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ANALYSIS OF EXHAUST EMISSION PROCESSES DURING THE REAL DRIVING EMISSIONS TEST

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Abstract:

The article deals with the study of exhaust emissions from a combustion engine in the Real Driving Emission (RDE) test. These tests are a simulation of real conditions of use of motor vehicles. Nowadays, RDE tests are mandatory for Light Duty Vehicle (LDV) and Heavy Duty Vehicle (HDV) vehicles and in the future, restrictive standard. Euro 7, which combines stricter limits with a comprehensive RDE test cycle, is becoming a challenge for current vehicle engineering. The paper presents the results of pollutant emission tests from a passenger car (PC). In the tests of LDV in the RDE test, the results of which are analyzed in the article, the Portable Emissions Measurement System (PEMS) mobile exhaust emission testing system was used. The processes describing the operating states of the vehicle and the combustion engine, as well as the processes of exhaust emission intensity and the intensity of the number of particulate (PN), were examined. The correlation between the considered processes was investigated. The emission of carbon monoxide, hydrocarbons, nitrogen oxides, particulate and carbon dioxide as well as the road PN were examined. The zero-dimensional statistical characteristics of the examined processes were also determined. The probability density and power spectral density of the processes were established. A great diversity was found in the properties of the process distributions, as well as in the dynamic properties of the processes. In the summary of the analysis of the results of the car speed process, the operating states of the combustion engine and the processes of exhaust emission intensity and the process of the intensity of PN in the RDE test, conclusions were formulated regarding, among others, course of the intensity of these compounds, correlation of the processes of pollution emission intensity and the intensity of the PN with the process of car speed, distribution of processes.

Keywords: *RDE test, exhaust emission, combustion engine operating states*

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1. Introduction

Many publications have dealt with the subject of testing vehicles in real use conditions. The subject of such research most often deals with the comparisons of pollutant emissions in both real use conditions and in homologation tests on a chassis dynamometer (Pielecha et al., 2016; Varella et al., 2018). Research also looks at the impact of car speed processes and the operating states of combustion engines on pollutant emissions (Andrych-Zalewska et al., 2022; Andrych-Zalewska et al., 2021; Kurtyka et al., 2019).

It is known from many empirical studies that the operational properties of motor vehicles and engines in real use conditions may differ significantly from the properties determined in repeated approval procedures (Pielecha et al., 2016; Varella et al., 2018). Exhaust emissions can be seen to be particularly sensitive to the operating conditions of the engines, and are determined by the operating conditions of motor vehicles (Andrych-Zalewska et al., 2022; Andrych-Zalewska et al., 2021; Kurtyka et al., 2019; Pielecha et al., 2016). Therefore, the concept of testing exhaust emissions from the combustion engines of motor vehicles in the conditions of real use, which are characterized by greater uniqueness than the conditions of approval tests carried out on chassis dynamometers, can be seen to be useful. This postulate is implemented as part of the RDE procedure (dieselnet.com, 2021; Worldwide emission standards 2020). The speed of a vehicle in real conditions during the RDE test can be treated as the implementation of a stochastic process (Papoulis, 2002), for which the general conditions imposed on the nature of the vehicle's motion are characteristic.

Testing vehicles exhaust emissions, in a laboratory as well as in actual conditions, is being partially implemented. RDE testing is performed only for PC and LDV. The tests concern the emission of nitrogen oxides (NOx) and the number of particulate (PN). In the future, it is also planned to study the emission of carbon monoxide (CO).

The RDE test procedure was developed by the European Union and applies to European vehicles (Annex IIIA of Regulation 692/2008) (Commission Regulation (EC) 715/2007; Commission Regulation (EU) 2016/427; Commission Regulation (EU) 2016/646; European Commission (2017) Regulation (EC) 2017/1151). The test requirements are based on European Union procedure and have also been adopted by other countries, such as the People's Republic of China. Introduction of this test procedure was carried out in four parts, adopted over time from March 2016 to November 2018 for Euro 6 vehicles. The procedure for exhaust emission tests is to carry them out with the use of a Portable Emissions Measurement System (PEMS).

On the basis of the test results, the compliance factors of the result of emission tests in real conditions, and the limit in the approval tests – CF (Conformity Factor) (dieselnet.com, 2021; Worldwide emission standards, 2020), are determined.

$$CF = NTEL/b_{Euro} \tag{1}$$

where:

b_{Euro} – the limit value of exhaust emissions and PN intensity test results according to Euro,

NTEL (Not-to-exceed limit) – the limit value of exhaust emission and the PN intensity results obtained in real conditions.

Table 1 presents the values of the compliance factor of the results of exhaust emission tests in actual conditions, and also the limit in approval tests (dieselnet.com, 2021; Worldwide emission standards, 2020).

Table 1. Values of the compliance factor of exhaust emission test results in real conditions, and also the limit in approval tests

Norm	CF_{NOx}	CF_{PN}
Euro 6d-TEMP	2.1	1.5
Euro 6d	1.43	1.5
Euro 6e	1.10	1.34

In the RDE tests of PC, whose results were analyzed in the article, the PEMS mobile exhaust emission testing system was used (PEMS Testing). The Semtech DS analyzer (Semtech-DS on board vehicle emissions analyzer, 2010) and the TSI 3090 EPSS™ (Engine Exhaust Particle Sizer™ Spectometer) analyzer (TSI 3090 EEPS™) were used for measuring emissions.

2. Literature review

Currently, when measuring exhaust gas emissions, the greatest attention is paid to road tests, called RDE tests, which are conducted with the use of mobile PEMS test equipment (Shen et al., 2018; Varella et al., 2011; Wang et al., 2019). This can be seen by the changes in the European Union regulations on emissions. The latest vehicle exhaust emission research done in traffic conditions reflects the actual ecological efficiency of the tested vehicles (Ramos et al., 2018; Weiss et al., 2018).

In (Ramos et al., 2018) the authors presented a statistical methodology for comparing two different driving patterns with their corresponding NO_x emissions from a diesel engine. Two types of driving patterns were analyzed as defined by the New European Driving Cycle (NEDC): driving in real conditions, and driving on a chassis dynamometer. Test results showed significant differences between the engine's fundamental variables when driving in real conditions and when driving according to NEDC procedures. Although the results were obtained using a deductive method, the authors conclude that actual driving NO_x emissions are significantly different from those in the NEDC test. The authors indicate that this is proof that the NEDC procedure is not a representative vehicle certification procedure.

The legitimacy of using RDE tests is presented in publication (Weiss et al., 2018). A comprehensive emission test of light road vehicles was carried out using portable emission measurement systems. The specific distance emissions of NO_x, CO and HC from both diesel and gasoline vehicles were found to be below the relevant emission limits. NO_x specific distance emissions from diesel vehicles (0.93 ± 0.39 [g/km]), including modern Euro 5 diesel vehicles (0.62 ± 0.19 g/km), exceeded the emission limits by $320 \pm 90\%$. CO specific distance exceeded laboratory emission by $21 \pm 9\%$, which suggests that stationary emission tests do not accurately capture on-road emissions from LDV.

The aim of article (Kurtyka et al., 2021) was to assess the emission of NO_x from two gasoline powered PC. The authors conducted the tests in accordance with the guidelines of the exhaust gas emission testing procedure in real driving conditions using the PEMS mobile measuring equipment. The impact of dynamic conditions (such as vehicle speed, acceleration, and the product of vehicle speed and acceleration) during the tests on NO_x emissions was calculated, showing the areas where their relationship was most prominent.

The authors of publication (Bielaczyc et al., 2020) presented the results of road emission tests in accordance with RDE. The tests were carried out on a Euro 6d-TEMP PC that had a GDI (Gasoline Direct Injection) engine and a particulate filter. The test was conducted at two temperature points within the "standard" temperature range for the tests: +25°C and +8°C. The results for regulated gas emissions, PN and CO_2/fuel consumption were shown and discussed. Cold start emissions were significantly higher at the lower test temperature. However, the long travel distance of the tests (~70–100 km), along with its urban driving phases (>16 km, often ~25 km), weakened the impact of this effect. Mathematical analyzes of the results from various parts of the route were presented.

Article (Merkisz et al., 2018) compares the data obtained in road tests with the latest legislative proposals for combustion engines in various applications. The exhaust emission tests for PC were carried out several times on the same test route, in line with the RDE procedure guidelines, where several criteria had to be met, including the distance of individual sections, the total travel time, and the dynamic characteristics of the test drive. The analysis was done using a two-dimensional operational density characteristics, which was expressed in vehicle velocity-acceleration coordinates. Thanks to this, it was possible to compare the dynamic properties and operating time density, as well as to ensure the validity of the conducted driving tests in terms of their feasibility and emission values. A comparison of the exhaust emissions of three types of propulsion systems: gasoline, diesel and hybrid was presented.

Article (Pielecha et al., 2020) presents the assessment (according to the latest RDE research) of the indicators of ecological vehicles in actual traffic conditions. It was proven that despite the fact that the vehicles complied with the emission limits when the tests were carried out on a chassis dynamometer, in actual operating conditions they were basically different. It was shown that gasoline engines, which emit significantly more particulate than diesel engines of the latest emission class (Euro 6d-Temp), should be closely monitored.

Article (Pielecha et al., 2018) compares data from road tests with regards to effective legislative tools for PC with different drives. Data was acquired on the test route as specified in the test guidelines. An external exhaust gas emission measurement PEMS system was used to record the data on the operating parameters of the engine and vehicle, and also to measure exhaust emissions. The following parameters were monitored: source values, engine speed and vehicle speed. The results were checked for their compliance with the test requirements. The road emission of individual real events for all vehicles, as well as the parameters of real driving (relative positive acceleration and the product of speed and positive acceleration) in various phases of the tests, were determined, which resulted in their juxtaposition. The impact of road tests on road conditions was determined based on the results of road emissions that may be generated for PC with different drives.

