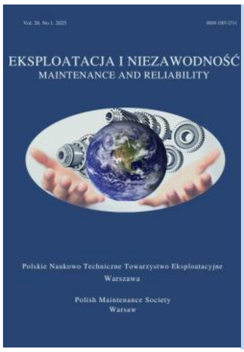

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The uniqueness of pollutant emission and fuel consumption test results for road vehicles tested on a chassis dynamometer

Indexed by:

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Highlights

- The issues of non-repeatability of exhaust emission and fuel consumption.
- Exhaust emissions in the WLTC test.
- Homologation procedures.

Abstract

The article considers the issues of non-repeatability of exhaust emission and fuel consumption test results for road vehicles tested on a chassis dynamometer. Empirical results of passenger car tests on a chassis dynamometer in the WLTC (Worldwide Harmonized Light Vehicles Test Cycle) test were used. Tests were conducted in four repeated sets to assess the repeatability of the test results. The road emission of hydrocarbons, non-methane hydrocarbons, carbon monoxide, nitrogen oxides, particulate matter and carbon dioxide, the road number of particulate matter and operational fuel consumption were determined. The coefficient of variation of the values measured in the four tests was determined, taken as a measure of the repeatability of the test results. The coefficient of variation of the road emission of carbon dioxide and operational fuel consumption is the lowest. No significant differences were found in the values of the measured exhaust emission.

Keywords

road vehicles, exhaust emission, fuel consumption, driving tests.

1. Introduction

Exhaust emission testing is an extremely important aspect of environmental protection, which is widely discussed in scientific and technical literature [4,25]. First of all, exhaust emissions have a direct impact on air quality and public health. The increase in emissions of harmful substances, such as nitrogen oxides (NOx), carbon dioxide (CO_2) and particulate matter (PM), contributes to the deterioration of air quality, which is why many studies focus on this problem [16,17]. Exhaust emission testing is a crucial tool in the context of legal regulations, as many countries are introducing increasingly stringent emission standards. Technical literature often analyzes how the development of exhaust catalyst technology, exhaust gas recirculation systems (EGR) or particulate filters (DPF) help reduce emissions from combustion engine vehicles [22]. This topic is also important in the context of energy transformation and the search for alternative energy sources [6,30]. More and more studies focus on comparing exhaust emissions associated with electric

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vehicles, hybrids and traditional combustion engines, as well as on the potential of biofuels and other low-emission fuels [12,24]. Issues related to exhaust emissions are also discussed in the context of innovations in transport, e.g. in the development of autonomous vehicles and intelligent fleet management systems, which aim to optimize fuel consumption and minimize emissions [13,23].

However, the key aspect in the field of exhaust emission measurements is to ensure their high precision and accuracy. For this reason, it is necessary to conduct detailed research on the sources and size of measurement errors that may affect the reliability of the obtained results. The need for a deeper analysis and understanding of these errors was the motivation for writing this article.

The difference between the measurement result and the actual value of the measured quantity is called the measurement error. Measurement errors are divided into: gross errors, random errors and systematic errors. Gross errors usually arise as a result of the observer's inattention or carelessness when reading or recording the results or as a result of a sudden change in measurement conditions.

Systematic errors result from the imperfections in measurement methods. They can be reduced by using more perfect and precise methods and devices, but it is impossible to completely eliminate systematic errors. Identified systematic errors should be taken into account by introducing appropriate corrections to the result. Random errors occur inevitably. They result from various random and unaccountable factors. Random errors are reduced by repeating the measurement multiple times – then there is partial compensation for random overestimating and underestimating deviations of the result.

This paper presents the results of exhaust emission and fuel consumption tests for a car engine in the WLTC (Worldwide Harmonized Light Vehicles Test Cycle) [29] driving test performed on a chassis dynamometer.

The aim of the paper was to assess the repeatability [15] of exhaust emission and fuel consumption test results in different phases of the WLTC driving test, which differed by vehicle driving speed. The secondary aim was to assess the testing method of exhaust emission and fuel consumption. The first method of testing involved the analysis of the concentrations of diluted exhaust gas components from measuring bags, while the second method was carried out by means of continuous testing of the diluted stream of exhaust gas components.

2. Literature review

The repeatability of exhaust emission and fuel consumption test results in driving tests is not a subject that is often researched in the literature. The most frequently presented test results are those from one-off tests, usually homologation tests [1,2,4].

It should be emphasized that the thermal state of the engine (vehicle) has a significant impact on the repeatability of the research data. The authors have been familiar with this topic for many years, as already in the article [7] a review of exhaust emissions from direct injection (DI) diesel engines in the initial period after start-up was made. The research was carried out in the "cold start" mode (cooling water and lubricating oil temperature to be equal to the ambient temperature) and "warm start" mode (after reaching the thermal equilibrium state).

The article [1] compares the test results in the WLTC and RDE (Real Driving Cycle) tests. The characteristics of the road exhaust emission and the road number of particulate matter values were determined, relative to the average driving speed, based n the values determined in the individual test phases with different average values.

