

## Cold start emissions from a gasoline engine in RDE tests at different ambient temperatures

The implementation of the 3rd package of the RDE test procedure has extended the test method by considering emissions from a cold start period into the total exhaust emissions from a vehicle. The article presents the research results of exhaust emissions of a vehicle equipped with a gasoline engine. The tests were carried out at two different ambient temperatures, in line with the requirements of the RDE test procedure for passenger cars, meeting the Euro 6d-Temp emissions standard. The obtained results were analyzed, i.e. there were compared the engine and vehicle operating parameters and the values of road exhaust emissions during the cold start at two different ambient temperatures. The summary presents the shares of the cold start phase for each exhaust emission compound in the urban part of the test and the entire RDE test, depending on the ambient temperature (8°C and 25°C).

Key words: cold start, RDE test, exhaust emissions, ambient temperature, gasoline engine

### 1. Introduction

Road transport is still considered the most important source of air pollution. Scientific research [16] indicates that the emission of harmful exhaust compounds has a negative impact not only on air quality but also on human health. This phenomenon is particularly visible in urban agglomerations. One of the European Union's tasks, set off for the coming years, is to continue and even intensify work on improving air quality. The European Commission's assumption is to achieve climate neutrality. However, to gain this, the level of air pollution should first be gradually reduced. To this end, among other, increasingly restrictive legal acts concerning vehicle exhaust emissions are introduced [2-6]. Meeting these requirements is not easy, so it is necessary to use more and more advanced exhaust after-treatment systems.

In recent years, many research papers on cold start emissions have been published (i.a. [13, 17, 19, 24, 30]). The need to take into account emissions from the cold start phase has been noticed not only in Europe but also worldwide. The authors of the articles [18, 26] pointed out the importance of the cold start issue as well as the necessity of further improvement of exhaust after-treatment systems. Whereas, the authors of the publications [8, 10, 11] suggested that NO<sub>x</sub> emission should be an issue addressed in subsequent updates of EU regulations. According to the authors of the publication [8], the NO<sub>x</sub> emissions from vehicles, equipped with a gasoline engine, are increasingly higher and consequently, particularly important in the context of urban air quality. The authors also pay attention to the value of the ambient temperature at which the RDE test is performed.

The authors of the articles [31, 33] came to the same conclusions. They determined the impact of different ambient temperatures (−7°C and 23°C) on the emission results of vehicles equipped with compression and spark-ignition engines. The aim of the test was to verify the results according to Euro 6 emissions standard and check if the exhaust emissions in the WLTC test increase during the cold season in comparison to higher ambient temperatures [7, 8]. The authors of this article noticed the need to develop a new and independent procedure allowing verification of the emissions level at low ambient temperatures.

### 2. RDE test conditions

Although the RDE test is performed under real traffic conditions, it is highly formalized. The requirements concern not only the vehicle conditioning for the test but also the provision of research conditions [1, 12, 14, 20-23]. According to [27, 28], this is necessary for the proper performance of the test and further analysis of the results obtained. The main requirements to be met during the test are shown in Fig. 1. Due to the vehicle speed, the test route is divided into three parts: urban, rural and motorway conditions. The test drive is carried out continuously, but there are a few exceptions [9]. The rural drive section can be interrupted by short periods of urban driving if urban areas are on the route. Driving on the motorway can interrupt short driving periods in urban or rural areas. The duration of the test is within the acceptable range, i.e. between 90 min and 120 min.

