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Correlation relationships of processes in the combustion engine in the RDE test

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The article presents considerations on the processes taking place in the combustion engine in the real driving operating conditions of a vehicle performing the RDE (Real Driving Emissions) test. The tests were carried out using a passenger car with a spark-ignition engine. The processes considered in the article were related to the engine operating states, exhaust emissions and fuel mass consumption, and the vehicle velocity, which determines the engine operating conditions. The RDE test was carried out using PEMS (Portable Emissions Measurement System) equipment, and the following variables were recorded: vehicle velocity, control, engine speed, relative torque and relative engine power, emission pollutant intensity of carbon monoxide, hydrocarbons, nitrogen oxides and carbon dioxide, the intensity of particle number and the fuel mass consumption intensity. The recorded signals were digitally processed, and the statistical properties of the variables and the mutual relation between the engine operating states were examined. The properties of the measured variables were investigated in the entire RDE test and in its constituent phases: the first, corresponding to vehicle traffic in cities, the second – outside cities, and the third – on highways and expressways. The pollutant specific distance emission and the particle number specific distance as well as the specific distance fuel mass consumption were determined in relation to the average vehicle velocity, and based on these results, the exhaust emissions and fuel mass consumption characteristics were created. Correlational studies of the considered variables were also performed. Pearson's linear correlation coefficients for the combinations of the measured variables were determined.

Key words: *correlation, Real Driving Emissions test (RDE), pollutant emission, fuel mass consumption, engine operating states*

1. Introduction

The processes occurring in combustion engines, characterizing their exhaust emissions and fuel mass consumption, are among the basic operational properties of engines [11, 12, 17]. These processes are determined by the engine operating states: control, engine speed, load, which can be measured using torque, and the engine's thermal state [11, 12, 17].

The operating states of a vehicle engine are determined by the vehicle's velocity and traffic resistance, which depend on, among others, the type and inclination of the road surface, as well as on the vehicle velocity, environmental conditions and temperature, which primarily influence the time it takes for the engine to reach a thermally stable state after an engine cold start [11, 12, 17].

In dynamic operating conditions, the relationship between the operational properties of combustion engines and their operating states takes the form of operators (or more specifically, the form of functionals) [11, 12, 17], and not as functions with numerical values [7]. For this reason, these properties generally differ under all conditions, making it necessary to test the engines under comparable conditions, in the case of automotive applications, determined by the vehicle velocity. Of course, the actual operating conditions of combustion engines are largely undetermined and, as a consequence, the operational properties in such conditions should be generally treated as random [9, 28, 29]. In such a case, probabilistic characterization of these variables can be assessed, such as probability density [9, 28, 29] or frequency characteristics [9, 28, 29].

This study aimed to assess the following:
- vehicle velocity
- engine steering
- engine speed
- relative engine torque
- relative effective power
- emission pollutant intensity of carbon monoxide, hydrocarbons, nitrogen oxides and carbon dioxide
- particle number intensity
- fuel mass consumption intensity

in the driving conditions of a passenger car in the RDE (Real Driving Emissions) test [20, 39], the phases of which characterize the vehicle's traffic: in cities, outside cities and on highways and expressways.

The nature of vehicle traffic in the RDE test corresponds to typical conditions of vehicle operation. Such conditions are taken into account in the pollutant emission assessment [21], which additionally considers driving in cities separately between driving in cities with traffic congestion and driving in cities without traffic congestion [8].

The aim of this research was to learn about selected properties of the studied processes. These properties were primarily:
- statistical characteristics of the measured variables [9, 25], in particular:
  - average value considering the test phases
  - their distribution characteristics
  - coefficient of variation, enabling the assessment of dynamic properties while taking into account test phases
- characteristics of pollutant specific distance emission, particle number specific distance and specific distance fuel mass consumption of the vehicle depending on the

average velocity in individual test phases and throughout the whole test
- Pearson's linear correlation coefficient [30, 31] of the combination of measured variables.

These properties were examined for the entire test and for individual test phases. Such tests were intended to enable the assessment of the sensitivity of variable properties to changes in vehicle operating conditions.

The innovative aspect of the conducted study is the fact that testing the measured variables properties was possible based on test results in a single test, unlike the commonly used standards for assessing the variable properties, engine operating conditions, exhaust emissions, and fuel mass consumption, which normally require obtaining data from multiple tests, corresponding to the variety of vehicle operating conditions [1, 2, 10, 18, 23].

Of particular note were the correlation studies [13–16] of variables characterizing exhaust emissions and fuel mass consumption, as well as variables of engine operating states and the vehicle velocity that determines them. The goal of these studies was to assess the interdependence of these values, which is particularly important when attempting to reduce the exhaust emissions of all pollutants and fuel mass consumption.

2. Literature review

Research of combustion engines properties in RDE tests has been the subject of many publications [3–6, 12, 22, 26, 33, 38]. The amount of new research increased over the recent years, thanks mainly to the introduction of portable exhaust emission testing equipment [32], which enabled previously unheard-of possibilities for testing vehicles in real operating conditions [36, 37].

Papers [3–5] present the research results of vehicle velocity, the operating states of the internal combustion engine and the processes characterizing the exhaust emissions in the RDE test, carried out in real driving conditions of the vehicle. The engine properties were tested in static and dynamic states. The obtained results confirmed that dynamic states have a greater influence on engine exhaust emissions.

The research results presented in [6] were obtained in the NEDC (New European Driving Cycle) [21, 39] and the Malta test, developed at the Poznan University of Technology. These tests were performed on a chassis dynamometer. The exhaust emission results of carbon monoxide, hydrocarbons and nitrogen oxides were provided relative to the static and dynamic states of the combustion engine. Dynamic states were determined depending on the value of the positive or negative derivative of torque and engine speed with respect to time. It was found that the impact of dynamic states on the exhaust emissions was greater in the Malta test, which was due to the fact that this test was based on a faithful simulation of velocity in the time domain.

Paper [12] concluded that internal combustion engines, as systems described by nonlinear models, do not have any properties that would not depend on their current state. The study contains the test results of a vehicle engine in dynamic states determined by the value of vehicle acceleration in vehicles driving tests simulating the real operation of passenger cars. During the tests, exhaust emissions and fuel mass consumption values were averaged for individual vehicle states. It was found that the investigated processes were very sensitive to both dynamic states and the type of vehicle driving tests performed.

The RDE testing procedure, tested in [22], included: vehicle selection and preparation, route design, route implementation, route verification and calculation of values characterizing the exhaust emissions, pollutant specific distance emission and the particle number specific distance.

Paper [26] presents the results of a four-cylinder turbocharged compression-ignition engine tests, belonging to the Euro 6 category, with a rated power of 126 kW. The tests, conducted on an engine dynamometer, were simulating the engine operating states in a light truck in the RDE test. The emissions of carbon monoxide, hydrocarbons, nitrogen oxides and carbon dioxide were measured. A procedure was developed to test the responsivity of engine properties to engine operating states depending on the driver's behavior.

The aim of [33] was to assess energy consumption and exhaust emissions from passenger cars equipped with various drive systems in real operation. Passenger cars with combustion engines of various emission classes, as well as the latest hybrid vehicles and electric vehicles, were used in the tests. This enabled a comparative assessment of energy consumption in various road traffic conditions, with particular emphasis on the urban phase, as well as the entire RDE test. The test results were analyzed to identify changes in fuel mass consumption and exhaust emissions that could be assigned to the technological progress of the vehicles.

The paper [38] describes the use of the Moving Average Window Method (MAW) and the load-averaging method to process the emission results of a light truck and its combustion engine in the RDE test. Empirical tests were carried out using a fleet of 10 vehicles. The use of both methods of averaging measurement results produced comparable results.

Correlational studies have a very extensive literature covering a wide range of applications, especially in medicine and genetics [19, 24, 27, 35]. Regarding the operational properties of combustion engines, however, the literature is relatively poor [13–16].

Authors of the paper [13] stated their goal was to examine the relationship between the emission of individual exhaust components (carbon monoxide, hydrocarbons, nitrogen oxides and carbon dioxide), fuel mass consumption and various dynamic conditions of engine operation. Empirical data was obtained by testing a passenger car with a spark-ignition engine on a chassis dynamometer in 12 different driving tests, both type approval and special tests. The results indicated that the strongest correlation occurred between carbon dioxide and hydrocarbon emissions and between fuel mass consumption and hydrocarbon and carbon dioxide emissions. The weakest correlation was found between carbon monoxide and nitrogen oxide emissions. The appropriate dimensionless characteristic of dynamic driving conditions turned out to be the average vehicle velocity. The correlation between hydrocarbon emissions and the average vehicle velocity was considered to be the strongest, while the correlation between nitrogen oxide emissions and the average vehicle velocity was found to be the weakest.

The correlation studied in [14] was between the emission pollutant intensity and the operating conditions of A spark-ignition engine in a passenger car was tested on a chassis dynamometer in many dynamic tests, both type approval and special tests. The engine properties were studied in various static and dynamic states.