Paper [2] describes the results of exhaust emission and fuel consumption tests in the WLTC test. Statistical characteristics of the exhaust emission rate, the particle number emission rate, the fuel mass consumption rate and the average speed were presented. Histograms of these values were determined and correlations between them were examined.

Many papers concern various exhaust emission and fuel consumption tests in real vehicle use conditions – in the RDE test [1, 3, 9].

An interesting proposal of the authors of [8] was an additional test method carried out on a chassis dynamometer, which was developed using the test results obtained from actual vehicle operation. The speed profiles were different than in standard homologation tests and reflected the more random nature of vehicle movement in reality. A high compliance of emissions in actual operating conditions with tests on a chassis dynamometer was achieved. This proposed method can be used for dedicated groups of vehicles, reflecting their actual emissions and fuel consumption.

The article [3] presents the test results in dynamic states in the RDE test, while the comparison of exhaust emission test results on a chassis dynamometer in the WLTC test and road conditions in the RDE test was presented in [9].

There are papers discussing the performance properties of combustion engines in various operating states [5,8]. Exhaust emission from combustion engines in various vehicle traffic conditions were analyzed in [5]: in traffic jams, in cities outside traffic jams, outside cities and on motorways and expressways.

The issues of combustion engine research results repeatability were discussed in many previous papers [10,11,14,15,18, 20,21,28].

Paper [11] discussed the analysis of measurement systems in terms of the repeatability of measurement results.

In turn, paper [18] presented the repeatability assessment of exhaust emission tests from a passenger car engine obtained in the chassis dynamometer conditions in the NEDC test in cold and hot start conditions.

The authors of [20] presented the exhaust emission test results from the compression-ignition engine in multiple implementations of the static WHSC (World Harmonized Stationary Cycle) [29] and the dynamic WHTC (World Harmonized Transient Cycle) [29] tests.

In [21] the results of empirical repeatability studies of a spark-ignition engine were presented. The repeatability of the maximum pressure of the medium in the cylinder was analyzed: at maximum load and at partial load.

Paper [28] was used to systematically assess the reasons for the non-reproducibility of empirical research results.

In publication [19], the author presented an overview of current research and a critical comparison of commonly used methods of testing engine exhaust emissions and methods that might supplement them in a significant manner.

In general, the issues of the research results repeatability when it comes to the properties of combustion engines, especially in dynamic states, have not been sufficiently systematized thus far, especially when considered in the conditions of real engine operation.

3. Research method

Exhaust emission and fuel consumption tests were performed on a chassis dynamometer in the WLTC test for a cold engine start, i.e. for a start at which the temperature of the engine, the coolant, lubricating oil and catalytic converter are the same as the ambient temperature (about 23 °C in laboratory setting). The WLTC test – speed profile for a passenger car was shown in Figure 1.

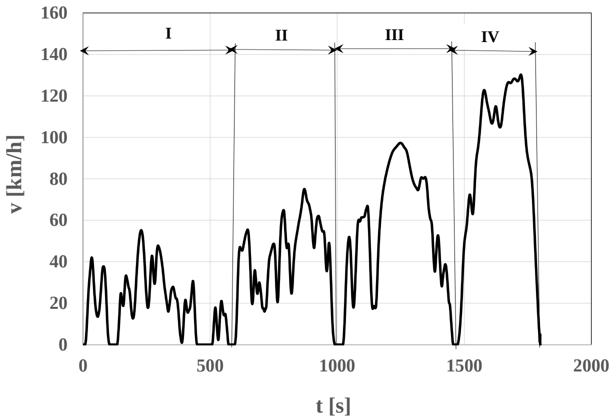

Fig. 1. Passenger car speed profile – v in the WLTC.

The WLTC consists of 4 phases:

- I – low speed phase – low,
- II – medium speed phase – middle,
- III – high speed phase – high,
- IV – very high speed phase – extra high.

The tests were performed using the method of measuring the concentrations of diluted exhaust gas components from measuring bags (Bags) as well as with the method of continuous testing of the diluted exhaust gas components (Modal DIL).

The exhaust gas components flow rate measurements were performed with low-pass filtration [10, 11, 26, 27]. A second-stage Savitzky-Golay filter [26, 27] was used to filter the data.

Four tests were performed. For the diluted exhaust gas tests using measuring bags, the following road emissions were determined: hydrocarbons – b_{THC}, non-methane hydrocarbons – b_{NMHC}, carbon monoxide – b_{CO}, nitrogen oxides – b_{NOx} and carbon dioxide – b_{CO2}. For continuous exhaust gas tests, the additional road emissions of particulate matter – b_{PM} and particle number – b_{PN} as well as the fuel consumption – Q were determined. These values were determined for the entire WLTC test as well as for its individual phases – speeds: low, middle, high and extra high.

For the results of the 4 tests, the following were determined:

- Average value – AV,
- Standard deviation – D,
- Coefficient of variation – W.

Where the coefficient of variation

$$W = \frac{D}{AV}$$

is considered inversely proportional to the data results repeatability value.

