Article citation info:
Wojciechowski H, Merkisz J. Results repeatability evaluation of exhaust emission data obtained in laboratory WLTC test conditions using stationary and PEMS analysers. Combustion Engines. 0000;XXX(X):xx-xx. https://doi.org/10.19206/CE-208399

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Results repeatability evaluation of exhaust emission data obtained in laboratory WLTC test conditions using stationary and PEMS analysers

ARTICLE INFO

Received: 10 June 2025
Revised: 4 July 2025
Accepted: 18 July 2025
Available online: 2 August 2025

The article presents an assessment of the repeatability of exhaust emission results in the WLTC test using two types of measurement systems: stationary laboratory analysers and a PEMS. The tests were conducted in laboratory conditions at BOSMAL Institute of Automotive Research and Development on a passenger car with a gasoline engine on a chassis dynamometer. The assessment included CO_2, CO, NO_x, THC emissions, and the particle number in each phase of the WLTC test and in the entire test. The coefficient of variation was used to assess the repeatability. The results showed greater repeatability of measurements in the case of laboratory analysers, especially for CO_2 and CO. The PEMS system showed greater variability, especially in the dynamic test phases. Despite this, the results validation confirmed the compliance of the PEMS system with regulatory requirements. The article emphasizes the importance of the precision of exhaust emission tests in the context of measurement technologies development and the implementation of more restrictive emission standards, and it indicates CO_2 as the most stable parameter for both systems.

Key words: *WLTC, PEMS, exhaust emissions, repeatability, analysers*

1. Introduction

Modern exhaust emission regulations require vehicle manufacturers to monitor the emissions more and more precisely in various operating conditions. Consequently, precise measurement and analysis of vehicle exhaust emissions are increasingly crucial in the context of reducing the negative impact of motorization on the environment. In addition to classic homologation tests on chassis dynamometers, emission tests in real conditions (RDE) are becoming increasingly important, carried out using smaller devices collectively classified as PEMS. Due to various environmental, operational, and hardware factors, these systems may show greater variability of measurement results compared to their stationary laboratory analyser counterparts. The aim of this article is to assess the repeatability of exhaust emission measurement results obtained in the WLTC test, performed using both of the above-mentioned measurement systems, with particular emphasis placed on the statistical analysis of the coefficient of variation. The issue of exhaust emission test results repeatability has been addressed in numerous research works, although it is still an area with a limited number of empirical analyses. Chłopek and Rostkowski [7] emphasized the importance of formalizing the repeatability assessment of combustion engines operating properties, including exhaust emissions. Studies have shown that CO and NO_x emission measurements are highly sensitive to random disturbances, which translates into difficulties in obtaining stable results. Jaworski et al. [13] conducted an emissions repeatability analysis in cold and hot engine start conditions in the NEDC test. The results confirmed the validity of using the coefficient of variation (CV) as an assessment tool for measuring reliability. Andrych-Zalewska et al. [2–4] focused on emission tests in dynamic conditions and in the RDE test. Their works emphasize the influence of engine operating states (e.g. torque, temperature) on the exhaust emission level, also paying attention to the differences resulting from the test methodology. One of the newer publications [2] analysed emission data from a full WLTC cycle and proposed methods for assessing the measurement data variability. The article by Merkisz et al. [14] is also particularly important, as it directly concerns the repeatability of WLTP test results. In this work, additional indicators were used besides CV (r – the ratio of extreme values to the mean and k – the cold/hot ratio), which allow for a broader interpretation of data variability.

The literature review shows that while the coefficient of variation remains the basic statistical measure of emissions repeatability, it is also important to take into account the environmental conditions, the thermal state of the engine, and the phase of the driving cycle in which the measurement was made.

2. Test method

The tests were carried out at the BOSMAL Automotive Research and Development Institute on the AVL Zoellner 48” Compact chassis dynamometer in laboratory no. 1 (Fig. 1). The dynamometer was fully integrated with the laboratory management system (AVL iGEM). The system was controlled by software that allowed not only to carry out exhaust emission tests in accordance with international test cycles (such as European cycles: WLTC, RTS95 – RDE, NEDC, WMTC; American: FTP-75, HWFET, US06; and the former Japanese cycle: JC08), but also allowed for measuring engine power in both static and dynamic conditions [6]. The laboratory system used the method of analysing diluted gases using the CVS system, collected in measuring bags, while the PEMS system recorded the emission of undiluted gases in real time. The coefficient of variation (CV), calculated separately for each phase of the cycle and the entire test, was used to assess repeatability. Each vehicle test that involves using portable exhaust measuring systems (PEMS) must be preceded by validation performed on a chassis dynamometer. The validation procedure is used to verify the correct installation and operation of the device. The PEMS system has been subjected to a validation procedure in accordance with Commission Regulation (EU) 2017/1151 and 2023/443 [9–12].