The general conclusion was that similar relationships and correlations that occur for carbon monoxide emissions were also present for hydrocarbon emissions.

Research results obtained in the paper [15] concern exhaust emissions from the compression-ignition engine of a light truck. The tests were carried out using a vehicle on a chassis dynamometer in the ECE R83 test with a warm engine start. The values of emission pollutant intensity were recorded, followed by a correlation analysis. The theories of Pearson, Spearman, Kendall and Kruskal were used in the study. The analysis showed a clear correlation between the tested variables. The probability of accepting the hypothesis of there being no correlation was zero, with an accuracy of at least six decimal places. The exception was the correlation test between carbon monoxide and carbon dioxide emission pollutant intensity, for which the probability of accepting the no-correlation hypothesis was approximately 5% at most.

Paper [16] presents the exhaust emission test results depending on the engine operating states that determine the emissions. The tests were carried out on an engine dynamometer using a Cummins 6C8.3 compression ignition engine under NRTC (Non-Road Transient Cycle) test conditions. Pearson's linear correlation, Spearman's rank correlation, Kruskal's gamma correlation and Kendall's tau correlation theory were used to analyze the correlation between the studied datasets. The obtained results indicated that it was statistically justified to treat the examined pairs of datasets of physical quantities as strongly correlated. Moreover, it was found that the values of the engine operating states had a similar impact on the emission pollutant intensity of carbon monoxide and hydrocarbons, while their impact on the emission pollutant intensity of nitrogen oxides was completely different. When it comes to carbon monoxide and hydrocarbon emissions, the factor with the greatest influence was found to be the engine speed. The engine torque and useful power had the greatest impact for nitrogen oxide emissions.

The reviewed available literature indicated that so far there was a small number of publications on the study of the properties of vehicle velocity, engine operating states, exhaust emissions and fuel mass consumption due to their statistical properties and mutual correlation relationships, especially in real operating conditions of vehicles.

3. Method

The research method consisted of:

1. Carrying out empirical tests of a passenger car in real driving conditions in the RDE test.
   Measuring and recording the data for:
   - vehicle velocity
   - engine steering
   - engine speed
   - relative engine torque
   - relative effective power
   - emission pollutant intensity: carbon monoxide, hydrocarbons, nitrogen oxides and carbon dioxide
   - particle number intensity
   - fuel mass consumption intensity.
2. Processing the obtained raw results of empirical tests to remove gross errors and reducing the share of high-frequency noise in the recorded signals thanks to the use of low-pass filtering. A second-stage Savitzky-Golay filter was used for filtration [34].
3. Studying the relationships between engine operating states, such as engine steering, engine speed, relative engine torque, and relative effective power, throughout the test and in its individual phases.
4. Determination of the pollutant specific distance emission, the particulate matter number specific distance and the specific distance fuel mass consumption of the vehicle throughout the test and in its individual phases.
5. Correlation studies of the following processes: engine operating states, intensity of emission pollutant, particle number intensity and fuel mass consumption intensity of the vehicle.
6. Formulation conclusions based on research results.

Engine steering in automotive applications is the relative value of the vehicle's engine steering setting, i.e. the engine steering pedal (accelerator pedal).

Relative torque is defined as the ratio of torque and torque on the external characteristic for the same engine speed.

Similarly, the relative effective power is the ratio of the resultant power to the net power on the external characteristic for the same engine speed.

The individual phases of the RDE test are:

- first phase, corresponding to urban driving – labelled – RDE – U
- second phase, corresponding to extra-urban driving – labelled – RDE – R
- third phase, corresponding to driving on motorways and expressways – labelled – RDE – H.

The test vehicle was a passenger car with a four-cylinder turbocharged spark-ignition engine, equipped with an automatic transmission. The engine was of the Euro 6 AP emissions class [20, 39].

Tests in real driving conditions in the RDE test were carried out using PEMS equipment [32]. A Semtech DS analyzer [36] and a TSI 3090 EPSS™ (Engine Exhaust Particle Sizer™ Spectometer) analyzer [37] were used to measure the exhaust emissions.

The equipment used in the tests was in line with the approval procedures requirements.

4. Test results

Figures 1–11 present the results of empirical research filtered with a low-pass filter.

Figure 1 shows the vehicle velocity in the RDE test.

In the first part (0–3732 s), the driving velocity was typical of urban driving. The average velocity was 24.3 km/h, and the maximum velocity was measured at 58.9 km/h. Between the time points 3732 s and 5469 s, the driving conditions resembled those on city outskirts, or suburban areas. The average velocity of the vehicle was 57.7 km/h and the maximum velocity was measured at 85.1 km/h. The third driving phase corresponded to motorway and expressway driving at (5469 –6000s). The average velocity in the third test phase was 107.2 km/h, and the maximum velocity was measured at 118.9 km/h. The average velocity throughout the test was 41.3 km/h. The variation coefficient of velocity was the highest in the first test phase – and equalled 0.73, in the second phase it was 0.37. In the third it reached 0.13, and the test average was 0.76.

Figure 2 shows the engine steering in the RDE test.

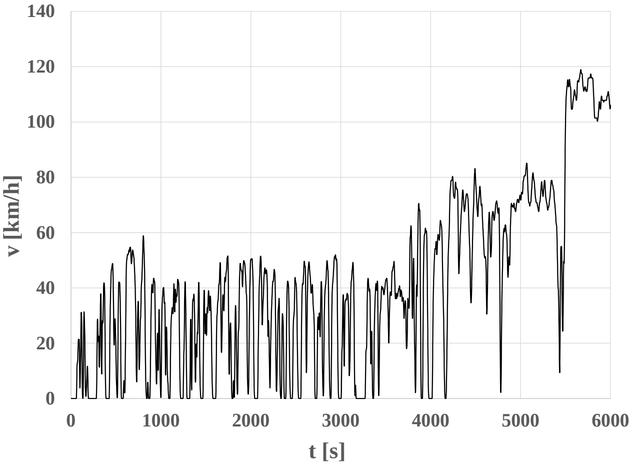

Fig. 1. Vehicle velocity in the RDE test

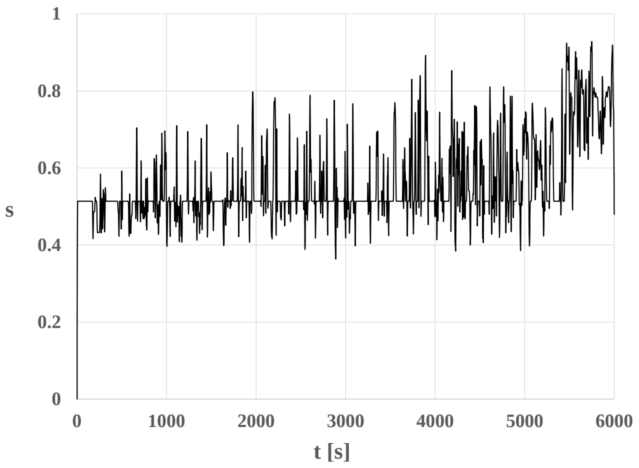

Fig. 2. Engine steering in the RDE test

The average steering value was 0.56, the maximum value was 0.96, and the coefficient of variation was 0.18. The most dynamic properties of the steering process were observed in the second phase of the test – the coefficient of variation was 0.17, while in the first phase it was 0.11, and in the third phase – 0.10.

Figure 3 shows the engine speed in the RDE test.

The engine speed is characterized by high variability. The coefficient of variation of the engine speed in the test was 1.08, in the first phase – 1.39, in the second – 0.79, and in the third – 0.18, so the least dynamic properties of the engine speed could clearly be found in the third test phase.

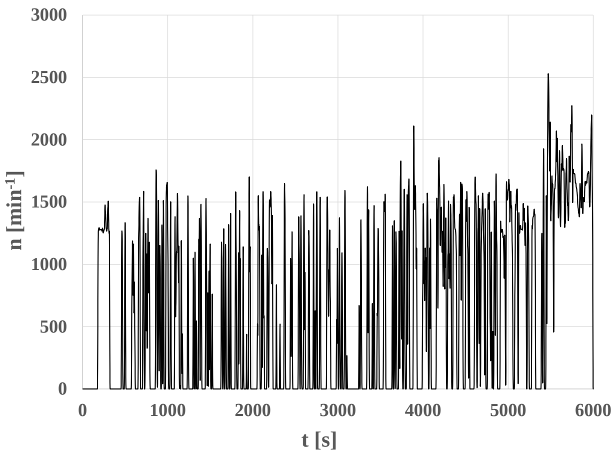

Fig. 3. Engine speed in the RDE test

Figure 4 shows the relative engine torque in the RDE test.