4. Test object and measuring equipment

The tests were carried out on an air-conditioned single-axle chassis dynamometer using equipment that met the requirements of homologation tests (fig. 2). The test was conducted on a passenger car with a spark-ignition engine (fig. 3). The car specifications were listed in Table 1.

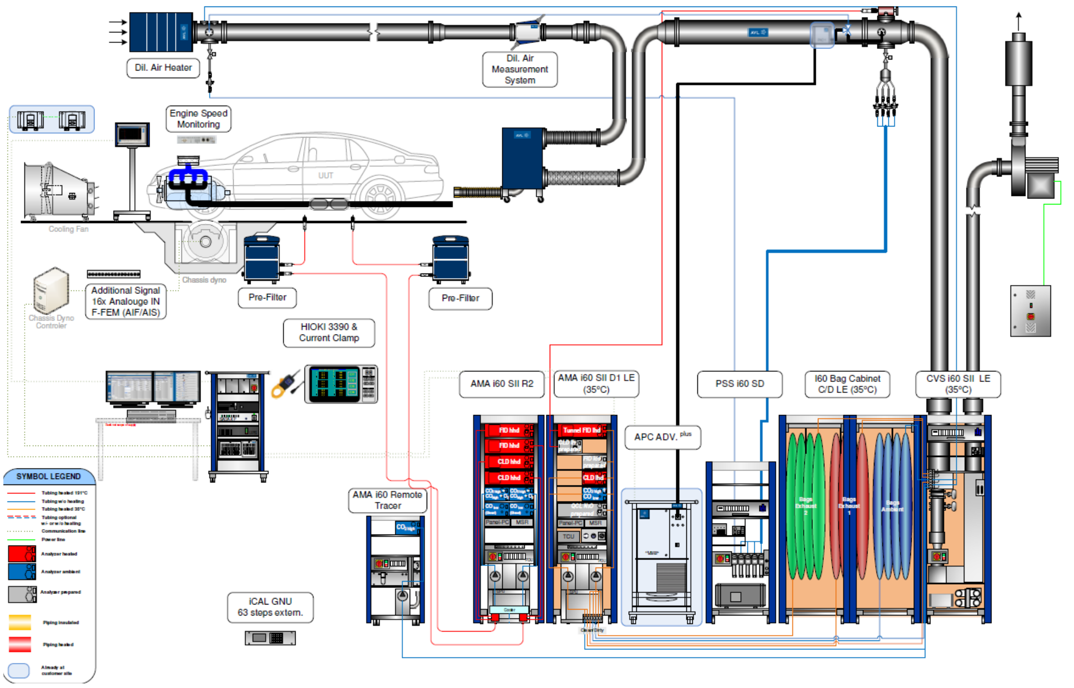

Fig. 2. Schematic diagram of the research laboratory with a single-roller chassis dynamometer.

Fig. 3. The references car on the chassis dynamometer during test

Tab.1. Data of the reference car used for the tests.

Brand	VW
Model	Golf VI
Fuel type	Gasoline
Engine type	GDI
Displacement [dm^3]	1.390
Engine power [kW]	90
Gearbox	Manual 6 gear
Brand	VW
Mileage [km]	165249
Exhaust emission standard	Euro 5

5. Results

Table 2 contains the research results specific distance emission of pollutants, specific distance particulate number and operational fuel consumption in the WLTC in four studies.

Tab. 2. Road exhaust emission and particle number as well as fuel consumption in the WLTC.

	mg/km				g/km	1/km	dm^3/100 km
	THC	NMHC	CO	NO_x	CO_2	PN	Q
Bags	244	220	1472	187	209.0	1.34E+13	9.19
Modal Dilute	240	215	1478	195	209.9		9.23
Bags	254	228	1221	148	210.2	1.67E+13	9.23
Modal Dilute	251	223	1218	155	211.2		9.27
Bags	323	295	1390	161	208.6	1.45E+13	9.18
Modal Dilute	321	292	1398	167	209.8		9.23
Bags	274	248	1361	166	209.3	1.49E+13	9.20
Modal Dilute	317	291	1335	181	209.6		9.02
AV (Bags)	273.8	247.8	1361.0	165.5	209.3	1.49E+13	9.20
AV (Modal Dilute)	282.3	255.3	1357.3	174.5	210.1		9.19
D (Bags)	30.42	29.12	90.50	14.04	0.59	1.19E+12	0.02
D (Modal Dilute)	36.98	36.36	95.04	14.99	0.63		0.10
W (Bags)	0.1111	0.1176	0.0665	0.0849	0.0028	0.0799	0.0020
W (Modal Dilute)	0.1310	0.1425	0.0700	0.0859	0.0030		0.0107

Tables 3 – 6 present the specific distance emission and specific distance particulate number, as well as operational fuel consumption in individual phases of the WLTC.

