vehicle to be driving for a maximum of 15 seconds after starting the engine (Figure 3). This condition was met in both cases and at the same time a similar character of the vehicle velocity profiles in the first 300 s of the RDE test is shown (slightly higher values of the maximum vehicle velocity were recorded for lower ambient temperature).

The comparison of the coolant temperature in both cases also showed that the RDE procedure requirements were met, *i.e.* it did not exceed the value of 70°C. For the cold start at the ambient temperature of 25°C, after 300 seconds since the engine started, the engine coolant temperature achieved a value of 69°C. For the ambient temperature of 8°C, the coolant temperature was only 57°C. The initial coolant temperature difference of 17°C, after 300 s since the engine started, has decreased down to 12°C. Therefore, a greater coolant temperature gradient was found for lower ambient temperature (Figure 4). A similar character of the changes was also observed during the analysis of exhaust gas temperature, measured at the end of the vehicle exhaust system. The difference occurring for the measurement time

Figure 3: Vehicle velocity after the cold start at different ambient temperatures

Figure 4: The coolant temperature after the cold start at different ambient temperatures

Figure 5: The exhaust gas temperature after the cold start at different ambient temperatures

($t = 0$ s) amounting to about 12°C has been compensated already after about 100 s, where the temperature of the exhaust gas was around 30°C. The further changes of exhaust gas temperature are very similar to each other, and the differences occurring in the period up to 300 s are very small (Figure 5).

The analysis of selected engine operating parameters allows to find very similar engine and vehicle operating conditions, and the parameter differentiating both measurements is the ambient temperature. On this basis, it is reasonable to take further actions that could be used to determine whether there are differences in concentration and emissions of exhaust compounds in the initial period of the engine (the vehicle) operation.

5.1 Ecological parameters

The recorded exhaust gas concentration changes characteristic in the first period ($t = 0 - 300$ s) after the cold start for two different ambient temperatures (8°C and 25°C) are shown below (Figure 6). The carbon dioxide concentration analysis indicates that during a cold start and warming up of an engine, the concentration was the same and amounted to about 15%. Slight fluctuations of this value were the result of a change in vehicle velocity – in dynamic conditions. However, the average value of this parameter is not affected by the ambient temperature at which a cold start took place. The characteristic of the carbon monoxide concentration shows a different pattern: the characteristic instantaneous increase in concentration after a cold start reaches the value of about 30,000 ppm. However, it decreases very quickly to its minimum value during the cold start at 25°C . This reduction takes place in about 20 seconds. On the other hand, for a cold start at 8°C , the first main concentration peak decreases. This decrease reaches about 5000 ppm, and only after approximately 70 seconds reaches the minimum value.

Figure 6: The change of exhaust gases concentration during the initial 300 s from the cold start for different values of ambient temperature for: carbon dioxide, carbon monoxide, nitrogen oxides, and particles number

6 The analysis of test results regarding the cold start period

Taking into account the mass flow rate of the exhaust gas, a quantitative evaluation of the engine exhaust emissions was carried out in the period of 300 s from the cold start in the considered ambient temperatures (Figure 7). In the case of carbon dioxide mass, it is higher by 16% (after 300 s from the engine started); if the measurement started at 8°C , in this case the mass of carbon dioxide was 677 g. For the cold start at a temperature of 25°C , this mass was equal to 587 g. The mass of carbon monoxide, during 300 s from the cold start at a temperature of 25°C , was 1.18 g and for the temperature of 8°C it was 195% higher (3.47 g). The smallest relative exhaust mass difference during the emission measurements at two different temperatures occurred for the nitrogen oxides emissions. In this case, a higher emission of nitrogen oxides was found for the cold start at a temperature of 25°C (by 11%) than at a temperature of 8°C (0.040 g and 0.036 g respectively). The particles number emitted during the initial 300 s from starting the engine has increased by 280% when the ambient temperature was lower from 25°C to 8°C ($7.5 \cdot 10^{10}$ and $2.8 \cdot 10^{10}$).

Figure 7: The mass of carbon dioxide, carbon monoxide, nitrogen oxides and particles number in first 300 s from the cold start for different values of an ambient temperature

Figure 8: The on-road emissions of carbon dioxide, carbon monoxide, nitrogen oxides, and particles number during the cold start for an ambient temperature of 8°C

The presented data was used to determine the road emissions (the conversion of emission values to mass per unit of distance) during the cold start (lasting 300 s) and the entire urban phase (lasting 3450 s). The comparison of the exhaust emission results of an engine cold start at an ambient temperature of 8°C to the results in the whole urban part of the RDE test is as follows (Figure 8):

- carbon dioxide road emissions in the cold start test (348 g/km) are higher by 64% than the average for the entire urban section of the RDE test (212 g/km),
- carbon monoxide road emissions in the cold start test (260 mg/km) are higher by 172% than the average for the entire urban section of RDE test (96 mg/km),
- nitrogen oxides road emissions in the cold start test (103 mg/km) are higher by 11% than the average for the entire urban section of RDE test (9.2 mg/km),
- the particles number road emissions in the cold start test ($2.2 \cdot 10^{10}$ 1/km) are higher by 138% than the average for the entire urban section of RDE test ($0.94 \cdot 10^{10}$ 1/km).