According to the Euro 6d standard, particulate number (PN) specific distance must be lower than 9.0×10^{11} km^{-1} while taking into consideration a Conformity Factor (CF) of 1.5 in real driving tests, which include the cold start. Publication (Ko at al., 2019) presents an analysis of the characteristics of PN specific distance in road traffic under the conditions of the cold start of a vehicle with GDI with regards to the selected parameters. The PN specific distance during the test were 2.71×10^{12} km^{-1} (without CS – catalytic stripper and GPF – gasoline Particle Filter), 1.72×10^{12} km^{-1} (with CS and without GPF), 1.47×10^{12} km^{-1} (without CS and with GPF) and 9.50×10^{11} km^{-1} (with CS and GPF). The average effects of CS on reducing specific distance PN were 35.4% and 32.2% in the city, 52.2% and 63.4% in the countryside, 22.8% and 88.6% on the motorway, and 35.6% and 36.5% on the total sections of the journey with and without the GPF, respectively. The average impact of the GPF on the reduction of PN specific distance were 42.7% and 39.9% in the city, 58.2% and 68.0% in the countryside, 27.9% and 89.3% on the motorway, and 44.8% and 45.6% on all sections of the journey with and without the CS, respectively.

The issue of cold start and warm-up measurements were also discussed in article (Merkisz et al. 2919), which discusses the importance of taking into account cold-start emissions during legislative RDE tests. The results of the tests of a vehicle with a gasoline engine are presented, with particular emphasis on the comparison of emission results: with the exclusion/inclusion of the cold engine start in the initial phase of the test. In addition to some theoretical arguments, the results of a test carried out using test procedures under real operating conditions were presented. PC that had a GDI engine (Euro 6c) was tested. The authors reported a lower than expected impact of associated emissions. This was because the distance traveled in the test was long (>48 km) to comply with the requirements, and the ambient temperature was not low. The implications for the testing process, emission control and future emission profile for vehicles with such engines were also discussed.

Article (Stoddard et al., 2017) analyzes the behavior of a Euro 6 diesel engine tested in dynamic conditions that corresponded to real emissions (RDE). The test cycles were done on an engine test stand that simulated the engine's operation. A computer tool was designed to define a cycle that takes into account different dynamic characteristics and driver behaviors. The tool was used to study the impact of the different characteristics on CO_2 emissions and exhausts, in particular CO, THC and NO_x. Various dynamic parameters, such as power, torque, engine speed or vehicle speed, were established. An RDE emission estimation tool based on steady-state maps was developed in order to help identify emission trends more clearly. The findings suggest that driving patterns that are characterized by lower engine speeds lead to lower emissions. In addition, the analysis of test cycles from stationary engine maps helped to estimate the final CO_2 and NO_x emissions, in turn enabling a real result to be obtained in tests carried out on an engine dynamometer or on the road.

RDE tests can be used to not just measure emissions from vehicles on the road. Non-road machines are a large group of machines, which are designed for a variety of tasks and mainly equipped with CI engines. These include vehicles that have driven systems with a maximum power of several kilowatts and even drives of up to thousands of kilowatts. Mobile machines, referred to as NRMM (Non-Road Mobile Machinery), can be distinguished here. The homologation standards themselves are less severe than for heavy duty vehicles (HDVs), although the engines are similar in design and performance. A selection of NRMM vehicles were tested (Siedlecki at al., 2020) using the PEMS apparatus. Information from the exhaust gas mass flow meter, and the temporary operating conditions of the engine from the CAN network, allowed the exhaust gas emissions to be determined. The results were compared with vehicles (from other groups) that were used in the Poznań agglomeration (Poland), with their emission level and its share compared to other means of transport then being determined.

RDE tests seem to also be justified in rail transport.

Publication (Merkisz “b” at al., 2017) concerns issues related to the ecological operation of vehicles used in rail transport. The article discusses problems related to the ecological operation of rail transport vehicles. The assessment of the vehicle's environmental performance is mainly based on the comparison of the current state of the engine (its emissions) with the permissible values for the emission of toxic exhausts. These values are relevant for specific screening tests for both vehicles and engines. Emission regulations are very important in the case of the domestic operating conditions of rail vehicles due to the wide variety of rolling stock that exists. Therefore, it becomes necessary to undertake the issue of evaluating emissions (in accordance with the RDE procedure) from rail vehicle engines in terms of their actual operating conditions.

Shaping the transport system requires decision support tools. It is not only necessary to meet the needs of the users of the transport system, but also to reduce the negative impact of transport on the environment. The paper (Merkisz “a” at al., 2017) reveals the impact that exhaust emissions data from real conditions has on the design process of a sustainable transport system. Claiming that a sustainable transport system will allow for conducting wide research, experimentation and simulation related to the distribution of traffic flow within the scope of the transport network.

3. Results of empirical research

The results of the empirical studies are presented in Figures 1-9. The results were presented after low-pass filtering with a fifth-order non-recursive linear filter in order to reduce the share of high-frequency noise in the signals (Bendat et al., 2010; Savitzky et al., 1964).

Figure 1 shows the car speed process during the test, The chart shows the driving phases of the car: in cities, outside cities, and on motorways and expressways.

The car speed process in the RDE test shown in Fig. 1 corresponds the engine operating states to the following processes: engine rotational speed - Fig. 2, relative engine torque - Fig. 3, relative useful power - Fig. 4.

The relative torque is related to the recorded maximum torque value. The relative net power of the engine, calculated as the product of torque and engine speed, is also related to the value of the maximum net power.

During the driving test, the processes of emission intensity were recorded using PEMS apparatus, the results of which are shown in Figures 5-8. Figure 9 shows the PN intensity rate.

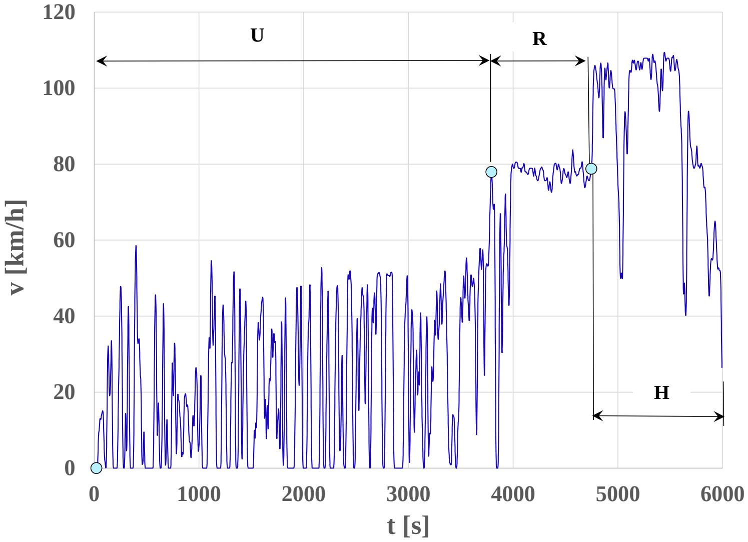

Fig. 1. Speed– v of the car during the RDE test: U – urban driving phase, R – extra-urban driving phase, H – motorway and expressway driving phase

