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NON-REPEATABILITY OF THE WLTP VEHICLE TEST RESULTS

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Abstract:

The paper presents results of considerations on the repeatability of the passenger car test results obtained in the WLTP procedure on a chassis dynamometer. The research concerned the aspects of exhaust emissions and fuel consumption. Measurements were carried out in the WLTC test with a cold engine start and then in four WLTC (Worldwide harmonized Light vehicles Test Cycle) tests with a hot engine start. The following values were measured: average specific distance emissions of hydrocarbons, non-methane hydrocarbons, carbon monoxide, nitrogen oxides, particulate matter and carbon dioxide, specific distance particulate number, and operational fuel consumption. Thus, it was possible to assess the impact of the engine's thermal state at start-up on the test results and the nature of test results repeatability with the start-up of a hot engine. The repeatability of the test results was assessed based on the coefficient of variation obtained in the individual tests and the relationship of the maximum difference between measurement results values in the individual tests for a hot engine start. The obtained test results turned out to be very diverse for the considered parameters and indicated low repeatability. Values of carbon dioxide emissions and operational fuel consumption were definitely the least varied in individual hot engine start tests. The exhaust emission of particulate matter varied the most in individual test iterations. However, the specific distance particulate number was relatively similar between individual tests, less so than the exhaust emission of other pollutants. In the case of different engine thermal state at start-up, the emitted particulate number varied the most in the test results, while the emission of carbon dioxide and operational fuel consumption varied the least. The repeatability of executing the velocity process in WLTC tests at hot engine and cold engine start-up was also examined as processes determining exhaust emissions and fuel consumption. These tests were much more repeatable than the exhaust emission and fuel consumption.

Keywords: *WLTP, WLTC, exhaust emission, repeatability*

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1. Introduction

Testing the Repeatability and Reproducibility (R&R) of measurement results is a statistical method used to assess the reliability of a measurement result and to search for causes of its variability.

The variability of the measurement result may depend on many factors, such as: the researchers performing the measurement, measurement tools, measurement methods, measurement conditions and the tested objects themselves.

Repeatability of measurement results is the ability to obtain a similar set of test results performed by the same researchers on the same test objects (ISO 21748:2017; Shenavarmasouleh & Arabnia, 2019; Ye et al., 2022).

Reproducibility of measurement results is the ability to obtain similar research results from the same object performed by different teams of researchers (ISO; Shenavarmasouleh & Arabnia, 2019).

The coefficient of variability can be used as a measure of the repeatability and reproducibility of measurement results (ISO; Shenavarmasouleh & Arabnia, 2019).

This article concerns the results of exhaust emissions and fuel consumption tests performed in the WLTP (Worldwide harmonized Light vehicles Test Procedure) (Andrych-Zalewska, 2023; DieselNet 2021; Hopwood & Shalders, 2020; Shreekrushna, 2019; Worldwide emission standards 2020/2021 & 2022/2023). The repeatability of the measurement results is caused by the repeatability of the internal combustion engine operating states that determine the specific distance exhaust emissions (herein referred to as for specific distance emissions) and fuel consumption (Andrych-Zalewska et al., 2019; Andrych-Zalewska et al., 2021).

The exhaust emissions intensity, the particulate number intensity and the intensity of fuel consumption of the engine – G, in dynamic operating states are determined by the engine operating states in an operator manner (a function other than a function with numerical values:

- speed – n, characterizing the frequency of engine operating cycles,
- engine load, which can be defined using torque – M_e, or effective power or mean effective pressure,
- engine thermal state – **TS**:

$$G(t) = R[n\,(t), M_e(t), \mathbf{TS}(t)] \tag{1}$$

where: R – some operator.

The thermal state of the engine is determined by the set of temperatures of the individual engine elements as well as the consumed operational substances (Andrych-Zalewska et al., 2021; Andrych-Zalewska, 2023).

The operating states of a vehicle combustion engine are determined by the vehicle velocity:

$$[n\,(t), M_e(t), \mathbf{TS}(t)] = S[v(t)] \tag{2}$$

where: S – some operator.

It follows that the exhaust emissions intensity, the particulate number intensity and the intensity of fuel consumption of the engine in dynamic operating states depend in an operational manner on the vehicle velocity (Andrych-Zalewska, 2023):

$$G(t) = F[v(t)] \tag{3}$$

where: F – operator.

For the random properties of the vehicle velocity, the processes describing exhaust emissions and fuel consumption also have random properties (Andrych-Zalewska, 2023), hence it is advisable to study these properties. Properties characterizing the variability of measured values include the repeatability of their characteristics and this was the reason for this study of the repeatability of car test results in driving cycles (Andrych-Zalewska et al., 2021; Andrych-Zalewska, 2023).

2. Literature review

Intensive research and significant financial commitment in automotive industry, in the field of combustion engines in particular, resulted in much progress being made. This article was aimed at finding methods of improving the useful properties of combustion engines. In the last few decades, the basic criteria used to determine progress in the quality of combustion engines were primarily related to exhaust emissions, and secondly to fuel consumption. The exhaust emission criteria are strictly ecological in nature, whereas fuel consumption is mostly economic, but also has an ecological secondary nature due to the limited natural resources. Other problems of internal combustion engines and road vehicles, such as durability, reliability and maintainability, are largely mastered already from the technological standpoint. A significant step in the progress of combustion engines was the improvement of their exhaust emission properties. This was evidenced by the significant reduction of the legal exhaust emissions limit values (DieselNet 2021; Worldwide emission standards 2020/2021 & 2022/2023): specific road exhaust emission and specific road particle number emission – for light vehicles (passenger cars, light trucks and L category vehicles such as motorcycles , mopeds, quads and microcars) as well as the specific exhaust emission and the specific particle number emissions – for heavy vehicles (in the case of trucks and buses).

There are many publications that provide test results of internal combustion engines exhaust emissions (Andrych-Zalewska, 2023; Chłopek & Rostkowski, 2015; Fayyazbakhsh, A. et al., 2022; Grigoratos et al, 2018; Saylam 2022).

Papers (Andrych-Zalewska et al., 2019; Andrych-Zalewska et al., 2021; Andrych-Zalewska, 2023) presented the exhaust emission test results of internal combustion engines obtained in dynamic operating conditions for passenger cars. These publications examined exhaust emissions in driving cycles carried out on a chassis dynamometer (in NEDC – New European Driving Cycle and WLTC, as well as in real driving conditions with the vehicle driving on the road in the RDE (Real Driving Emissions) test (Hopwood & Shalders, 2020; Shreekrushna, 2019; Worldwide emission standards 2020/2021 & 2022/2023). A significant sensitivity of exhaust emissions to the combustion engine operating states, both static and – especially – dynamic, was observed, varying for each of the different emitted substances and particle number.

Systematic trends in the road specific emission reduction of substances harmful to the health and life of living organisms as well as gases that contribute to the intensification of the greenhouse effect in the atmosphere were also outlined in literature (Fayyazbakhsh et al., 2022).

Paper (Grigoratos et al., 2018) provides the research results on particle emissions from road transport. Attention was paid to sources of particle emissions other than the engine exhaust, such as tribological vapors in vehicles (mainly the mechanical clutch and braking system) and their interactions with the environment (interaction of road tires with the road surface). There was a certain contradiction between environmental protection and safety criteria in the case of particle emissions from the interaction of road tires with the road surface.

There are numerous materials in the papers from the JCR Conference and Workshop in Thessaloniki, Greece (Mamarikas et al., 2019). The materials mainly concern methods of exhaust emissions testing in the case of road transport, as well as modelling of exhaust emissions from combustion engines.

The greenhouse gas emissions from natural and anthropogenic sources were examined in (Reitz et al., 2020)., including deom transport, in the years 1991 – 2010. It was found that in the transport sector overall, road transport dominated in terms of greenhouse gas emissions, caused by the use of internal combustion engines powered by fossil fuels. It was thus concluded that there was an urgent need to replace fossil fuels as energy carriers in transport with renewable sources of energy.

Paper (Saylam, 2022). describes an innovative approach to reducing exhaust emissions from compression-ignition engines, by fuelling the engines with mixtures of diesel oil, with additives such as n-dodecane and n-xylene. High effectiveness in reducing exhaust emissions, especially those of carbon monoxide and organic compounds, was found when using alcohol additives.

Due to significant technological progress in the field of combustion engines, especially in terms of their exhaust emissions, engine testing has become increasingly more difficult – often the concentrations of pollutants in the exhaust gases are at the very detection limit of the measurement equipment. In such a situation, the repeatability and reproducibility of measurement results is very important to establish. However, most of the work in the field of combustion engines is, understandably, devoted to the aspect of exhaust emissions, but not to the repeatability and reproducibility of measurement results.

The aspect of test results repeatability for road vehicles and combustion engines is not a common topic in the literature. This topic was approached explicitly occasionally in previous papers (Andrych-Zalewska, 2023; Chłopek & Rostkowski, 2015; Chłopek & Szczepański, 2015; Maurya, 2019; Shenavarmasouleh & Arabnia, 2019).

The paper (Chłopek & Rostkowski, 2015; Chłopek & Szczepański, 2015) presents the theoretical basis for the analysis of the operating properties of an internal combustion engine in random conditions. The results of theoretical considerations were illustrated with tests of the unique ecological properties of a car engine (based on exhaust emissions and fuel consumption data) in the conditions of type-approval tests in accordance with the ECE R83.05 regulation (ECE – Economic Commission for Europe), (DieselNet 2021; Hopwood & Shalders, 2020; 2019; Worldwide emission standards 2020/2021 & 2022/2023). A significant sensitivity of the ecological properties of engines to random disturbances, especially carbon monoxide and nitrogen oxide emissions, was observed. It was significant that the dispersion of the test-averaged values of velocity, operational fuel consumption and specific distance carbon dioxide emissions was only about 2%, while for for specific distance emissions of carbon monoxide, hydrocarbons and nitrogen oxides this dispersion was more than an order of magnitude greater. Research conducted using such values justifies the approach of treating sets of values averaged in a test as normal.

A measure for assessing the repeatability of properties of test objects was proposed in (Chłopek & Rostkowski, 2015). As an applied example of such assessment of the combustion engines unique properties, the test results of the Detroit Diesel Series 50 engine were provided. Specific exhaust emissions and specific fuel consumption were assessed in the dynamic HDDTT (Heavy Duty Diesel Transient Test) and ETC (European Transient Test), (DieselNet 2021; Worldwide emission standards 2020/2021 & 2022/2023). For internal combustion engines, the lack of repeatability of the combustion and operation processes was clear. This aspect is what causes the properties of combustion engines to differ significantly, even under comparable operating conditions. This tends to be true even in static engine operating conditions. Formalizing the measure of the repeatability of the test results made it possible to use this method to study the properties of combustion engines, which are currently particularly critical for any engine assessment. The exhaust emission values are characterized by such properties.