Requirements	Urban	Rural	Motorway
Vehicle speed	0–60 km/h	60–90 km/h	> 90 km/h
Distance share	29–44 %	23–43 %	23–43 %
Min distance	16 km	16 km	16 km
Average speed	15–40 km/h	–	–
Total stop time	6–30 %	–	–
Individual stops	≤ 300 s	–	–
V > 100 km/h	–	–	≥ 5 min
V > 145 km/h	–	–	< 3%*

Total test duration: 90–120 min  
Start/end test elevation difference: ≤ 100 m  
\* Max speed of 145 km/h may be exceeded by: 15 km/h for < 3% of the motorway time duration

Fig. 1. The RDE test requirements [25-28]

Package 3 [27] of the RDE test procedure has introduced primarily the inclusion of cold-start period emissions in the entire RDE test. The definition of cold start is as follows – the period from the first start of a combustion engine until the point when the combustion engine has run cumulative for 5 min. The cold start period ends once the coolant temperature has reached 70°C for the first time but

no later than after 5 min from the initial engine start. The main requirements for a cold start are listed in Fig. 2.

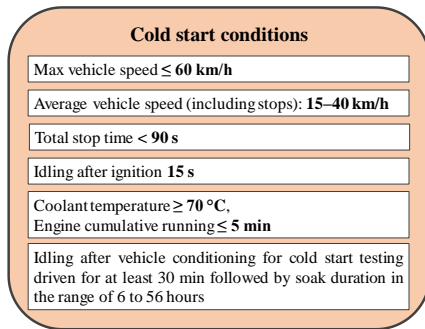


Fig. 2. Cold start requirements [32]

The 4<sup>th</sup> [28] package of the RDE test procedure modified the calculation of total exhaust emissions but also specified the exhaust emissions obtained in the urban part (compared to total emissions in the test). This article aims to determine the shares of specific exhaust compounds during the cold start phase and in the entire test, depending on the ambient temperature (8°C and 25°C).

### 3. Research methodology

#### 3.1. Research object

One of the popular midsize passenger car class was used for testing. The vehicle was equipped with a gasoline engine that met the Euro 6d-Temp emissions norm. The exhaust after-treatment system consists of a 3-way catalytic converter and a particulate filter. Details of the vehicle used are shown in Table 1.

Table 1. Characteristics of the passenger car used in testing

Curb weight	1450 kg
Engine type	turbocharged gasoline engine with direct injection
Displacement volume	1.6 dm <sup>3</sup>
Maximum power	130 kW
Emission standards	Euro 6d-Temp
The after-treatment system	three-way catalytic converter with a particulate filter

#### 3.2. Test route and exhaust emission measurements

The test route has been designated in accordance with RDE requirements and divided into 3 sections; urban, rural and motorway (Fig. 3). The driving distances, shares of the individual portion of the test have been chosen so that they meet the requirements described in [26].

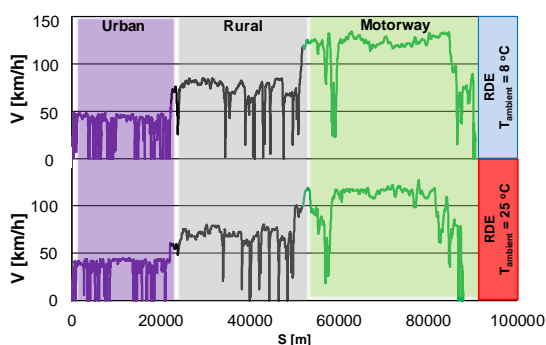


Fig. 3. Vehicle speed profiles in both RDE test drives

The authors carried out two test drives on the same research route in the city of Poznan and its surroundings by the same driver. Measurements were conducted in two different ambient temperatures (8°C and 25°C). For measuring the concentration of exhaust compounds, a PEMS apparatus was used. Besides, the GPS signal was recorded at a frequency of 1 Hz during testing. The research equipment used was compliant with the European Union requirements concerning the measurement of harmful exhaust compounds from passenger cars under real driving conditions.

### 4. The analysis of recorded parameters

#### 4.1. Engine operating parameters of the vehicle

The first stage of the analysis was to validate the performance of road tests with the requirements of the RDE test procedure. All parameters were verified by appropriate procedures and no deviations from the required values were found. However, in the case of this article the most important was to check the validity of the cold start emission parameters and the boundary conditions (these parameters were discussed in the next point).