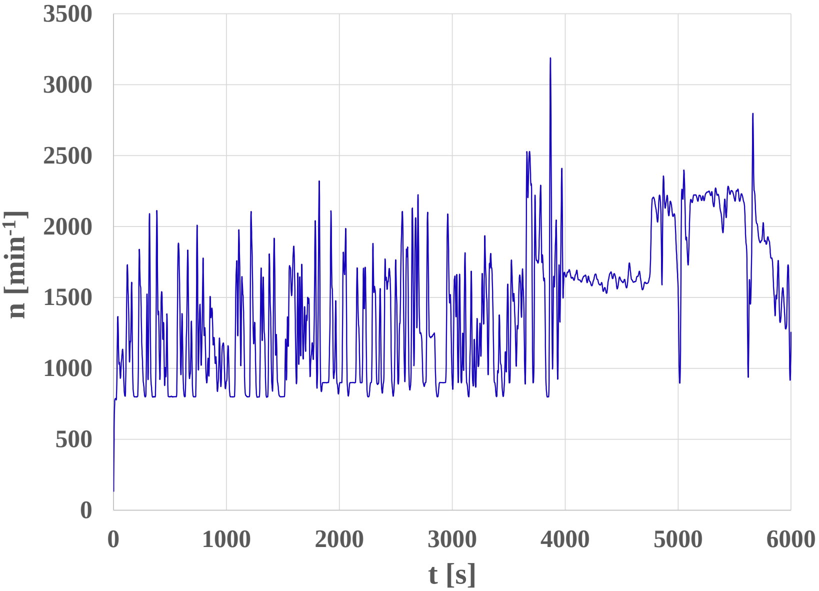

Fig. 2. The rotational speed – n of the car engine during the RDE test

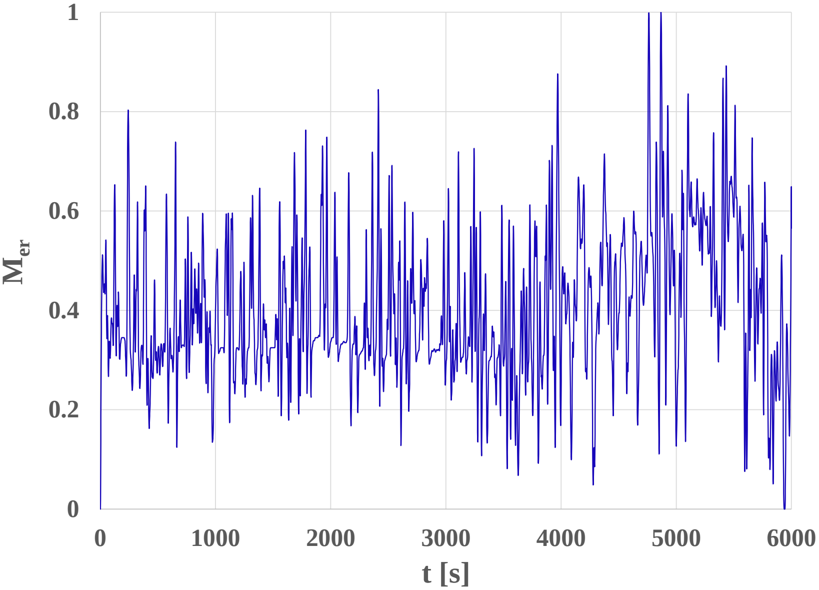

Fig. 3. The relative torque – M_e of the car engine during the RDE test

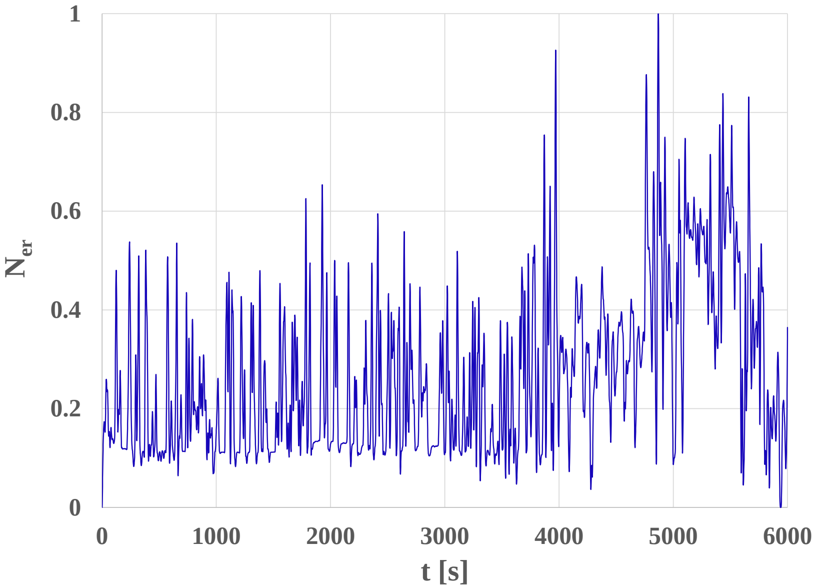

Fig. 4. The relative useful power – Ne of the car engine during the RDE test

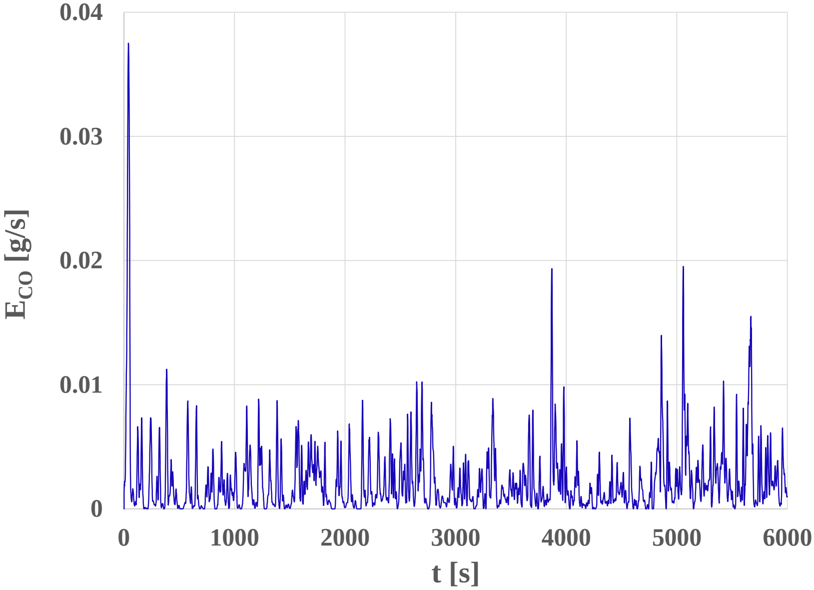

Fig. 5. CO emission rate– E_{CO} during the RDE test

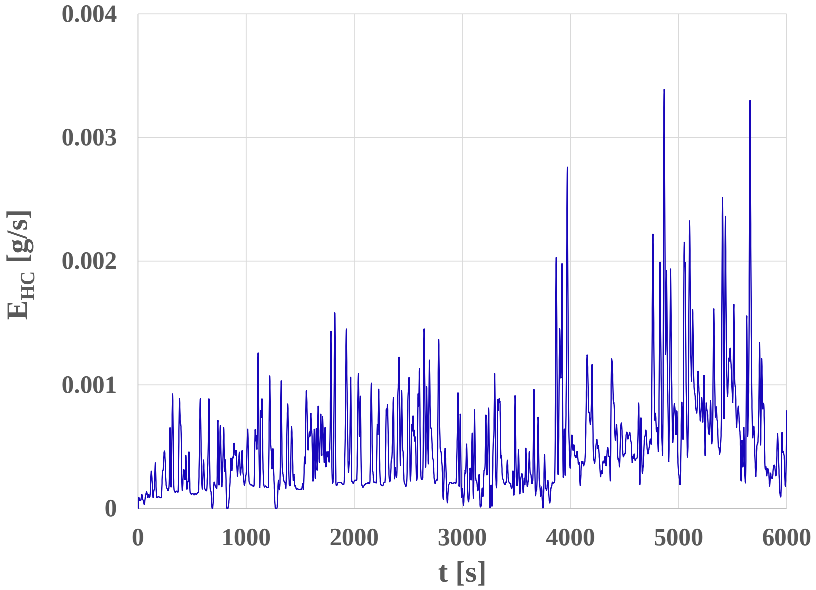

Fig. 6. HC emission rate – E_{HC} during the RDE test

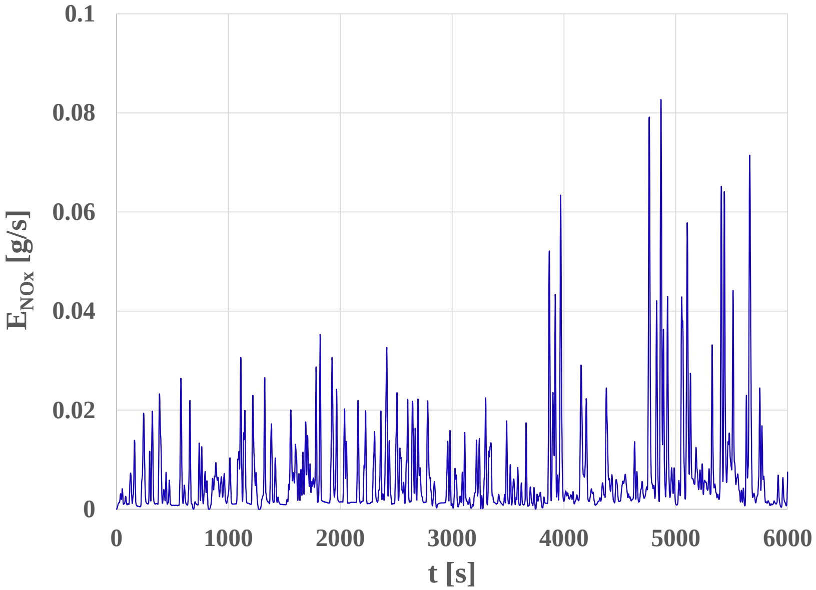

Fig. 7. NO_x emission rate – E_{NOx} during the RDE test

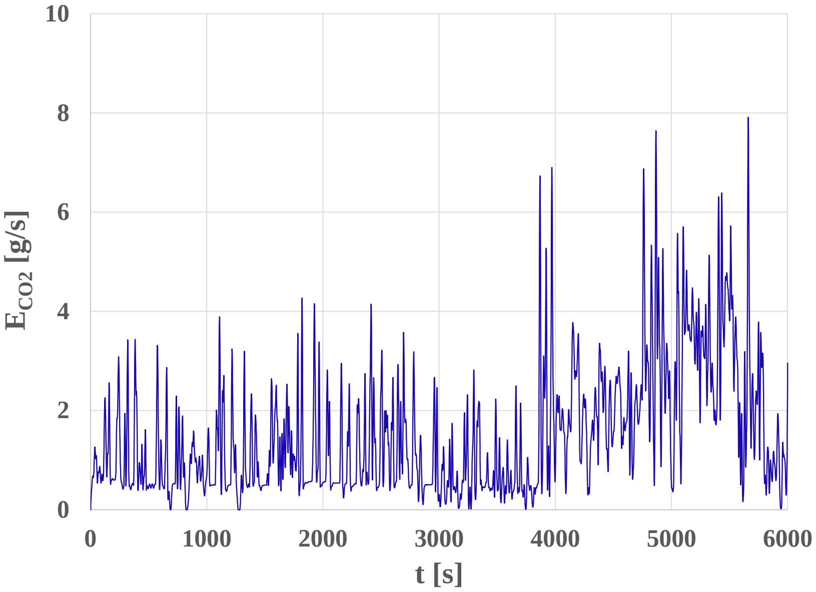

Fig. 8. CO_2 emission rate – E_{CO2} during the RDE test

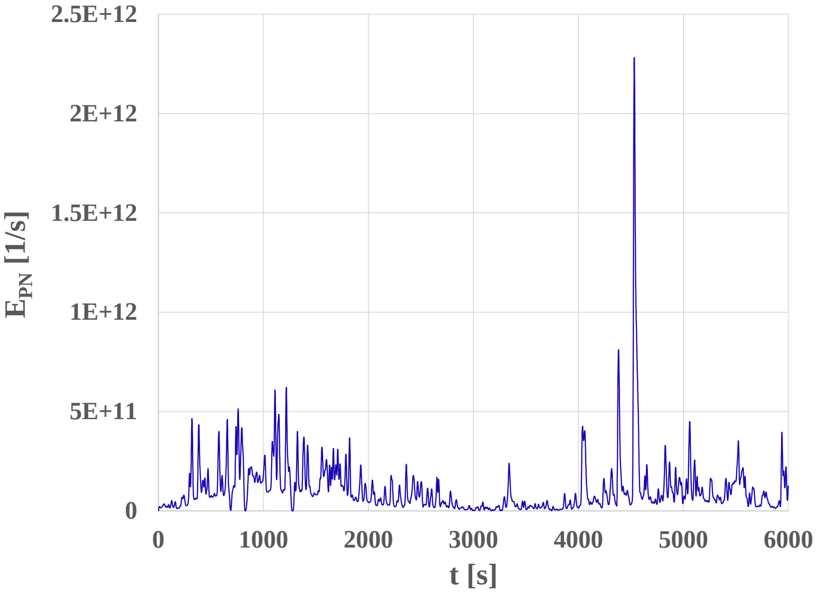

Fig. 9. PN intensity rate – E_{PN} during the RDE test

It is significant that the highest values of the exhaust emission intensity and the intensity of PN occur in the driving phase of the car in traffic conditions on motorways and expressways.