In (Aliramezani, 2022) it was stated that the repeatability of engine operating states resulting from measurements was the result of inevitable limitations in the data gathering process. For quantities that have a clear physical interpretation, the coefficient of variation can be used as the inverse of the coefficient of measurement results repeatability. The cited paper systematized the reasons for the non-repeatability of measurement results as a result of random phenomena and imperfections in the results analysis. The fuzzy set theory was used to assess the causes of the engine operating states non-repeatability. Examples of the application of fuzzy set theory to assess the reasons for the non-repeatability of engine exhaust emission measurement results were presented.

A results repeatability assessment, presented in (Jaworski et al., 2018), for tests of exhaust emissions of a passenger car engine on a chassis dynamometer in the NEDC test (DieselNet 2021; Worldwide emission standards 2020/2021 & 2022/2023) in the engine cold-start and hot-start conditions. The tests were carried out in a climatic chamber. The analysis included emissions of carbon monoxide, hydrocarbons, non-methane hydrocarbons, methane, nitrogen oxides and carbon dioxide. The authors concluded that their coefficient of variation could be used to assess the repeatability of measurement results.

Test results obtained with a stationary compression-ignition engine powered by mixtures of diesel oil and n-butanol were analyzed in (Jamrozik et al., 2021). The test results of the combustion process (chamber gas pressure and heat release rate) and emissions of the dual-fuel engine were compared with the test results of a conventional engine powered only by diesel fuel. Moreover, the stability of the engine operation was also examined. It was found that the addition of n-butanol improved the stability of engine operation and contributed to reducing exhaust emissions of carbon monoxide, hydrocarbons and particulate matter.

The repeatability and reproducibility (R&R) of particulate number measurements from the Cummins ISX engine in FTP test conditions (Federal Test Procedure), (DieselNet 2021; Worldwide emission standards 2020/2021 & 2022/2023) were measured in (Kha et al., 2015). Repeatability and reproducibility values were determined for 53 tests. The obtained repeatability and reproducibility of measurement results was 2.5% and 31.7% of the average value, respectively.

Paper (Kordos & Nieoczym, 2016) presents the results of empirical research on the repeatability of the BMW N43 B20 AY spark ignition engine, in which a gasoline direct injection system was used for mixture creation. The values of the non-repeatability index of the maximum gas pressure in the cylinder were analyzed for two different engine operating conditions: at maximum load and at partial load. The index values were calculated based on the measurement results in 100 cycles at five engine speeds. It was found that the repeatability of the maximum indicated pressure during operation of the tested engine was greater at partial engine load than at maximum load.

Paper (Maurya, 2019) presents the test results of combustion process stability in the engine cylinder. The mean effective pressure was used as a quantity characterizing the combustion process. The coefficient of variation and the histogram of the mean effective pressure were analyzed. The theory of chaotic time series was used in the analysis. Research has shown that the cyclical variability of measurement results has a non-linear, deterministic structure depending on the engine operating conditions.

3. Research method

The empirical research methodology included testing a passenger car in accordance with the WLTP Class 3b procedure (DieselNet 2021; Worldwide emission standards 2020/2021 & 2022/2023). A test was performed by starting a cold engine and then a test was performed four more with a hot engine start. Table 1 presents basic information about the research object.

Table 1. Basic information about the research object

Research object	Passenger car
Engine circulation	Four-stroke engine
Type of ignition	Spark ignition engine
Engine turbocharging	Yes
Number and arrangement of cylinders	Four-cylinder in-line engine
Engine displacement	999 cm^3
Rated power	81 kW
Automatic transmission	Yes
Category due to pollutant emissions	Euro 6 AP

The tests were performed on a chassis dynamometer using equipment meeting the requirements of type approval procedures regarding exhaust emissions.

The laboratory is an advanced, climate-controlled facility for performing emissions, fuel consumption and performance tests over a range of driving cycles and a broad range of ambient conditions. Emissions testing is carried out with the aid of sampling bags, raw and diluted modal analysis and a dilution tunnel (for vehicles with spark ignition engine and with compression ignition engine). These facilities permit the execution of a wide range of emissions tests, including:

- CVS (Constant Volume Sampler) bag diluted and raw tailpipe emissions testing to international standards
- modal analysis of diluted and raw tailpipe gases,
- modal analysis of raw exhaust sampled from two locations (nominally pre cat & post cat, but the sampling locations are flexible),
- measurement and archival of temperatures from up to eight thermocouples mounted at different locations on the vehicle and on the exhaust line,
- measurement of the air-fuel ratio and the EGR (Exhaust Gas Recirculation) percentage,
- catalytic converter efficiency testing (and determination of light-off time) for elimination of: hydrocarbons, methane, non-methane hydrocarbons, carbon monoxide, nitrogen oxide, nitrogen dioxide and nitrogen oxides,
- carbon dioxide emissions and fuel consumption measurement according to EU (European Union) standards,
- opacity measurements according to EU standards,
- gravimetric and numerical quantification of particulate matter emission,
- measurement of unregulated compounds such as, nitrous oxide, ammonia using an additional analyser AVL AMAi60.

A schematic diagram of the upgraded laboratory is presented in Figure 1.

The base of the laboratory is a climatic chamber within which emissions, fuel consumption and performance measurements are performed at temperatures ranging from -35 °C to +60 °C. Such a temperature range far exceeds current legislative requirements; the 95 °C temperature range capability is a response to the current and future requirements of engine and vehicle development projects, cold startability at low temperatures, etc, and oil, fuel and catalyst manufacturers' testing demands. The chamber is equipped with temperature and humidity control systems, which facilitate the maintenance of the desired temperature and humidity levels. During operation of the chamber, (including during the execution of emission and vehicle performance tests), the chamber permits:

- temperature control over the range -35 °C to +60 °C,
- control accuracy (temperature tolerance): ±1.0 °C (under static conditions, with zero heat load); ±1.2 °C (during emissions tests); ±2 °C (during performance tests),
- control over the humidity value during emissions tests: from 5.5 g to 15.0 g of water per 1 kg of dry air at temperatures ranging from +20 °C to +35 °C,
- variation in humidity level: ≤ 5 %,
- temperature gradient (with the chamber empty): 0.5 °C/min during warm-up and cool-down phases.

To sum up, BOSMAL laboratory meets the requirements of the PN-EN ISO/IEC 17025:2018-02 standard. Describing the test conditions in more detail, it can be written that:

- cell temperature: (22.64 ÷ 22.93) °C,
- relative humidity: (38.75 ÷ 40.13) %,
- barometric pressure: (972.5 – 973.6) hPa.

Values of the following parameters were measured: vehicle velocity, specific distance emissions of hydrocarbons, non-methane hydrocarbons, carbon monoxide, nitrogen oxides, particulate matter and carbon dioxide, as well as the particulate number and fuel consumption. The data acquisition rate was 10 Hz. The recorded measurement results were processed by a second order Savitzky-Golay filter (Dorran; Gallagher, 2020; Schmid, 2022) to reduce high-frequency noise in the recorded signals.

These values of velocity were determined for individual phases of the WLTC (Worldwide harmonized Light vehicles Test Cycle) test – Figure 2 (DieselNet 2021; Worldwide emission standards 2020/2021 & 2022/2023):

- low velocity phase – (0 ÷589) s,
- medium velocity phase – (589 ÷ 1022) s,
- high velocity phase – (1022 ÷ 1477) s,
- very high velocity phase – (1477 ÷ 1800) s
- as well as for the whole test.

The WLTC test is characterized by a large variation in driving velocity in individual phases, and at the same time, the dynamic properties of the acceleration process were similar in individual phases – Figure 3. The average absolute acceleration values in individual test phases were similar – Figure 4.

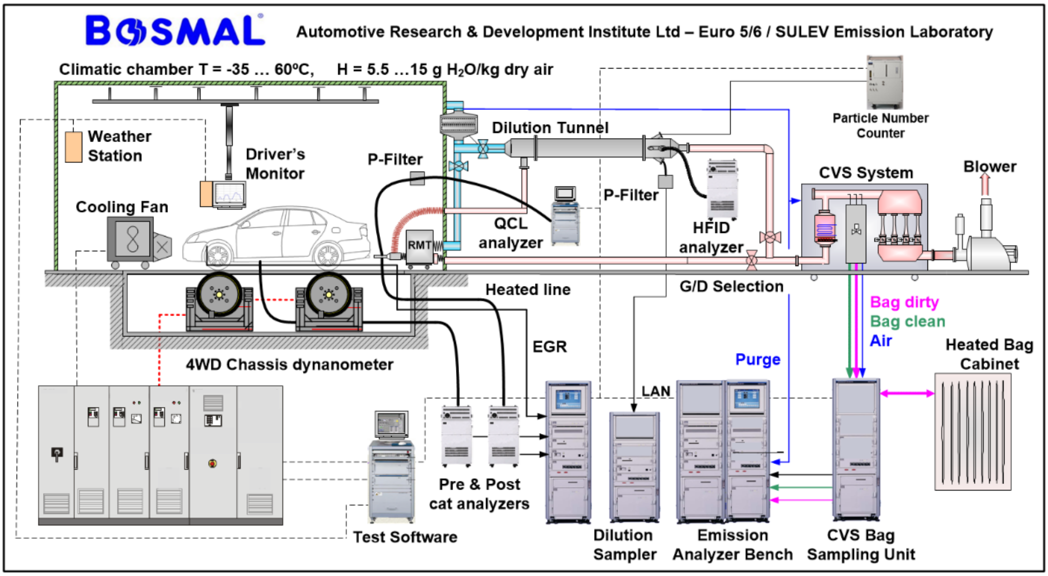

Fig. 1. Schematic diagram of the upgraded laboratory, showing the climatic chamber, chassis dynamometer, dilution tunnel, emissions sampling bags and all analysers, including the recently-added modal raw exhaust analyzer lines