Therefore, the analysis of vehicle speed during the cold start period has been made. It is required to start driving for a maximum of 15 seconds after starting the engine (Fig. 4). This condition was met in both cases and at the same time a similar character of the vehicle speed profiles in the first 300 s of the RDE test is shown. Slightly higher values of the maximum vehicle speed were recorded for the lower ambient temperature.

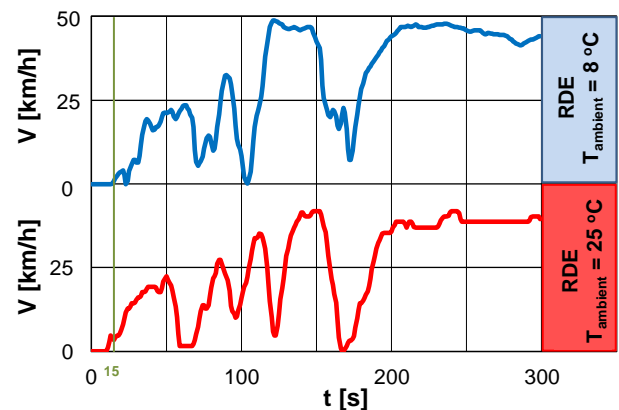


Fig. 4. Vehicle speed during the cold start phase at different ambient temperatures

The comparison of the coolant temperature in both cases also shown that the requirements of the RDE test procedure have been met, i.e. it did not exceed the value of 70°C. For the cold start at the ambient temperature of 25°C, 300 s from the engine start, the coolant temperature achieved a value of 69°C. For the ambient temperature of 8°C, the coolant temperature was only 57°C. Firstly, the initial coolant temperature difference of 17°C but after 300 s (since the engine was started) it decreased to 12°C. Therefore, a greater coolant temperature gradient was found for lower ambient temperature (Fig. 5).

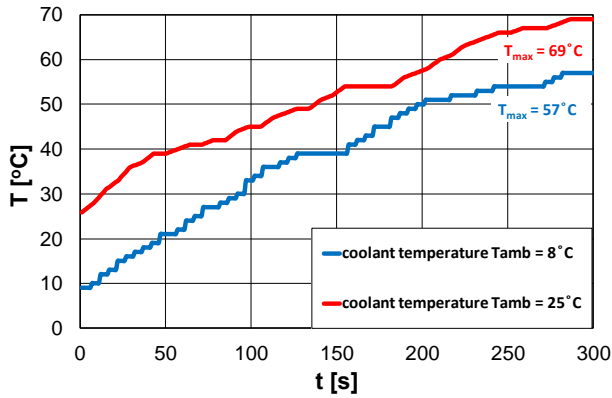


Fig. 5. The coolant temperature during the cold start phase at different ambient temperatures

A similar character of the changes was also observed during the analysis of exhaust temperature, measured at the end of the vehicle exhaust system. The difference for the measurement time ( $t = 0$  s), amounting to about 12°C, is compensated already after about 100 s, where the exhaust temperature is around 30°C. The further profile of exhaust temperature is very similar to each other, and the differences occurring in the period up to 300 s are very small (Fig. 6).

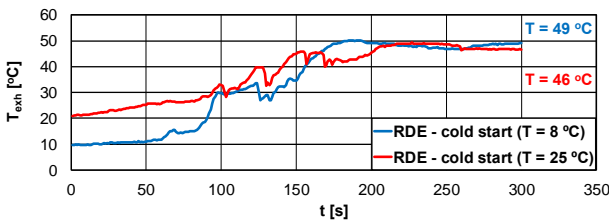


Fig. 6. The exhaust temperature during the cold start phase at different ambient temperatures

#### 4.2. Ecological parameters

The recorded profile of emission intensity changes in the cold start period ( $t = 0-300$  s) for two different ambient temperatures (8°C and 25°C) are shown in Figs. 7–10.