The course of emission intensity of HC, NOx and CO_2 show some similarity. A more in-depth analysis will be presented on the basis of correlation studies of the exhaust emission rate of exhaust and PN, and the speed of the car.

4. Test results analysis

The analysis of correlation studies was carried out on standardized processes (Lane et al., 2003). A study was done on the correlation dependences of the standardized emission rate of exhaust and the standardized NP emission rate on the standardized speed of the car. An exemplary result of such tests is shown in Figure 10.

The correlation between the gaseous substances emission rate and the PN intensity rate was also studied - an example of the test result is shown in Figure 11.

Full results of the correlation studies between the examined processes are presented in Tables 2 and 3.

Table 2 presents the coefficient of determination (Lane et al., 2003) of the car speed process with the process of calculating the emission rate of gases and PN, whereas Table 3 shows the coefficient of determination with regards to the calculated emission in addition to the PN.

The value of the determination coefficient of the car speed process with the processes of exhaust emission intensity and the intensity of PN was very diverse for various exhaust gas components. The highest value was for CO_2 emission rate, closely followed by HC. The smallest value of the coefficient of determination was for the particle number intensity, followed by the CO emission intensity.

The value of the coefficient of determination between the PN and other measured substances emission rates was very diverse. The correlation between the HC and CO_2 emission rate was by far the strongest. The same applies to the HC emission rate and that of NO_x. These facts will confirm the conclusions formulated intuitively on the basis of the evaluation of the time courses of the emission rates of the exhausts in question.

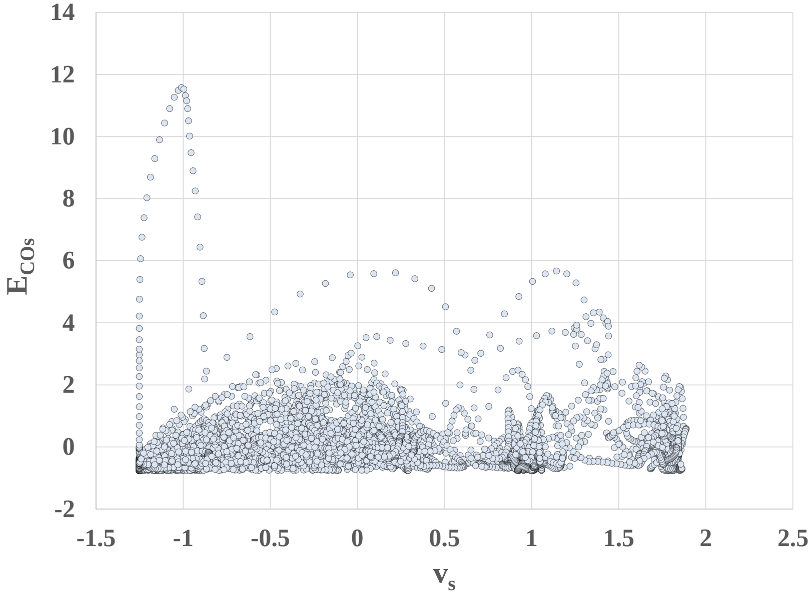

Fig. 10. Dependence of the standardized CO emission rate - E_{CO} on the standardized speed of the car – v

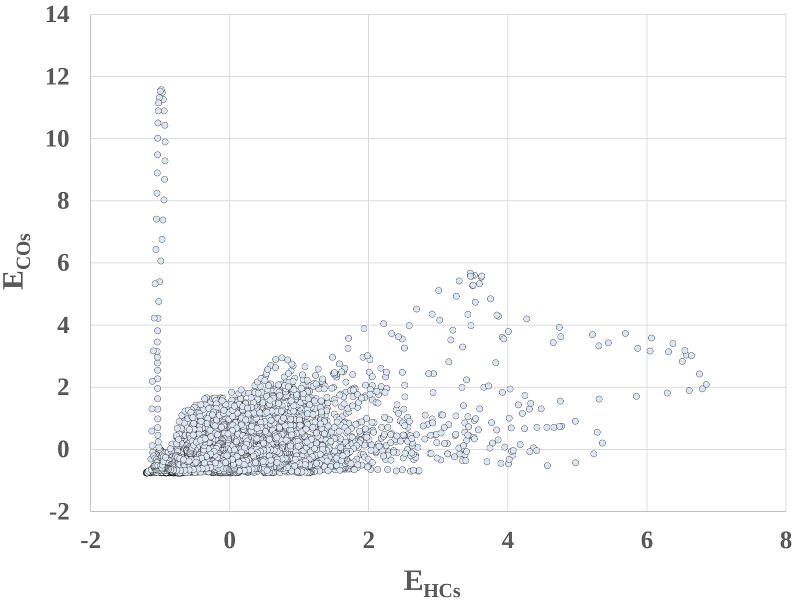

Fig. 11. Dependence of the standardized CO emission factor - E_{CO} on the standardized HC emission allowance - E_{HC}

Table 2. Coefficient of determination of the car speed process with the process of calculating the energy expenditure and the number of a specific particle

Process	R^2
E_{CO}	0.0132
E_{HC}	0.2778
E_{NOx}	0.0939
E_{CO2}	0.3970
E_{PN}	0.0129

Table 3. Coefficient of determination between the processes of gaseous exhaust emission rate and particle number rate

Processes		R^2
E_{CO}	E_{HC}	0.1649
E_{CO}	E_{NOx}	0.1712
E_{CO}	E_{CO2}	0.1138
E_{CO}	E_{PN}	0.0091
E_{HC}	E_{NOx}	0.8365
E_{HC}	E_{CO2}	0.8537
E_{HC}	E_{PN}	0.0570
E_{NOx}	E_{CO2}	0.0502
E_{NOx}	E_{PN}	0.0502
E_{CO2}	E_{PN}	0.0773

Figure 12 presents the zero-dimensional statistical characteristics (Lane et al., 2003) of the car speed curve, Figures 13-15 – the engine speed, relative torque and relative engine power, Figures 16-19 – the exhaust emission rate, and Figure 20 – the PN intensity rate.

The mean value and the median of the processes were close to each other. Apart from the rotational speed, for all other variables the average value was greater than the median. The relative value of the standard deviation was relatively large in the case of the processes of car speed and relative useful engine power.

For all variables, the mean value was greater than the median, and the values of these quantities was small in relation to the range, and even in relation to the standard deviation.

Figures 21-23 show the kurtosis, skewness and coefficient of variation (Lane et al., 2003) of the tested processes.

The kurtosis of the car speed and engine speed processes is negative, although the absolute value is small. The distributions of these processes are therefore platykurtic (Lane et al., 2003), but their negative flattening is not large. The kurtosis of the remaining processes is positive, so these are leptokurtic distributions (Lane et al., 2003), and its kurtosis value for the processes of relative torque, relative useful power and CO_2 emission intensity is not large, so their flattening is also not large. The highest value of kurtosis is for PN intensity process, and then for the CO emission intensity process.