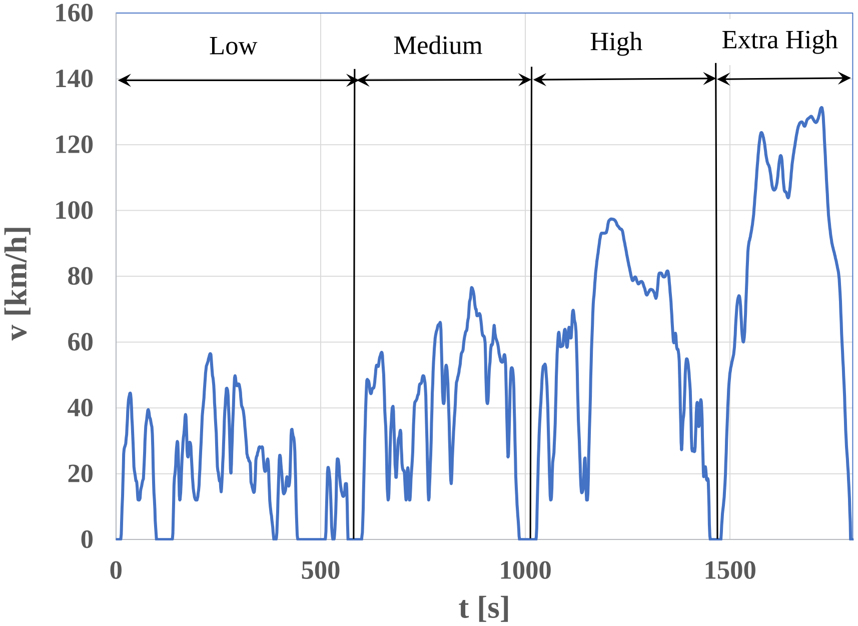

Fig. 2. Vehicle velocity – v in the WLTC

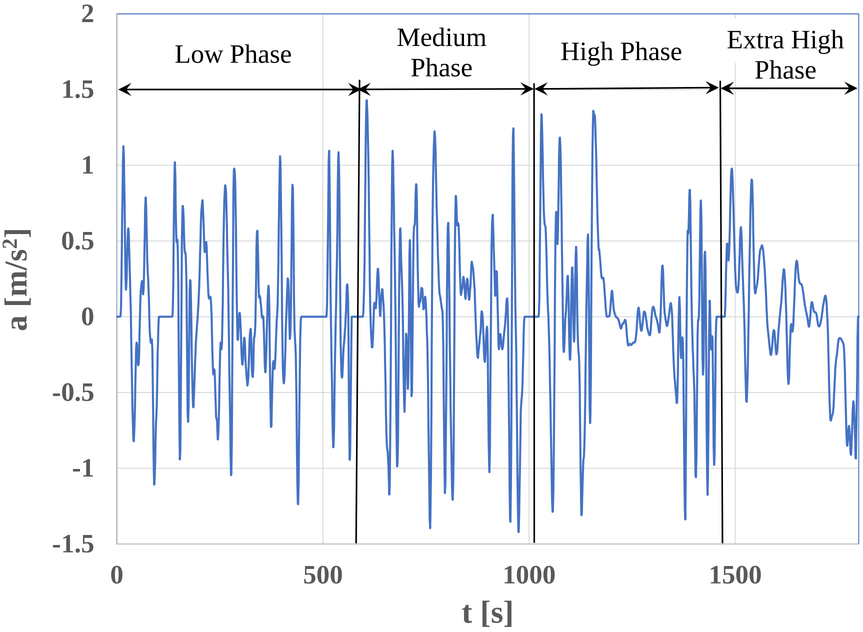

Fig. 3. Vehicle acceleration – a in the WLTC

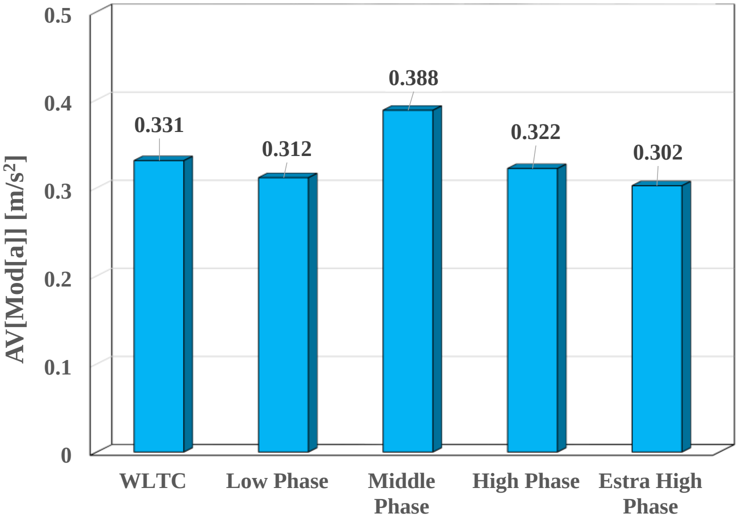

Fig. 4. The average absolute acceleration values in individual phases of the WLTC test – AV[Mod[a]]

The repeatability of the research results was assessed based on their irregularity.

The irregularity of the test results was assessed based on two variables: the coefficient of variation of the test results obtained in the individual tests, and the ratio of the difference between the extreme values of the measurement results in the individual tests, for a hot engine start:

$$W[X] = \frac{D[X(H)]}{AV[X(H)]} \tag{4}$$

where: AV – average value of measurement results – X(H) in the four WLTC tests with hot engine start,
D – standard deviation of measurement results – X(H) in the four WLTC tests with hot engine start – H.

$$r = \frac{Max[X[H]]-Min[X[H]]}{AV[X(H)]} \tag{5}$$

where: Min[X(H)] – minimum value of measurement results obtained in test with a hot engine start,
Max[X(H)] – maximum value of measurement results obtained in test with a hot engine start.

The ratio of the measurement results between the cold engine start – X[C] and the average value of measurement results for the tests with hot engine start – AV[x[H]] was also determined as:

$$k = \frac{X[C]}{AV[X(H)]} \tag{6}$$

where: X(C) – measurement results obtained in test with a cold engine start.

4. Results

Figure 5 shows the vehicle velocity in the WLTC tests with the four tests with the hot engine start.

The repeatability of the obtained velocity was very high, hence these tests are practically indistinguishable when presented on a graph.

Figure 6 shows a comparison of the average vehicle velocity in individual phases of the WLTC test for the cold engine start and the four tests with a hot engine start.

Figures 5 and 6 clearly show high repeatability of individual vehicle velocity results in the WLTC test.

Figure 7 shows the average vehicle velocity in individual phases of the four WLTC tests with hot engine start, as well as the average velocity and standard deviation of the average vehicle velocity in individual phases of the four tests. A high repeatability of individual WLTC test results with a hot engine start can be seen. This was confirmed by the coefficient of variation of the average vehicle velocity – Figure 8.

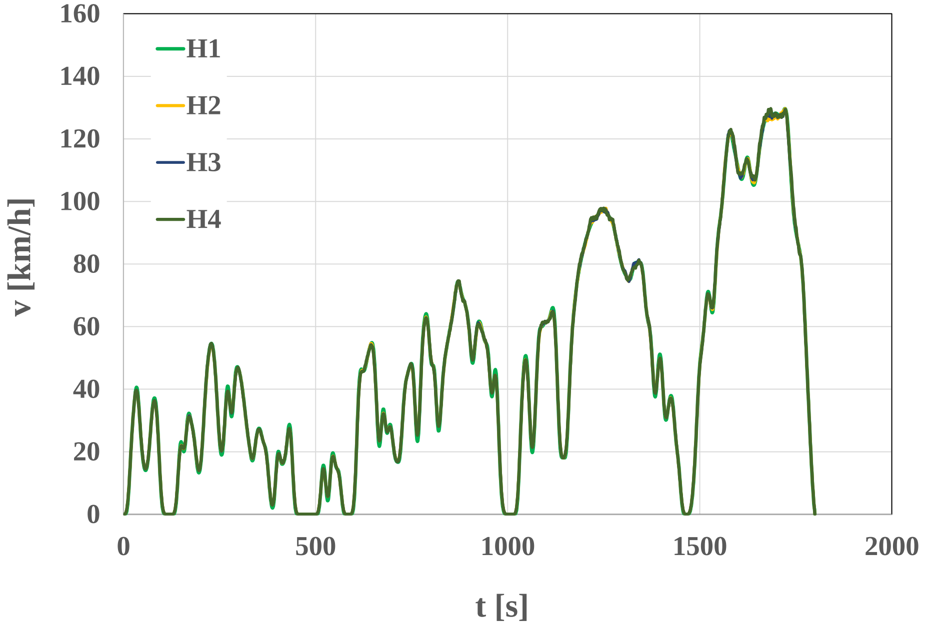

Fig. 5. Vehicle velocity – v in four WLTC tests with a hot engine start – H1, H2, H3 and H4

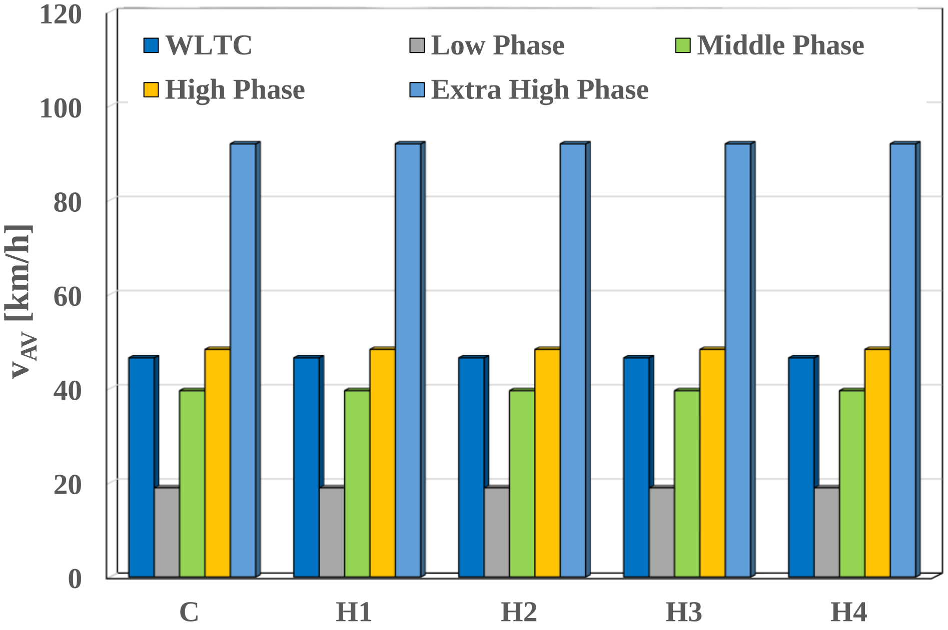

Fig. 6. Average vehicle velocity – v_{AV} in individual phases of the WLTC test with a cold engine start – C and in the four WLTC tests with hot engine start – H1, H2, H3 and H4

