Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal, 2026, 20(4), 505–517
https://doi.org/10.12913/22998624/215000
ISSN 2299-8624, License CC-BY 4.0

Received: 2025.10.28
Accepted: 2026.02.15
Published: 2026.03.01

Quantifying fuel consumption in internal combustion engine through pollutant emission analysis: Interlaboratory comparison

Borys Adamiak[1], Monika Andrych-Zalewska[2], Zdzisław Chłopek[3], Jakub Lasocki[4], Jerzy Merkisz[5*]

[1] BOSMAL Automotive Research and Development Institute Ltd. Sarni Stok 93, 43-300 Bielsko-Biała, Poland
[2] Faculty of Mechanical Engineering, Wrocław University of Science and Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wroclaw, Poland
[3] Institute of Environmental Protection – National Research Institute, National Centre for Emissions Management. Słowicza 32, 02-170 Warszawa, Poland
[4] Faculty of Automotive and Construction Machinery Engineering, Warsaw University of Technology, Narbutta 84, 02-524 Warszawa, Poland
[5] Faculty of Civil and Transport Engineering, Poznan University of Technology, Pl. M. Skłodowskiej-Curie 5, 60-965 Poznań, Poland
* Corresponding author's e-mail: jerzy.merkisz@put.poznan.pl

ABSTRACT

One of the commonly used methods for determining fuel consumption in internal combustion engines is based on the carbon mass balance. It assumes a direct relationship between the mass of fuel burned in the engine and the mass of emitted carbon-containing substances. Therefore, the accuracy and repeatability of fuel consumption results depend on the quality of measurement method used for determining pollutant emission. This paper focuses on the results of motor vehicle pollutant emissions and fuel consumption obtained in interlaboratory tests. Two different chassis dynamometer laboratories were compared, both using two measurement methods: 1) analysis of the concentrations of diluted exhaust components collected in bags, 2) continuous analysis of the emission intensity of diluted exhaust components. The tests were conducted in the Worldwide harmonized light vehicle test cycle using a passenger car with a spark-ignition engine. Significant differences were observed in the results obtained in two laboratories. The average specific distance emission of particle mass had the highest non-repeatability, whereas the specific distance emission of hydrocarbons and carbon dioxide had the lowest. The latter led to high repeatability in fuel consumption as determined by the carbon mass balance method, particularly in the case of the method that measured the concentrations of exhaust gases collected in bags.

Keywords: exhaust emission, fuel consumption, carbon balance, interlaboratory tests, results repeatability.

INTRODUCTION

The ever-increasing number of vehicles, both for the transportation of people and goods, in private or commercial ownership, contribute significantly to the overall levels of airborne pollutants in the atmosphere. Concerns about global warming and public health are driving researchers to explore innovative methods for effectively controlling vehicle emissions [1]. At the same time, the issue of pollutant emission is inextricably linked to fuel consumption: an obvious relationship indicates that the more fuel is burned, the more exhaust gases are released into the environment [2]. For this reason, most developed countries in the world have established or proposed limits for light- and heavy-duty vehicles in terms of fuel consumption or, alternatively, measures closely related to it, such as carbon dioxide (CO_2) emission or greenhouse gas (GHG) emission in general [3]. It is estimated that these limits currently apply to automotive markets where more than 85% of passenger cars are sold globally [4]. Meeting both current and upcoming vehicle fuel consumption and emission standards presents major challenges, as these regulations are becoming increasingly stringent.

Therefore, closely monitoring fuel consumption and pollutant emission from vehicles is essential. However, vehicles and their engines, due to their complexity, require advanced testing methods, using equipment that closely controls test conditions and is capable of measuring small concentrations of pollutants in the exhaust gases. Tests are usually carried out on an engine dynamometer or a chassis dynamometer, with the first variant used for engines only, and the second for entire vehicles. Light vehicle engines, i.e. passenger cars and light commercial vehicles, are tested in the vast majority of cases on a chassis dynamometer. This corresponds to the classification of test methods in the legal regulations on homologation. On a chassis dynamometer, vehicles are tested using driving cycles, such as Worldwide Harmonized Light Vehicles Test Cycles (WLTC) and New European Driving Cycle (NEDC), which represent a standardized course of vehicle velocity over time [5]. In recent decades, a very rich literature has been published on this subject, which allows for wide access to test results.

Lv et al. [6] utilized a chassis dynamometer to examine the emission characteristics of two gasoline vehicles, one meeting Euro 5 standards and the other Euro 6, using six different fuel types. The findings revealed significant variations in engine performance between the two vehicles under identical test conditions, which influenced their emission profiles. Both fuel consumption and exhaust emission factors were found to be greater in the WLTC cycle compared to the NEDC cycle. The research octane number (RON) and ethanol content in the fuels had a considerable impact on pollutant emission. For the Euro 5 vehicle, greater RONs resulted in smaller carbon monoxide emission (CO) and particle number (PN), as well as a decrease in nitrogen oxides (NO_x) emission during the WLTC cycle. Conversely, for the Euro 6 vehicle, increasing RON led to reductions in CO and NO_x emission but an increase in PN number. When compared to standard gasoline, ethanol-gasoline blends (E10) reduced NO_x emission and PN number but increased CO emission in the Euro 5 vehicle. For the Euro 6 vehicle, E10 resulted in greater PN number and NO_x emission but smaller CO emission. Furthermore, particles number emission were primarily in the nucleation mode, with size distribution peaks at approximately 18 nm and 40 nm. Overall, gasoline with a high RON appears to be better suited for Euro 6 vehicles than ethanol-gasoline blends.

Ko et al. [7] focused on the NO_x emission characteristics of a Euro 6 diesel vehicle, measured with NO_x sensors positioned before and after the Lean NO_x Trap (LNT) on a chassis dynamometer. The vehicle was tested under both NEDC and WLTC cycles at varying temperatures (23 °C, 14 °C, and -5 °C). The WLTC cycle led to more frequent LNT regenerations than the NEDC, correlating with increased mileage and acceleration frequency, which resulted in a smaller NO_x conversion rate for the WLTC. Smaller ambient temperatures significantly raised NO_x concentrations due to poor fuel-air mixing, reduced combustion efficiency, and decreased EGR rates. During cold start, NO_x emission were primarily in the form of NO due to the LNT's inability to reach the light-off temperature for chemical reactions. For LNT regeneration, EGR rates dropped, and fuel consumption rose to release stored NO_x. The study examined NO, NO_2, N_2O, and NH_3 emission during regeneration and offers insights to optimize engine management systems under a varied range of conditions, supporting future emission standards such as WLTC and low-temperature requirements.