Tab. 3. Specific distance emission, specific distance particulate number and specific distance fuel consumption in the „low" phase of the WLTC in four studies.

	mg/km				g/km	1/km	dm^3/100 km
	THC	NMHC	CO	NO_x	CO_2	PN	Q
Bags	244	220	1472	187	209.0	1.34E+13	9.19
Modal Dilute	240	215	1478	195	209.9		9.23
Bags	254	228	1221	148	210.2	1.67E+13	9.23
Modal Dilute	251	223	1218	155	211.2		9.27
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Modal Dilute	321	292	1398	167	209.8		9.23
Bags	274	248	1361	166	209.3	1.49E+13	9.20
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AV (Bags)	273.8	247.8	1361.0	165.5	209.3	1.49E+13	9.20
AV (Modal Dilute)	282.3	255.3	1357.3	174.5	210.1		9.19
D (Bags)	30.42	29.12	90.50	14.04	0.59	1.19E+12	0.02
D (Modal Dilute)	36.98	36.36	95.04	14.99	0.63		0.10
W (Bags)	0.1111	0.1176	0.0665	0.0849	0.0028	0.0799	0.0020
W (Modal Dilute)	0.1310	0.1425	0.0700	0.0859	0.0030		0.0107

Tab. 4. Specific distance emission, specific distance particulate number and specific distance fuel consumption in the „middle" phase of the WLTC in four studies.

	mg/km				g/km	1/km	dm^3/100 km
	THC	NMHC	CO	NO_x	CO_2	PN	Q
Bags	5	3	72	48	150.0	2.63E+12	6.51
Modal Dilute	7	4	72	47	150.8		6.54
Bags	8	5	80	58	150.4	4.34E+12	6.52
Modal Dilute	8	5	81	59	151.3		6.56
Bags	7	4	81	55	151.4	2.74E+12	6.57
Modal Dilute	7	5	81	55	152.3		6.61
Bags	7	4	78	53	150.6	3.24E+12	6.53
Modal Dilute	6	4	84	50	148.0		6.28
AV (Bags)	6.75	4.00	77.75	53.50	150.6	3.24E+12	6.53
AV (Modal Dilute)	7.00	4.50	79.50	52.75	150.6		6.50
D (Bags)	1.09	0.71	3.49	3.64	0.51	6.77E+11	0.02
D (Modal Dilute)	0.71	0.50	4.50	4.60	1.60		0.13
W (Bags)	0.1614	0.1768	0.0449	0.0680	0.0034	0.2090	0.0035
W (Modal Dilute)	0.1010	0.1111	0.0566	0.0873	0.0106		0.0197

Tab. 5. Specific distance emission, specific distance particulate number and specific distance fuel consumption in the „high" phase of the WLTC in four studies.

	mg/km				g/km	1/km	dm^3/100 km
	THC	NMHC	CO	NO_x	CO_2	PN	Q
Bags	2	1	142	16	147.3	7.69E+11	6.40
Modal Dilute	3	2	142	16	149.1		6.47
Bags	2	2	122	21	146.2	9.65E+11	6.35
Modal Dilute	2	2	123	22	148.3		6.44
Bags	2	2	120	16	146.4	8.27E+11	6.36
Modal Dilute	2	2	120	16	148.3		6.43
Bags	2	2	128	18	146.7	8.54E+11	6.37
Modal Dilute	2	2	135	27	144.7		6.14
AV (Bags)	2.00	1.75	128	17.75	146.7	8.54E+11	6.37
AV (Modal Dilute)	2.25	2.00	130	20.25	147.6		6.37
D (Bags)	0.00	0.43	8.60	2.05	0.42	7.12E+10	0.02
D (Modal Dilute)	0.43	0.00	8.92	4.60	1.71		0.13
W (Bags)	0.0000	0.2474	0.0672	0.1153	0.0028	0.0834	0.0029
W (Modal Dilute)	0.1925	0.0000	0.0686	0.2273	0.0116		0.0210

Tab. 6. Specific distance emission, specific distance particulate number and specific distance fuel consumption in the „extra high" phase of the WLTC in four studies.

	mg/km				g/km	1/km	dm^3/100 km
	THC	NMHC	CO	NO_x	CO_2	PN	Q
Bags	7	5	318	47	188.9	1.43E+12	8.21
Modal Dilute	8	6	318	48	192.3		8.36
Bags	9	6	414	41	188.5	1.32E+12	8.20
Modal Dilute	10	7	413	41	192.0		8.35
Bags	9	6	401	40	189.1	1.34E+12	8.22

	mg/km				g/km	1/km	$dm^3/100$ km
	THC	NMHC	CO	NO_x	CO_2	PN	Q
Modal Dilute	9	6	400	40	192.5		8.37
Bags	8	6	378	43	188.8	1.36E+12	8.21
Modal Dilute	9	7	422	36	185.5		7.89
AV (Bags)	8.25	5.75	377.8	42.8	188.8	1.36E+12	8.21
AV (Modal Dilute)	9.00	6.50	388.3	41.3	190.6		8.24
D (Bags)	0.83	0.43	36.83	2.68	0.22	4.15E+10	0.01
D (Modal Dilute)	0.71	0.50	41.31	4.32	2.94		0.20
W (Bags)	0.1005	0.0753	0.0975	0.0627	0.0011	0.0304	0.0009
W (Modal Dilute)	0.0786	0.0769	0.1064	0.1048	0.0154		0.0247

Figures 4 – 12 are a graphic representation of the vehicle tests in the WLTC.