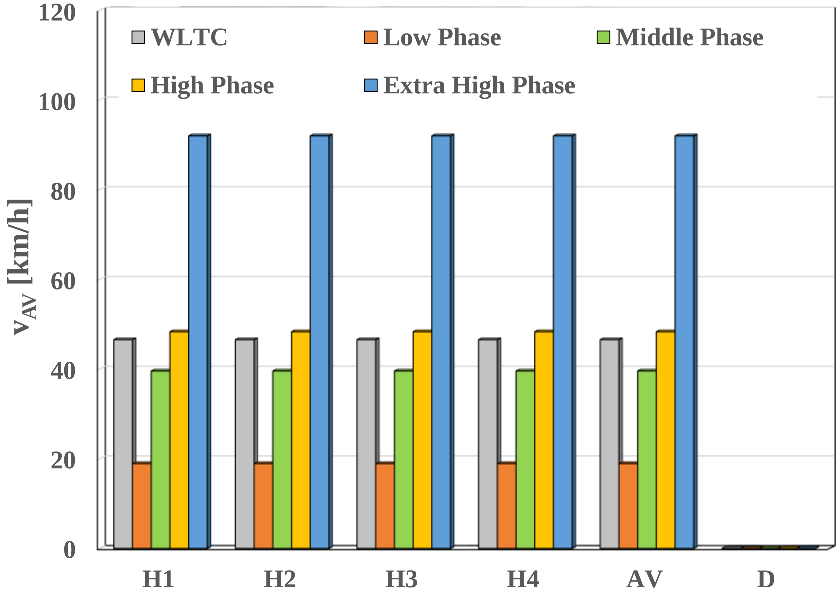

Fig. 7. Average vehicle velocity – v_{AV} in individual phases of the four WLTC tests done with hot engine start – H1, H2, H3 and H4 and the averaged velocity values – AV along with the standard deviation of average vehicle velocity – D in individual phases of the test

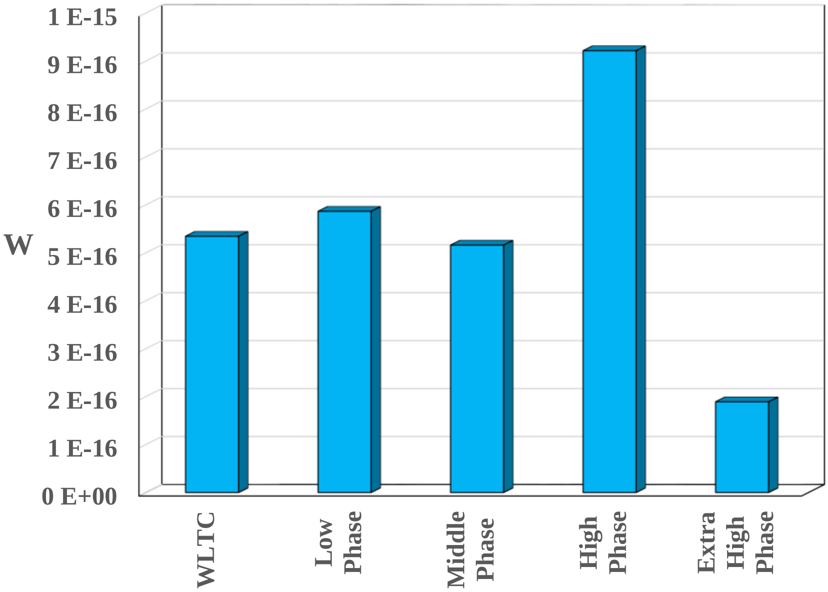

Fig. 8. Coefficient of variation of the average vehicle velocity – W in individual phases of the four WLTC tests performed with hot engine start

Very small coefficient of variation values for the average vehicle velocity in individual phases of the four performed WLTC tests with hot engine start indicate high repeatability of the vehicle velocity driving.

The distance travelled by the car in individual test phases was repeatable. The values of the duration of the test phases, average speed and distance travelled by the vehicle were presented in Table 2.

Very high repeatability of test performance could clearly be seen. The coefficient of variation of test duration, average speed and distance travelled by the vehicle was far below 0.01.

Tab. 2. Travel characteristics of the vehicle in the test

		t	**v_{AV}**	**L**			**t**	**v_{AV}**	**L**
		[s]	**[km/h]**	**[km]**			**[s]**	**[km/h]**	**[km]**
C	LPh	586.0	19.0	3.1	**H4**	LPh	589.0	19.0	3.1
	MPh	423.0	40.5	4.8		MPh	426.0	40.6	4.8
	HPh	458.0	56.3	7.2		HPh	453.0	56.3	7.1
	EHPh	333.0	89.2	8.3		EHPh	333.0	89.3	8.3
	WLTC	1800.0	46.5	23.3		WLTC	1801.0	46.2	23.1
H1	LPh	589.0	19.0	3.1	**AV**	LPh	588.0	19.0	3.1
	MPh	430.0	40.5	4.8		MPh	426.4	40.5	4.8
	HPh	455.0	56.3	7.1		HPh	454.6	56.3	7.1
	EHPh	325.0	89.2	8.1		EHPh	331.2	89.2	8.2
	WLTC	1800.0	46.5	23.3		WLTC	1800.6	46.3	23.2
H2	LPh	588.0	19.1	3.1	**D**	LPh	1.095	0.041	0.009
	MPh	427.0	40.5	4.8		MPh	2.245	0.044	0.025
	HPh	453.0	56.3	7.1		HPh	1.855	0.020	0.028
	EHPh	333.0	89.2	8.3		EHPh	3.124	0.032	0.079
	WLTC	1801.0	46.1	23.1		WLTC	0.490	0.188	0.088
H3	LPh	588.0	19.1	3.1	**W**	LPh	0.0019	0.0022	0.0028
	MPh	426.0	40.6	4.8		MPh	0.0053	0.0011	0.0053
	HPh	454.0	56.4	7.1		HPh	0.0041	0.0004	0.0039
	EHPh	332.0	89.2	8.2		EHPh	0.0094	0.0004	0.0096
	WLTC	1801.0	46.1	23.1		WLTC	0.0003	0.0041	0.0038

Where:
C – test with cold engine start,
H1, H2, H3, H4 – tests with hot engine start,
t – test phase duration,
v_{AV} – average speed in a test phase,
L – distance travelled in a test phase,
LPh – Low Phase,
MPh – Medium Phase,
HPh – High Phase,
EHPh – Extra High Phase.

Test results were gathered for the WLTC tests, one of which was done with cold engine start and four iterations of the WLTC tests were done for hot engine start (Figures 9 – 24).

The strong influence of the engine's thermal state at start-up on specific distance hydrocarbon emissions can be clearly observed. The ratio of specific distance emissions of hydrocarbons when starting a cold engine and specific distance emissions of hydrocarbons when starting a hot engine ranged from 12 to 15.

The repeatability of specific distance hydrocarbon emissions in the four WLTC tests with hot engine start was concluded to be high – the coefficient of variation of measurement results was low at approximately 0.09.

The influence of the engine's thermal state at start-up on specific distance emissions of non-methane hydrocarbons was found to be even greater than on specific distance emissions of all hydrocarbons. Specific distance emissions of non-methane hydrocarbons with a cold engine start were 22 to 35 times greater than specific distance emissions of non-methane hydrocarbons for a hot engine start.The non-repeatability of non-methane hydrocarbons specific distance emissions in the four WLTC tests with hot engine start was greater than for specific distance emissions of hydrocarbons. The coefficient of variation of measurement results was approximately 0.16. The influence of the engine's thermal state at start-up on specific distance carbon monoxide emissions was much less significant in the test. The ratio of specific distance emission of carbon monoxide with cold engine start and specific distance emission of carbon monoxide with hot engine start was approximately 3.5.

The non-repeatability of specific distance carbon monoxide emissions in the four WLTC tests with hot engine start was similar to that of specific distance ad hydrocarbon emissions – the coefficient of variation of measurement results was approximately 0.08.

The influence of the engine's thermal state at start-up on specific distance emissions of nitrogen oxides was smaller than in the case of specific distance emissions of carbon monoxide. The ratio of specific distance emissions of nitrogen oxides with a cold engine start and the specific distance emissions of nitrogen oxides with a warm engine start was approximately 2.2.

Also in the case of specific distance emissions of nitrogen oxides in the four WLTC tests with a hot engine start, the repeatability was similar to that of specific distance emissions of hydrocarbons and carbon monoxide – the coefficient of variation of measurement results was approximately 0.07.

Unlike other exhaust substances, the specific distance emissions of particulate matter with a hot engine start were greater than specific distance emissions with a cold engine start – by approximately 1.6 to 3 times.

Specific distance particulate emissions in the four WLTC tests with hot engine start had the lowest repeatability – the coefficient of variation of measurement results was the highest, at approximately 0.27.

The specific distance particulate number has been shown to be most affected by the engine's thermal state at start-up in the test. The specific distance particulate number for cold engine start conditions was approximately 100 times greater than specific distance particulate number for the hot engine starts.

Despite the previous low repeatability for the specific distance particulate number in terms of its mass, the repeatability of the specific distance particulate number in the four WLTC tests with a hot engine start was low – the coefficient of variation of the measurement results was only approximately 0.04.

The impact of the engine's thermal state at startup during the test on specific distance carbon dioxide emissions was insignificant. The specific distance emission of carbon dioxide when starting a cold engine was approximately 3% higher than the specific distance emission of carbon dioxide when starting a hot engine.

The specific distance carbon dioxide emissions in the four WLTC tests with a hot engine start have shown very high measurement repeatability – the coefficient of variation of the measurement results was only about 0.002.

Due to its close correlation with carbon dioxide emissions, the operational fuel consumption was impacted about the same by the engine's thermal state at start-up as specific distance carbon dioxide emissions. In the case of operational fuel consumption in the four WLTC tests with hot engine start, the repeatability of measurement results was the same as for specific distance carbon dioxide emissions – the coefficient of variation of measurement results was low at 0.002.