Borucka et al. [8] pointed out certain shortcomings of the homologation tests carried out in accordance with the WLTP (Worldwide harmonized Light Vehicle Test Procedure), because the results differ from tests in real operating conditions, especially in terms of fuel consumption (CO_2 emission). They proposed their own test procedure, also carried out on a chassis dynamometer, which provides a more random course of vehicle velocity as a function of time, measured in real road traffic conditions. They also proposed adapting this procedure for a specific group of vehicles or a group of users, which will bring the laboratory results closer to real ones. This original procedure is to be a supplement to the homologation tests.

Although dynamometer tests are conducted using standard driving cycles that mimic real driving conditions as closely as possible, they may still fall short of accurately representing real-world driving and the resulting emission of pollutant. Therefore, in recent years, considerable scientific efforts have been devoted to measuring and analysing real driving emissions (RDE) from vehicles.

Claßen et al. [9] present the results of exhaust emission tests from a car combustion engine in the RDE test. The tests included not only the emission of exhaust components specified in the homologation regulations, but also nitrogen dioxide, nitrous oxide, ammonia, formaldehyde and the number of particles larger than 10 nm. Luján et. al. [10] analysed the properties of a light truck compression-ignition engine tested in dynamic real driving conditions in the RDE test, that has been simulated on a chassis dynamometer. The operating states of the combustion engine and exhaust emission were tested. Pielecha et al. [11] present the exhaust emission tests results from a passenger car engine in the RDE test. Based on the obtained results, the exhaust emission conformity factors characterized in relation to exhaust emission in homologation tests were determined. Wang et al. [12] compare the effects of using different methods of processing exhaust emission test results from car engines in RDE tests. The tests were performed for 10 vehicles, which made it possible to formulate statistical conclusions. Yan et al. [13] present the results of exhaust emission tests from 3 vehicle engines in the WLTC, CLCT (China Light-Duty Vehicle Test Cycle) and RDE tests. It was found that the engine operating states in the CLCT test were more similar to the operating states in the RDE test than those of the WLCT test. Czerwinski et al. [14] provided insights from testing various Portable Emissions Measurement Systems (PEMS) under both chassis dynamometer and real-world driving conditions. Initially, the measuring systems were installed on a gasoline vehicle, and results were compared using standard test cycles such as NEDC, WLTC, and CADC. In the next phase, nanoparticle emission from three diesel vehicles were measured using PN-PEMS. These tests demonstrated strong correlation with CPC during dynamometer testing and highlighted the diesel particulate filter's (DPF) effectiveness in reducing nanoparticles during real-world operation. Merkisz et al. [15] presented an pollutant emission study on passenger cars tested in real driving conditions (RDE) using PEMS equipment. Notably, the RDE tests were conducted under Polish conditions, where specific parameters may differ from those in other EU countries. Emission correction coefficients were established to quantify variations in driving pollutant emission relative to laboratory-based ('chassis dyno') tests or actual use compared to EU emission standards. Recognizing that, current pollutant emission limits specified for chassis dynamometer testing were applied to RDE testing, the authors propose introducing conformity range coefficients as a 'safety factor' for exhaust emissions measured on the chassis dyno. Using these coefficients, the ecological performance of vehicles with different pollutant emission classes and design features (such as fuel supply systems) was analysed. This study enabled an ecological assessment of passenger vehicles across various pollutant emission classes and suggests strategies for pollutant emission reductions in specific pollutants. The methodologies outlined here may also be applicable to other vehicle types, including heavy-duty and alternative-fuel vehicles.

In fact, there are not many studies available that focus strictly on the analysis of exhaust emission of pollutants from automotive engines and fuel consumption by road vehicles due to measurement systems, different laboratories and repetitions of studies in specialist literature. Most publications concern the results of exhaust emission tests from automotive combustion engines and fuel consumption by vehicles. Few publications concern the repeatability of exhaust emission test results. Jaworski et al. [16] present results of repeatability assessment of exhaust gas emission tests from passenger car engines obtained in chassis dynamometer conditions in the NEDC test for both a cold engine start-up and warm engine start-up. Luján et al. [17] applied the latest European Community regulations, detailing steps to perform an RDE cycle on an engine test bench. After implementing WLTC and RDE cycles, this study evaluated the uncertainty and repeatability of the test results across multiple repetitions under consistent conditions. Uncertainty values were calculated for key engine operation parameters and exhaust emission, with a particular focus on NOx emission, a critical pollutant for diesel engines. By following the outlined methodology, NOx uncertainty values were reduced to 3.13% and 3.9% for the RDE and WLTC cycles, respectively, marking a significant advance in the precision of emission measurements.

Finally, there are publications on comparisons of tests performed in different laboratories also known as 'Inter-laboratory Correlation' [18–20]. Unfortunately, some of these studies were performed relatively long ago and to a limited extent [19]. The most interesting are interlaboratory studies on the same engine and vehicle, the so-called Golden Vehicle. Giechaskiel et al. [18]

state the importance and necessity of such studies in terms of the reliability of the obtained results. In addition, they found the required and relatively high convergence of the conducted assignments between laboratories. Trikka et al. [21], however, draw attention to the challenges associated with interlaboratory tests conducted in real road conditions using PEMS. According to European Commission [22] regulation, such equipment should be validated by comparison with chassis dynamometer tests. This is due to the fact that RDE test results exhibit high non-repeatability [23] because they strongly depend on the route on which the test is performed and the current traffic conditions. Therefore the Authors proposed their own concept for the interlaboratory tests of PEMS.

This paper concerns the very important issue of determining fuel consumption in light vehicle tests. In fact, vehicle fuel consumption values are currently determined in type-approval tests based on pollutant emissions, and not direct measurement of fuel flow. While this may not be obvious to a wider group of stakeholders, it is an established and recognized standard method, sanctioned by law [24]. This is due to practical reasons: during chassis dynamometer or RDE tests, there is no need to interfere with the vehicle's original fuel system, which would significantly complicate the test procedures. In contrast, determining fuel consumption based on pollutant emissions, which must be recorded in type-approval tests anyway, is carried out in accordance with the carbon mass balance method. This method assumes a direct relationship between the mass of fuel burned in the engine and the mass of emitted carbon-containing substances. Therefore, the accuracy and repeatability of fuel consumption test results depend on the quality of measurement method used for determining pollutant emission.

The goal of this paper was to analyse the repeatability of test results concerning pollutant emission and fuel consumption by vehicles, with an emphasis on comparing the results obtained using different measurement systems with different configurations, generations and measurement methods, conducted in two different laboratories. The comparative studies were conducted as part of inter-station tests, which aim to verify the reliability of the results. Pollutant emission and fuel consumption were tested on a chassis dynamometer using a passenger car. The test procedure consisted of the WLTC test with cold engine start-up. Two methods were used to determine pollutant emission in each laboratory: measurement of the concentrations of diluted exhaust components collected in measuring bags, and continuous measurement of the emission intensity of diluted exhaust components.