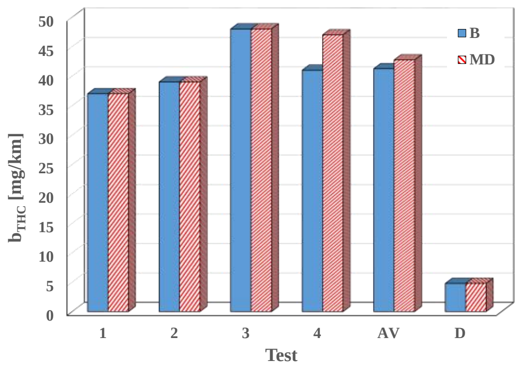

Fig. 4. Hydrocarbon specific distance emission – b_{THC} in the 4 studies of WLTC as well as the mean value and the standard deviation: B – tests of diluted exhaust gases in measurement bags BAG, MD – tests of diluted stream of exhaust gases (Modal DIL).

The highest value of specific distance of hydrocarbon was in the third test, and the greatest difference between the test results using both methods was in the fourth test.

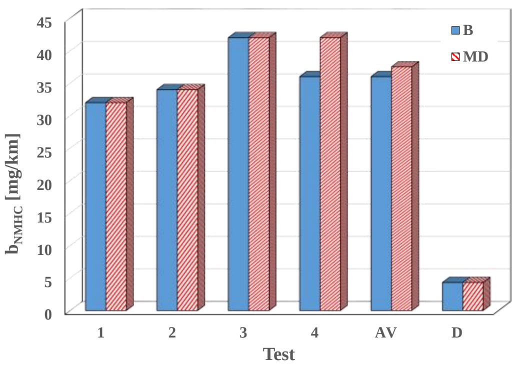

Fig. 5. Non-methane hydrocarbon specific distance – b_{NMHC} in the 4 studies of WLTC as well as the mean value and the standard deviation: B – tests of diluted exhaust gases in measurement bags BAG, MD – tests of diluted stream of exhaust gases (Modal DIL).

In the case of non-methane hydrocarbons, the relationship of the test results is similar to that for hydrocarbons.

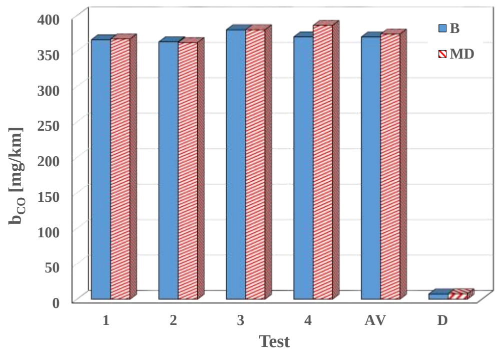

Fig. 6. Carbon monoxide specific distance – b_{CO} in the 4 studies of WLTC as well as the mean value and the standard deviation: B – tests of diluted exhaust gases in measurement bags BAG, MD – tests of diluted stream of exhaust gases (Modal DIL).

There are no significant differences in the research results for the individual test phases or between the two research methods.

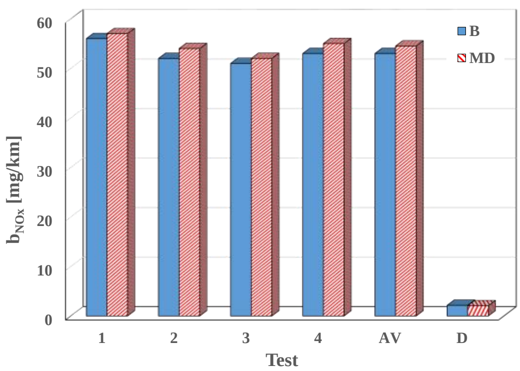

Fig. 7. Nitrogen oxides specific distance – b_{NOx} in the 4 studies of WLTC as well as the mean value and the standard deviation: B – tests of diluted exhaust gases in measurement bags BAG, MD – tests of diluted stream of exhaust gases (Modal DIL).

There are no big differences for the results of individual studies and for both methods.

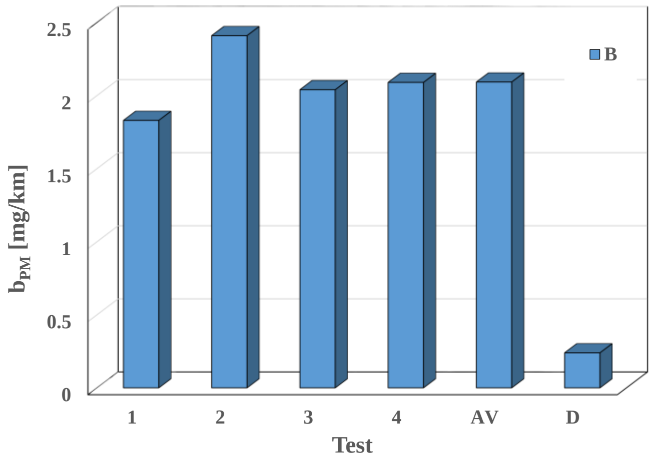

Fig. 8. Particulate matter specific distance – b_{PM} in the 4 studies of WLTC as well as the mean value and the standard deviation: B – tests of diluted exhaust gases in measurement bags BAG, MD – tests of diluted stream of exhaust gases (Modal DIL).