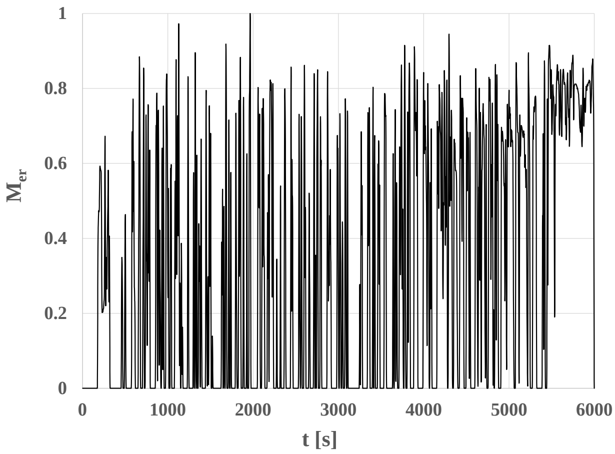

Fig. 4. Relative engine torque in the RDE test

The coefficient of variation of the relative torque in the test was 1.06, in the first phase – 1.38, in the second – 0.79, and in the third – 0.14. By far, the least dynamic properties of the relative torque were observed in phase three of the test.

Figure 5 shows the relative effective engine power in the RDE test.

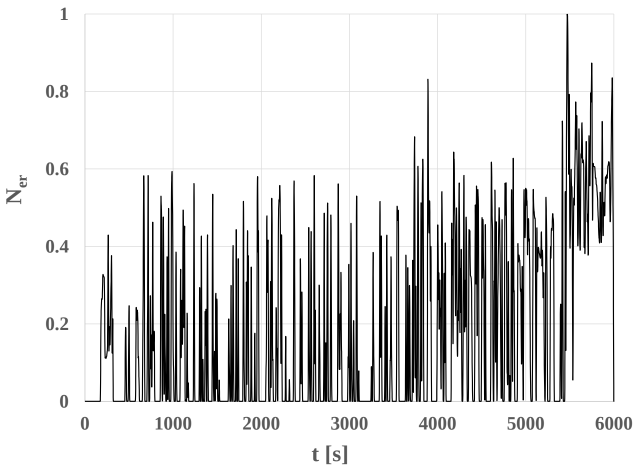

Fig. 5. Relative effective engine power in the RDE test

By far the highest average relative effective engine power was – understandably – in the third phase of the test. The coefficient of variation of the relative effective power in the test was 1.23 in the first phase – 1.59, in the second – 0.89, and in the third – 0.25.

Figures 6–9 present the emission pollutant intensity in the RDE test, and Fig. 10 – the particle number in the RDE test.

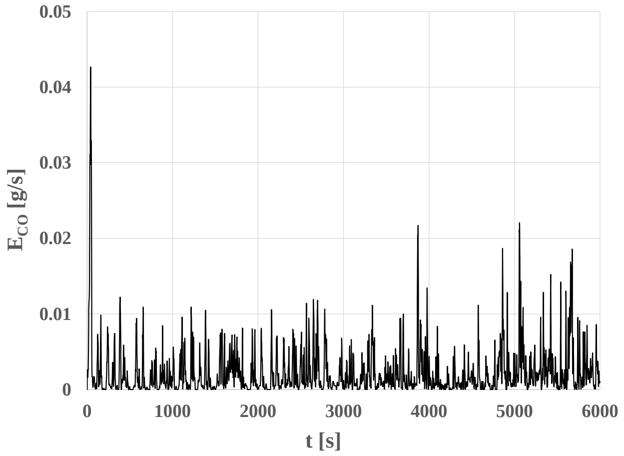

Fig. 6. Carbon monoxide emission pollutant intensity in the RDE test

The average carbon monoxide emission pollutant intensity in the test was 0.0023 g/s, in the first phase of the test – 0.0022 g/s, in the second – 0.0023 g/s, and in the third – 0.0031 g/s. No significant differences were found in the average carbon monoxide emission pollutant intensity value in individual test phases. The coefficient of variation of carbon monoxide emission pollutant intensity in the test was 1.46 in the first phase – 1.57, in the second – 1.33, and in the third – 1.17. The most dynamic properties of the carbon monoxide emission pollutant intensity occurred in the first phase of the test, which was related to the cold start of the engine.

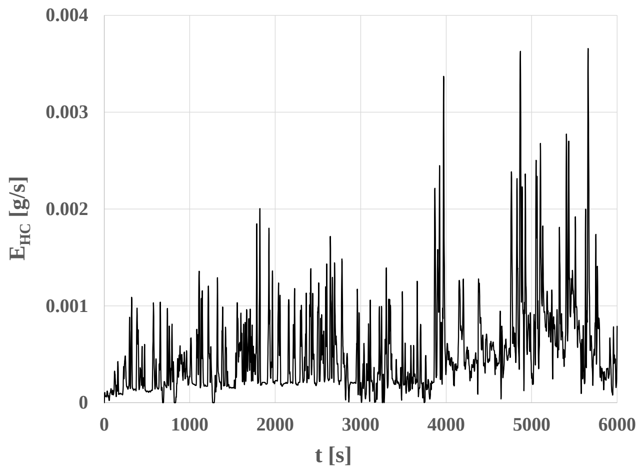

Fig. 7. Hydrocarbon emission pollutant intensity in the RDE test

The average hydrocarbon emission pollutant intensity in the test was 0.00050 g/s, in the first phase of the test – 0.00037 g/s, in the second – 0.00075 g/s, and in the third – 0.00067 g/s. The coefficient of variation of the hydrocarbon emission pollutant intensity in the test was 0.89 in the first phase – 0.82, in the second – 0.74, and in the third – 0.82. No significant differences were found in the coefficient of variation values of the hydrocarbon emission pollutant intensity in individual test phases nor in the test as a whole.

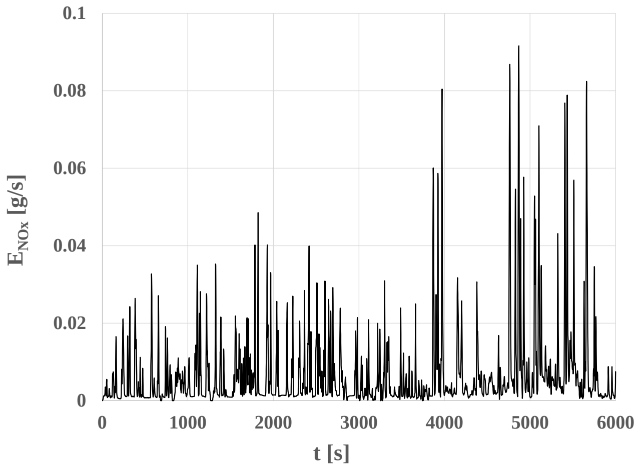

Fig. 8. Nitrogen oxides emission pollutant intensity in the RDE test

The average nitrogen oxide emission pollutant intensity in the test was 0.0067 g/s, in the first phase of the test – 0.0051 g/s, in the second – 0.0096 g/s, and in the third – 0.0074 g/s. The coefficient of variation of nitrogen oxide emission pollutant intensity in the test was 1.57, in the first phase – 1.28, in the second – 1.55, and in the third – 1.66. The lowest average value of the nitrogen oxide emission pollutant intensity was observed in the first phase of the test for the lowest engine load, which was related to the lowest driving velocity in this phase.

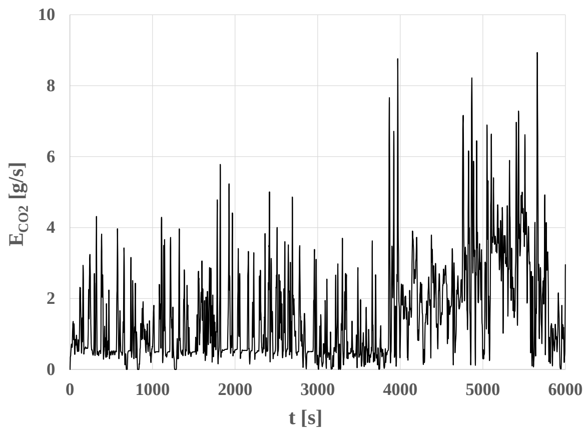

Fig. 9. Carbon dioxide emission pollutant intensity in the RDE test

The average carbon dioxide emission pollutant intensity in the test was 1.51 g/s, in the first phase of the test – 1.00 g/s, in the second – 2.42 g/s, and in the third – 2.07 g/s. The relatively high average value of the carbon dioxide emission pollutant intensity in the first phase of the test was related to the high fuel mass consumption resulting from A cold engine starts. The coefficient of variation of carbon dioxide emission pollutant intensity in the test was 0.89, in the first phase – 0.87, in the second – 0.63, and in the third – 0.80.