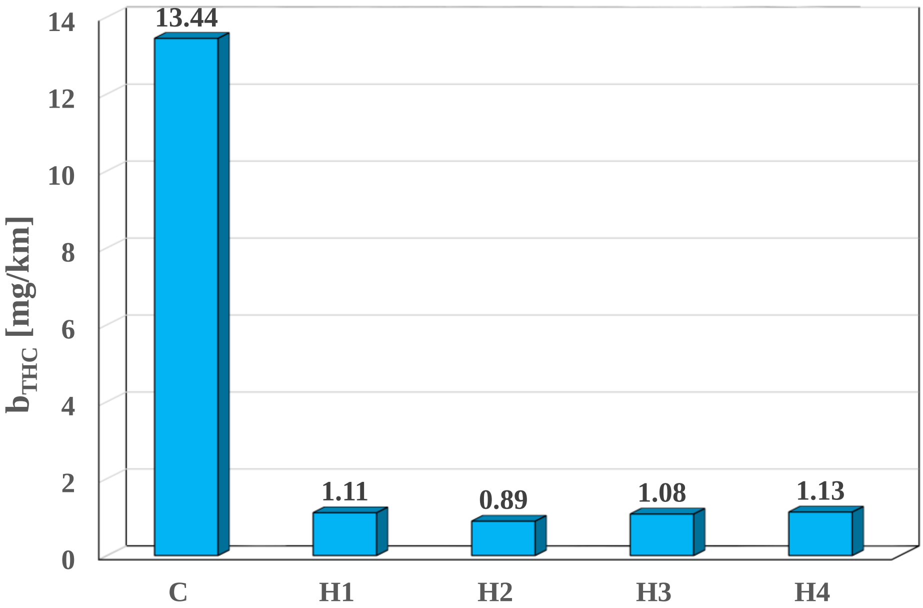

Fig. 9. Specific distance emissions of hydrocarbons – b_{THC} in the WLTC test with cold engine start – C and in four WLTC tests with hot engine start – H1, H2, H3 and H4

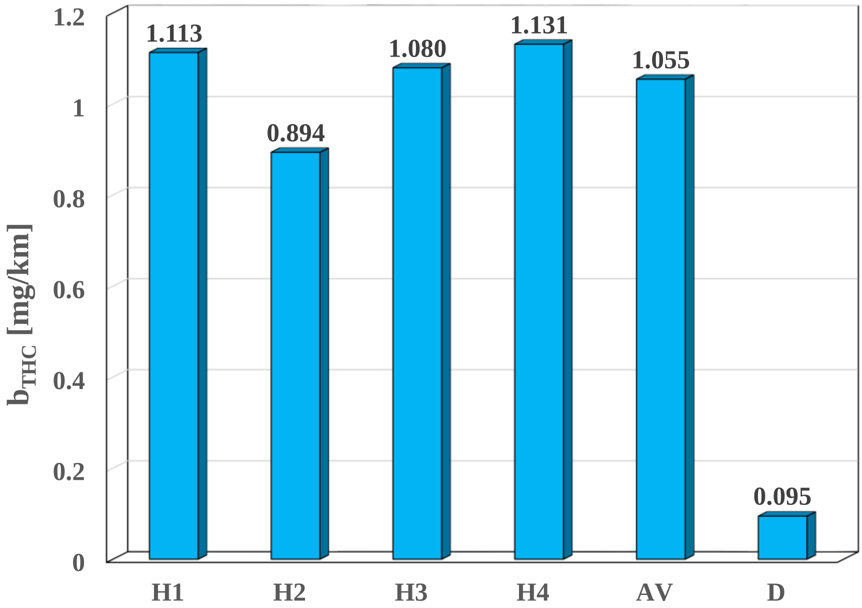

Fig. 10. Specific distance emissions of hydrocarbons – b_{THC} in the four WLTC tests with hot engine start – H1, H2, H3 and H4 as well as the averaged value – AV and standard deviation – D of the specific distance emission of hydrocarbons

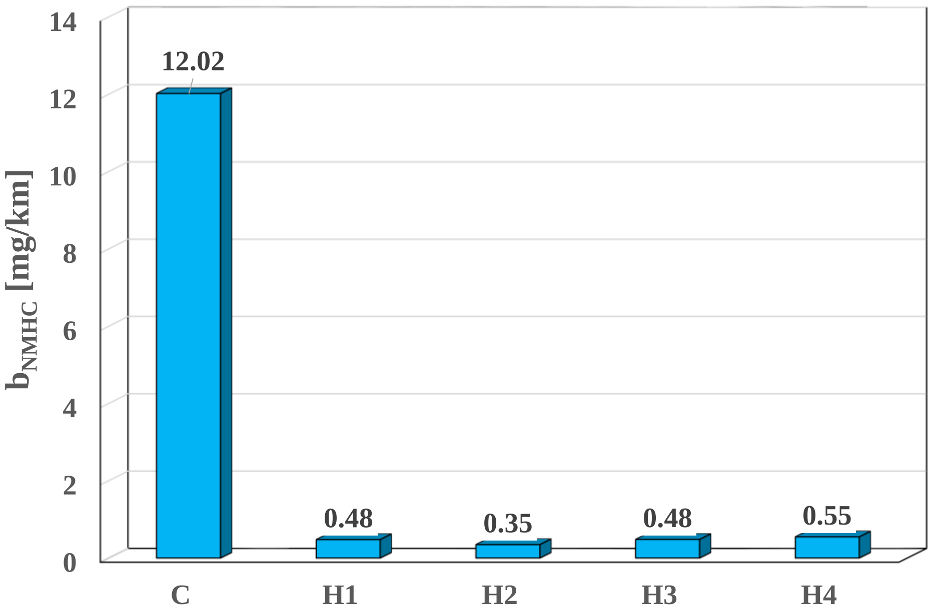

Fig. 11. Specific distance emissions of non-methane hydrocarbons – b_{NMHC} in the WLTC test with cold engine start – C and in four WLTC tests with hot engine start – H1, H2, H3 and H4

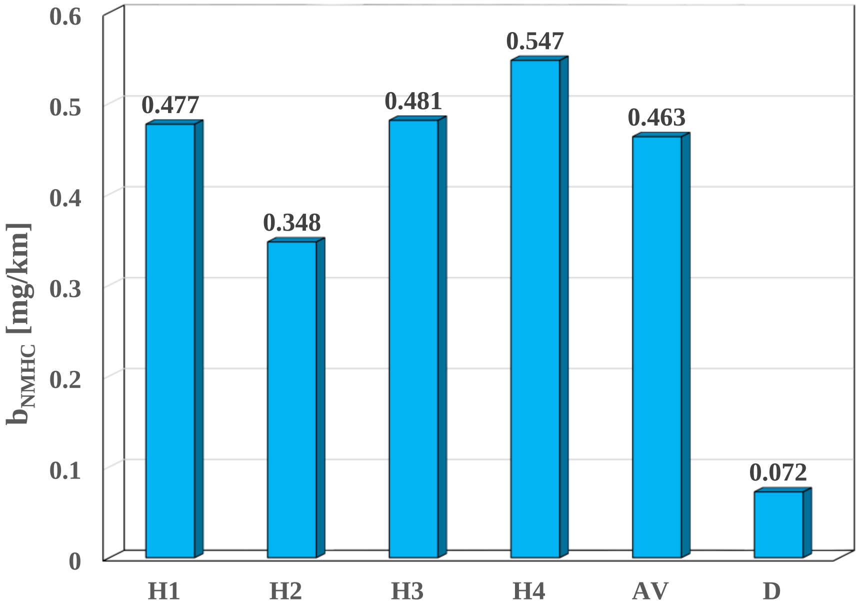

Fig. 12. Specific distance emissions of non-methane hydrocarbons – b_{NMHC} in the four WLTC tests with hot engine start – H1, H2, H3 and H4 as well as the averaged value – AV and standard deviation – D of the specific distance emission of non-methane hydrocarbons

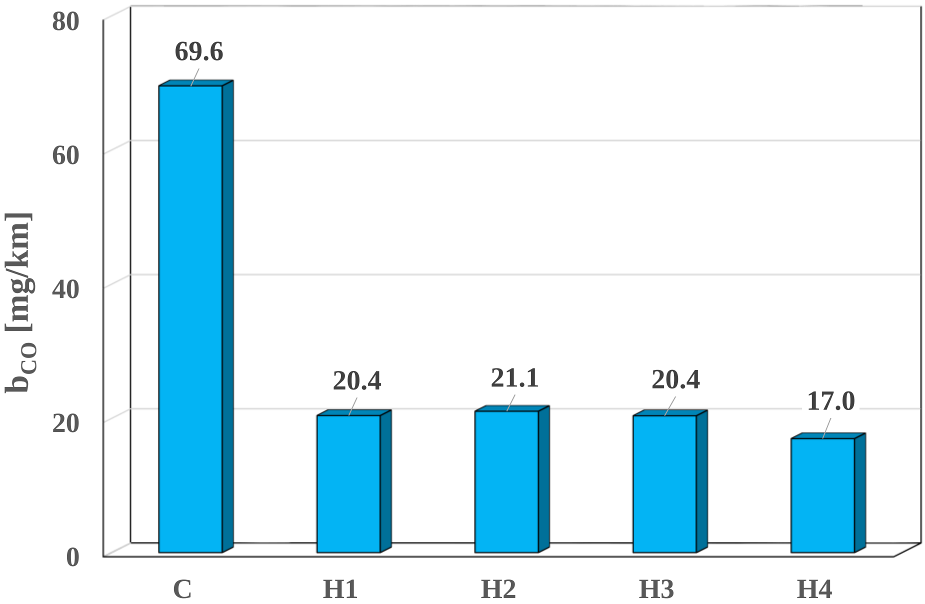

Fig. 13. Specific distance emissions of carbon monoxide – b_{CO} in the WLTC test with cold engine start – C and in four WLTC tests with hot engine start – H1, H2, H3 and H4

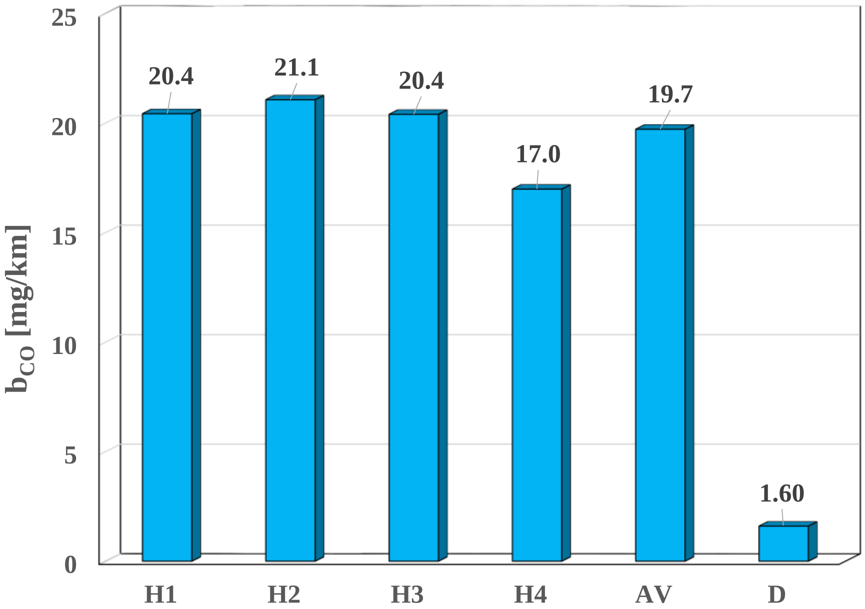

Fig. 14. Specific distance emissions of carbon monoxide – b_{CO} in the four WLTC tests with hot engine start – H1, H2, H3 and H4 as well as the averaged value – AV and standard deviation – D of the specific distance emission of carbon monoxide