The carbon monoxide mass is almost 3 times higher at the ambient temperature of 8°C (3.47 g) in comparison to the value of 25°C (1.21 g). The average value of the emission intensity is 0.011 g/s (at the ambient temperature of 8°C) and 0.004 g/s (at 25°C). For the cold start at the ambient temperature of 25°C, the highest value of emissions intensity is 0.09 g/s. While for the temperature of 8°C this value is twice higher (Fig. 7).

The analysis of carbon dioxide emission intensity shows that during the cold start and warming the engine, the mass of this compound is about 16% higher at the ambient temperature of 8°C (687 g) than at 25°C (592 g). The average value of the emission intensity is 2.19 g/s and 1.89 g/s, respectively. The fluctuations between the results of test drives were caused by the changes in the dynamic motion conditions. However, the average value of this parameter is not affected by the ambient temperature at which the cold engine started (Fig. 8).

The analysis of nitrogen oxides emission intensity shows that for this exhaust compound the relations are completely different than for the previous compounds. For

the higher ambient temperature (25°C) the main increase of nitrogen oxides intensity (up to 0.005 g/s) is observed at the first 50 seconds after the engine started. During the cold start phase, the mass of this compound is equal to 0.400 g and the average value of the emission intensity is 0.0293 g/s. In the case of lower ambient temperature (8°C), the intensity of nitrogen oxides is about 11% higher than at 25°C. For the value of 8°C, the highest values of emission intensity are reached at the first 100 s and then they are being reduced (Fig. 9).

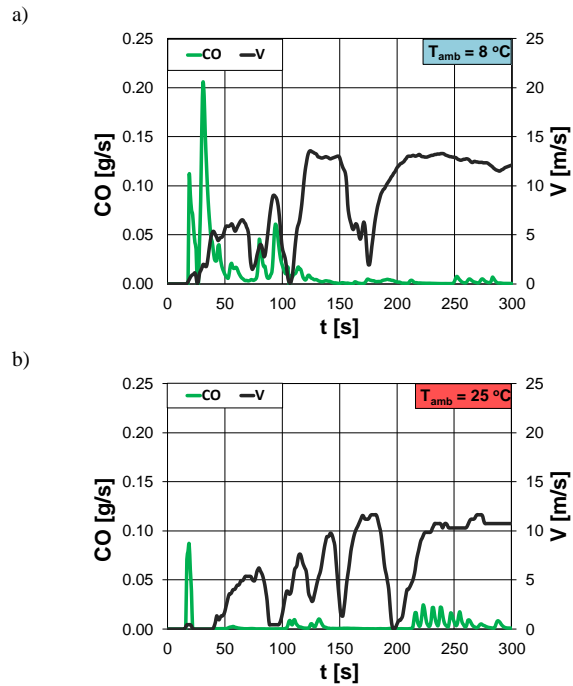


Fig. 7. Emission intensity of carbon monoxide and vehicle speed during cold start at ambient temperature of 8°C (a) and 25°C (b)

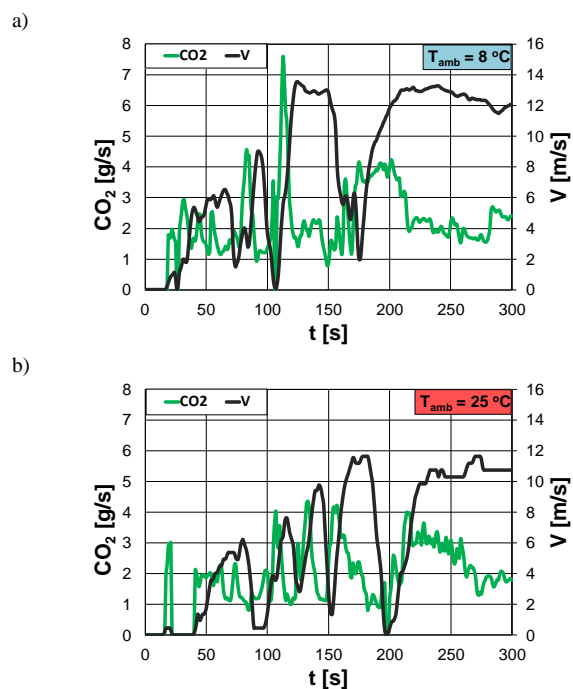


Fig. 8. Emission intensity of carbon monoxide and vehicle speed during cold start at ambient temperature of 8°C (a) and 25°C (b)