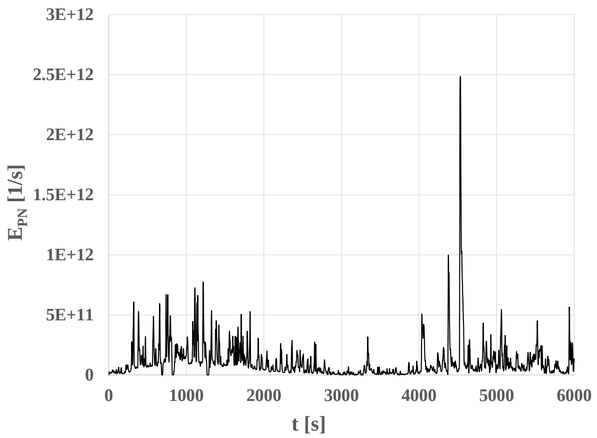

Fig. 10. Particle number intensity in the RDE test

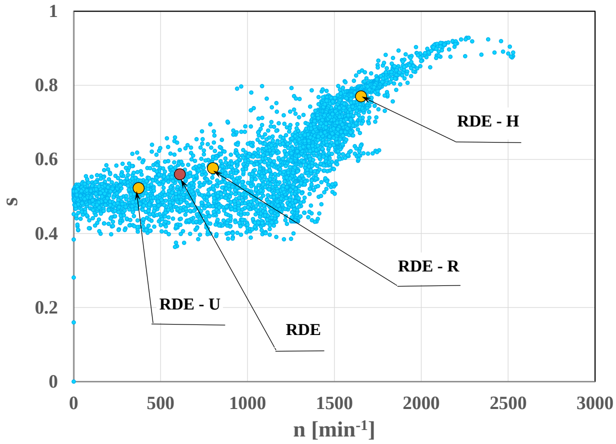

Fig. 12. Relationship between engine steering and engine speed in the RDE test

The average particulate number intensity in the test was 1.091E+11 1/s, in the first phase of the test – 1.0044E+11 1/s, in the second phase – 1.313E+11 1/s, and in the third phase – 9.714E+10 1/s. No significant differences in the average particle number intensity values was found in the individual test phases. The coefficient of variation of particulate number intensity in the test was 1.51, in the first phase – 1.31, in the second – 1.91, and in the third – 0.96.

Figure 11 shows the vehicle fuel mass consumption intensity in the RDE test. The average fuel mass consumption intensity of the vehicle in the test was 0.57 g/s, in the first phase of the test – 0.40 g/s, in the second – 0.89 g/s, and in the third – 0.69 g/s. The coefficient of variation of the fuel mass consumption intensity of the vehicle in the test was 0.81 in the first phase – 0.73, in the second – 0.59, and in the third – 0.80.

The carbon dioxide emission pollutant intensity and the fuel mass consumption intensity were approximately linearly related.

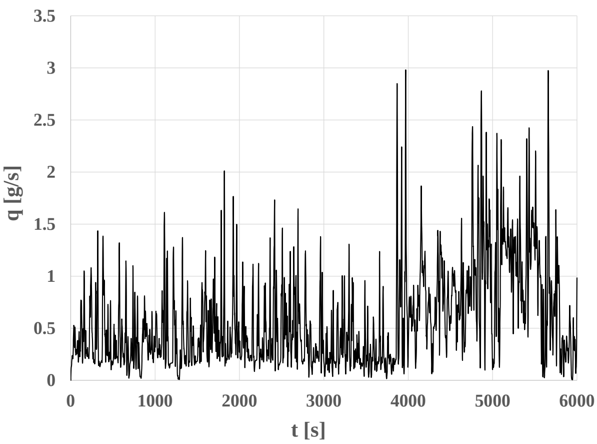

Fig. 11. Fuel mass consumption intensity of the vehicle in the RDE test

5. Results analysis

Figures 12–15 show the relationships between the engine operating states in the RDE test. The average values were marked on the charts: for the whole test the point was labelled as RDE, for the first phase, corresponding to urban driving – RDE – U, for the second phase, corresponding to driving in rural areas – RDE – R, and for the third phase corresponding to motorway and highway driving – RDE – H.

The relationship between engine operating states in the RDE test and the engine speed was similar for: engine steering, relative torque and relative effective power. The sets of operating states were characterized by significant dispersion, which resulted from the large coefficient of variation, as shown in Fig. 2–5. For all variables in Fig. 12–14, both the independent variables and the dependent variables, their average values were typically the smallest for the first phase, slightly larger for the whole test, even larger for the second phase and the largest for the third phase.

Table 1 presents the statistical characteristics [25] of the vehicle velocity, pollutant specific distance emission, particle number specific distance and specific distance fuel mass consumption for the test as well as for its individual phases. The tables contain the following dimensionless statistical characteristics:

- Min – minimum value
- Max – maximum value
- R – range
- AV – average value
- M – median
- D – standard deviation
- K – kurtosis
- S – skewness
- W – coefficient of variation.

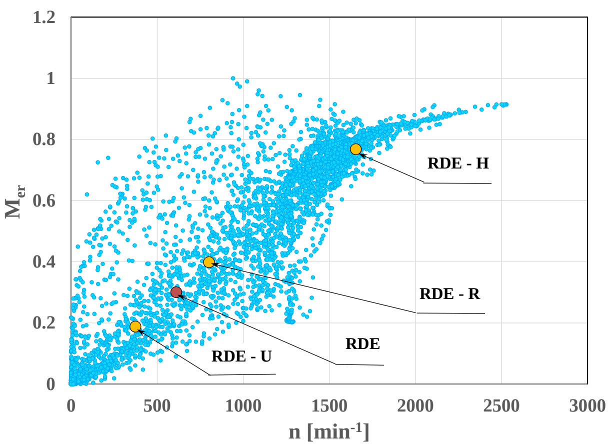

Fig. 13. The relative engine torque vs the engine speed in the RDE test

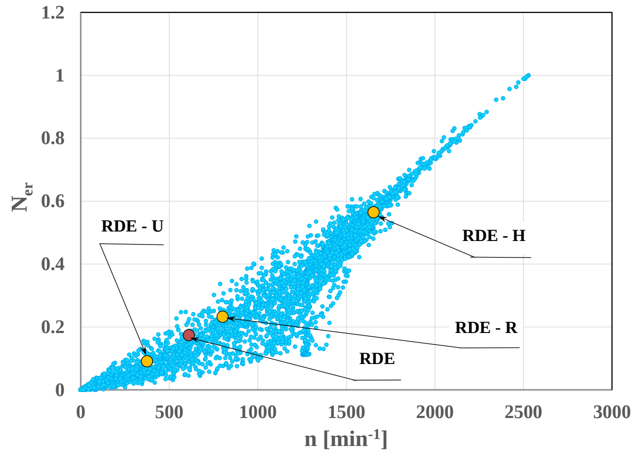

Fig. 14. Relative effective engine power vs engine speed in the RDE test

Very large statistical differences were found in vehicle velocity, engine operating states and emission pollutant intensity, particle number intensity and fuel mass consumption intensity of the vehicle. Significant differences were also noted between the results of the whole test and its individual phases.

It should be noted that:

– the distributions of the emission pollutant intensity and the particle number intensity as well as the fuel mass consumption intensity of the vehicle throughout the test and in its individual phases were viscokurtic
– vehicle velocity distributions were leptokurtic in individual test phases, and their distribution was platykurtic throughout the test as a whole
– the distributions of exhaust emissions, particulate number and fuel mass consumption of the vehicle throughout the test and in its individual phases were characterized by left-sided asymmetry
– in the case of vehicle velocity and internal combustion engine operating states, there was a significant variation in distribution asymmetry throughout the test and in its individual phases
– the coefficients of variation values for the nitrogen oxide emission pollutant intensity and the particle number intensity were the highest, which proves the strongest dynamic properties of these variables