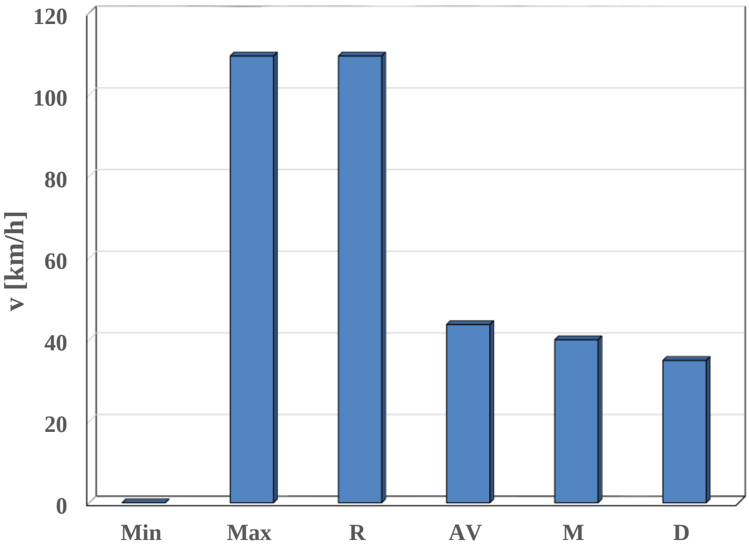

Fig. 12. Vehicle speed data – v

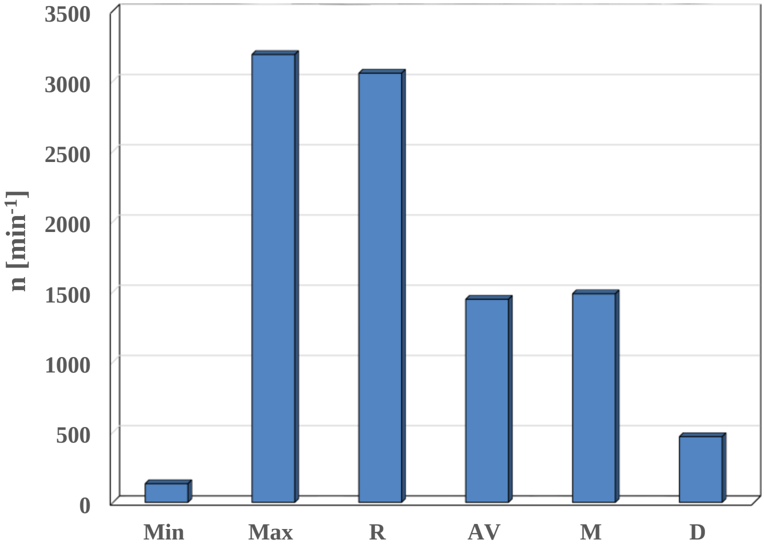

Fig. 13. Engine speed data – n

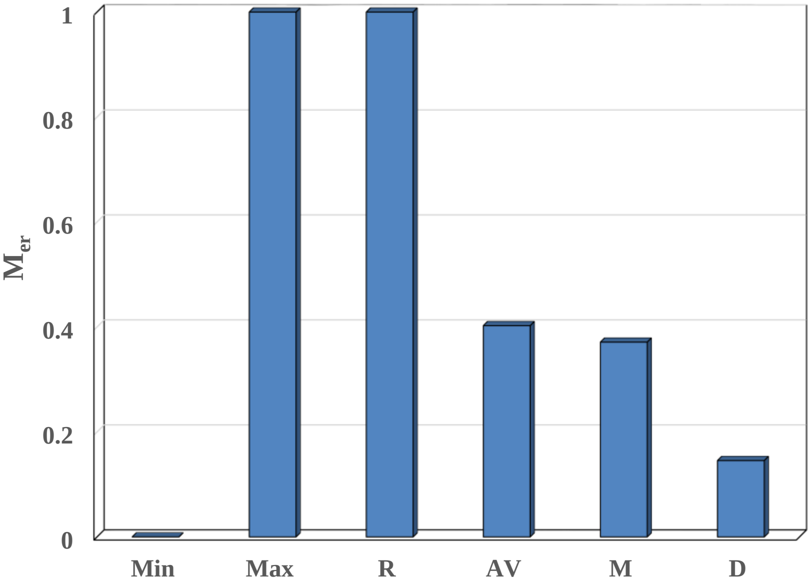

Fig. 14. Engine torque data – M_{er}

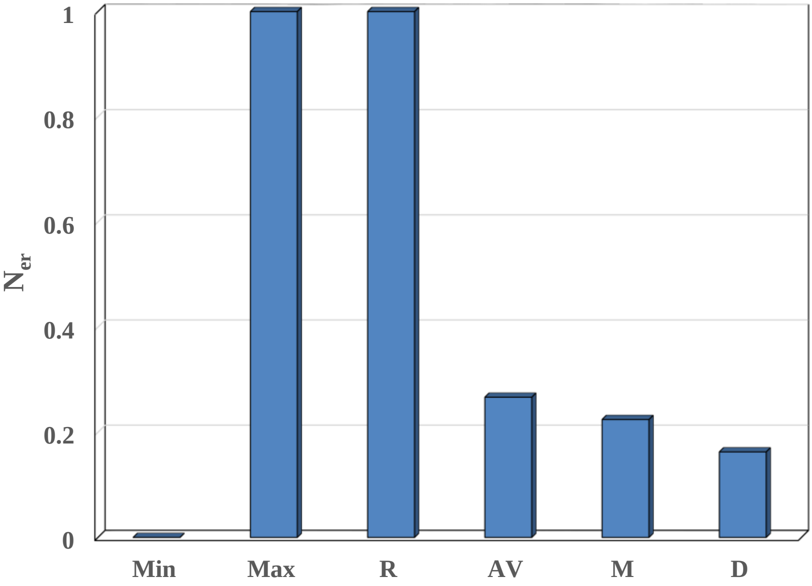

Fig. 15. Engine power data – N_{er}

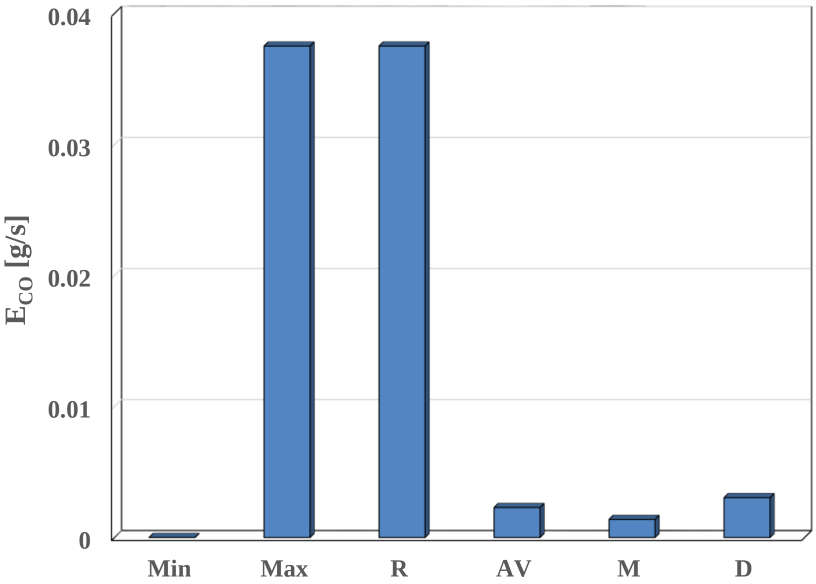

Fig. 16. CO emission rate – E_{CO}

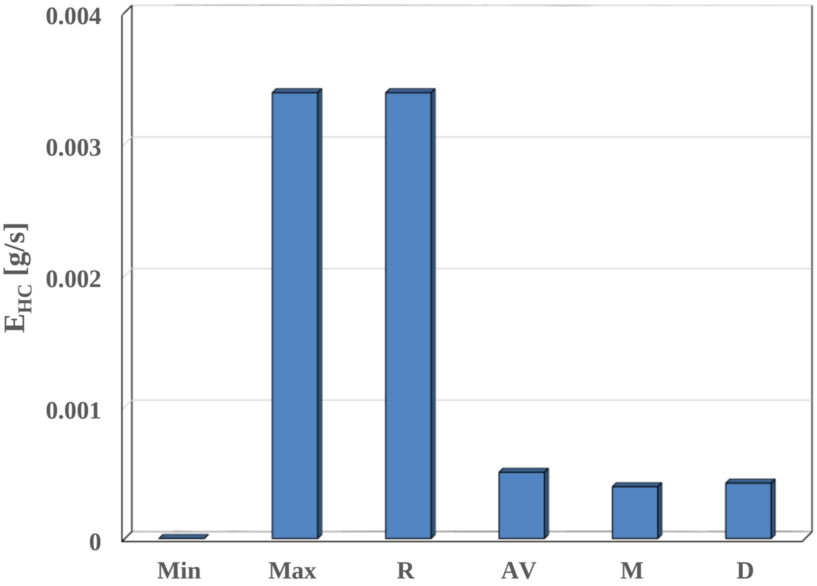

Fig. 17. HC emission rate – E_{HC}

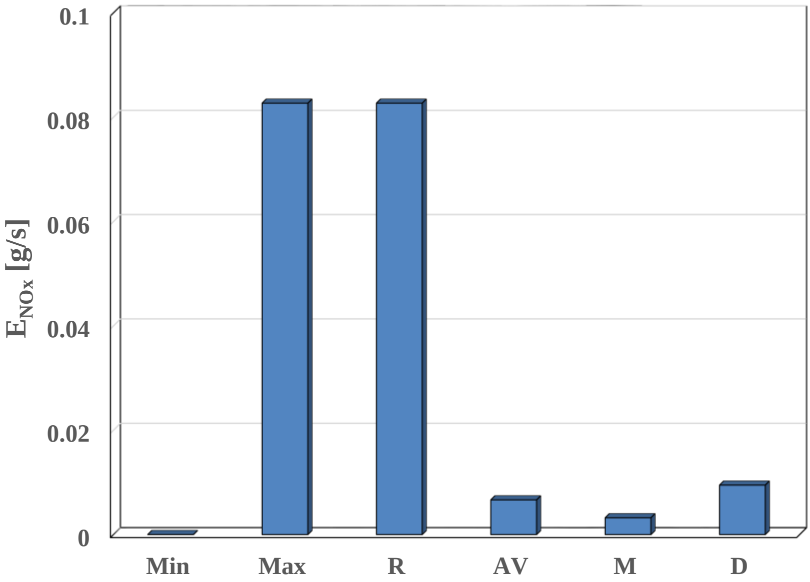

Fig. 18. NO_x emission rate – E_{NOx}

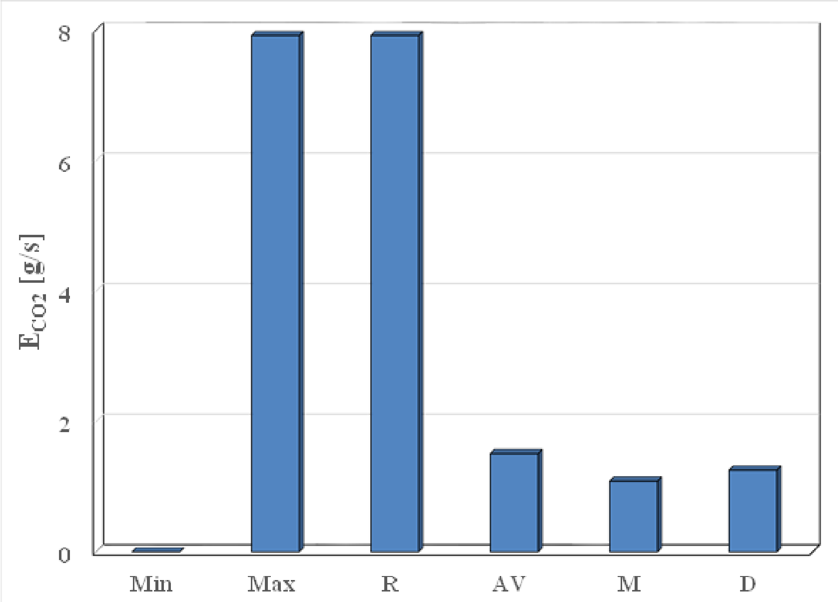

Fig. 19. CO_2 emission rate – E_{CO2}

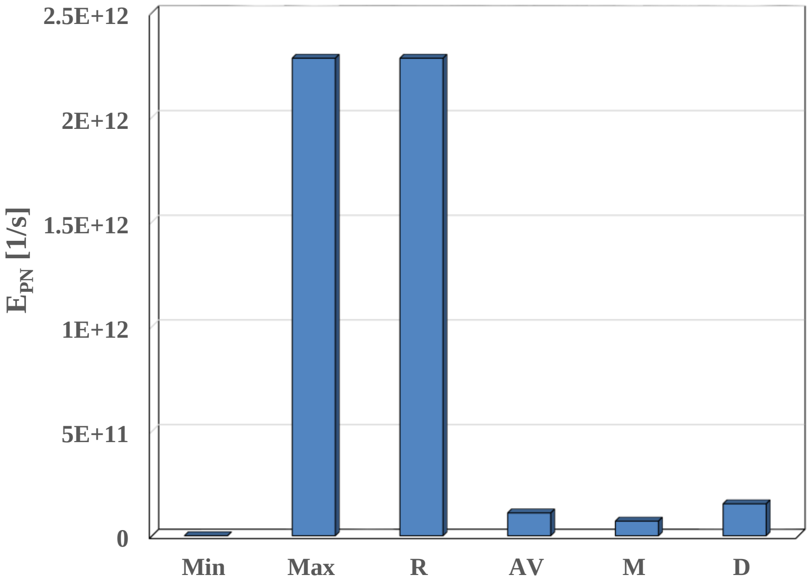

Fig. 20. PN intensity rate – E_{PN}

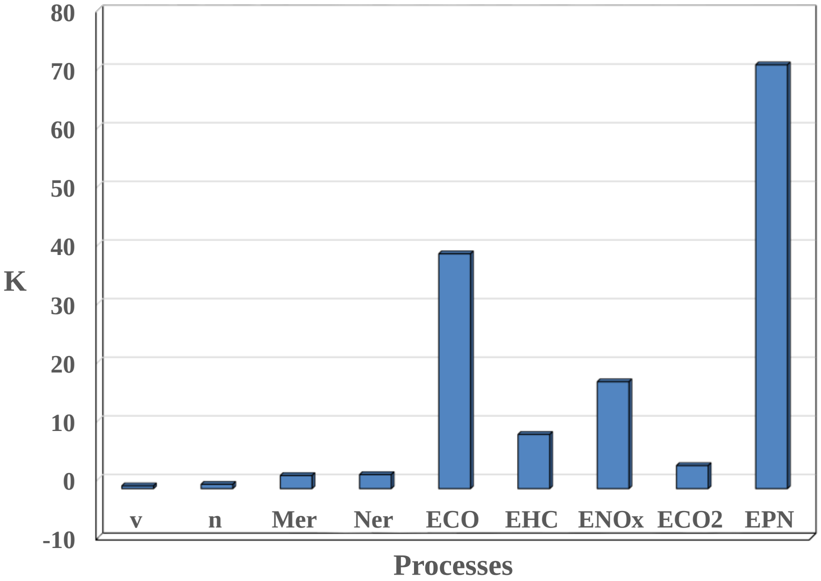

Fig. 21. Kurtosis – K of the examined processes

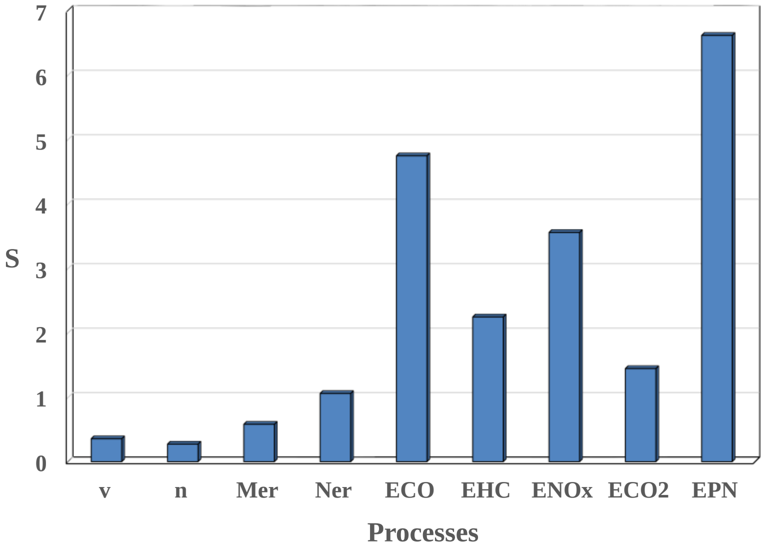

Fig. 22. Skewness – S of the examined processes

The skewness of the distributions of the examined processes is positive, and therefore these distributions have right-sided asymmetry (Lane et al., 2003). As in the case of kurtosis, the highest value of skewness is for PN intensity process and for the CO emission intensity process. The smallest value is for the car speed and engine speed processes.

Conclusions formulated on the basis of the assessment of the kurtosis and skewness of the distributions of the examined processes are confirmed by the determined results of the probability density of the processes.

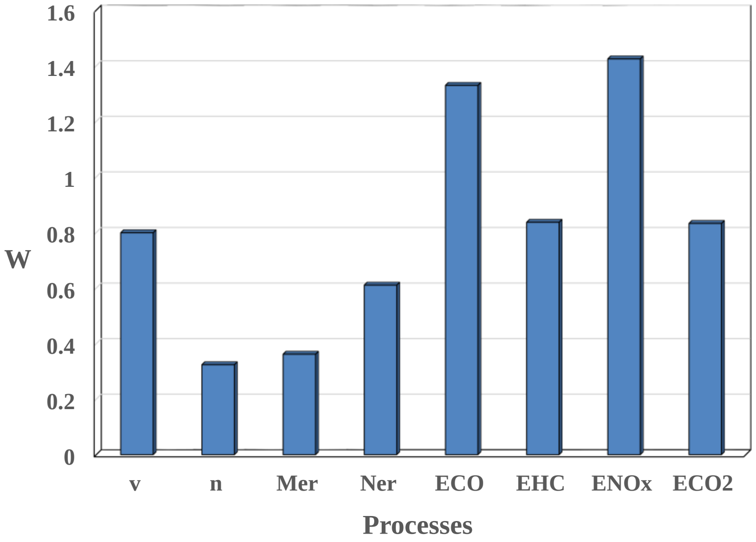

Fig. 23. Coefficient of variation – W of the tested processes

The coefficient of variation has a significantly different value. The processes of the emission intensity of NO_x and CO are characterized by the greatest variability. The smallest variability characterizes the processes of engine operation states: engine speed and torque.

Research in the field of these values was carried out for standardized processes (Lane et al., 2003). The test results are shown in Figures 24 - 32.