The air conditioning system in laboratory No. 1 enabled the following functions [1]:
- Temperature control in the range from +14°C to +28°C
- Maintaining a stable temperature during tests with an accuracy of ±2.0°C
- Regulating the humidity level from 5.5 to 12.2 grams of water per kilogram of dry air at temperatures between +14°C and +28°C
- Maintaining the target relative humidity with an accuracy of ±5% during tests.

The tests were conducted on a chassis dynamometer in accordance with the WLTP cycle procedures. The WLTP procedure has been used in Europe since September 2017, replacing the older NEDC cycle. As with the NEDC and EPA, the WLTP test is conducted in a laboratory setting. However, the WLTP cycle (Fig. 2) is divided into four parts, which correspond to different speed ranges: low, medium, high, and very high. The entire test lasts 30 minutes and covers 23.25 km of distance. The test route is a combination of urban and motorway conditions – 52% being city driving and 48% being on the motorway. The average test speed is 46.5 km/h, and the maximum speed is 131 km/h [5]. Unlike the NEDC, the WLTP test considers different vehicle equipment levels and tire and wheel configurations. The tire/wheel combination has an impact on the fuel consumption and vehicle range, as it changes the aerodynamics and increases the unsprung mass, depending on the wheel and tire size.

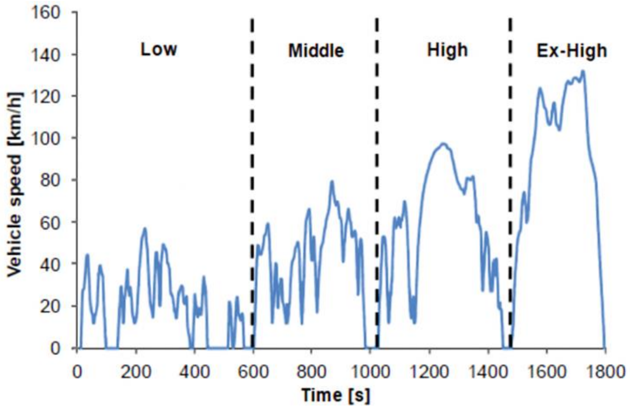

Fig. 2. The WLTP test cycle [5]

The vehicle used for the tests was a Skoda Scala with a 1.0 TSI petrol engine (Euro 6), equipped with a 5-speed manual gearbox. Emissions were measured simultaneously using a stationary laboratory system and PEMS. The test was performed five times by one experienced driver. Before each test, the car was thermally stabilized at a temperature of 21°C, as outlined by the regulations.

Table 1. Data of the vehicle used in the study

Vehicle designation	Car
Brand	Skoda
Model	Scala
Fuel type	Petrol
Engine type	TSI
Engine displacement [dm^3]	1
Power [kW]	81
Transmission	Manual 5-speed
Emission standard	Euro 6
Vehicle mileage [km]	7208