Table 1. the statistical characteristics of the tested variables for the test as well as for its individual phases

	v	s	n	M_{er}	N_{er}	E_{CO}	E_{HC}	E_{NOx}	E_{CO2}	E_{PN}	q_F
	km/h		min^{-1}			g/s	g/s	g/s	g/s	1/s	g/s
RDE											
Min	0	0	0	0	0	0	0	0	0	0	0
Max	118.9	0.93	2529	1	1	0.043	0.0037	0.092	8.93	2.49E+12	2.98
R	118.9	0.93	2529	1	1	0.043	0.0037	0.092	8.93	2.49E+12	2.98
AV	41.3	0.56	611	0.30	0.17	0.002	0.0005	0.007	1.51	1.09E+11	0.57
M	38.6	0.51	312	0.17	0.05	0.001	0.0004	0.003	1.02	6.62E+10	0.42
D	31.4	0.10	659	0.32	0.21	0.003	0.0005	0.010	1.35	1.65E+11	0.46
K	–0.23	1.49	–1.26	–1.43	–0.11	32.68	8.71	18.69	3.05	76.19	2.69
S	0.60	1.35	0.51	0.46	1.00	4.41	2.41	3.82	1.57	6.85	1.49
W	0.76	0.18	1.08	1.06	1.23	1.46	0.90	1.57	0.89	1.51	0.81
RDE – U											
Min	0	0	0	0	0	0	0	0	0	0	0
Max	58.9	0.80	1758	1	1	0.043	0.0020	0.049	5.78	7.74E+11	2.01
R	58.9	0.80	1758	1	1	0.043	0.0020	0.049	5.78	7.74E+11	2.01
AV	41.3	0.56	611	0.30	0.17	0.002	0.0005	0.007	1.51	1.09E+11	0.57
M	66.0	0.53	963	0.49	0.23	0.001	0.0006	0.004	2.25	6.72E+10	0.83
D	21.3	0.10	632	0.31	0.21	0.003	0.0006	0.015	1.52	2.50E+11	0.53
K	0.97	0.10	–1.52	-1.61	–1.03	12.16	4.68	9.21	1.34	45.41	0.86
S	–1.33	0.81	–0.10	-0.14	0.32	3.06	1.97	2.97	0.95	6.06	0.80
W	0.52	0.17	1.04	1.04	1.19	1.35	1.10	2.25	1.01	2.29	0.93
RDE – R											
Min	0	0.38	0	0	0	0	0	0	0	2.09E+07	0.02
Max	85.1	0.92	2460	1	1	0.022	0.0036	0.092	8.76	2.49E+12	2.98
R	85.1	0.54	2460	1	1	0.022	0.0036	0.092	8.76	2.49E+12	2.96
AV	57.7	0.58	801	0.40	0.23	0.002	0.0007	0.010	2.42	1.31E+11	0.89
M	66.0	0.53	963	0.49	0.23	0.001	0.0006	0.004	2.25	6.72E+10	0.83
D	21.3	0.10	632	0.31	0.21	0.003	0.0006	0.015	1.52	2.50E+11	0.53
K	962	923	885	846	808	769	730	692	653	615	24377
S	–1.33	0.81	–0.10	–0.14	0.32	3.06	1.97	2.97	0.95	6.06	0.80
W	0.37	0.17	0.79	0.79	0.89	1.33	0.74	1.55	0.63	1.91	0.59
RDE – H											
Min	24.8	0.5	0	0	0	0	0.0001	0	0.02	1.05E+10	0.01
Max	118.9	0.93	2529	1	1	0.019	0.0037	0.082	8.93	5.65E+11	2.97
R	94.2	0.45	2529	1	1	0.019	0.0036	0.082	8.92	5.54E+11	2.97
AV	107.2	0.77	1654	0.77	0.56	0.003	0.0007	0.007	2.07	9.71E+10	0.69
M	109.8	0.78	1654	0.80	0.57	0.002	0.0005	0.003	1.63	6.77E+10	0.54
D	14.2	0.08	300	0.11	0.14	0.004	0.0006	0.012	1.65	9.28E+10	0.55
K	1.10	0.39	–1.35	–1.60	–0.47	12.18	4.62	9.17	1.23	45.54	0.80
S	–3.80	–0.55	–1.10	–3.58	–0.26	1.96	2.51	3.54	1.16	1.83	1.16
W	0.13	0.10	0.18	0.14	0.25	1.17	0.82	1.66	0.80	0.96	0.80

– the relationship between the mean and median values of individual processes varied throughout the test and in its individual phases.

Such a significant variation in the dimensionless statistical characteristics of the emission pollutant intensity and the particle number intensity as well as the vehicle's fuel mass consumption intensity indicated a significant impact of the engine operating states, determined by the vehicle velocity, on these variables. In the case of the emission pollutant intensity and the particle number intensity, this was due to very low values of these quantities, sometimes near the determination limit.

Table 2 shows the vehicle's average velocity, pollutant specific distance emission, particle number specific distance and specific distance fuel mass consumption of the vehicle throughout the test and in its individual phases.

Table 2. Pollutant specific distance emission, particle number specific distance and specific distance fuel mass consumption of the vehicle throughout the test and in its individual phases

	v_{AV}	b_{CO}	b_{HC}	b_{NOx}	b_{CO2}	b_{PN}	q
	km/h	g/km				1/km	g/km
RDE	41.3	0.195	0.033	0.465	90.2	9.07E+12	36.02
RDE – U	24.3	0.332	0.056	0.789	153.1	1.54E+13	61.16
RDE – R	57.7	0.070	0.023	0.290	73.0	3.95E+12	26.87
RDE – H	107.2	0.015	0.003	0.037	10.2	4.81E+11	3.41

Figures 15–20 present the characteristics of pollutant specific distance emission, particle number specific distance and specific distance fuel mass consumption of the vehicle depending on the average speed in individual test phases and in the test as a whole. The datapoint sets were approximated with an exponential function. The approximating function was chosen due to the small number of points.

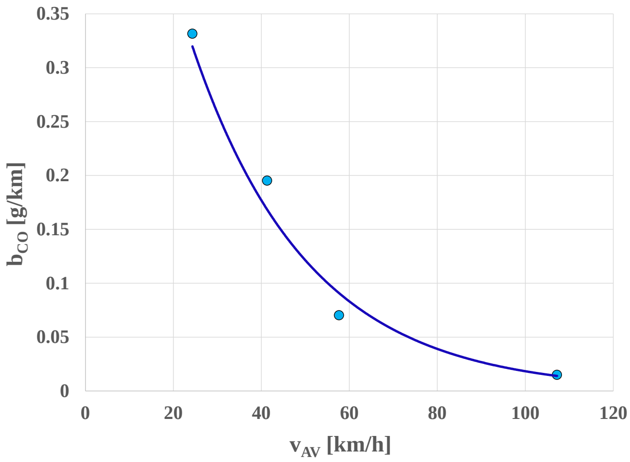

Fig. 15. Carbon monoxide pollutant specific distance emission relative to average velocity

The determined characteristics show a clear regularity, consistent with established knowledge, such as with characteristics created by conducting numerous empirical tests with different average velocity. Similar characteristics of exhaust emissions and fuel mass consumption are also commonly obtained using software such as HBEFA INFRAS [23] or COPERT [18].

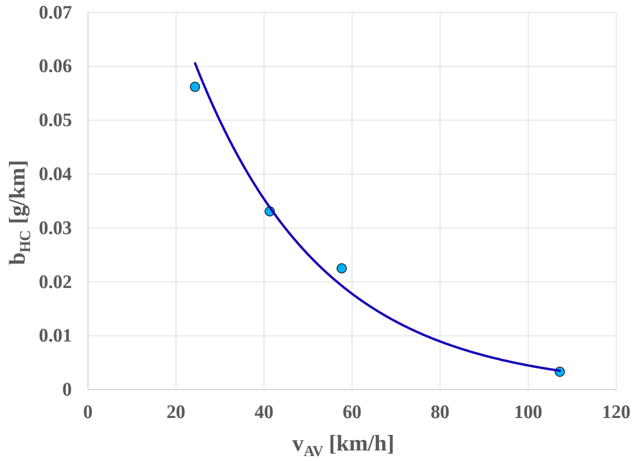

Fig. 16. Hydrocarbons pollutant specific distance emission relative to average velocity

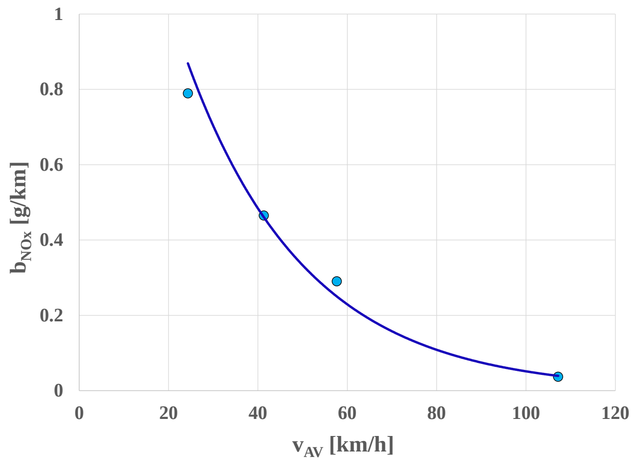

Fig. 17. Nitrogen oxides pollutant specific distance emission relative to average speed

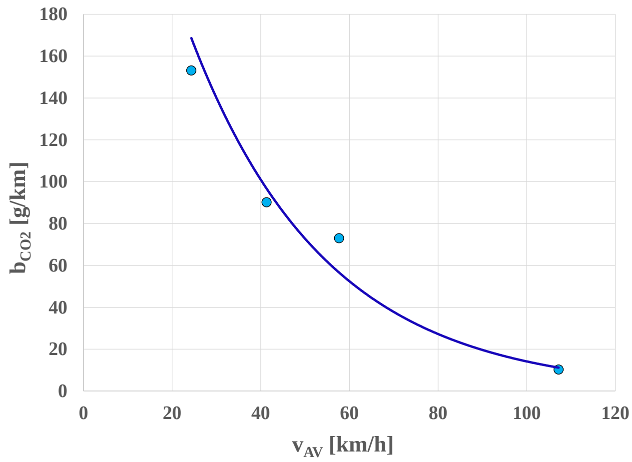

Fig. 18. Carbon dioxide pollutant specific distance emission relative to average velocity

Table 3 presents Pearson's linear correlation coefficients between the measured variables.