The remainder of this paper is structured in the following way. Section 2 provides detailed information on the equipment of the two laboratories considered in the comparative study and the technical specifications of the vehicle used. Section 3 describes proposed method and criteria for assessing the repeatability of test results. Section 4 presents and compares the results of tests performed in two laboratories and using two measurement methods in each of them. Finally, section 5 summarizes the main conclusions drawn from this research.

MEASURING EQUIPMENT AND TEST VEHICLE

The equipment of two research laboratories located at the BOSMAL Automotive Research and Development Institute Ltd. was used for the tests. At the Exhaust Emissions Research Division of the BOSMAL Institute, exhaust emission and fuel consumption tests are carried out every year in the combustion engine testing laboratories to confirm the validity of the results. This paper is based on data from inter-station tests involving two emissions research laboratories:

- Laboratory No. 1 with measuring station No. 1 (hereinafter designated as Lab 1),
- Laboratory No. 2 with measuring station No. 2 (hereinafter designated as Lab 2).

Figures 1 and 2 show the functional diagrams and equipment of both Lab 1 and Lab 2, respectively.

The main equipment of the laboratories were air-conditioned and climatic chambers, where all types of chassis dynamometer tests were carried out. The chambers were equipped with temperature and humidity control systems.

The air-conditioning system of Lab 1 enables the following:

- temperature regulation in the range from +14 °C to +28 °C,
- maintaining the set temperature during the tests with the accuracy of ±2.0 °C,
- humidity adjustment range during the tests: (5.5–12.2) g H_2O/kg of dry air,
- maintaining the set relative humidity during the tests in the range of ±5%.

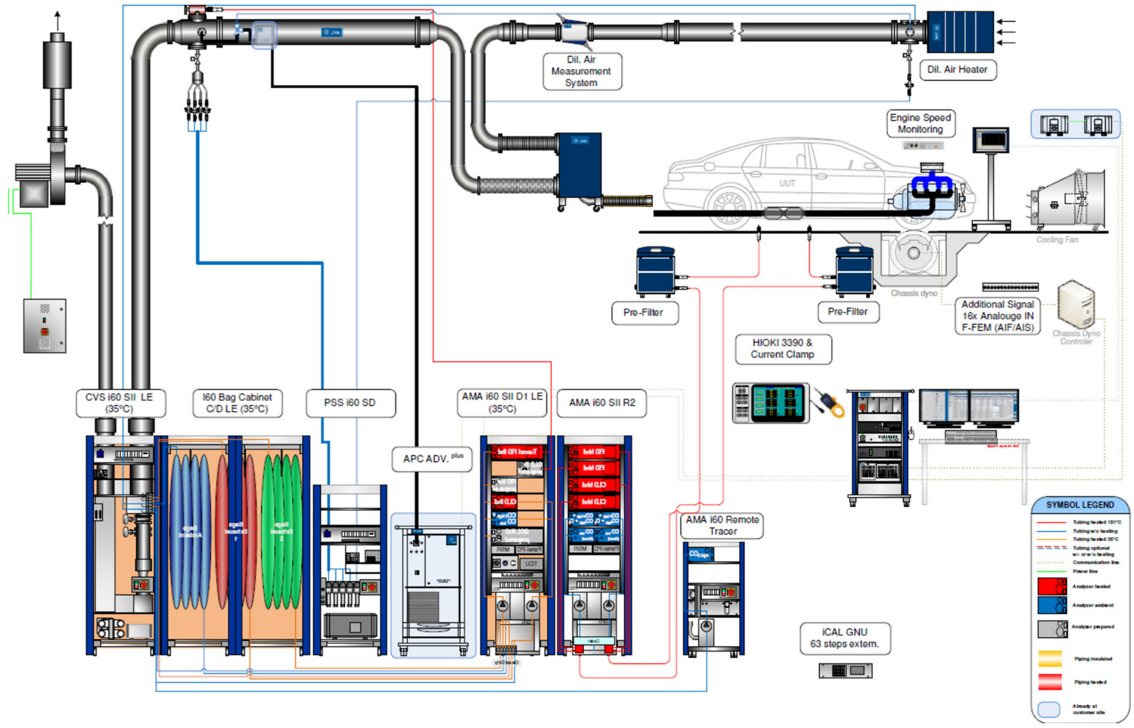

Figure 1. Functional diagram and equipment of the Lab 1

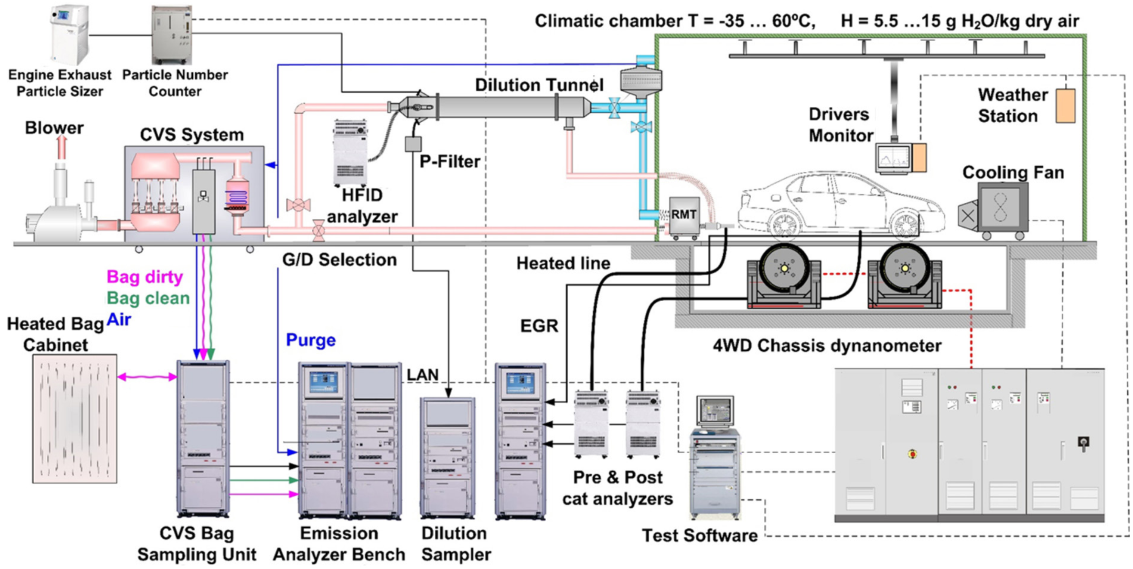

Figure 2. Functional diagram and equipment of the Lab 2

The temperature control capabilities in Lab 2 enable the implementation of current and future requirements for engine and vehicle development, such as the possibility of cold starting at low temperatures, etc., as well as the testing requirements of manufacturers of oils, fuels, various vehicle components or exhaust gas treatment systems.