Regarding the number of particulates at the ambient temperature of 25°C, there is a peak (up to 1.45E+09) in the first 40 s after the engine started. At the ambient temperature of 8°C, this peak occurs earlier (t = 30 s) and reaches 1.20E+10 (Fig. 10). The particles number, in the period of 300 s from starting, increased by almost 4 times during the reduction of temperature value from 25°C to 8°C (7.5E+10 and 2.8E+11). The research results of emission intensity (Fig. 7) were used to determine the road emissions (converting the mass per unit of the road) during the cold start phase (lasting 300 s).

The reduction of the ambient temperature (from 25°C to 8°C) during the cold start (in the considered period of 300 s) results in (Fig. 11):

- an increase by 68% of CO road emissions,
- an increase by 15% of CO<sub>2</sub> road emissions,
- a decrease by 50% of NO<sub>x</sub> road emissions,
- an increase by 47% of PN road emissions.

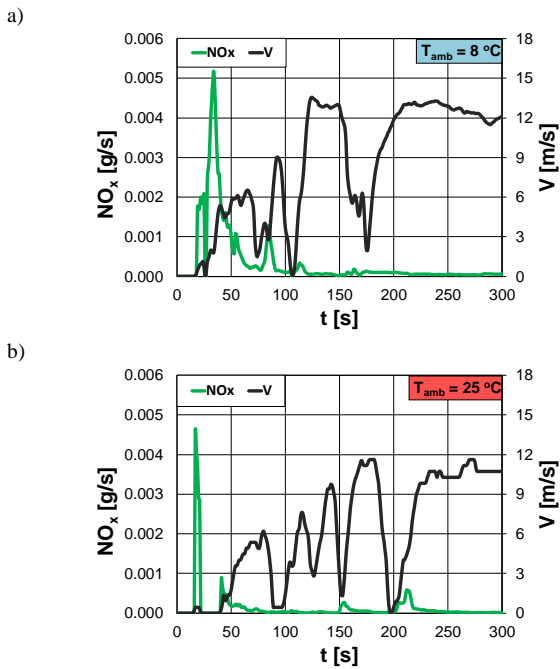


Fig. 9. Emission intensity of nitrogen oxides and vehicle speed during cold start at ambient temperature of 8°C (a) and 25°C (b)

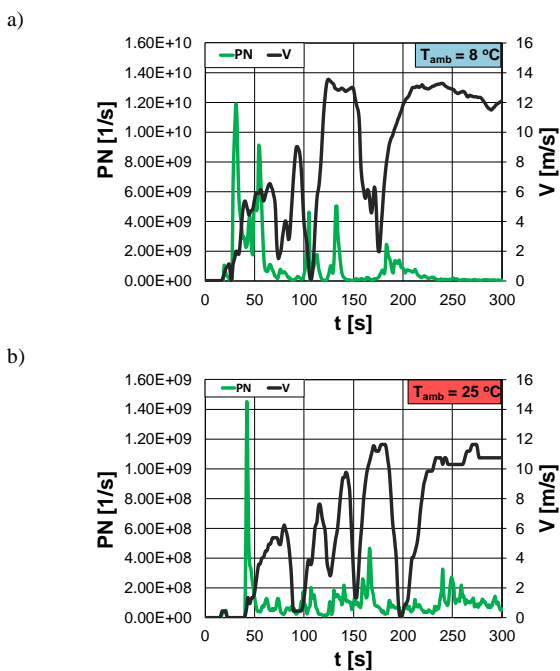


Fig. 10. Emission intensity of particle numbers and vehicle speed during cold start at ambient temperature of 8°C (a) and 25°C (b)