Figures 21–31 present Pearson's linear correlation coefficients between the measured variables. Figure 21 shows the correlation coefficient between the vehicle velocity and the other variables. The Pearson linear correlation coefficient of the vehicle velocity was the greatest, as would be expected, with the engine operating states – the largest value being with the engine steering (0.49).

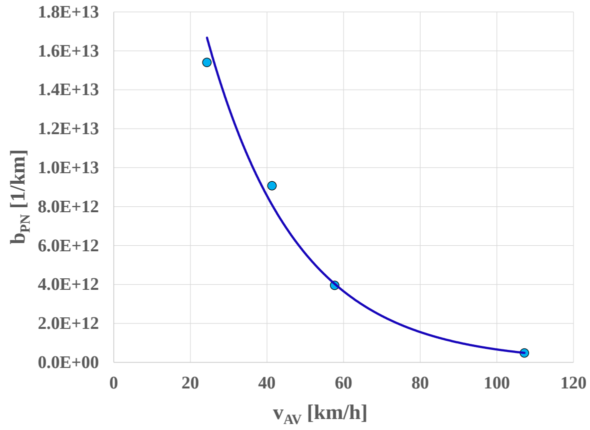

Fig. 19. Particle number specific distance emission relative to the average velocity

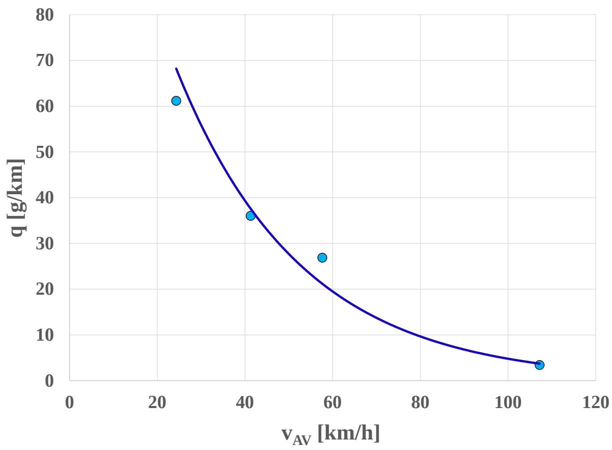

Fig. 20. Specific distance fuel mass consumption relative to average velocity

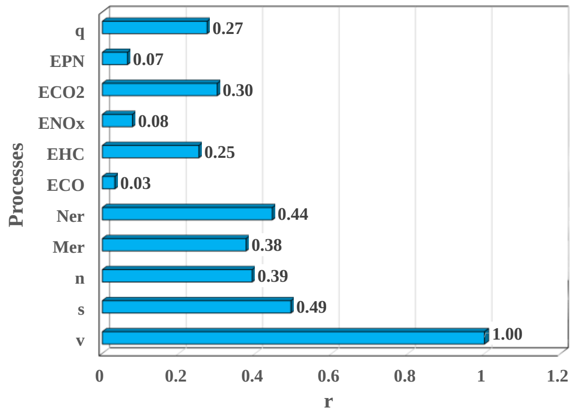

Fig. 21. Pearson's linear correlation coefficient of the vehicle velocity and the following variables: vehicle velocity, engine steering, engine speed, relative engine torque, relative engine effective power, engine fuel mass consumption intensity, emission pollutant intensity of: carbon monoxide, hydrocarbons, nitrogen oxides and carbon dioxide, and particle number intensity

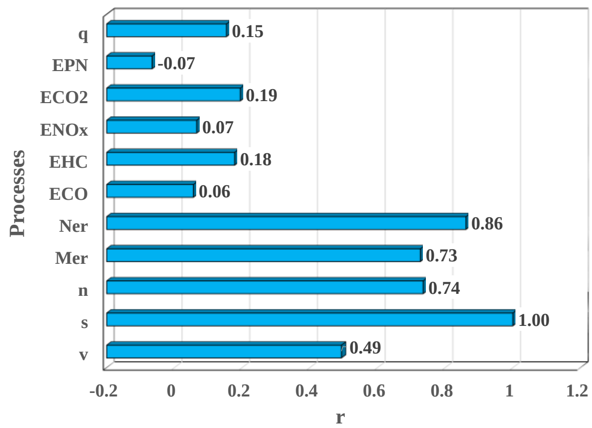

Fig. 22. Pearson's linear correlation coefficient of the engine steering and the following variables: vehicle velocity, engine steering, engine speed, relative engine torque, relative engine effective power, engine fuel mass consumption intensity, emission pollutant intensity of: carbon monoxide, hydrocarbons, nitrogen oxides and carbon dioxide, and particle number intensity

Figure 22 shows the linear correlation coefficient between engine steering and the other variables. The Pearson linear correlation coefficient values of the vehicle velocity with the emission pollutant intensity of carbon monoxide and nitrogen oxides as well as with the particle number intensity were the smallest – in all these cases the obtained correlation coefficients were less than 0.1.

The largest value of the Pearson linear correlation coefficient of the engine steering was for the engine operating states – the value of the correlation coefficient was greater than 0.7, then the value for the engine steering correlation was large also for the vehicle velocity – at almost 0.5. The correlation coefficient of the engine steering with the particle number intensity was the smallest and slightly negative (–0.07).

Table 3. Pearson's linear correlation coefficients between the measured variables

	v	s	n	M_{er}	N_{er}	E_{CO}	E_{HC}	E_{NOx}	E_{CO2}	E_{PN}	q
v	1.00	0.49	0.39	0.38	0.44	0.03	0.25	0.08	0.30	0.07	0.27
s	0.49	1.00	0.74	0.73	0.86	0.06	0.18	0.07	0.19	–0.07	0.15
n	0.39	0.74	1.00	0.94	0.96	–0.02	0.15	0.05	0.19	0.02	0.17
M_{er}	0.38	0.73	0.94	1.00	0.94	–0.02	0.16	0.05	0.19	0.00	0.16
N_{er}	0.44	0.86	0.96	0.94	1.00	0.00	0.17	0.05	0.21	0.00	0.17
E_{CO}	0.03	0.06	–0.02	–0.02	0.00	1.00	0.38	0.37	0.32	0.11	0.30
E_{HC}	0.25	0.18	0.15	0.16	0.17	0.38	1.00	0.91	0.93	0.27	0.90
E_{NOx}	0.08	0.07	0.05	0.05	0.05	0.37	0.91	1.00	0.81	0.25	0.79
E_{CO2}	0.30	0.19	0.19	0.19	0.21	0.32	0.93	0.81	1.00	0.30	0.98
E_{PN}	0.07	–0.07	0.02	0.00	0.00	0.11	0.27	0.25	0.30	1.00	0.30
q	0.27	0.15	0.17	0.16	0.17	0.30	0.90	0.79	0.98	0.30	1.00

Figure 23 shows the linear correlation coefficient between the engine speed and the other variables.

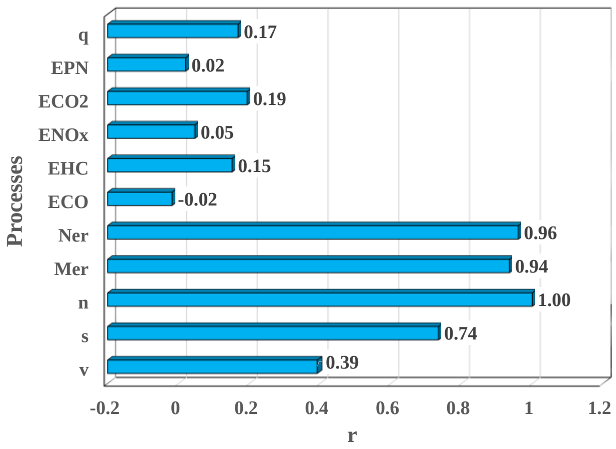

Fig. 23. Pearson's linear correlation coefficient of the engine speed and the following variables: vehicle velocity, engine steering, engine speed, relative engine torque, relative engine effective power, engine fuel mass consumption intensity, emission pollutant intensity of: carbon monoxide, hydrocarbons, nitrogen oxides and carbon dioxide, and particle number intensity

The largest Pearson linear correlation coefficient of the engine speed was found for the engine operating states, primarily for the relative effective power and relative torque – the value of the correlation coefficient for those was greater than 0.9, so the correlation can be considered very strong. The correlation between the engine speed and the engine steering was much weaker – the obtained correlation coefficient was less than 0.75. The weakest correlation was found between the engine speed and the emission pollutant intensity, particle number intensity and fuel mass consumption intensity. For carbon monoxide emission intensity, the correlation coefficient was slightly negative (–0.02).