The largest specific distance emission of particulate matter is in the second study.

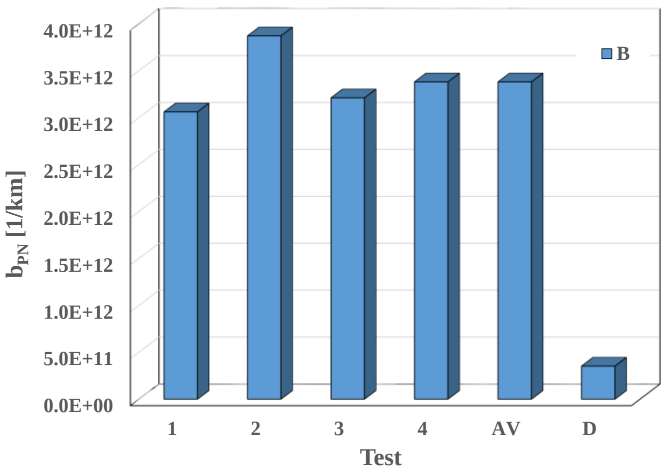

Fig. 9. Specific distance of particulate number – b_{PN} in the 4 studies of WLTC as well as the mean value and the standard deviation: B – tests of diluted exhaust gases in measurement bags BAG, MD – tests of diluted stream of exhaust gases (Modal DIL).

The properties of the specific distance particulate number were similar to those of the specific distance emission of particulate matter.

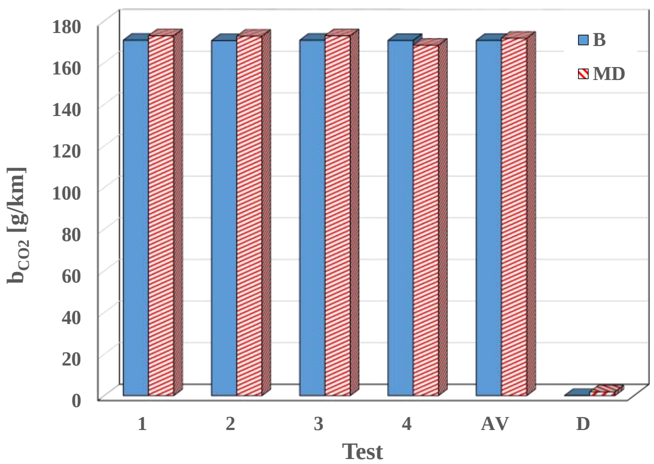

Fig. 10. Carbon dioxide specific distance emission – b_{CO2} in the 4 studies of WLTC as well as the mean value and the standard deviation: B – tests of diluted exhaust gases in measurement bags BAG, MD – tests of diluted stream of exhaust gases (Modal DIL).

There are no large differences in operational fuel consumption in individual studies and for both methods.

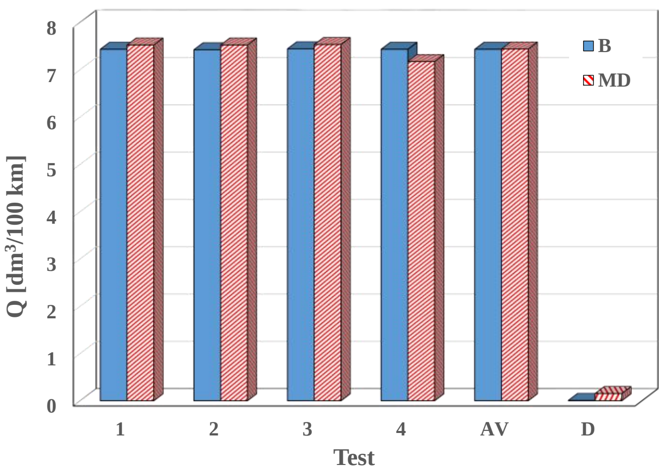

Fig. 11. Operational fuel consumption – Q in the 4 studies of WLTC as well as the mean value and the standard deviation: B – tests of diluted exhaust gases in measurement bags BAG, MD – tests of diluted stream of exhaust gases (Modal DIL).

The test results of operational fuel consumption relationships were similar to those for specific distance carbon dioxide emission.

Figure 12 shows the coefficient of variation of specific distance of emission of pollutants and specific distance of particulate number and operational fuel consumption in the 4 studies of the WLTC.