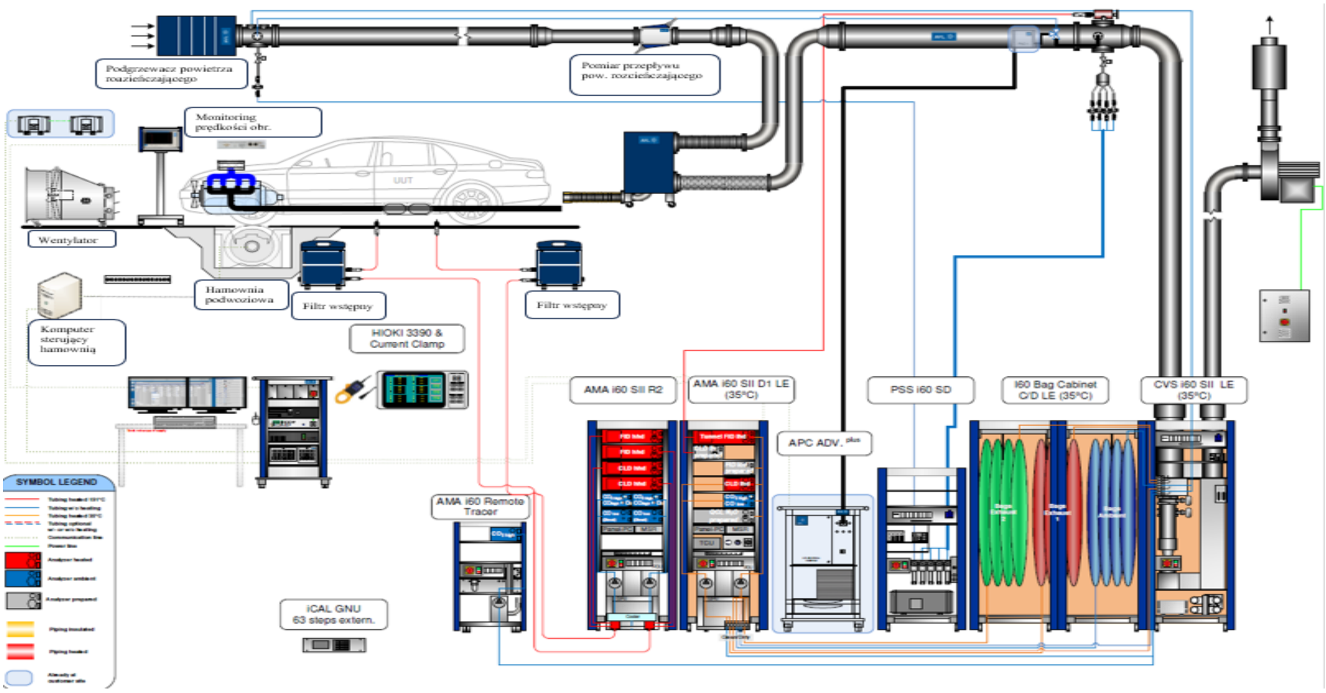

Fig. 1. Laboratory 1 equipment and setup schematic [1]

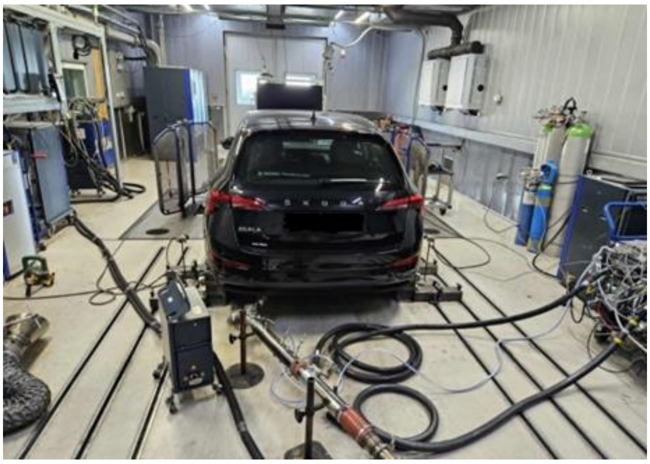

Fig. 3. The test vehicle during testing on the chassis dynamometer in the laboratory

To assess the repeatability of emission results, a detailed statistical analysis was performed. For each phase of the WLTC test, i.e. LOW, MIDDLE, HIGH, Ex-HIGH and the entire WLTC cycle, the arithmetic mean, standard deviation and coefficient of variation (CV) [15] were determined. The arithmetic mean was used to determine the typical emission level in each test phase, while the standard deviation was used to assess the dispersion of the results around the mean, indicating the stability of the measurements.

The main assessment method relied on the coefficient of variation (CV), which was calculated according to the formula:

$$CV = \frac{\sigma}{\mu} \cdot 100\ [\%] \qquad (1)$$

where: σ – is the standard deviation, and μ is the arithmetic mean for a given phase; CV – shows the relative variability of the data, regardless of the mean emission scale, which allows for results repeatability comparison in phases with significantly different emission levels.

To assess the repeatability of measurement results in detail, a percentage-based classification of the coefficient of variation (CV) was used, in accordance with recommendations from statistical and technical literature [8, 14, 15].

- CV < 25% – Low variability (very good repeatability): Results are stable, and the data is distributed relatively close to the mean value
- 25% ≤ CV < 45% – Moderate variability (moderate repeatability): Data points show a moderate amount of scatter but are still acceptable in most cases
- 45% ≤ CV < 100% – Higher variability (low repeatability): Results are very widely distributed, requiring further analysis to identify sources of instability
- CV ≥ 100% – Very high variability (very low repeatability): Results are extremely widely distributed and should not be considered reliable without further verification.

3. Results

3.1. Repeatability of the stationary laboratory measurement results

Figures 4–8 show the results of THC, CO, NO_x, particle number (PN), CO_2, emission measurements obtained using stationary laboratory analysers. The graphs show the mean emission values and the corresponding coefficients of variation (CV) in the individual phases of the WLTC as well as overall values for the entire test.

Based on the analysis conducted using laboratory analyzers, it can be concluded that hydrocarbon emissions exhibit very good repeatability in all phases of the WLTC cycle. The coefficient of variation (CV) did not exceed 25% in any phase of the test.

In the analysis of carbon monoxide (CO) emissions, the coefficient of variation was lowest in the LOW phase (4.81%), confirming very good measurement repeatability, while the highest value (17.36%) was observed in the Ex-HIGH phase. For the entire test, the CV was 5.93%, which indicates very good repeatability overall (Fig. 5).