The probability density characteristics of the car speed process are very different from the probability density characteristics of the engine operating state processes. The characteristic of the probability density of the car speed process is strongly asymmetric with the dominant frequency of the occurrence of the minimum value corresponding to the speed equal to 0 km/h. The characteristics of the probability density of engine operating state processes show some similarity, especially in the case of torque and useful power processes - in these cases there are clear global maxima. In the case of a rotational process, there are several local peaks in the probability density characteristic.

The characteristics of the probability density of the gaseous components and PN ion rate show considerable similarity. There is a characteristic occurrence of the maxima for small process values.

The study of processes in the frequency domain was carried out using the fast Fourier transform (Bendat et al., 2010; Otnes et al., 1978; Ralston et al., 2001) for samples consisting of 4096 initial elements of the recorded processes. The processed sets were filtered using the Hamming time window (Bendat et al., 2010; Otnes et al., 1978; Ralston et al., 2001), and then standardized. The results of the rough estimator of the power spectral density of the processes were subjected to piecewise smoothing (Bendat et al., 2010; Otnes et al., 1978; Ralston et al., 2001), with 20 values being covered.

Figure 33 shows the spectral power density of the following processes: standard car speed, standard car engine speed, standard car torque, and standard car useful power.

The strongest dynamic properties are characterized by the car speed and engine speed processes. The weakest dynamic properties are for the useful power process.

Figure 34 shows the power spectral density of the following processes: standard CO emission intensity, standard HC emission intensity, standard NO_x emission intensity, standard CO_2 emission intensity, and standard PN intensity.

The strongest dynamic properties are in the case of the CO emission intensity process, with the weakest being for NO_x emission intensity process.