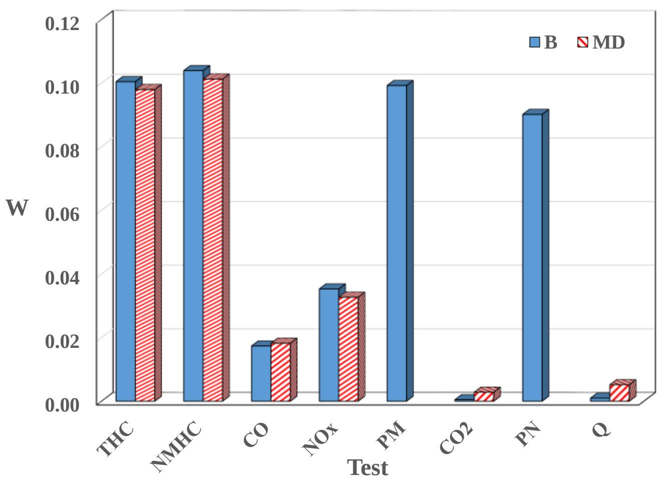

Fig. 12. Coefficient of variation of specific distance emission of pollutants and specific distance number of particulate matter as well as operational fuel consumption – W in the 4 phases of the WLTC: B – test of diluted exhaust gases in measurement bags BAG, MD – tests of diluted stream of exhaust gases (Modal DIL).

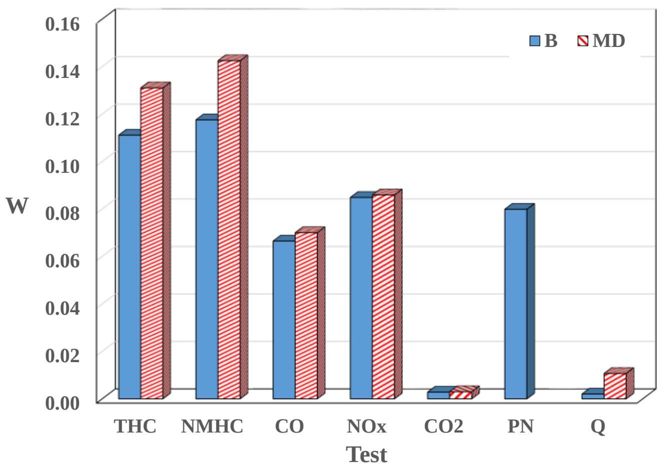

Fig. 13. Coefficient of variation of specific distance emission of pollutants and specific distance number of particulate matter as well as operational fuel consumption – W for the „low" phase of the 4 phases in the WLTC: B – tests of diluted exhaust gases in measurement bags BAG, MD – tests of diluted stream of exhaust gases (Modal DIL)

The coefficient of variation values for specific distance carbon dioxide emission and operational fuel consumption was definitely the smallest, and the largest for specific distance emission of hydrocarbons, non-methane hydrocarbons along with particulate matter and the specific distance number of particulate matter. The coefficient of variation for specific distance emission of carbon monoxide and nitrogen oxides was significantly smaller.

Figures 13 – 16 show the coefficient of variation for specific distance specific distance emission of measured pollutants and the specific distance number of particulate matter and operational fuel consumption in the 4 individual phases of the WLTC test.

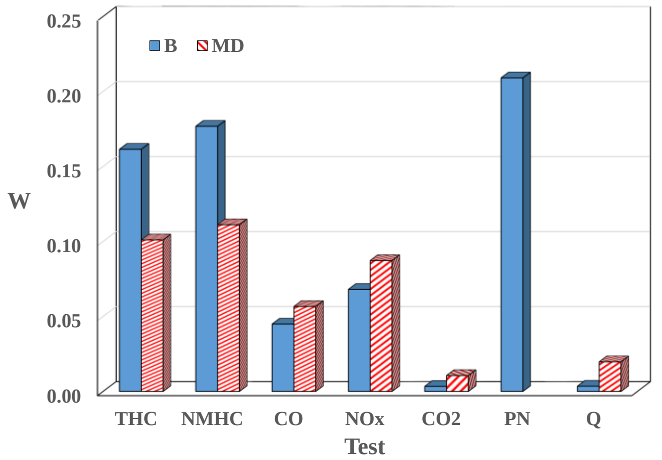

Fig. 14. Coefficient of variation of specific distance emission of pollutants and specific distance number of particulate matter as well as operational fuel consumption – In the „middle" phase of the 4 phases in the WLTC: B – tests of diluted exhaust gases in measurement bags BAG, MD – tests of diluted stream of exhaust gases (Modal DIL).

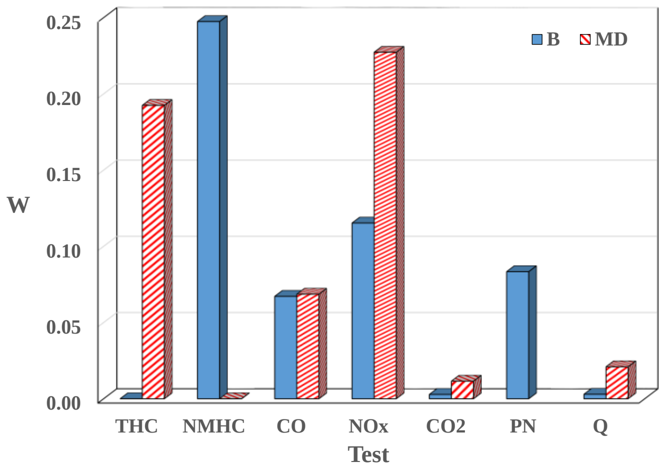

Fig. 15. Coefficient of variation of specific distance emission of pollutants and specific distance number of particulate matter as well as operational fuel consumption – In the „high" phase of the 4 phases in the WLTC: B – tests of diluted exhaust gases in measurement bags BAG, MD – tests of diluted stream of exhaust gases (Modal DIL).