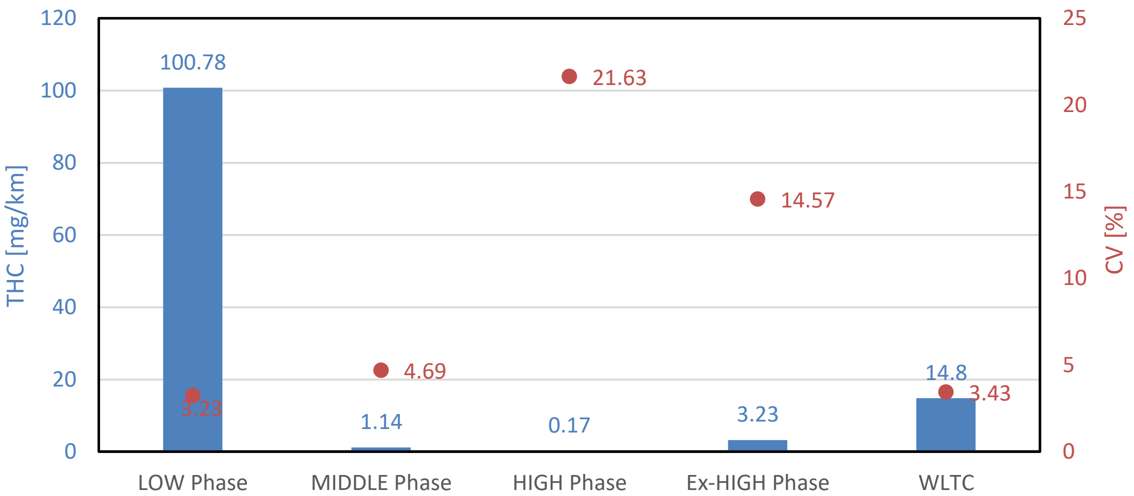

Fig. 4. Mean results of road emission of hydrocarbons with coefficient of variation in WLTC tests measured using stationary laboratory analysers

In the conducted analysis of nitrogen oxides (NO_x) emissions, the LOW phase showed the highest measurement stability, confirmed by a coefficient of variation (CV) of 1.77%, which indicates very good repeatability. This phase demonstrated the lowest data dispersion, making it the most reliable in terms of data quality. NO_x variability exceeded 25% in the HIGH (31.13%) and Ex-HIGH (27.91%) phases, which classifies them as having good repeatability. These results are consistent with the findings of Merkisz et al. [14], where dynamic WLTC phases led to increased NO_x dispersion – Fig. 6.

PN emission were characterized by very good repeatability in the LOW, MIDDLE, Ex-HIGH phases and the entire test, where the coefficient of variation did not exceed 25%. In contrast, the HIGH phase showed a CV of 43.58%, which, according to the adopted scale, places this result at the upper limit of good repeatability – Fig. 7. Increased variability is typical for this phase, especially under sudden load changes, as also noted in study [4].

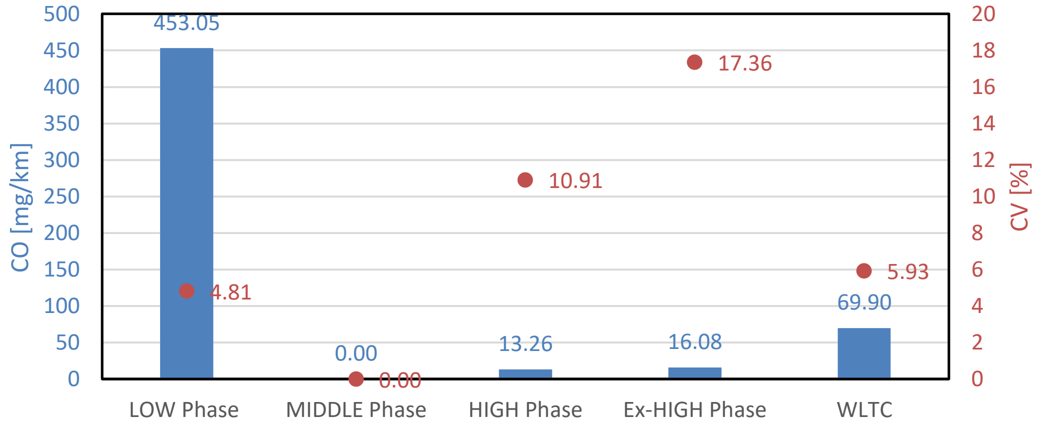

Fig. 5. Mean results of road emission of carbon monoxide with coefficient of variation in WLTC tests measured using stationary laboratory analysers

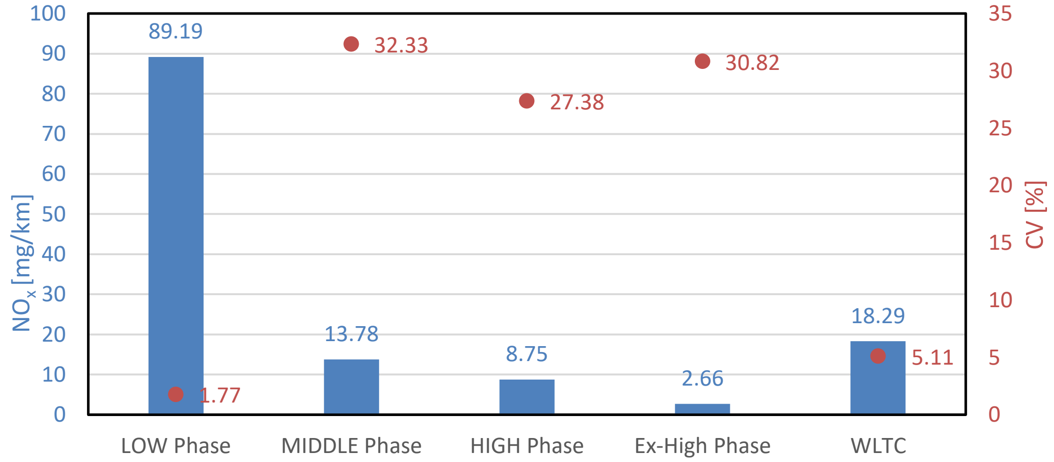

Fig. 6. Mean results of road emission of nitrogen oxides with coefficient of variation in WLTC tests measured using stationary laboratory analysers