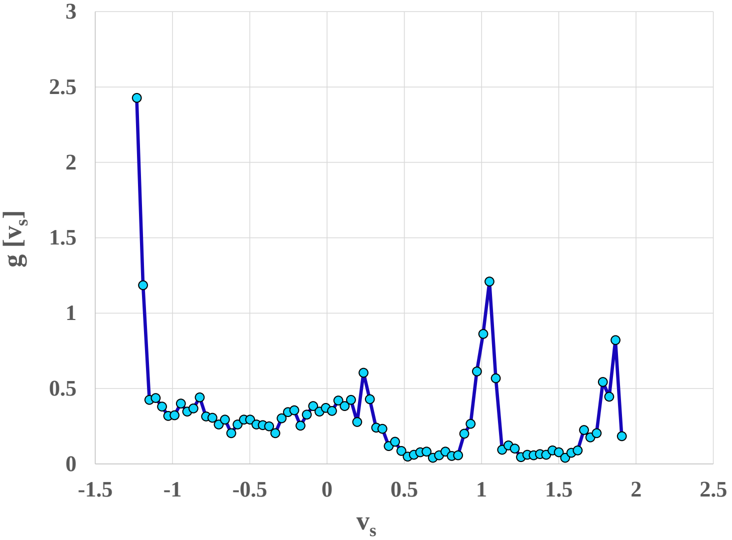

Fig. 24. Probability density – g of the process of the standardized speed of the car – v

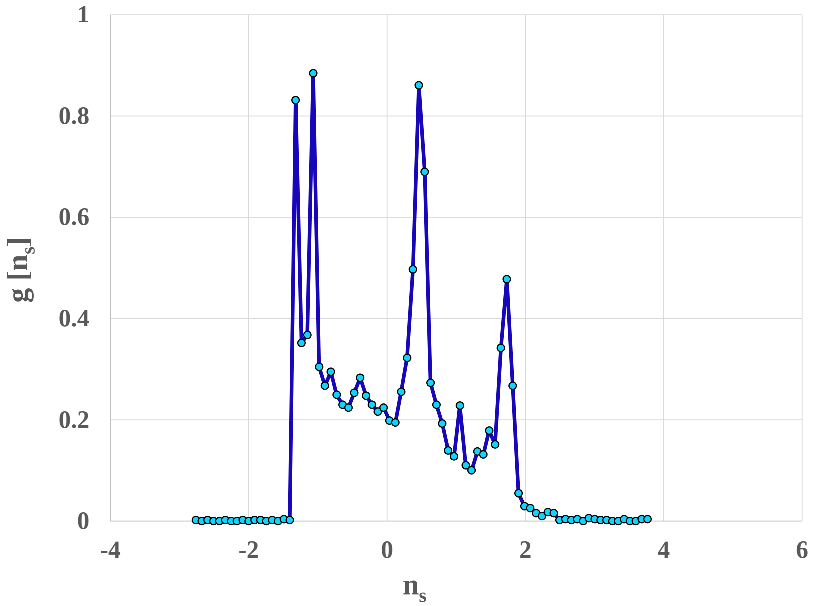

Fig. 25. Probability density – g of the process of standardized car engine rotational speed – n

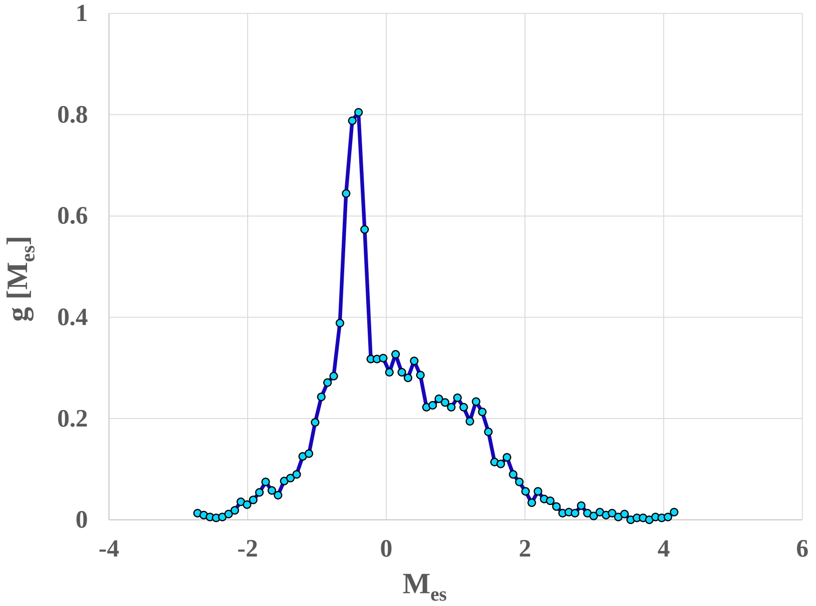

Fig. 26. Probability density – g of the process of vehicle engine torque– M_e

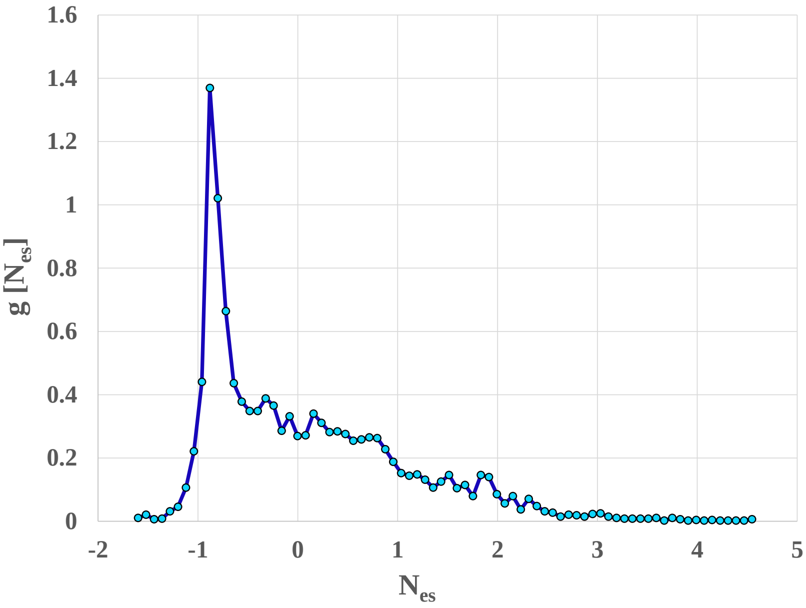

Fig. 27. Probability density – g of the process of the standardized useful power of a car engine – Ne

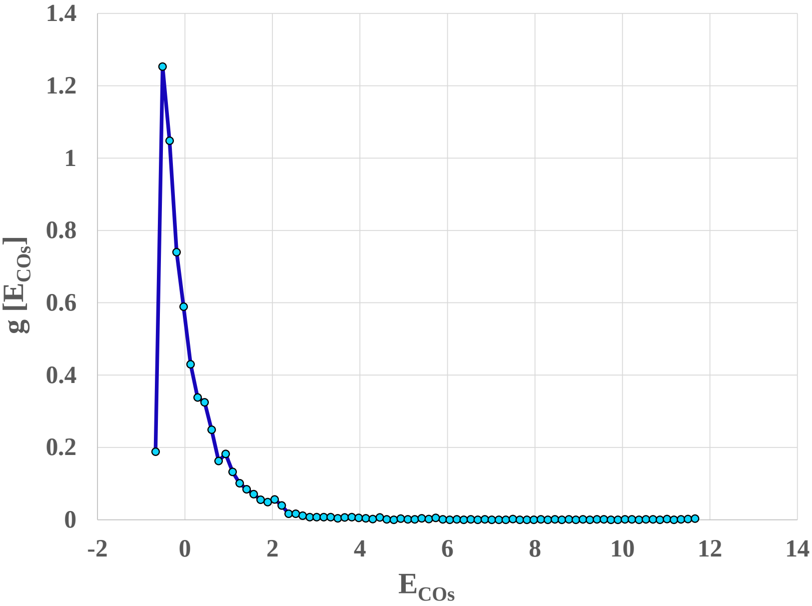

Fig. 28. Probability density – g of the process of the standardized intensity of CO emission – E_{CO}

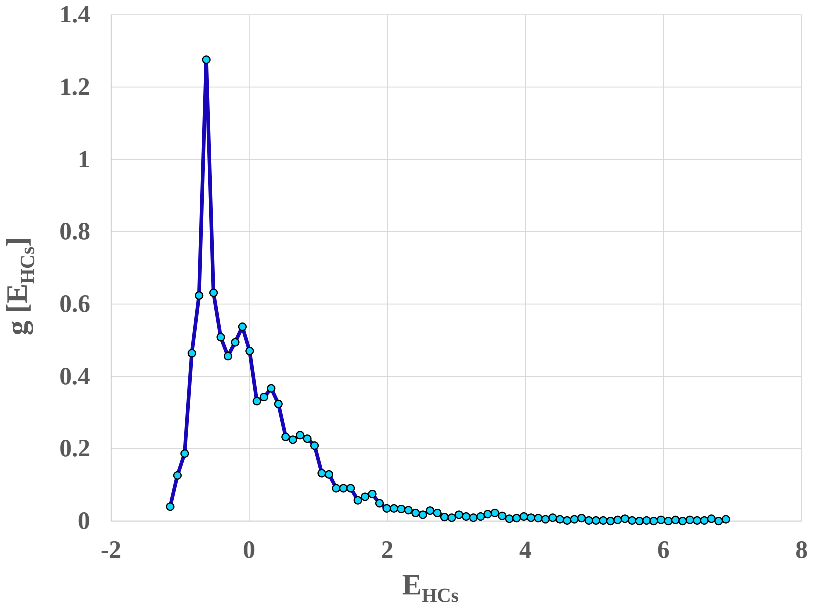

Fig. 29. Probability density – g of the standardized HC emission rate process – E_{HC}