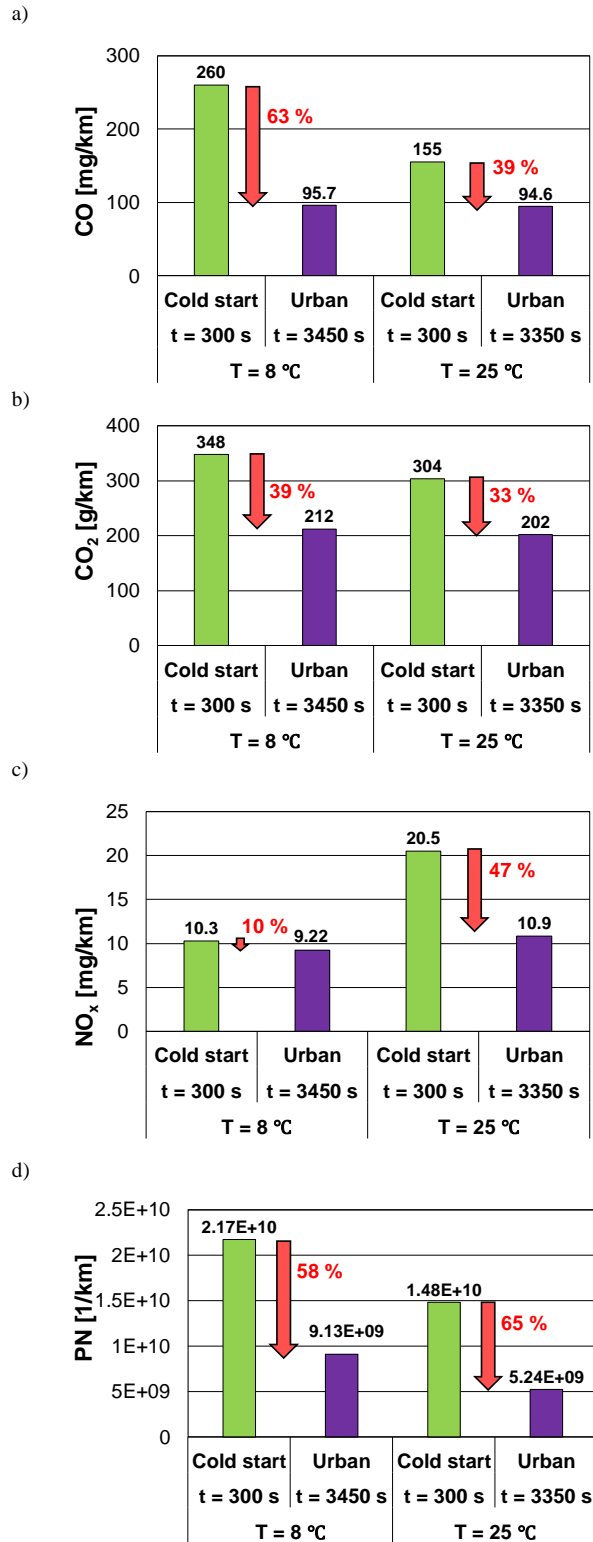


Fig. 11. Road emissions of CO (a), CO<sub>2</sub> (b), NO<sub>x</sub> (c), PN (d) at two different ambient temperatures

Comparing the cold start phase for different ambient temperatures in the urban part of the RDE test and in the entire RDE test are shown in Fig. 12 and 13. For the value of ambient temperature equal to 8°C, the results are as follows:

1. The share of CO emissions during the cold start (300 s) in relation to the urban part of RDE test is 26.0%; and in the relation to the entire RDE test it increases to 10.8%.
2. The share of CO<sub>2</sub> emissions during the cold start (300 s) in relation to the urban part of the RDE test is 11.6%; and in the relation to the entire RDE test it decreases to 3.40%.
3. The share of NO<sub>x</sub> emission during the cold start (300 s) in relation to the urban part of RDE test is 10.6%; and in the relation to the entire RDE test it decreases to 2.92%.
4. The share of PN emissions during the cold start (300 s) in relation to the urban part of RDE test is 22.7%; and in the relation to the entire RDE test it decreases to 0.05%.