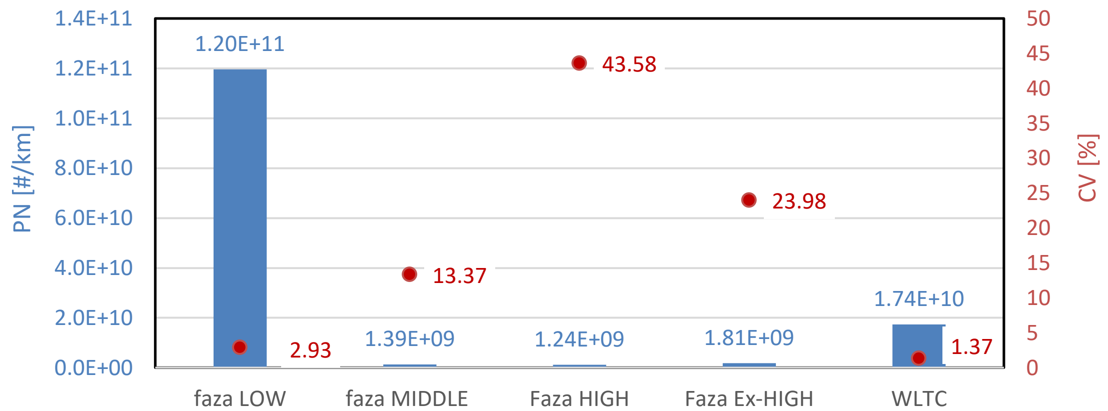

Fig. 7. Mean results of road emission of particle number with coefficient of variation in WLTC tests measured using stationary laboratory analysers

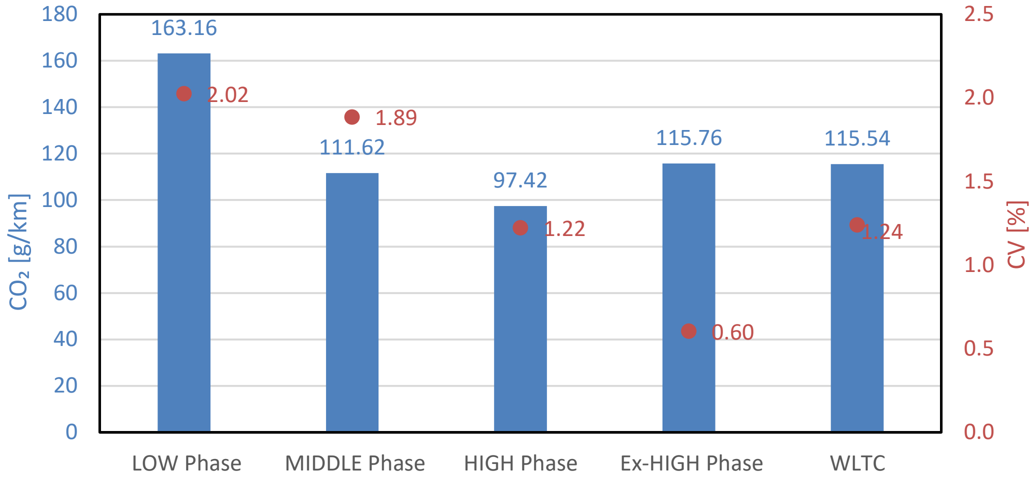

Fig. 8. Mean results of road emission of carbon dioxide with coefficient of variation in WLTC tests measured using stationary laboratory analysers

CO_2 emission demonstrated very good repeatability – CV did not exceed 2% in any phase, reaching a minimum of 0.42% in the LOW phase. This result aligns with the literature [14], where CO_2 was the least variable among all measured exhaust components. Such stable outcomes indicate high measurement quality for stationary CO_2 analyzers (Fig. 8).

Measurements performed at the laboratory using stationary laboratory analysers showed high emission results repeatability for most of the tested substances. The most stable was the CO_2 emission, for which the coefficient of variation (CV) did not exceed 2% in all WLTC phases. THC and CO emissions were also characterized by very good repeatability – in the entire cycle, CV values were 3.43% and 5.93%, respectively. NO_x emission was well repeatable in the LOW and MIDDLE phases of the test, while in the HIGH and Ex-HIGH phases the variability was notably increased (CV above 27%). The greatest variability was obtained for PN emissions – especially in the HIGH phase (CV = 43.58%), which indicates measurement difficulties related to the dynamic operation of the engine. However, for the entire WLTC cycle, CV values for PN and NO_x remained low, confirming generally very good repeatability of measurements.