Figure 24 shows the linear correlation coefficient between the relative engine torque and the other variables.

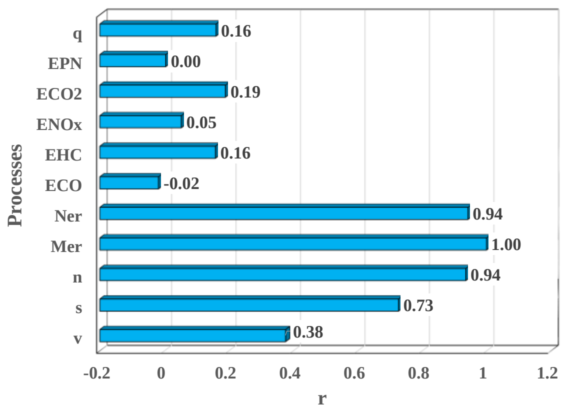

Fig. 24. Pearson's linear correlation coefficient of the engine torque and the following variables: vehicle velocity, engine steering, engine speed, relative engine torque, relative engine effective power, engine fuel mass consumption intensity, emission pollutant intensity of: carbon monoxide, hydrocarbons, nitrogen oxides and carbon dioxide, and particle number intensity

The largest Pearson linear correlation coefficient of the relative engine torque was found for the engine operating states, primarily with the engine speed and relative effective power – the coefficient value was calculated to be 0.94. The value of the correlation coefficient for engine steering was lower – at 0.73. The smallest correlation coefficient was, as in the case of engine speed, with the carbon monoxide emission intensity – in this case the correlation coefficient was slightly negative and reached –0.02.

Figure 25 shows the linear correlation coefficient between the relative effective power of the engine and the other variables.

The nature of the correlation coefficient of the relative effective power with the other variables was very similar to that of engine speed and relative torque.

Figures 26–29 present the linear correlation coefficients of emission intensity of pollutants and the other variables.

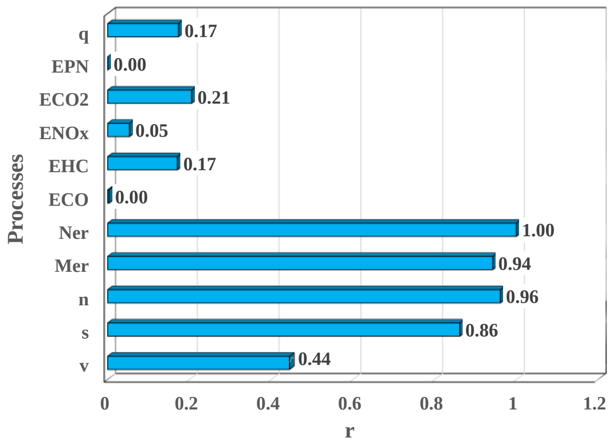

Fig. 25. Pearson's linear correlation coefficient of the engine relative effective power and the following variables: vehicle velocity, engine steering, engine speed, relative engine torque, relative engine effective power, engine fuel mass consumption intensity, emission pollutant intensity of: carbon monoxide, hydrocarbons, nitrogen oxides and carbon dioxide, and particle number intensity

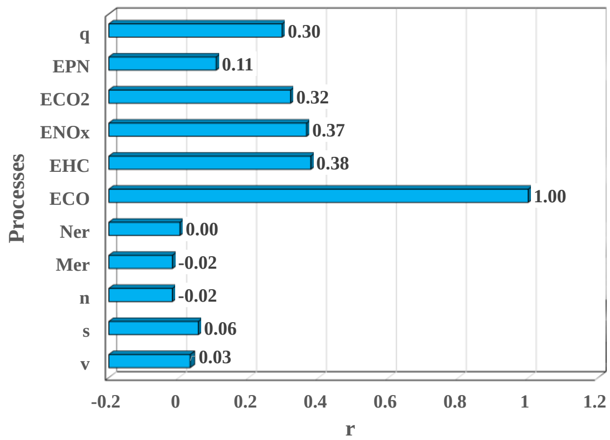

Fig. 26. Pearson's linear correlation coefficient of the carbon monoxide emission pollutant intensity and the following variables: vehicle velocity, engine steering, engine speed, relative engine torque, relative engine effective power, engine fuel mass consumption intensity, emission pollutant intensity of: carbon monoxide, hydrocarbons, nitrogen oxides and carbon dioxide, and particle number intensity

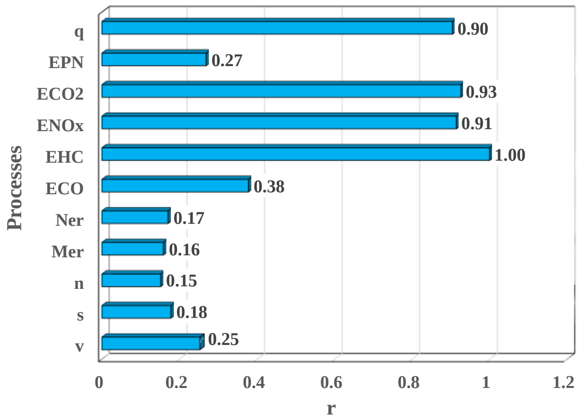

Fig. 27. Pearson's linear correlation coefficient of the hydrocarbon emission pollutant intensity and the following variables: vehicle velocity, engine steering, engine speed, relative engine torque, relative engine effective power, engine fuel mass consumption intensity, emission pollutant intensity of: carbon monoxide, hydrocarbons, nitrogen oxides and carbon dioxide, and particle number intensity

The values of the Pearson's linear correlation coefficients of the carbon monoxide emission pollutant intensity with the emission pollutant intensity of other substances and the fuel mass consumption intensity of the vehicle were similar. All were between 0.3–0.4. The correlation with the particle number intensity was much weaker – the value of the correlation coefficient was only 0.11. Moreover, the correlation between the carbon monoxide emission intensity and the engine operating states and vehicle velocity was very weak.

There was a very strong correlation between the hydrocarbon emission intensity and the emission pollutant intensity of nitrogen oxides, carbon dioxide and fuel mass consumption intensity – the value of the correlation coefficient was found to be greater than 0.9. The correlation with the carbon monoxide emission pollutant intensity was weaker – the correlation coefficient was equal to 0.38, and even weaker with the particle number intensity where the correlation coefficient was 0.27. The correlation of hydrocarbon emission intensity with engine operating states and the vehicle velocity was stronger than in the case of carbon monoxide emission intensity.

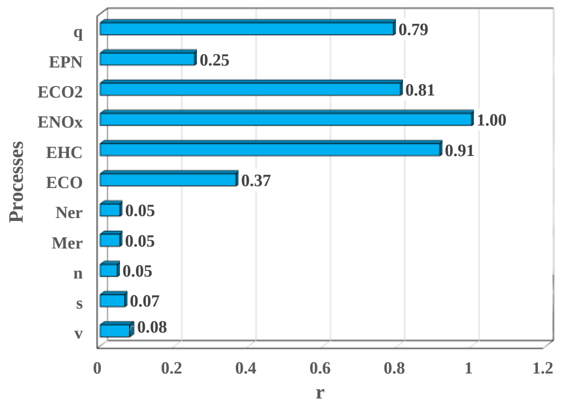

Fig. 28. Pearson's linear correlation coefficient of the nitrogen oxides emission pollutant intensity and the following variables: vehicle velocity, engine steering, engine speed, relative engine torque, relative engine effective power, engine fuel mass consumption intensity, emission pollutant intensity of: carbon monoxide, hydrocarbons, nitrogen oxides and carbon dioxide, and particle number intensity

The strongest correlation was observed between the nitrogen oxide emission intensity and the hydrocarbon and carbon dioxide emission intensity as well as with the fuel mass consumption intensity – the correlation coefficient values were between 0.8–0.9. The correlation of the nitrogen oxide emission intensity was stronger with the carbon monoxide emission intensity – the correlation coefficient value was 0.37 than with the particle number intensity (the correlation coefficient was 0.25).

Predictably, the strongest correlation was between the carbon dioxide emission intensity and the fuel mass consumption intensity of the vehicle – these processes are known to be approximately linearly related.