The parameters of the climatic chamber in Lab 2 enable the following:

- temperature control from -35 °C to +60 °C,
- maintaining the target temperature with an accuracy of ±1.0 °C (for static conditions) and ±1.2 °C (during vehicle tests),
- maintaining the target relative humidity during tests with an accuracy of ±5%,
- temperature change by 0.5 °C/min throughout the heating and cooling phase,
- humidity value regulation during tests: (5.5–15) g H_2O/kg for temperatures in the range of +20 °C to +35 °C.

The installed software enables quick control of the climatic chamber, which results in proper temperature stabilization before starting the given tests. Table 1 presents a comparison of the basic parameters of the ambient conditions in both laboratories (Lab 1 and Lab 2).

The chassis dynamometers used for the tests were both AVL models Zoellner 48" Compact installed in two different environments: an air-conditioned laboratory and a climatic chamber. These dynamometers were integrated with the laboratory management systems HORIBA STARS VETS and AVL iGEM, operated using advanced software. The software provided functionality for testing exhaust emission in compliance with variety of international driving test cycles, including both standard driving cycles as specified in the regulations and non-regulation cycles that are intended to extend the test conditions for research and development. In addition, the system enables engine power measurements to be performed under dynamic and static conditions

Lab 1 was equipped with a 2WD chassis dynamometer designed for testing vehicles with single-axle drive systems. In contrast, Lab 2 featured a 4WD chassis dynamometer, enabling the testing of vehicles with four-wheel drive capabilities. Both dynamometers allow testing of vehicles with an axle load of up to 2000 kN. The rollers were designed with AC motors placed between them. Fans used to cool the vehicle drive during tests simulate air flow for the simulated vehicle velocity (0–150) km/h. Additionally, the chassis dynamometer located in Lab 2 had an extended function enabling testing of motorcycles, mopeds and scooters in the range of simulated inertial mass from 150 kg to 454 kg. Comprehensive specifications for the test stands can be found in Table 2.

Both dynamometer systems are used to conduct homologation tests and have therefore been designed in accordance with the requirements of the regulations contained in the relevant national and worldwide regulations, including United Nations Global Technical Regulation (UN GTR) No. 15, European Commission (EC) Regulations No. 715/2007, 692/2008 and 595/2009, United States Environmental Protection Agency (US EPA) requirements for emissions specification C100081T1, EPA Analog Identification Methodology (AIM), California Air Resources Board (CARB) acceptance regulations, required vehicle testing procedures as described in EPA 40 Code of Federal Regulation (CFR) 1066, as well as Japan regulations TRIAS 31-J042(3)-01 and TRIAS 99-006-01.

The tested vehicle was a passenger car. A popular model was selected, sold in large quantities by the manufacturer on the world market, with a state-of-the-art spark-ignition combustion engine and exhaust gas after-treatment system. The vehicle technical parameters are provided in Table 3.

METHODS

The same research program was carried out for the vehicle in both laboratories. It consisted of conducting the WLTC test three times. The test conditions and vehicle preparation were consistent with the requirements of the WLTP procedure [22]. This included, among other things, starting the vehicle test with a cold engine. Therefore, the coolant, lubricating oil, and catalytic converter were initially at ambient temperature of the laboratory (approximately 23 °C).

Two methods were used to perform the measurements in both laboratories:

- measurement of the concentration of diluted exhaust gases collected in measuring bags (hereinafter designated as "method A");
- continuous measurement of the emission intensity of diluted exhaust gases (hereinafter designated as "method B").

Specific distance emission (emission relative to the distance driven) of gaseous pollutants, i.e. nitrogen oxides (e_{NOX}), hydrocarbons (e_{THC}), non-methane hydrocarbons (e_{NMHC}), carbon monoxide (e_{CO}) and carbon dioxide (e_{CO2}) was determined with the use of both methods, A and B. In

Table 1. Ambient conditions in the two laboratories (Lab 1 and Lab 2)

Parameter	Unit	Lab 1	Lab 2
Temperature range	°C	+14/+28	-35/+60
Temperature tolerance	°C	±2.0	±1.2
Humidity	g H_2O/kg of dry air	5.5–12.2	5.5–15.0
Humidity tolerance	%	±5	±5

Table 2. Parameters of the chassis dynamometers in the two laboratories under consideration

Parameter	Unit	Lab 1	Lab 2
Number of rollers	-	2	4
Diameter of rollers	mm	1219.2	1219.2
Number of tested vehicle axles	-	1	2
Tested vehicle wheelbase	mm		2000–4600
Rated power	kW	153	153
Max. power	kW	258	258
Max. velocity	km/h	200	250
Simulated mass for 2WD vehicles	kg	454–5448	454–5448
Simulated mass for 4WD vehicles	kg		800–5448
Simulated mass for motorcycles	kg	2	150–454

Table 3. Technical parameters of the tested vehicle

Parameter	Unit	Data
Combustion system	-	Spark ignition
Fuel type	-	Gasoline
Supply system	-	Direct injection
Engine stroke volume	dm^3	1.390
Rated power	kW	90
Gearbox	-	Manual 6-gear
Mileage	km	165 500
Exhaust emission generation	-	Euro 5

the case of exhaust particles, which are limited in the Euro 5 emission standard for direct-injection spark-ignition engines [22], specific distance emission (e_{PM}) and specific distance number (e_{PN}) were determined only using method A.

Fuel consumption (*FC*) expressed in dm^3/100 km was calculated by applying the carbon balance method. According to the European Commission [22] regulations, for a vehicle with a spark-ignition engine supplied with gasoline (E10), the following formula is used:

$$FC = \frac{0.1206}{\rho}(0.829 \cdot e_{HC} + 0.429 \cdot e_{CO} + 0.273 \cdot e_{CO2}) \tag{1}$$

where: ρ – density of the gasoline [kg/dm^3].