3.2. Repeatability of the PEMS exhaust measurement results

Figures 9–12 present the test result data obtained using PEMS in a laboratory setting. These results show the mean emission levels and CV factors for all tested exhaust components in the four test phases of the WLTC as well as overall results for the entire test.

The hydrocarbon emission results obtained using the PEMS system indicate a very good level of repeatability across all phases of the WLTC test. The highest result stability was observed in the LOW phase, where the coefficient of variation reached 4.25%. In the HIGH phase, the CV value reached 20.48%, which still falls within the very good repeatability category, although the data already show a higher degree of variability.

Among the analyzed CO results, the highest measurement stability was observed in the LOW phase, where the coefficient of variation was 5.34%. In the MIDDLE and Ex-HIGH phases, CV values exceeded 25%, indicating good repeatability in these parts of the test. For the entire WLTC cycle, a CV of 8.59% was obtained, confirming very good overall repeatability of the results.

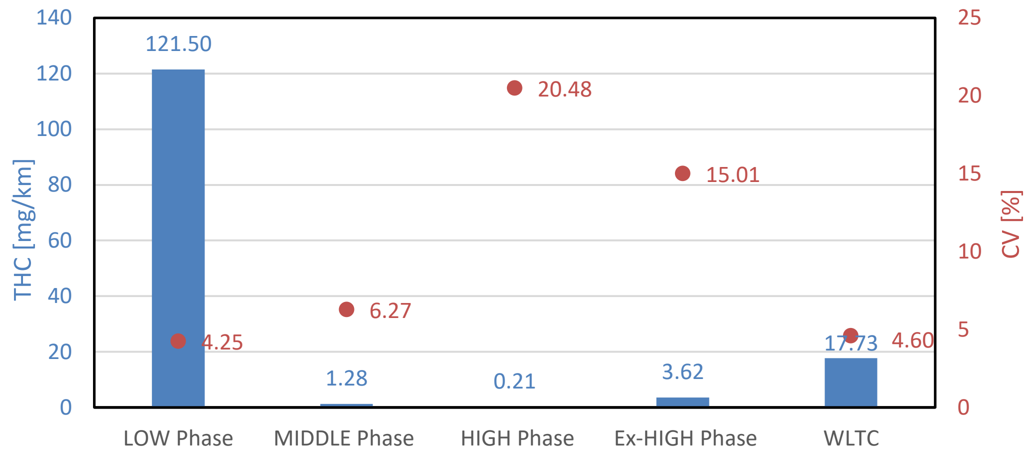

Fig. 9. Mean results of road emission of hydrocarbons with coefficient of variation in WLTC tests measured using PEMS

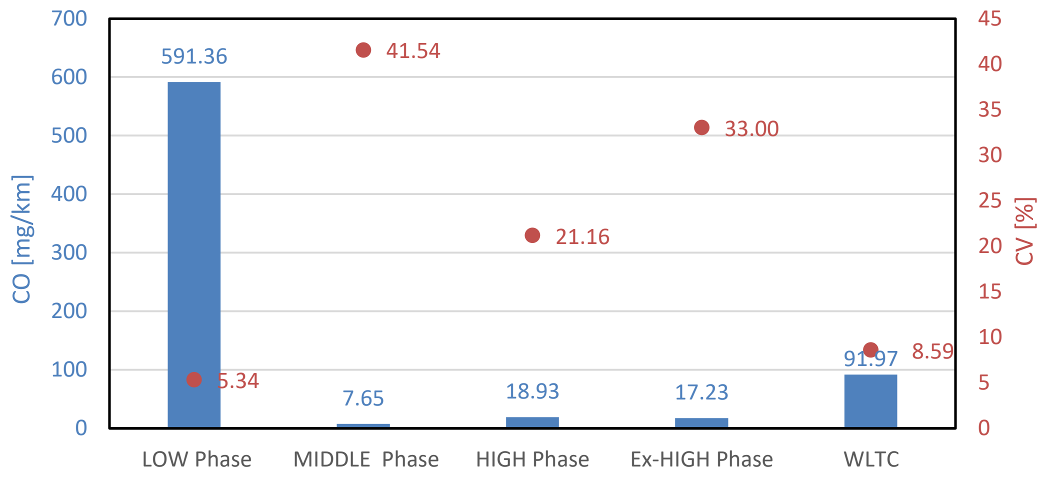

Fig. 10. Mean results of road emission of carbon monoxide with coefficient of variation in WLTC tests measured using PEMS

Nitrogen oxides (NO_x) emission measured using the PEMS system shows differences in repeatability levels depending on the WLTC phase. The most repeatable results were observed in the LOW phase, where the coefficient of variation (CV) was 2.62%. NO_x variability was noticeable in the Ex-HIGH phase (CV = 36.22%) and HIGH phase (29.87%), which indicates good repeatability. These results are consistent with similar studies [14], which indicated increased NO_x scatter in dynamic phases of WLTC, and with [7], where NO_x was shown to be highly sensitive to random disturbances in engine operating conditions.