Accordingly, the emissions of carbon monoxide flow rates should increase significantly in the first period after the cold start at the lower ambient temperature of 8°C compared to the value measured at 25°C. The concentration of nitrogen oxides behaves much differently from the analysis of the previous compound. For a higher temperature of the

Figure 9: The on-road emissions of carbon dioxide, carbon monoxide, nitrogen oxides, and particles number during the cold start for an ambient temperature of 25°C

cold start (25°C) an increased concentration of nitrogen oxides (up to 300–400 ppm) is observed during the first 50 seconds after the engine start. At this point in time (50 s), the concentration of nitrogen oxides during a cold start at 8°C is several times higher (80 ppm) than at 25°C (10 ppm). The time it takes the measured concentration values of this compound to reach values below 10 ppm is similar and equals about 100 s. Regarding the number of particulates, increased values for cold start at 8°C were observed, this increase was about 100 times the value in the first 70 s after the cold start. The average value of the particulate concentration for the cold start at 25°C was $1 \cdot 10^4$ 1/cm³, and for the cold start at 8°C this value changed from an initial $1 \cdot 10^6$ 1/cm³ to a value of $1 \cdot 10^4$ 1/cm³ (300 s after cold start). After about 230 seconds from the cold start, the numerical concentration of solid particles in both cases stabilized at $1 \cdot 10^4$ 1/cm³.

The changes in road emissions of exhaust compounds during the cold start at a temperature of 25°C in relation to the whole urban part of the RDE test are as follows (Figure 9):

- carbon dioxide road emissions are higher by 51% (304 g/km and 202 g/km respectively),
- carbon monoxide road emissions are higher by 64% (155 mg/km and 95 mg/km respectively),

Figure 10: The share of exhaust emissions during the cold start in relation to the urban part of the RDE test, and the entire RDE test for an ambient temperature of 8°C

Figure 11: The share of exhaust emissions during the cold start in relation to the urban part of the RDE test, and the entire RDE test for an ambient temperature of 25°C

- nitrogen oxides road emissions are higher by 89% (20.5 mg/km and 10.9 mg/km respectively),
- particles number road emissions are higher by 182% ($1.5 \cdot 10^{10}$ 1/km and $0.52 \cdot 10^{10}$ 1/km respectively).

The comparing of the cold start phases for different ambient temperatures in the urban section of the test and in the entire RDE test, it was found that:

- 1) for the cold start at a temperature of 8°C (Figure 10):
- 2) the share of carbon dioxide emissions during the cold start (300 s) relative to the urban part of the RDE test is 11.6%, and to the entire RDE test, it decreases to 3.4%,
 - the share of carbon monoxide emissions during the cold start (300 s) relative to the urban part of the RDE test is 26%, and to the entire RDE test, it decreases to 10.7%,
 - the share of nitrogen oxides emissions during the cold start (300 s) relative to the urban part of the RDE test is 10.6%, and to the entire RDE test, it decreases to 2.9%,
 - the share of particles number emissions during the cold start (300 s) relative to the urban part

of the RDE test is 22.7%, and to the entire RDE test, it decreases to 0.1%,

- 3) for the cold start at a temperature of 25°C (Figure 11):

- the share of carbon dioxide emissions during the cold start (300 s) relative to the urban part of the RDE test is 9.8%, and to the entire RDE test, it decreases to 3.4%,
- the share of carbon monoxide emissions during the cold start (300 s) relative to the urban part of the RDE test is 10.6%, and to the entire RDE test, it decreases to 4.6%,
- the share of nitrogen oxides emissions during the cold start (300 s) relative to the urban part of the RDE test is 12.3%, and to the entire RDE test, it decreases to 3.4%,
- the share of particles number emissions during the cold start (300 s) relative to the urban part of the RDE test is 18.4%, and to the entire RDE test, it decreases to 0.15%.

7 Conclusions

In the third regulatory RDE package, the pollutants exhaust emission results from the engine at cold start is included in the total exhaust emissions assessment. It causes an increase in the on-road exhaust emissions. This is mainly due to the time required to heat the exhaust after treatment devices, and at the same time to the pressure of the exhaust for as much emissions reduction as possible in the first period after the cold start.

The tests were performed in the ambient temperature range, in accordance with the current regulation on exhaust emission measurements under real traffic conditions. As expected, the results obtained during the cold start phase differed significantly.

The reduction of the ambient temperature (from 25°C to 8°C) during the cold start (in the considered period of 300 s) resulted in:

- an increase by 16% of carbon dioxide mass (and hence in fuel consumption),
- an increase by 195% of carbon monoxide mass,
- a decrease by 11% of nitrogen oxides mass,
- an increase by 280% of particles number.

The emissions from the cold start phase were also compared with the emission results obtained in the urban part only, but also in the entire RDE test.

The share of the cold start in the urban part and in the entire RDE test is the highest when measured from a temperature of 8°C. The values are as follows:

- for carbon dioxide on-road emissions: 11.6% (the urban part) and 3.4% (the entire RDE test),
- for carbon monoxide on-road emissions: 26% and 10.7%,
- for nitrogen oxides on-road emissions: 10.6% and 2.9%,
- for particles number on-road emissions: 22.7% and 0.1%.

The share of the cold start at a temperature of 25°C in the urban part and the entire RDE test is as follows:

- for carbon dioxide on-road emissions: 9.8% (the urban part) and 3.4% (the entire RDE test),
- for carbon monoxide on-road emissions: 10.6% and 4.6%,
- for nitrogen oxides on-road emissions: 12.3% and 3.4%,
- for particles number on-road emissions: 18.4% and 0.15%.

Detailed determination of exhaust gas emissions in individual phases, including a cold start period, will undoubtedly allow for even greater development of exhaust gas aftertreatment systems. Such analyses of conventional vehicles exhaust emissions will simplify emission tests for alternative vehicles. Moreover, such detailed analyses of the most problematic parts of the emission tests will contribute to the improvement of research methods.

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