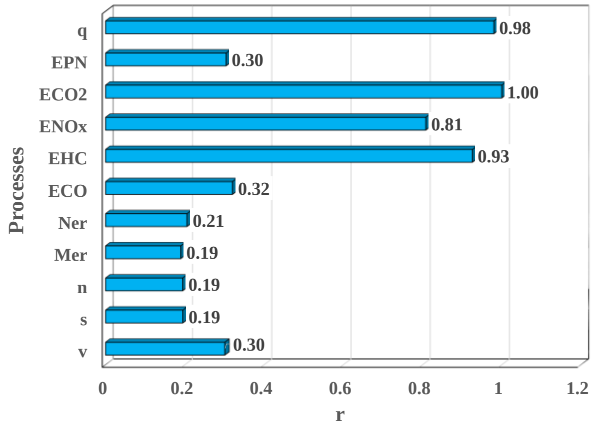

Fig. 29. Pearson's linear correlation coefficient of the carbon dioxide emission pollutant intensity and the following variables: vehicle velocity, engine steering, engine speed, relative engine torque, relative engine effective power, engine fuel mass consumption intensity, emission pollutant intensity of: carbon monoxide, hydrocarbons, nitrogen oxides and carbon dioxide, and particle number intensity

Figure 30 shows the linear correlation coefficient of the particle number intensity and the other variables. There was also a very strong correlation between the carbon dioxide emission intensity and the emission pollutant intensity of hydrocarbons and nitrogen oxides. The value of the correlation coefficient of the carbon dioxide emission intensity with both the carbon monoxide emission intensity and particle number intensity was 0.3. The value of the correlation coefficient of carbon dioxide emission intensity with engine operating states and the vehicle velocity was also similar – in the range of 0.2–0.3.

The value of the correlation coefficient of the particle number intensity with the emission pollutant intensity of carbon dioxide, hydrocarbons and nitrogen oxides, as well as the fuel mass consumption intensity was in the range of 0.25–0.3, lowest among them for the emission intensity of carbon monoxide (0.11). The correlation of the particle number intensity with the engine operating states and the vehicle velocity was very weak.

Figure 31 shows the linear correlation coefficient between the fuel mass consumption intensity and the other variables.

The nature of the correlation between the fuel mass consumption intensity of the vehicle and the other variables was understandably very similar to that of the carbon dioxide emission intensity that was strongly correlated with it.

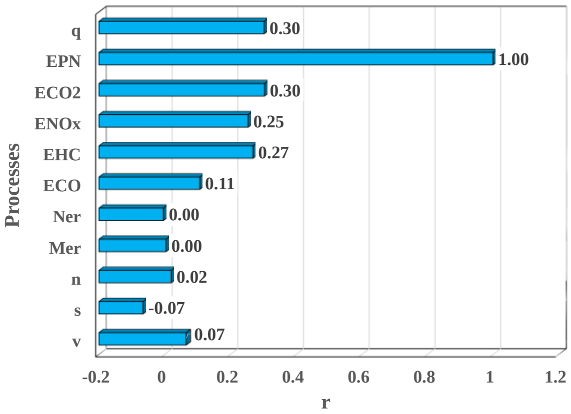

Fig. 30. Pearson's linear correlation coefficient of the particle number intensity and the following variables: vehicle velocity, engine steering, engine speed, relative engine torque, relative engine effective power, engine fuel mass consumption intensity, emission pollutant intensity of: carbon monoxide, hydrocarbons, nitrogen oxides and carbon dioxide, and particle number intensity

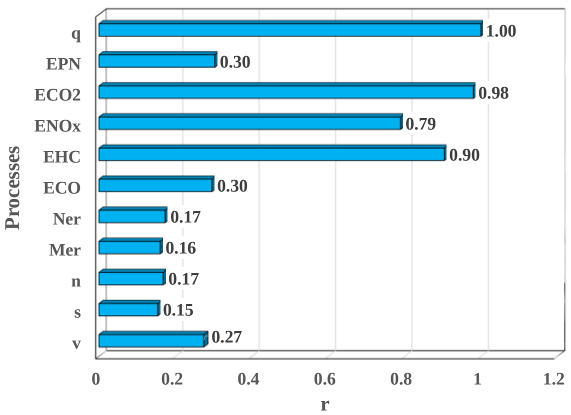

Fig. 31. Pearson's linear correlation coefficient of the engine fuel mass consumption intensity and the following variables: vehicle velocity, engine steering, engine speed, relative engine torque, relative engine effective power, engine fuel mass consumption intensity, emission pollutant intensity of: carbon monoxide, hydrocarbons, nitrogen oxides and carbon dioxide, and particle number intensity

Conclusions

Testing engines of road vehicles in real operating conditions provides the opportunity to obtain information about the engine properties that significantly exceed similar information that could be gained using tests in laboratory conditions. The possibilities of performing such tests were reduced due to technical limitations, especially in the field of exhaust emission tests. However, since the development of portable emission measurement systems (PEMS), these limitations have been significantly reduced. Nevertheless, financial constraints remain, as exhaust emissions and fuel mass consumption testing in real operating conditions tends to be a relatively expensive type of research.

The data obtained from the conducted research was analyzed, leading to the following conclusions:

1. The operating conditions of the combustion engine in the RDE test vary significantly in the phases corresponding to different traffic conditions: in cities, outside cities and on highways and expressways. This applies to all the following processes: engine steering, engine speed, relative torque and relative effective power. The influence of the engine speed on the engine operating states in the RDE test was similar. The sets of operating states were characterized by considerable dispersion, which resulted from their high coefficient of variation. Engine operating states vary greatly. For all engine operating states their average values were typically the smallest for the first test phase, larger for the entire test average, even larger for the second phase, and the largest for the third test phase.
2. There are very large statistical differences in vehicle velocity, engine operating states and emission pollutant intensity, particle number intensity and fuel mass consumption intensity of the vehicle, as well as large differences in the entire test as compared to its individual phases. The large differences in the dimensionless statistical characteristics of the emission pollutant intensity and the particle number intensity as well as the vehicle's fuel mass consumption intensity indicate a significant sensitivity of these values to the changes in engine operating states, which are determined by the vehicle velocity.

   There was a significant difference in the nature of the data points distributions of the studied variables: these were viscometric distributions for the emissions pollutant intensity and the particle number intensity as well as the fuel mass consumption intensity by the vehicle and engine steering. However, for the vehicle velocity, engine speed, relative torque and relative effective power, the distributions were platykurtic in most phases.

   The distribution of the data points of emission pollutant intensity, the particle number intensity and the fuel mass consumption intensity throughout the test and in its individual phases was characterized by left-sided asymmetry. In the remaining cases, the asymmetry of distributions varied.

   The strongest dynamic properties were for the nitrogen oxide emission intensity and particle number intensity, which resulted from the highest value of their coefficient of variation.

   The relationship between the mean and median values of individual variables varied significantly throughout the test and in its individual phases.
3. The vehicle's emission and fuel mass consumption characteristics have shown a clear regularity that is consistent with expectations, e.g., with characteristics determined from empirical studies conducting multiple tests at different average velocities. The characteristics of exhaust emissions and fuel mass consumption determined using software such as HBEFA INFRAS or COPERT were also similar.
4. Significant differences in the correlations of the studied variables were found. The engine operating states and the vehicle velocity were closely correlated with each other and much less correlated with the corresponding values of exhaust emissions. The correlation of variables describing the exhaust emissions also turned out to be varied. The least correlated variable with the emission pollutant intensity of hydrocarbons, nitrogen oxides, carbon dioxide and the fuel mass consumption intensity was the carbon monoxide emission intensity and the particle number intensity. These results were quite

surprising, because previous studies usually showed significant consistency in the results of emission tests with reducing properties: carbon monoxide and hydrocarbons in relation to the results of emission tests of substances with oxidizing properties such as nitrogen oxides, whereas in the case of this study, this regularity was not confirmed.

It would be advisable to consider the possibility of continuing research on the subject of this article. The following activities were proposed:

1. Carrying out empirical test with a larger number of repetitions. This would make it possible to assess the repeatability of research results, and in the case of a significantly larger number of tests, to treat research results in a probabilistic manner.
2. Carrying out studies for various driving test types, determined as a result of empirical tests in various traffic conditions, corresponding to driving in traffic congestion, in urban areas without traffic congestion, outside cities and on highways and expressways.

   It would be particularly useful to perform empirical tests for various vehicle velocity, which would correspond to driving in specific conditions.
3. Performing drive tests for road vehicles of categories other than passenger cars, such as: light trucks, trucks, city buses, long-distance buses and L category vehicles (motorcycles and mopeds, quads and microcars).

Nomenclature

AV	average value operator
b	specific distance pollutant emission/specific distance particulate number
CO	carbon oxide
CO_2	carbon dioxide
COPERT	COmputer Programme to calculate Emissions from Road Transport
D	standard deviation
E	pollutant emission intensity/particle number intensity
EPSS™	Engine Exhaust Particle Sizer™ Spectrometer
HBEFA	Handbook Emission Factors for Road Transport
HC	hydrocarbons
INFRAS	Infrastruktur-, Umwelt- und Wirtschaftsberatung
K	kurtosis
M	median
Max	maximum value
M_{er}	relative engine torque
Min	minimum value
n	engine speed
N_{er}	relative engine effective power
NO_x	nitrogen oxides
PEMS	Portable Emissions Measurement System
PN	particle number
q_F	fuel mass consumption intensity
R	range/dispersion
RDE	Real Driving Emissions
s	engine steering
S	skewness
t	time
v	vehicle velocity
W	coefficient of variation

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