The distribution of road PN emission results across individual WLTC phases shows clear differences in variability levels. The lowest coefficient of variation (CV), and thus the highest measurement repeatability, was observed in the LOW phase, where CV was 7.34%. In the MIDDLE phase, the CV reached 18.15%, also indicating very good repeatability. The highest data dispersion was recorded in the HIGH phase, with CV reaching 56.45%, which classifies this phase as having low repeatability. The Ex-HIGH phase had a CV of 26.91%, indicating moderate repeatability. The high PN variability confirms the observations in [4], which highlight the sensitivity of this exhaust component to the dynamic nature of the test.

The CO_2 emission data across individual WLTC phases indicate very good measurement repeatability in all analyzed stages of the test. The CV for the entire cycle was 3.27%. Although slightly higher than in laboratory conditions, the results confirm high measurement quality throughout the test range. Similar behavior of CO_2 as the most stable parameter was also observed in the study [14].

PEMS measurements generally showed very good repeatability of CO_2 and THC emission results over the entire WLTC test, with CV values of 3.27% and 4.60%, respectively. The LOW and MIDDLE phases were more stable than the dynamic phases of the test cycle. For CO and NO_x emissions, a clear increase in data variability was observed in the HIGH and Ex-HIGH phases, to CV = 33.00% and CV = 36.22%, respectively. The greatest data dispersion was obtained for PN emissions, especially in the HIGH phase (CV = 56.45%). Nevertheless, for the full WLTC cycle, the coefficient of variation value for all measured exhaust components was at a level characterized by very good repeatability. The results indicate that PEMS measurements under dynamic conditions may require further optimization in terms of stability and calibration.

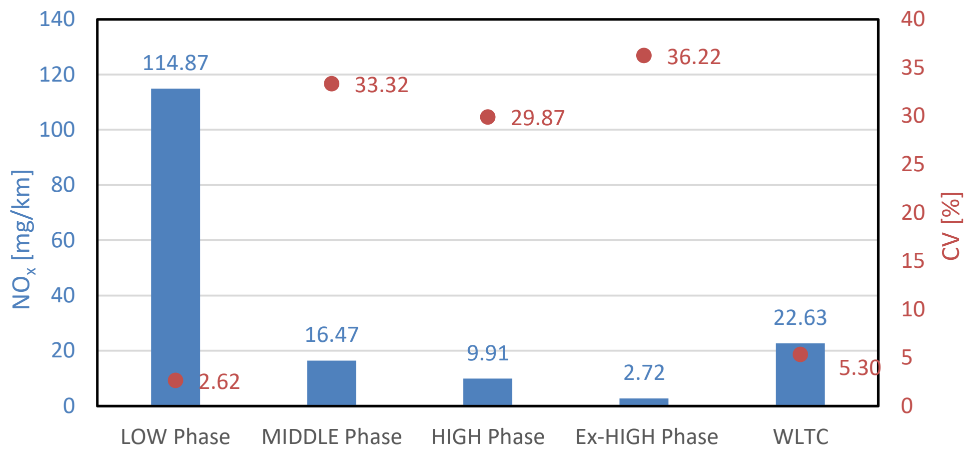

Fig. 11. Mean results of road emission of nitrogen oxides with coefficient of variation in WLTC tests measured using PEMS

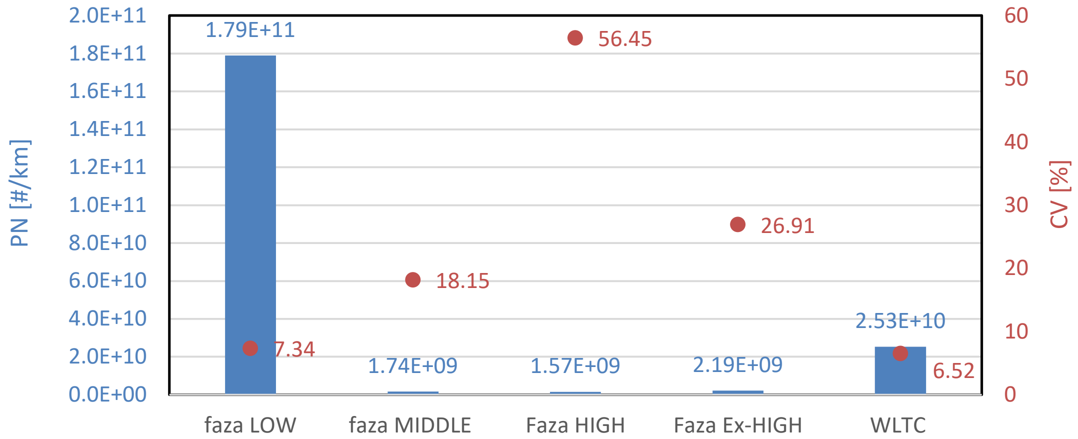

Fig. 12. Mean results of road emission of particle number with coefficient of variation in WLTC tests measured using PEMS