The analysis of continuous measurement results in method B was performed using low-pass filtering of test results in order to reduce high-frequency noise in the test results. A second-stage Savitzky-Golay filter was used for low-pass filtering [25]. The mean value (AV) and standard deviation (SD) were calculated for the results of the three tests performed in one laboratory. Based on the above statistical parameters, the coefficient of variation (CV) was determined according to the formula:

$$CV = \frac{SD}{AV} \tag{2}$$

Finally, the coefficient of non-repeatability (CZ) of the average specific distance emission of exhaust components and the specific distance number of particles, in three tests performed in two laboratories for the two described measurement methods, was determined. The authors proposed to use the following formula for this coefficient:

$$CZ = \frac{2 \cdot |AV(x_1) - AV(x_2)|}{|AV(x_1) + AV(x_2)|} \tag{3}$$

where: x_1 – result obtained in Lab 1, x_2 – result obtained in Lab 2.

RESULTS

Tables 4 and 5 present results of vehicle testing, where pollutant emissions were determined using measurement methods A and B while fuel consumption was calculated according to the carbon balance method (Equation 1). The tables contain values obtained for three WLTC tests (labelled 1–3) conducted in each of the laboratories, as well as the calculated AV and SD.

The obtained results along with the mean value and standard deviation were represented in Figures 3–5 to facilitate their interpretation. Each graph consists of two parts: blue bars refer to the results obtained in Lab 1, while red bars refer to the results from Lab 2. The bars corresponding to measurements performed using method A are filled with solid colour, while those performed using method B are hatched. This makes it possible to visually compare results obtained in two laboratories and using two methods on one graph.

Figure 3 a–e concerns gaseous pollutants. For organic compounds, there were significant differences found between the laboratories. The mean value for Lab. 2 is slightly larger, but so is the standard deviation. Interestingly, it is clearly visible that in Lab. 1 there were no differences between the results obtained by methods A and B. In contrast, in Lab. 2 differences between the

Table 4. Results of measurements carried out at Lab 1

Quantity	Unit	Measurement method	Test number			AV	SD
			1	2	3		
e_{THC}	mg/km	A	37	39	48	41.3	3.81
		B	37	39	48	41.3	3.81
e_{NMHC}	mg/km	A	32	34	42	36	3.4
		B	32	34	42	36	3.4
e_{NOx}	mg/km	A	56	52	51	53	0.82
		B	57	54	52	54.3	1.03
e_{CO}	mg/km	A	366	363	380	369.7	6.99
		B	367	362	380	369.7	7.38
e_{CO2}	g/km	A	170.8	170.6	170.8	170.7	0.083
		B	172.9	172.7	172.9	172.8	0.083
e_{PM}	mg/km	A	1.83	2.41	2.04	2.1	0.16
		B	–	–	–	–	–
e_{PN}	1/km	A	3.06 E+12	3.87 E+12	3.21 E+12	3.38 E+12	2.8 E+11
		B	–	–	–	–	–
FC	dm³/100 km	A	7.43	7.42	7.44	7.43	0.008
		B	7.52	7.52	7.53	7.52	0.004

Table 5. Results of measurements carried out at Lab 2

Quantity	Unit	Measurement method	Test number			AV	SD
			1	2	3		
e_{THC}	mg/km	A	39	52	35	42	6.98
		B	44	57	41	47.3	6.58
e_{NMHC}	mg/km	A	36	48	30	38	7.36
		B	39	51	37	42.3	5.77
e_{NOx}	mg/km	A	41	51	56	49.3	2.83
		B	43	57	65	55	4.32
e_{CO}	mg/km	A	425	391	438	418	19.26
		B	395	360	402	385.7	17.29
e_{CO2}	g/km	A	170.8	170.9	169.5	170.4	0.579
		B	170.2	168.4	166.8	168.5	0.77
e_{PM}	mg/km	A	1.68	1.37	2.05	1.7	0.28
		B	–	–	–	–	–
e_{PN}	1/km	A	2.95 E+12	3.12 E+12	2.84 E+12	2.97 E+12	1.14 E+11
		B	–	–	–	–	–
FC	dm³/100 km	A	7.27	7.28	7.22	7.26	0.025
		B	7.25	7.17	7.1	7.17	0.034

methods occur for each measurement, with method B always giving higher values. The above observations are true for both THC and NMHC. A careful analysis of the NO_X data shows that the variability in this case is greater than that discussed above. For this exhaust pollutant, non-repeatability of measurements occurred not only in Lab. 2 but also in Lab. 1. Method B typically produced higher results. It should be emphasized, however, that in Lab 2 the differences between methods A and B are greater than in Lab. 1. The standard deviation calculated for the methods is also greater in Lab. 2. CO follows the trends indicated by the results for organic substances: THC