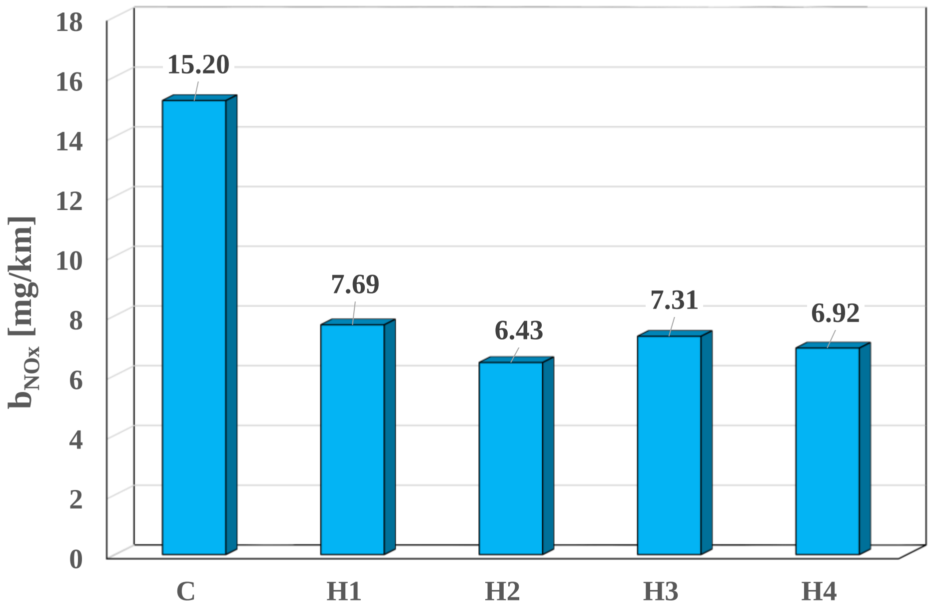

Fig. 15. Specific distance emissions of nitrogen oxides – b_{NOx} in the WLTC test with cold engine start – C and in four WLTC tests with hot engine start – H1, H2, H3 and H4

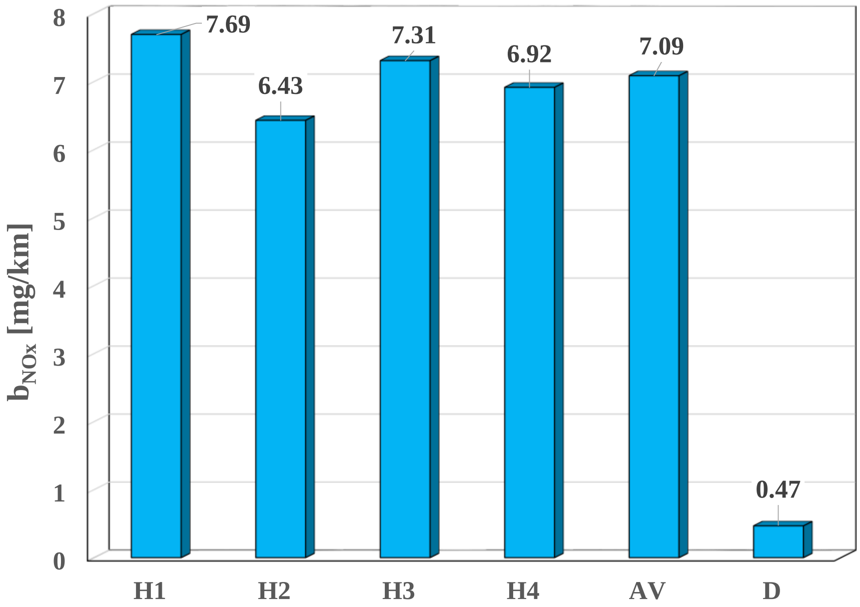

Fig. 16. Specific distance emissions of nitrogen oxides – b_{NOx} in the four WLTC tests with hot engine start – H1, H2, H3 and H4 as well as the averaged value – AV and standard deviation – D of the specific distance emission of nitrogen oxides

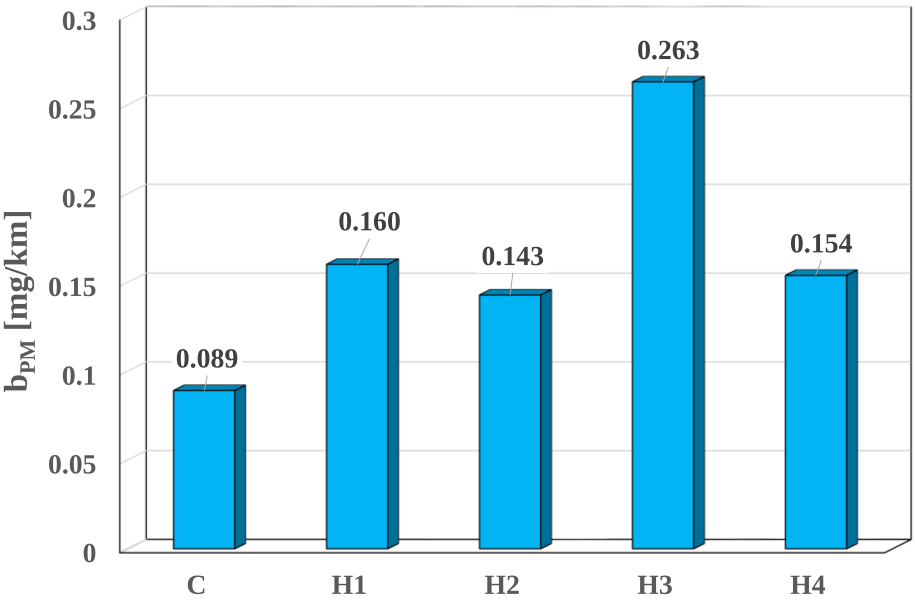

Fig. 17. Specific distance emissions of particulate matter – b_{PM} in the WLTC test with cold engine start – C and in four WLTC tests with hot engine start – H1, H2, H3 and H4

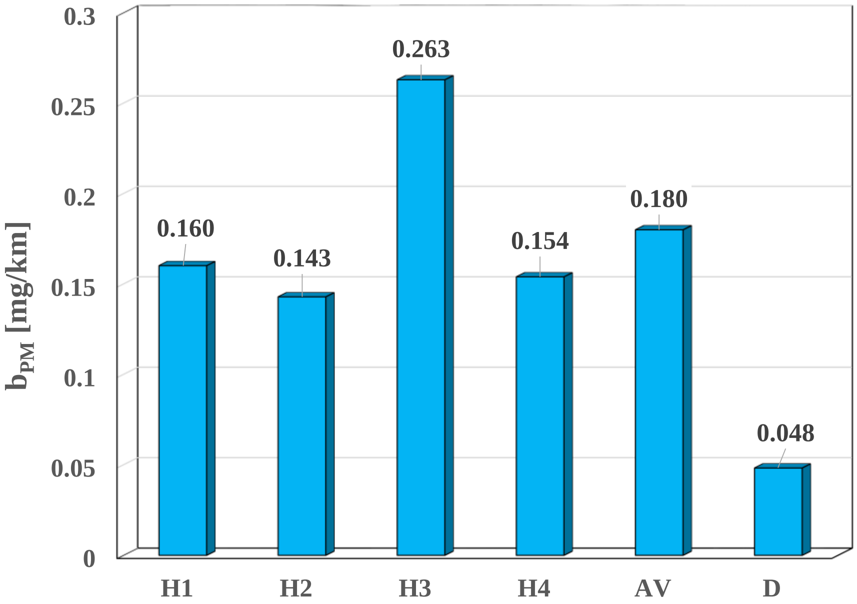

Fig. 18. Specific distance emissions of particulate matter – b_{PM} in the four WLTC tests with hot engine start – H1, H2, H3 and H4 as well as the averaged value – AV and standard deviation – D of the specific distance emission of particulate matter

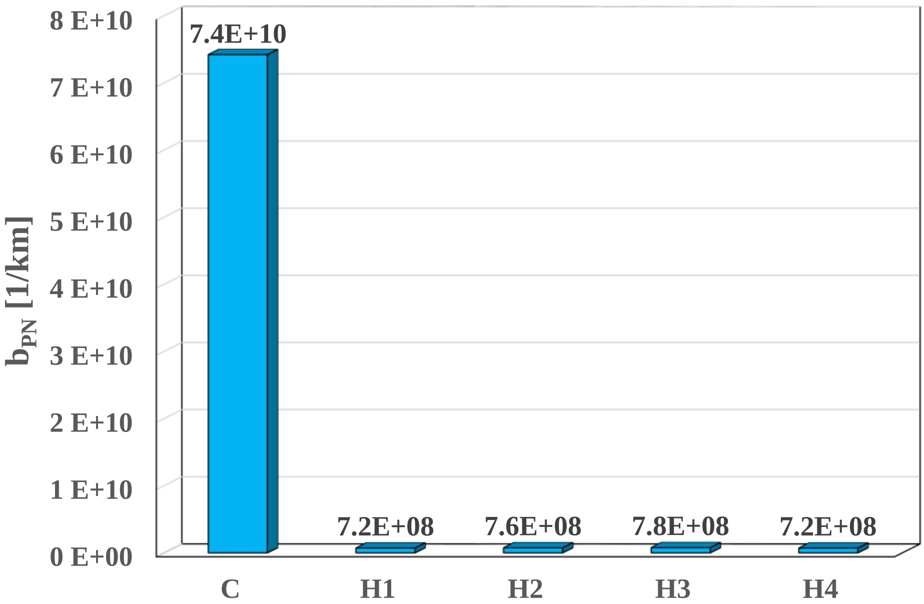

Fig. 19. Specific distance particulate number – b_{PN} in the WLTC test with cold engine start – C and in four WLTC tests with hot engine start – H1, H2, H3 and H4