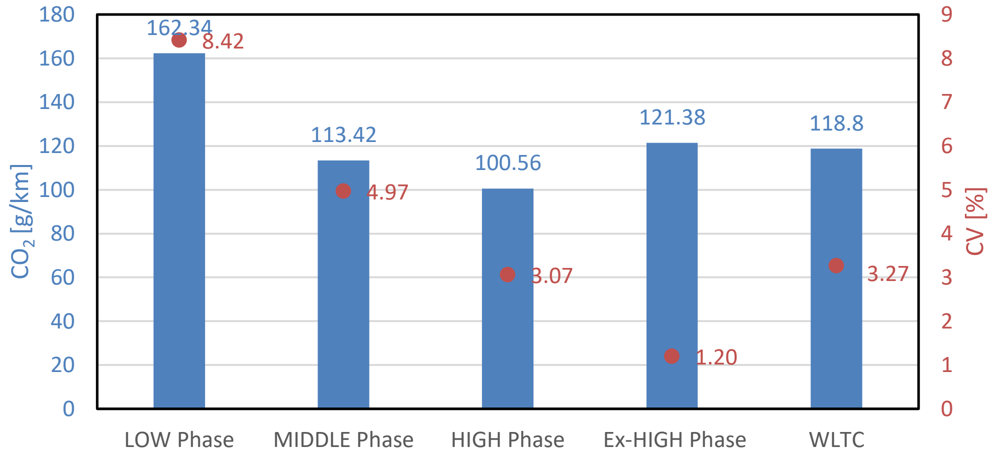

Fig. 13. Mean results of road emission of carbon dioxide with coefficient of variation in WLTC tests measured using PEMS

4. Conclusions

The conducted studies have shown that the repeatability of exhaust emission results in the WLTC test depends on both the measurement system used and the type of exhaust component analysed. Laboratory analysers generally provided higher stability of measurement results than PEMS devices, especially in dynamic test phases. CO_2 emissions were the most stable in both systems, while the greatest variability was noted for PN and NO_x emissions.

Main conclusions:

- For CO_2, CV values did not exceed 3.27% in the entire test in any of the systems used – this confirms the stability of this compound's emissions regardless of the test conditions
- THC showed very good repeatability in both systems, with slightly greater variability in the HIGH and Ex-HIGH test phases
- NO_x and CO results were more variable, especially in dynamic conditions, which indicates the sensitivity of the combustion process to variable loads and temperatures
- The greatest variability was shown by the PN emission results, reaching CV values exceeding 50% in the HIGH phase for the PEMS measurement
- The dynamic phases of the WLTC influenced the increase in the coefficient of variation, which suggests the need for further development of validation procedures and measurement technology for these test conditions
- Validation of the results showed that the absolute and relative differences for all analysed components were within acceptable limits. Despite the higher variability of the results, the PEMS measurements met the validation criteria set out in the EU regulations, which confirms its usefulness in measuring emissions in road traffic.

The impact of transport on the natural environment is multifaceted, and a full assessment of this impact requires detailed analyses that take into account various operating and technological conditions. The results of the research conducted in this work constitute a significant contribution to the field of analysis of the repeatability of exhaust emission results, but they do not answer all questions related to the construction and functionality of measurement systems. Therefore, the following directions for further research were proposed:

1. Expanding comparative analyses, conducting tests on a larger number of vehicles equipped with different types of engines:
   - Compression ignition engines (Diesel)
   - Vehicles powered by alternative fuels such as LPG, CNG, or hydrogen

- Engines with different displacements, which would allow for assessing the impact of engine size on the repeatability of emission results

2. Tests in different atmospheric conditions:
   - Temperatures below 10°C and above 30°C, to determine the impact of atmospheric conditions on measurement results
   - Different levels of humidity and atmospheric pressure
3. Development of measurement technologies, development of new technological solutions that will increase the precision of mobile measurement systems in dynamic operating conditions:
   - Increasing the resistance of measurement systems to vibrations and changes in environmental conditions.
   - Improving the measurement methods for the particle number, especially in the dynamic test phases.

Nomenclature

CO	carbon monoxide
CO_2	carbon dioxide
CV	coefficient of variation
CVS	constant volume sampler
ECE	fuel consumption test in the urban driving cycle
GDI	gasoline direct injection
HDV	heavy duty vehicle
LDV	light duty vehicle
NEDC	New European Driving Cycle
NO_x	nitrogen oxides
PEMS	portable emissions measurement system
PM	particulate mass
PN	particulate number
RDE	real driving emissions
THC	total hydrocarbons
WLTC	Worldwide Harmonized Light Vehicles Test Cycles
WLTP	Worldwide Harmonized Light Vehicles Test Procedure
WMTC	World Motorcycle Test Cycle

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