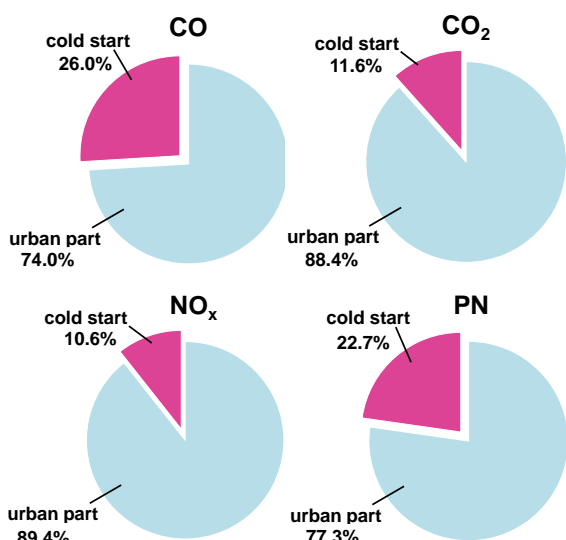


Fig. 12. Share of CO, CO<sub>2</sub>, NO<sub>x</sub> and PN emissions in urban section during cold start at 8°C

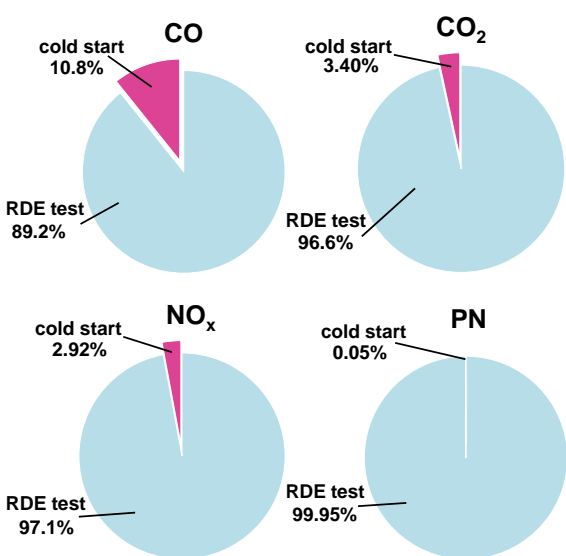


Fig. 13. Share of CO, CO<sub>2</sub>, NO<sub>x</sub> and PN road emissions in the entire RDE test during cold start at 8°C

In the case of the ambient temperature equals to 25°C the results are as follows (Fig. 14 and 15):

1. The share of CO emissions during the cold start (300 s) in relation to the urban part of RDE test is 10.7%; and in the relation to the entire RDE test it decreases to 4.63%.
2. The share of CO<sub>2</sub> emissions during the cold start (300 s) in relation to the urban part of the RDE test is 9.80%; and in the relation to the entire RDE test it decreases to 3.40%.
3. The share of NO<sub>x</sub> emission during the cold start (300 s) in relation to the urban part of RDE test is 12.3%; and in the relation to the entire RDE test it decreases to 3.42%.
4. The share of PN emissions during the cold start (300 s) in relation to the urban part of RDE test is 18.4%; and in the relation to the entire RDE test it decreases to 0.05%.