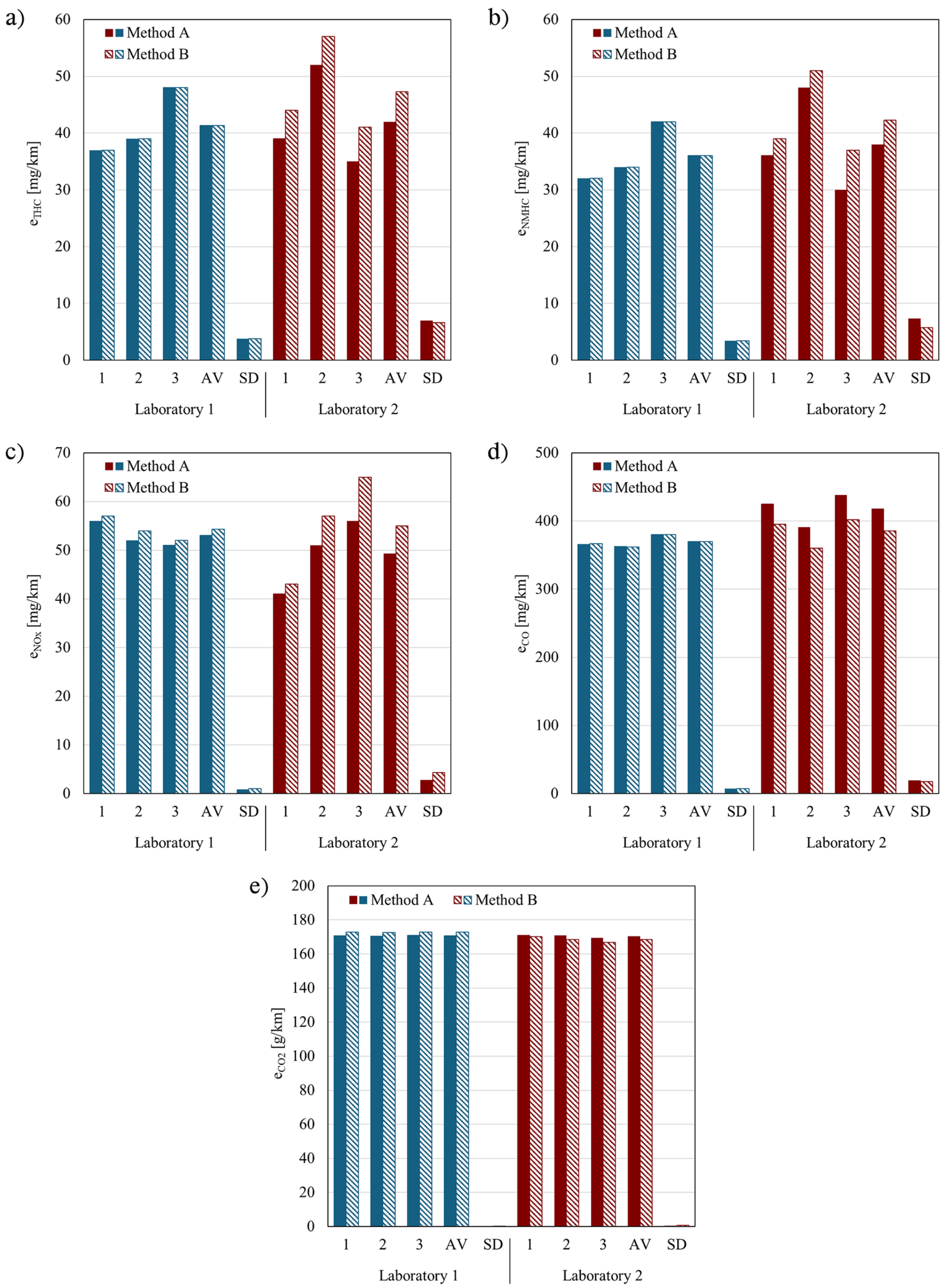

Figure 3. Comparison of vehicle test results in Laboratory 1 and 2 using measurement methods A and B, in terms of specific distance emission: a) HC, b) NMHC, c) NO_X, d) CO, e) CO_2; 1–3 – test number, AV – average value, SD – standard deviation

and NMHC. The significant difference is that in Lab. 2 higher numerical values were obtained for method A. As expected, the least sensitive results were those for CO_2. The repeatability of measurements in scope of this pollutant is high for both laboratories. This results in a very small value of standard deviation.

Figure 4 is devoted exclusively to particles emission. As mentioned earlier, only method A was used to determine the values of the quantities considered for this pollutant. Both in terms of specific distance emission and specific distance number, the results obtained in Lab. 1 have higher values. For particles mass emission, the repeatability was, once again, greater in Lab 1 than in Lab 2. The opposite was true for the specific distance number of particles, for which the results obtained in Lab. 2 had a much smaller scatter.

Finally, Figure 5 compares the fuel consumption determined in Lab.1 and 2. The analysis of this graph reflects the conclusions previously formulated for CO_2. This is understandable, since in the carbon mass balance method, fuel consumption largely depends on CO_2 emissions. The accuracy of the measurement of the concentration of this substance in the exhaust gases is therefore of the greatest importance for the overall fuel consumption result.

The above observations can be precisely quantified by taking the CV as a measure of the variability of test results. The CV values for

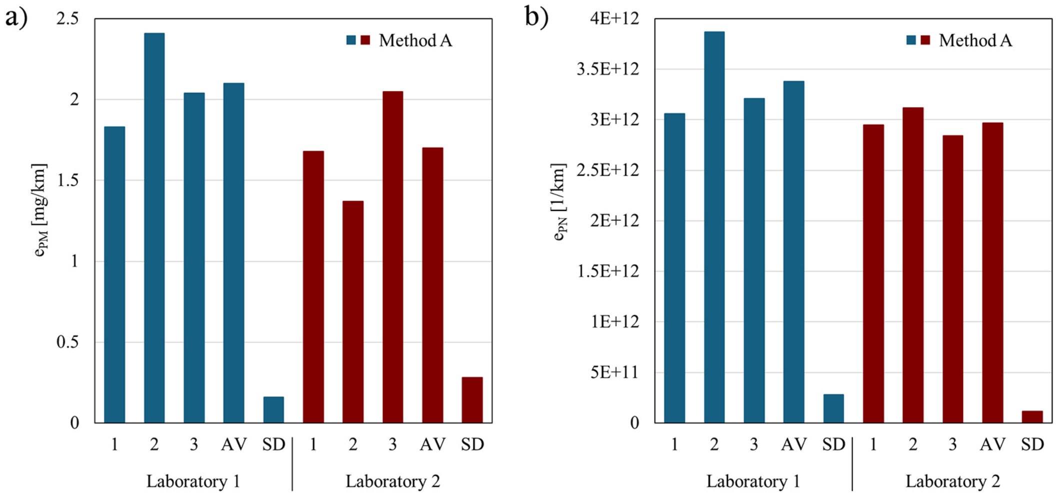

Figure 4. Comparison of vehicle test results in Laboratory 1 and 2 using measurement method A, in terms of: a) specific distance emission of particles, b) specific distance number of particles; 1–3 – test number, AV – average value, SD – standard deviation

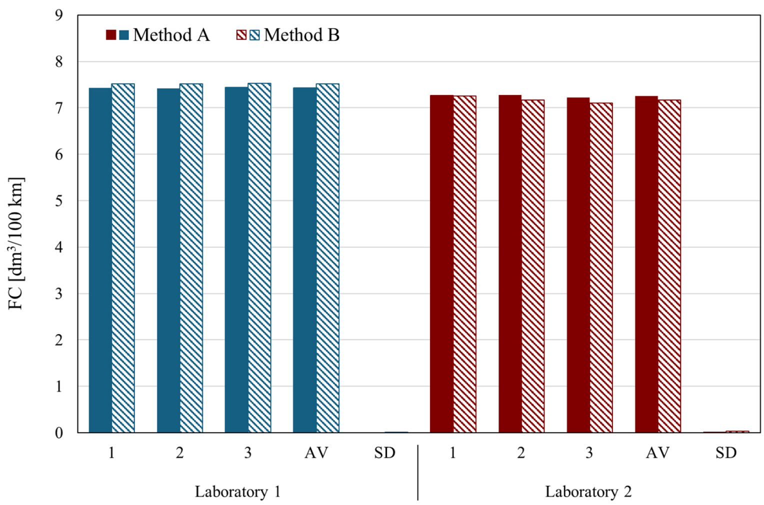

Figure 5. Comparison of vehicle test results in Laboratory 1 and 2 using measurement method A, in terms of: a) specific distance emission of particles, b) specific distance number of particles; 1–3 – test number, AV – average value, SD – standard deviation

each of the analysed quantities can be found in Figure 6. Noteworthy is the high CV value for organic compounds: THC and NMHC. In second place are the quantities related to particles: PM and PN. For Lab 2, the differences between the CV of the measured emission values were much greater for the two measurement methods than in the case of Lab 1.