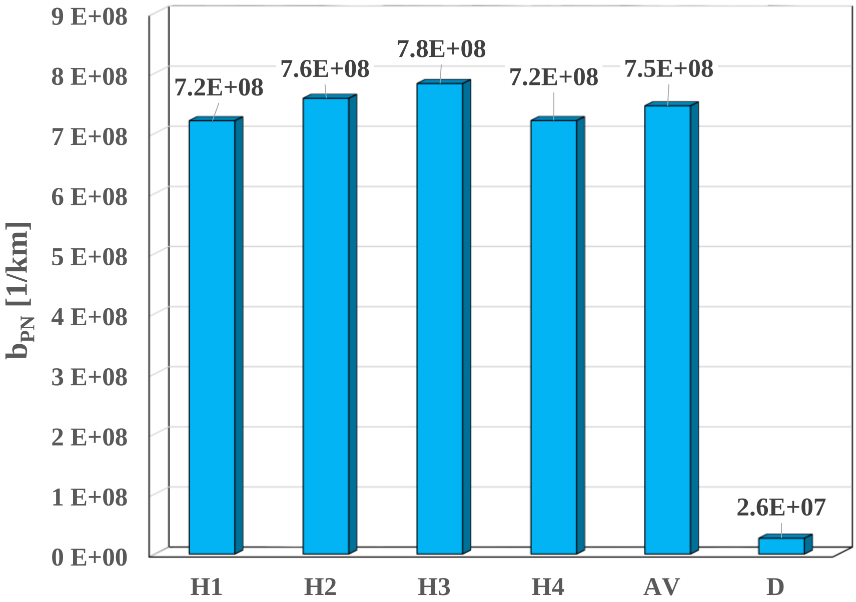

Fig. 20. Specific distance particulate number– b_{PN} in the four WLTC tests with hot engine start – H1, H2, H3 and H4 as well as the averaged value – AV and standard deviation – D of the specific distance particulate number

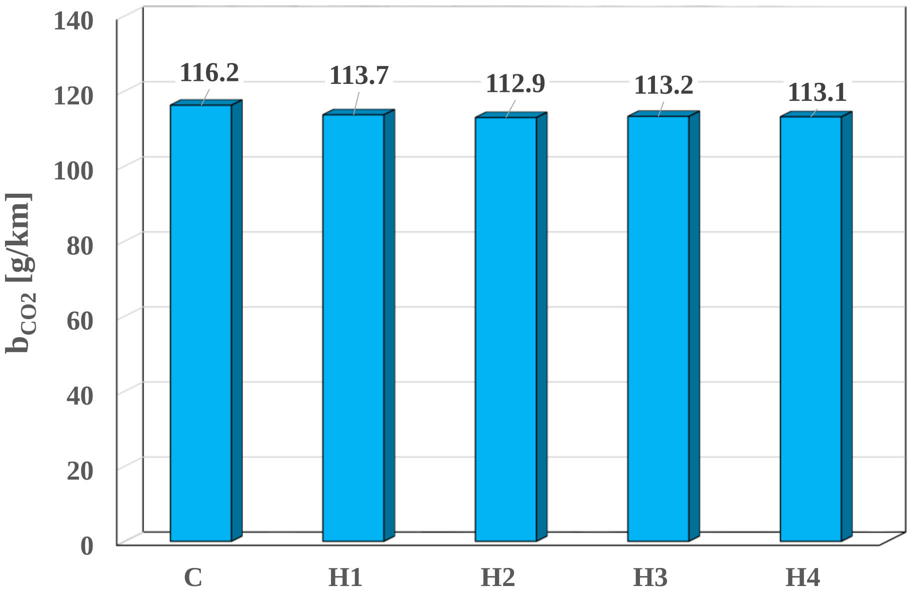

Fig. 21. Specific distance emissions of carbon dioxide – b_{CO2} in the WLTC test with cold engine start – C and in four WLTC tests with hot engine start – H1, H2, H3 and H4

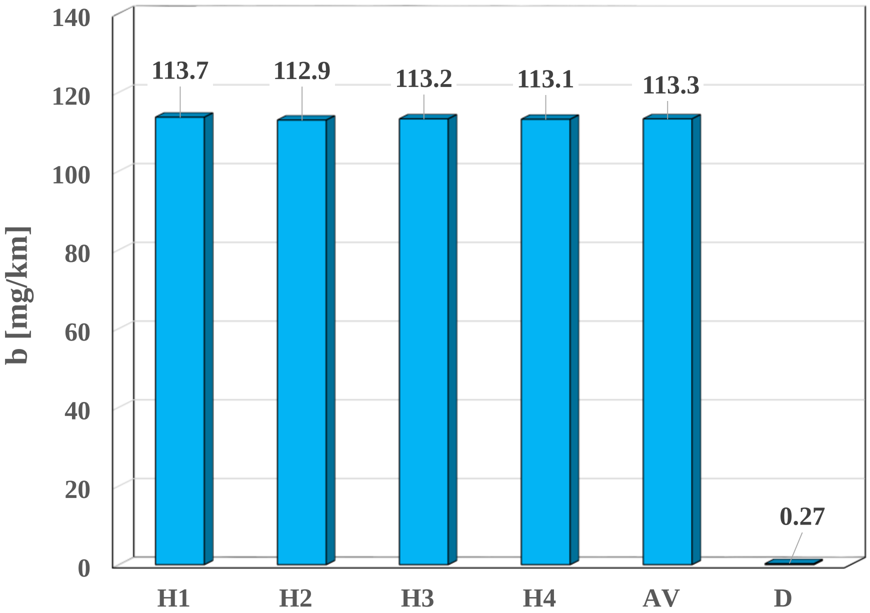

Fig. 22. Specific distance emissions of carbon dioxide – b_{CO2} in the four WLTC tests with hot engine start – H1, H2, H3 and H4 as well as the averaged value – AV and standard deviation – D of the specific distance emission of carbon dioxide

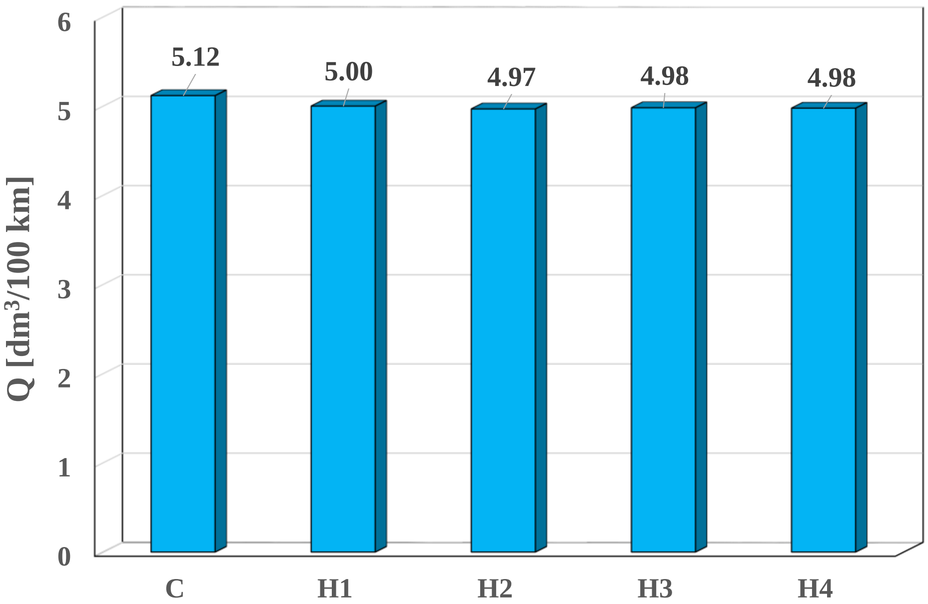

Fig. 23. Operational fuel consumption – Q in the WLTC test with cold engine start – C and in four WLTC tests with hot engine start – H1, H2, H3 and H4

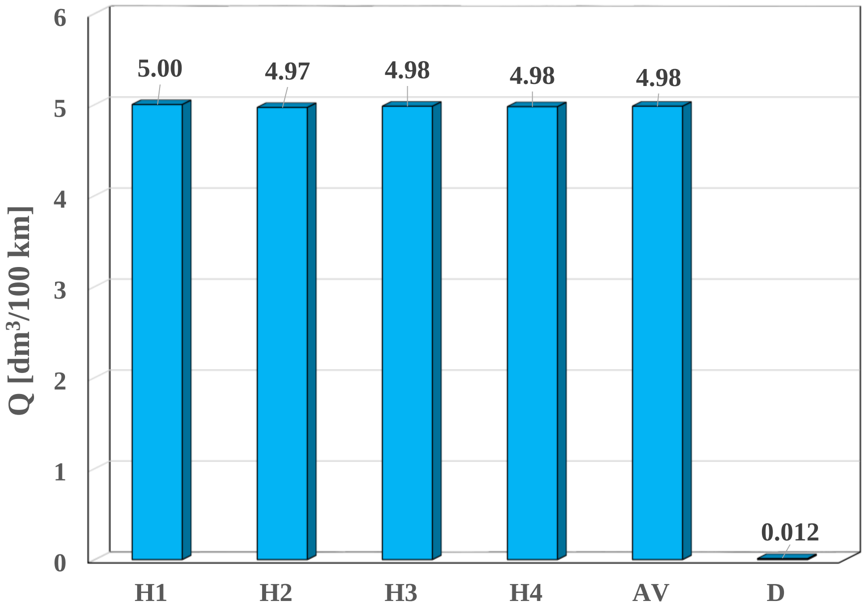

Fig. 24. Operational fuel consumption – b in the four WLTC tests with hot engine start – H1, H2, H3 and H4 as well as the averaged value – AV and standard deviation – D of the operational fuel consumption

Figure 25 shows a comparison of the coefficients of variation of specific distance emissions, the specific distance particulate number, and the operational fuel consumption in the four WLTC tests with a hot engine start.

The lowest repeatability was observed for specific distance emissions of particulate matter – the coefficient of variation was greater than 0.26. The measurements of specific distance carbon dioxide emissions and operational fuel consumption had the highest repeatability – the coefficient of variation was approximately 0.002. The average value of the coefficient of variation of test results for all values was approximately 0.088.

Figure 26 shows the ratio of the extreme measurement result values in the test with cold engine start and the average measurement result values in the tests with hot engine start.

The highest calculated value of the ratio between the maximum and minimum values measured in the test with a cold engine start and from the average value of measurement results for the hot engine start was found for the for specific distance emission of particulate matter – it was over 0.66, the lowest value – for specific distance emission of carbon dioxide and operational fuel consumption was about 0.006. The average values of this ratio of minimum and maximum measured values for both cold and hot engine starts was approximately 0.23.