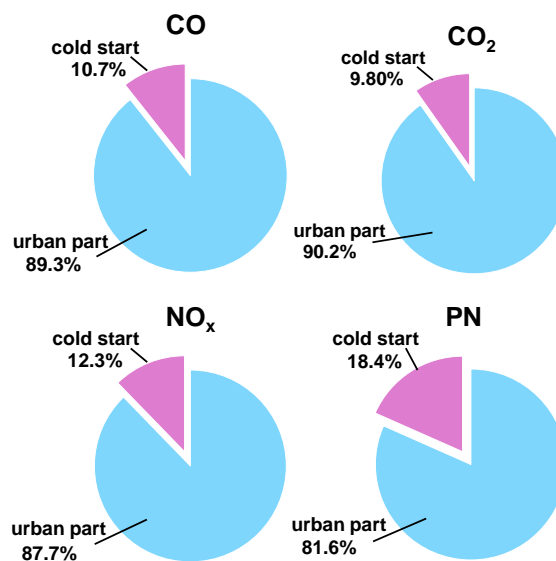


Fig. 14. Share of CO, CO<sub>2</sub>, NO<sub>x</sub> and PN emissions in urban section during cold start at 25°C

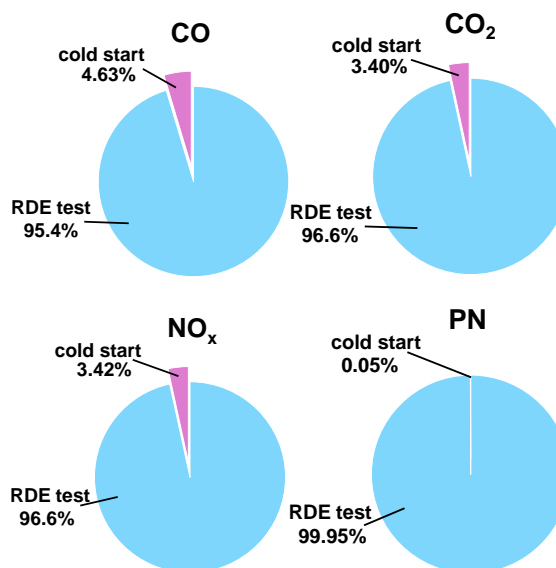


Fig. 15. Share of CO, CO<sub>2</sub>, NO<sub>x</sub> and PN road emissions in the entire RDE test during cold start at 25°C



## 5. Summary and conclusions

The RDE test procedure is still being developed and improved. Package 3 extended this road emission test by taking into account the emissions from cold start phase to the total value of exhaust emissions.

The article presents and discuss the research results on the impact of ambient temperature (8°C and 25°C) during the cold start phase of the gasoline engine in emission road tests. The measurements were carried out in compliance with the latest legislative procedures applicable to passenger cars. After the analysis of the engine operating parameters, there were defined its ecological parameters (emission intensity and road emissions) in the cold start period ( $t = 300$  s). Finally, there were determined the shares of CO, CO<sub>2</sub>, NO<sub>x</sub> and PN emissions in urban part and in the entire RDE test; during the cold start at 8°C and 25°C (Table 2).

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

300 s) results in an increase of all exhaust compounds, except NO<sub>x</sub>. The share of this compound is greater at the higher ambient temperature. This trend is caused by the combustion process in the engine and the formation of nitrogen oxides. Another reason is warming of exhaust after-treatment system. It is necessary to modify and improve exhaust after-treatment systems so that they fulfil their function at a lower operating temperature.

Table 2. Characteristics of the passenger car used in testing

	T <sub>amb</sub> = 8°C		T <sub>amb</sub> = 25°C	
	Share in the urban part	Share in the RDE test	Share in the urban part	Share in the RDE test
CO	26.0%	10.8%	10.7%	4.63%
CO <sub>2</sub>	11.6%	3.40%	9.80%	3.40%
NO <sub>x</sub>	10.6%	2.92%	12.3%	3.42%
PN	22.7%	0.05%	18.4%	0.05%

## Acknowledgements

This study was funded by Projects 05/52/DSPB/1278.

## Nomenclature

CO	carbon monoxide
CO <sub>2</sub>	carbon dioxide
GPS	Global Positioning Signal
NO <sub>x</sub>	nitrogen oxides

PEMS	Portable Emissions Measurement System
PN	particle number
RDE	Real Driving Emissions
WLTC	Worldwide Harmonized Light Vehicles Test Cycle

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