Table 6 presents the exact values of the non-repeatability coefficient (CZ) calculated for the measurement results obtained in the two laboratories, according to Equation 3.

To facilitate comparisons between the CZ corresponding to emissions of individual substances and fuel consumption, a summary graph was created (Figure 7). The non-repeatability value was the greatest for the average specific distance emission of particles in three tests conducted in laboratories 1 and 2. Its value was around 0.2. The lowest non-repeatability coefficient in tests in the two laboratories was found for the specific distance emission of CO_2 and HC and the vehicle fuel consumption, determined based on the method of testing diluted exhaust gases from measuring bags (method A).

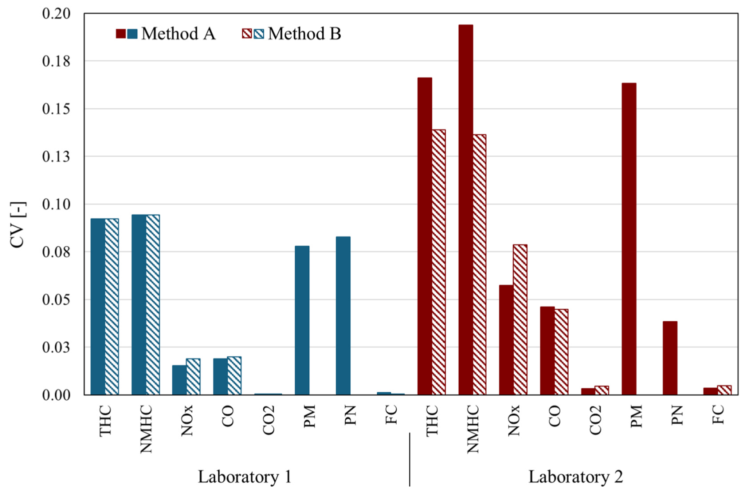

Figure 6. The coefficient of variation for vehicle test results obtained in Laboratory 1 and 2 using measurement methods A and B

Table 6. The coefficient of non-repeatability of test results between Laboratories 1 and 2 using measurement methods A and B

Quantity	Measurement method	Test number			All tests
		1	2	3	
e_{THC}	A	0.053	0.286	0.313	0.016
	B	0.173	0.375	0.157	0.128
e_{NMHC}	A	0.118	0.341	0.333	0.054
	B	0.197	0.400	0.127	0.154
e_{NOx}	A	0.309	0.019	0.093	0.058
	B	0.280	0.054	0.222	0.012
e_{CO}	A	0.149	0.074	0.142	0.123
	B	0.073	0.006	0.056	0.043
e_{CO2}	A	0.000	0.002	0.008	0.002
	B	0.016	0.025	0.036	0.026
e_{PM}	A	0.085	0.550	0.005	0.207
	B	–	–	–	–
e_{PN}	A	0.037	0.215	0.122	0.129
	B	–	–	–	–
FC	A	0.022	0.019	0.030	0.024
	B	0.037	0.048	0.059	0.048

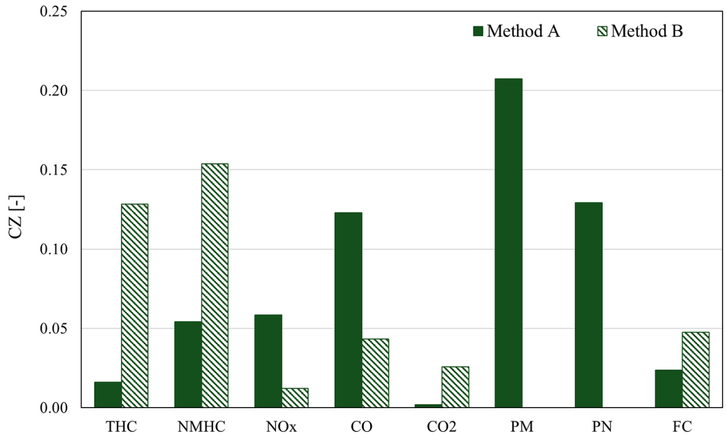

Figure 7. The coefficient of non-repeatability of test results obtained in Laboratories 1 and 2 using measurement methods A and B

CONCLUSIONS

Based on the conducted research and analyses, the following conclusions were drawn:

1. The results of specific distance emission tests of organic compounds (hydrocarbons and non-methane hydrocarbons), carbon monoxide and nitrogen oxides have shown large differences between the two laboratories. In Lab 1, there were no large differences between the two measurement methods. Whereas in Lab 2, the test results between the two measurement methods were more diversified.
2. The non-repeatability of the results of specific distance emission measurements of organic compounds, carbon monoxide and nitrogen oxides, was much smaller for Lab 1. The coefficient of variation of these values for Lab 1 was also smaller than 0.1 for organic compounds, and smaller than 0.02 for carbon monoxide and nitrogen oxides. In Lab 2, these values were found to be approximately twice as large. The non-repeatability of specific distance emission of pollutant and specific distance number of particles was also significantly smaller for Lab 1. The non-repeatability of specific distance emission of carbon dioxide and operational fuel consumption of the vehicle were the smallest observed.
3. The non-repeatability based on the 3 tests in laboratories 1 and 2 was the highest for the average specific distance emission of particles mass (approximately 0.2), while being the lowest for specific distance emission of carbon dioxide and hydrocarbons and operational fuel consumption of the vehicle, as determined by the method of testing diluted exhaust gases from measuring bags.

The general conclusions from the conducted exhaust emission tests lead to confirm the fact that the results of exhaust emission tests from combustion engines are very sensitive to the research methods used, the equipment with which they were conducted, the conditions in which the tests were performed, and even the research personnel involved. It follows from this that the results of comparative tests should be treated with great caution, and that any conclusions formulated on this basis often constitute knowledge of a significantly relative accuracy.