Figure 27 is a logarithmic scale graph where the ratio of the fringe measurement results of specific distance exhaust emissions, the specific distance particulate number and operational fuel consumption for the cold and hot engine start was presented.

The ratio between highest and lowest value results for the cold engine start and the average value for hot engine start reached its highest value for the measurement data of specific distance particulate number – where it was almost 100, followed by organic compounds: hydrocarbons – about 13 and non-methane hydrocarbons – about 26. However, in the case of for specific distance particulate emissions, the result obtained for a cold engine start were lower than the result for a hot engine start – the ratio was approximately 0.5. The average value of the measurement results ratio obtained for a cold engine start and the average value of 4 results for hot engine start, along with variability of test results for all values was approximately 18.3.

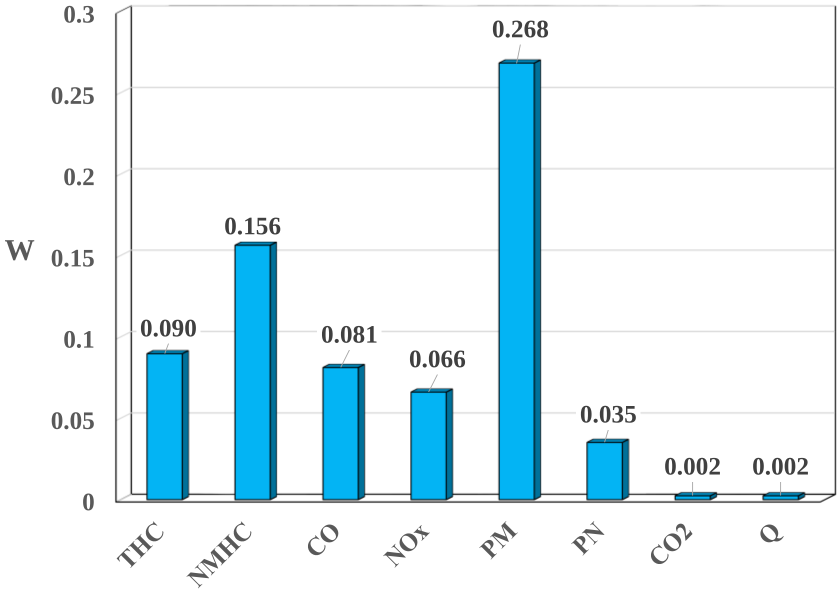

Fig. 25. Coefficient of variation – W for specific distance emissions of hydrocarbons – THC, non-methane hydrocarbons – NMHC, carbon monoxide – CO, nitrogen oxides – NO_x, particulate matter – PM and carbon dioxide – CO_2, as well as the particulate number – PN and operational fuel consumption – Q

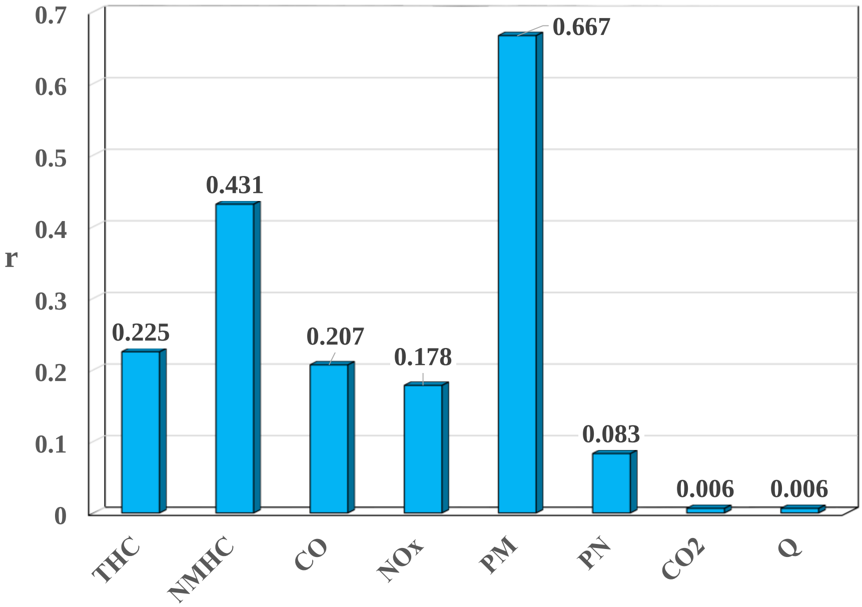

Fig. 26. Ratio of minimum and maximum values of the measured parameters – r in the cold engine start test as well as the average of the tests with hot engine start

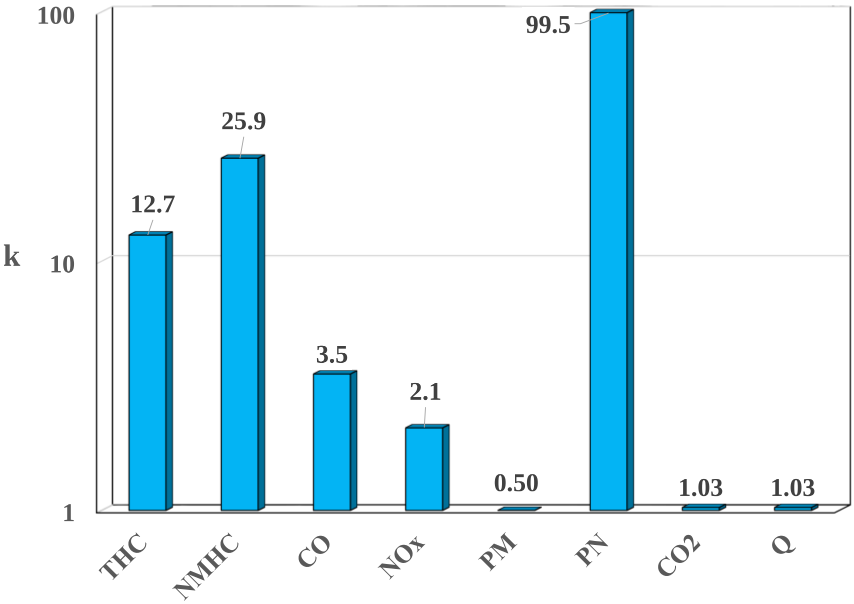

Fig. 27. Ratio of measurement results for tests with a cold engine start and the average value of test results for hot engine start – k

5. Conclusions

The following conclusions could be drawn from all obtained results:

1. The repeatability of test results varies greatly for the considered parameters measured. Specific distance carbon dioxide emissions and operational fuel consumption were definitely the least sensitive to the thermal state of the engine in individual tests. The specific distance particulate matter emission was found to be the most responsive to the differences in the thermal state of the engine during individual tests. This was concluded using the results of both the analysis of the coefficient of variation values of the measured parameters for individual tests as well as the ratio of the maximum and minimum values of measurement results in the single test with cold engine start and the average value of the four tests with hot engine start.
   However, the specific distance particulate number was relatively unaffected by the differences between individual tests. It was less affected than the specific distance exhaust emission of other measured substances.
2. The specific distance particulate number was the most affected by the thermal state of the engine at start-up, while the specific distance carbon dioxide emission and operational fuel consumption were the least affected by the thermal state of the engine in terms of variability in measured results.

It is possible to significantly expand the scope of research on the repeatability of test results in vehicle drive tests. This could be done primarily by:

- assessment of the repeatability of the vehicle velocity in the test, because the driving velocity and its changes determine the occurring engine operating states (Chłopek & Rostowski, 2015; Chłopek & Szczepański, 2015), which in turn determine the exhaust emissions and fuel consumption,
- performing correlation studies of the repeatability of test results for specific distance exhaust emissions, the specific distance particulate number emission and operational fuel consumption, as well as for the results of vehicle velocity repeatability tests,
- carrying out extension of tests, analogous to those described in this article, performed with a cold engine start,
- assessment of the results repeatability for tests in individual test phases, which differ significantly in the characteristics of the vehicle velocity, primarily for the maximum and average values,
- repeatability assessment for the emission intensity results for hydrocarbons, non-methane hydrocarbons, carbon monoxide, nitrogen oxides and carbon dioxide, the particulate number and the engine fuel consumption,
- repeatability assessment for the exhaust emission results and fuel consumption in tests other than WLTC and in real vehicle driving conditions, in particular in the RDE (Real Driving Emissions) test (Andrych-Zalewska, 2023; DieselNet 2021; Hopwood & Shalders, 2020; Shreekrushna, 2019; Worldwide emission standards 2020/2021 & 2022/2023).

The results of assessing the repeatability of test results obtained in the WLTP indicated the advisability of performing at least several tests and averaging the test results.

Nomenclature

a	– acceleration
AV	– average value
C	– test with a cold engine start
CO	– carbon monoxide
CO_2	– carbon dioxide
CVS	– Constant Volume Sampler
D	– standard deviation
ECE	– Economic Commission for Europe
EGR	– Exhaust Gas Recirculation
EHPh	– Extra High Phase
ETC	– European Transient Cycle
EU	– European Union
F	– some operator
FTP	– Federal Test Procedure
G	– exhaust emission intensity, particulate number intensity and intensity of fuel consumption of the engine
H1	– 1. test with a hot engine start,
H2	– 2. test with a hot engine start,
H3	– 3. test with a hot engine start,
H4	– 4. test with a hot engine start,
HDDTT	– Heavy Duty Diesel Transient Test
HPh	– High Phase
k	– the ratio of measurement results for the cold engine start and the average value of

average value of measurement results for the hot engine start
L – road distance in phase
LPh – Low Phase
Max – maximum value
M_e – engine torque
Min – minimum value
Mod – absolute value
MPh – Medium Phase
n – engine speed
N_2O – nitrous oxide
NEDC – New European Driving Cycle
NH_3 – ammonia
NMHC – non-methane hydrocarbons
NO_x – nitrogen oxides
PM – particulate matter
PN – particulate number
Q – operational fuel consumption
R – some operator
r – the ratio of maximum and minimum value results for the cold engine start and the measurement results for the hot engine start
R&R – Repeatability and Reproducibility
RDE – Real Driving Emissions
S – some operator
t – phase time duration
t – time
T –WLTC test duration
THC – total hydrocarbons
TS – engine thermal state
v – velocity
v_{AV} – average vehicle
W – coefficient of variation
WLTC – Worldwide harmonized Light vehicles Test Cycle
WLTP – Worldwide harmonized Light vehicles Test Procedure

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