The coefficient of variation value for specific distance emission of carbon dioxide and operational fuel consumption was the smallest, and the coefficient of variation for organic compounds was the largest. The coefficient of variation for specific distance emission of carbon monoxide and nitrogen oxides and the number of particulate matter was similar.

A high value of the coefficient of variation of the specific distance emission of organic compounds and the specific distance number of particulate matter was observed. The value of the specific distance emission of carbon monoxide and nitrogen oxides was significantly lower, and the lowest was found for carbon dioxide and operational fuel consumption.

Very high repeatability was found for the specific distance emission of hydrocarbons using the method of tests of diluted exhaust gases in measurement bags, as well as for the specific distance emission of non-methane hydrocarbons determined by the method of diluted stream of exhaust gases.

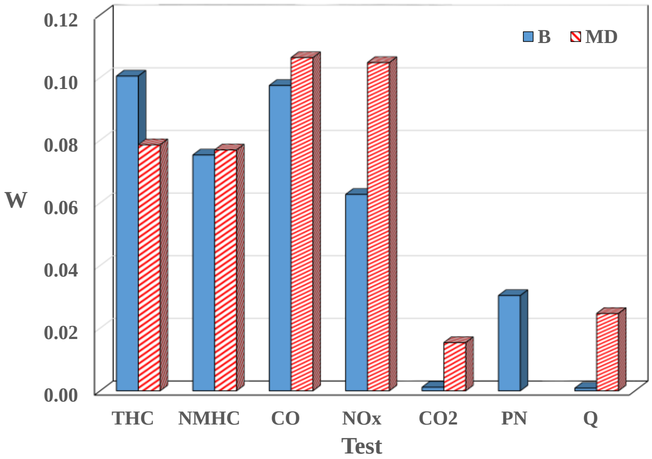

Fig. 16. Coefficient of variation of specific distance emission of pollutants and specific distance number of particulate matter as well as operational fuel consumption – In the „extra high" phase of the 4 phases in the WLTC: B – tests of diluted exhaust gases in measurement bags BAG, MD – tests of diluted stream of exhaust gases (Modal DIL).

A large difference was found in the coefficient of variation of the specific distance emission of exhaust pollutants and the specific distance emission of particulate matter as well as the specific distance number of particulate matter depending on the test phases and measurement methods.

In general, it can be stated that the non-repeatability of the test results in the different phases of the WLTC test differed significantly. It is important to note that there are also significant differences when using different test methods.

6. Conclusions

As a result of the conducted tests, the following conclusions were made:

1. No significant effect of cold start on exhaust emission and fuel consumption was found. Only in the case of nitrogen oxide emission was the specific distance emission in the "low" phase slightly higher than in the other test phases. In the case of other measured substances, engine load was the decisive factor. This was particularly visible in the case of exhaust emission and the number of particulate matter.
2. The coefficient of variation of organic compound and particulate matter emission, as well as nitrogen oxides in high-speed phases, was the highest. The coefficient of variation of carbon dioxide specific distance emission and operational fuel consumption was the lowest.
3. No significant differences were found in the values of specific distance emission for: organic compounds, carbon monoxide, nitrogen oxides and carbon dioxide and operational fuel consumption, determined by the methods of: analysis of diluted exhaust gas components concentrations from measuring bags and continuous testing of diluted exhaust gas components.
4. Significant variations in the coefficient of variation values of the data obtained in different test phases was observed. No clear regularity was found in these variations.

It is considered advisable to continue works on measuring the repeatability of exhaust emission and fuel consumption test results in conditions other than standard tests – primarily in tests involving vehicle speed processes, which are the implementation of stochastic processes of vehicle speed processes in various conditions of their movement. This requires the implementation of very extensive empirical research programs. Research in real conditions of vehicle operation using PEMS systems could be of particular value, additionally for various cumulative categories of vehicles, not only passenger cars, but also light trucks, trucks, city and long-distance buses and category L vehicles (motorcycles, mopeds, quads and microcars).

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Nomenclature

AV – average values

B – diluted exhaust gases measurement from measuring bags BAG

b – road pollutant emissions/road particle number

BAG – measuring bags

CO – carbon monoxide

CO2 – carbon dioxide

D – standard deviation

MD – continuous measurement of a diluted exhaust stream (Modal DIL)

NMHC – non-methane hydrocarbons

NOx – nitrogen oxides

PM – particulate matter

PN – particle number

Q – fuel consumption

t – time

THC – hydrocarbons

v – vehicle speed

W – coefficient of variation

WLTC – Worldwide Harmonized Light Vehicles Test Cycle