REFERENCES

1. Jonidi Jafari A., Charkhloo E., Pasalari H. Urban air pollution control policies and strategies: A systematic review. J. Environ. Health Sci. Eng. 2022; 19: 1911–40. https://doi.org/10.1007/s40201-021-00744-4
2. Ghisolfi V., Tavasszy L.A., Correia G.H.dA., Chaves G.dL.D., Ribeiro G.M. Freight transport decarbonization: A systematic literature review of system dynamics models. Sustainability 2022; 14(6): 3625. https://doi.org/10.3390/su14063625
3. Agarwal A.K. and Mustafi N.N. Real-world automotive emissions: Monitoring methodologies, and control measures. Renew. Sustain. Energy Rev. 2021; 137: 110624. https://doi.org/10.1016/j.rser.2020.110624
4. International Council on Clean Transportation (ICCT). Passenger vehicle greenhouse gas emissions and fuel consumption. 2024. https://theicct.org/pv-fuel-economy/
5. Giakoumis E.G. Driving and Engine Cycles. Athens: Springer; 2017. https://doi.org/10.1007/978-3-319-49034-2
6. Lv Z., Yang L., Wu L., Peng J., Zhang Q., Sun M., Mao H., Min J. Comprehensive analysis of the pollutant

characteristics of gasoline vehicle emissions under different engine fuel and test cycles. Energies 2022; 15(2): 622. https://doi.org/10.3390/en15020622

7. Ko J., Jin D., Jang W., Myung C., Kwon S., Park S. Comparative investigation of NOx emission characteristics from a Euro 6-compliant diesel passenger car over the NEDC and WLTC at various ambient temperatures. Appl. Energy 2017; 187: 652–62. https://doi.org/10.1016/j.apenergy.2016.11.105
8. Borucka A., Wisniowski P., Mazurkiewicz D., Swiderski A. Laboratory measurements of vehicle exhaust emissions in conditions reproducing real traffic. Measurement 2021; 174: 108998. https://doi.org/10.1016/j.measurement.2021.108998
9. Claßen J., Krysmon S., Dorscheidt F., Sterlepper S., Pischinger S. Real driving emission calibration – Review of current validation methods against the background of future emission legislation. Appl. Sci. 2021; 11: 5429. https://doi.org/10.3390/app11125429
10. Pielecha J., Merkisz J., Markowski J., Jasiński R. Analysis of passenger car emission factors in RDE tests. E3S Web Conf. 2016; 10: 00073. https://doi.org/10.1051/e3sconf/20161000073
11. Luján J.M., Piqueras P., de la Morena J., Redondo F. Experimental characterization of real driving cycles in a light-duty diesel engine under different dynamic conditions. Appl. Sci. 2022; 12: 2472. https://doi.org/10.3390/app12052472
12. Wang Z., Wu P., Yu N., Zhang Y., Wang Z. Analysis of the influence of RDE test data processing methods on the emission results of China 6 light duty vehicles. E3S Web Conf. 2021; 268: 01022. https://doi.org/10.1051/e3sconf/202126801022
13. Yan F., Wang Y., Zheng S., Meng Y., Xie J. Research on the correlation between test cycles and RDE test. In: Sugumaran V., Xu Z., Shankar P., Zhou H., editors. Application of Intelligent Systems in Multi-modal Information Analytics (MMIA 2019). Adv. Intell. Syst. Comput. Cham: Springer; 2019. p. 1152–9. https://doi.org/10.1007/978-3-030-15740-1_146
14. Czerwinski J., Comte P., Zimmerli Y., Reutimann F. Testing emissions of passenger cars in laboratory and on-road (PEMS, RDE). Combust. Engines 2016; 166(3): 17–23. https://doi.org/10.19206/CE-2016-326
15. Merkisz J., Pielecha J., Bielaczyc P., Woodburn J. Analysis of emission factors in RDE tests as well as in NEDC and WLTC chassis dynamometer tests. SAE Tech. Pap. 2016; 2016-01-0980. https://doi.org/10.4271/2016-01-0980
16. Jaworski A., Kuszewski H., Ustrzycki A., Balawender K., Lejda K., Woś P. Analysis of the repeatability of the exhaust pollutants emission research results for cold and hot starts under controlled driving cycle conditions. Environ. Sci. Pollut. Res. 2018; 25: 17862–77. https://doi.org/10.1007/s11356-018-1983-5
17. Luján J.M., Bermudez V., Pla B., Redondo F. Engine test bench feasibility for the study and research of real driving cycles: Pollutant emissions uncertainty characterization. Int. J. Engine Res. 2022; 23(7): 1103–15. https://doi.org/10.1177/14680874211007999
18. Giechaskiel B., Casadei S., Rossi T., Forloni F., Di Domenico A. Measurements of the emissions of a “golden” vehicle at seven laboratories with portable emission measurement systems (PEMS). Sustainability. 2021;13(16):8762. https://doi.org/10.3390/su13168762
19. Giechaskiel B., Muñoz-Bueno R., Colombo R., Manfredi U., Dilara P. PMP inter-laboratory correlation exercise: Report on Part 3: JRC tests in July 06. Luxembourg: Office for Official Publications of the European Communities 2007. https://publications.jrc.ec.europa.eu/repository/bitstream/JRC40294/reqno_jrc40294_pmp_jrc_3_final%5B2%5D.pdf
20. Grigoratos T., Mathissen M., Vedula R., Mamakos A., Agudelo C., Gramstat S., Giechaskiel B. Interlaboratory study on brake particle emissions—Part I: Particulate matter mass emissions. Atmosphere 2024; 14(3): 498. https://doi.org/10.3390/atmos14030498
21. Trikka M., Valentini S., Cotogno G., Canevari P., Melas A., Clairotte M., Otura Garcia M., Giechaskiel B. A concept for on-road inter-laboratory correlation exercises with portable emission measurement systems (PEMS). Processes 2025; 13(3): 702. https://doi.org/10.3390/pr13030702
22. European Commission. Commission Regulation (EU) 2017/1151 of 1 June 2017 supplementing Regulation (EC) No 715/2007 of the European Parliament and of the Council on type-approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information, amending Directive 2007/46/EC of the European Parliament and of the Council, Commission Regulation (EC) No 692/2008 and Commission Regulation (EU) No 1230/2012 and repealing Commission Regulation (EC) No 692/2008. 2008. https://eur-lex.europa.eu/EN/legal-content/summary/worldwide-harmonised-light-duty-vehicles-test-procedure-wltp-and-real-driving-emissions-rde.html
23. Giechaskiel B., Clairotte M., Valverde-Morales V., Bonnel P., Kregar Z., Franco V., Dilara P. Framework for the assessment of PEMS (Portable Emissions Measurement Systems) uncertainty. Environ Res. 2018; 166: 251–60. https://doi.org/10.1016/j.envres.2018.06.012
24. Pavlovic J., Fontaras G., Broekaert S., Ciuffo B., Ktistakis M.A., Grigoratos T. How accurately can we measure vehicle fuel consumption in real world operation? Transp. Res. D Transp. Environ. 2021; 90: 102666. https://doi.org/10.1016/j.trd.2020.102666
25. Savitzky A. and Golay M.J.E. Smoothing and differentiation of data by simplified least squares procedures. Anal. Chem. 1964; 36(8): 1627–39. https://doi.org/10.1021/ac60214a047