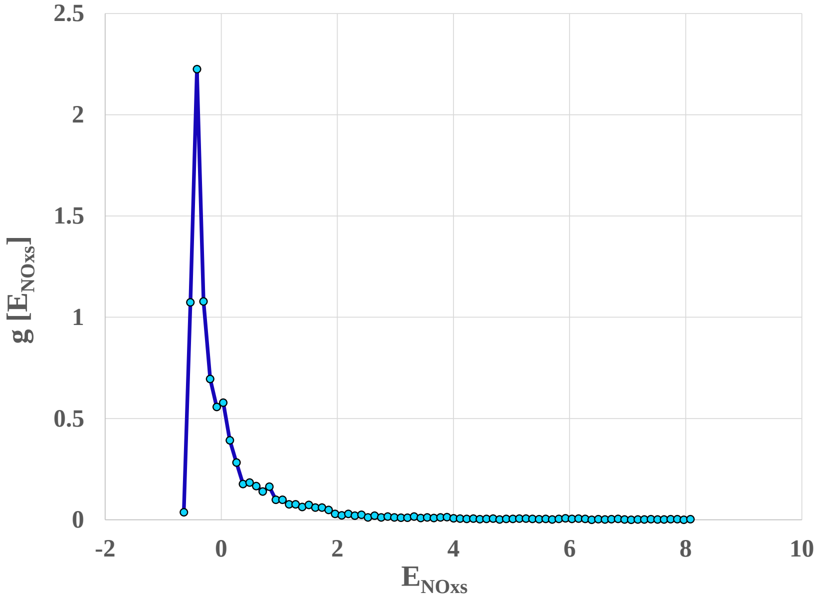

Fig. 30. Probability density – g of the process of the standardized emission rate of NO_x – E_{NOx}

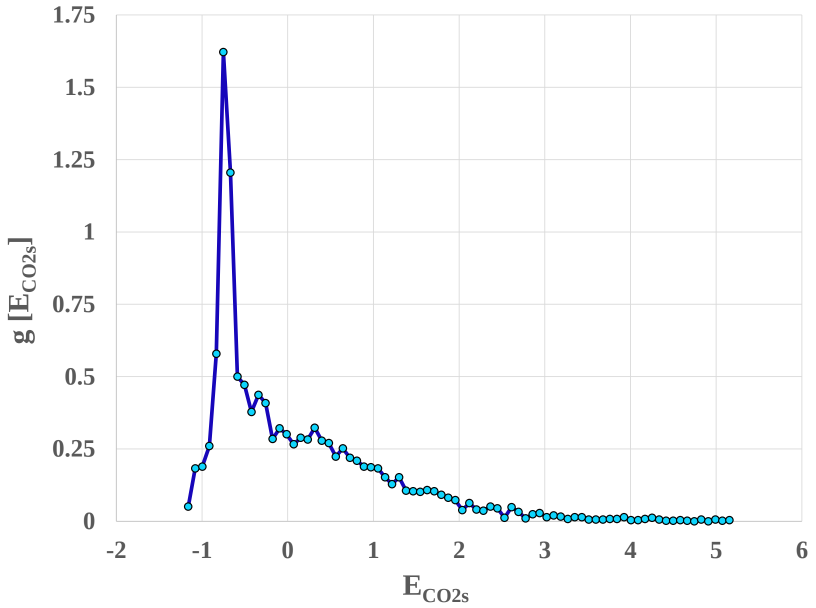

Fig. 31. Probability density – g of the standardized CO_2 emission intensity process – E_{CO2}

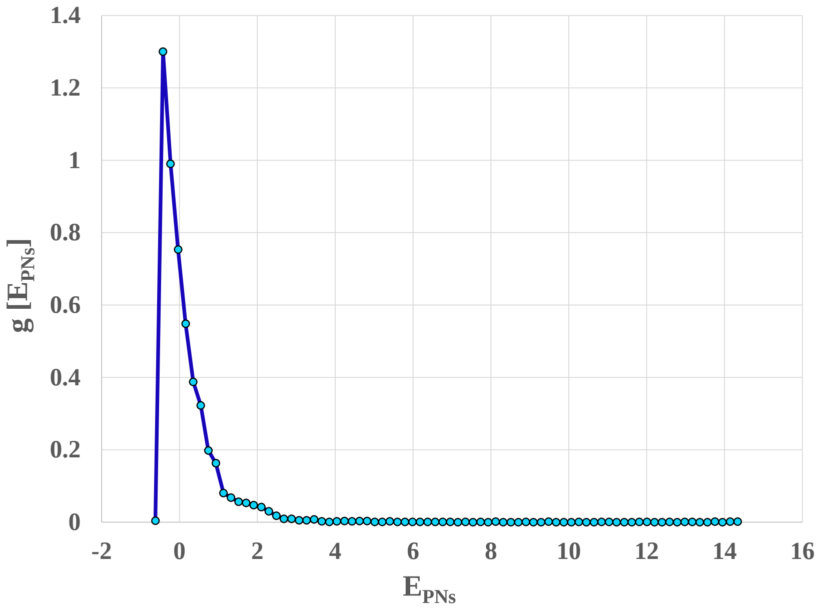

Fig. 32. Probability density – g of the process of standardized PN intensity – E_{PN}

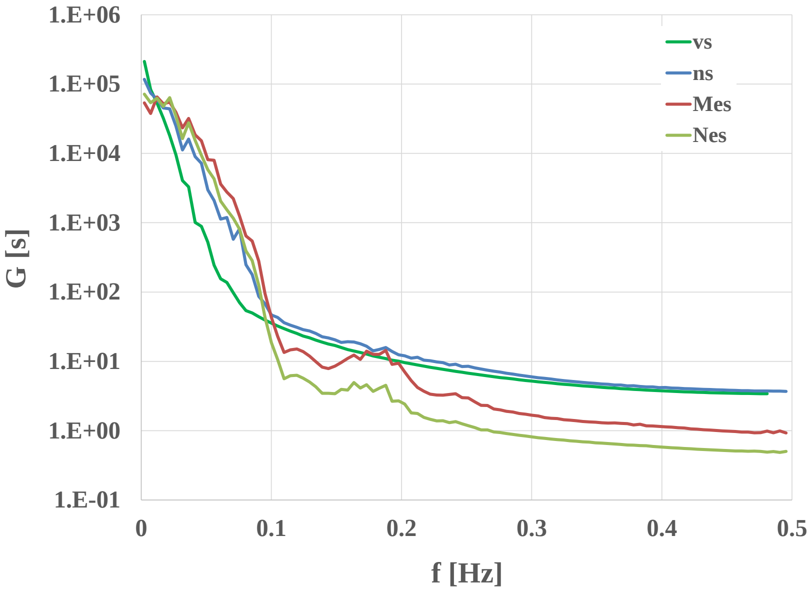

Fig. 33. Spectral power density – G of the processes: standard car speed – vs, standard car engine speed – ns, standard car torque – Mes, standard car useful power – Nes

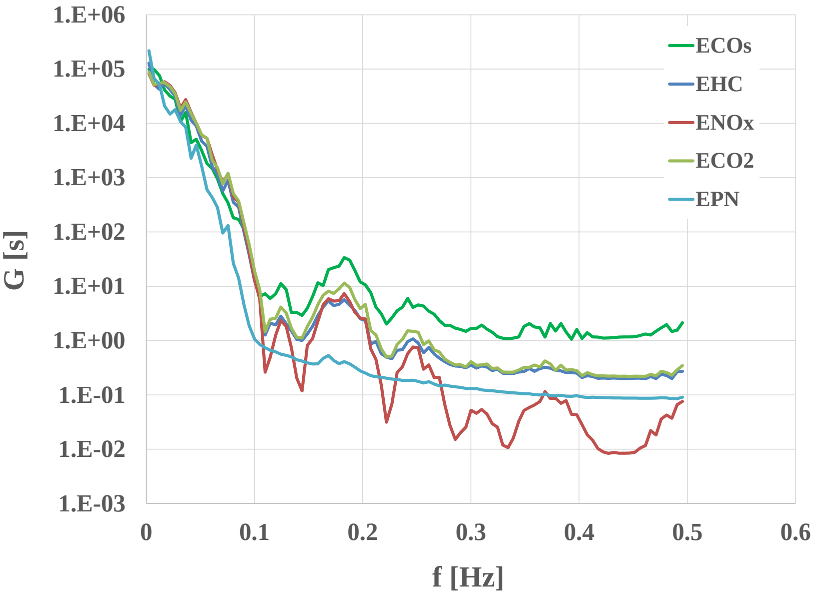

Fig. 34. Spectral power density – G of the processes: standard CO emission rate – ECOs, standard HC emission rate – EHCs, standard NOx emission rate – ENOxs, standard CO_2 emission rate – ECO_2s, standard PN intensity – EPNs

5. Summary

When summarizing the analysis of the test results of the car speed process, the operating states of the combustion engine, the processes of exhaust emission intensity and the process of the PN intensity during the RDE test, the following conclusions can be drawn:

1. The courses of emission intensity of HC, NO_x and CO_2 show some similarity. The highest values of the exhaust emission intensity and the intensity of PN occur in the driving phase of the car in traffic conditions on motorways and expressways.
2. The correlation of the processes of exhaust emission intensity and the intensity of PN with the car speed process is diversified: it is the strongest in the case of CO_2 emission intensity, closely followed by HC. The correlation between the processes of exhaust emission intensity and the intensity of PN is also differentiated. By far the strongest correlation is between the intensity of HC emissions and the intensity of CO_2 emissions, and also between the intensity of HC emissions and the intensity of NO_x emissions.
3. On the basis of the zero-dimensional statistical characteristics of car speed processes, engine operating states, exhaust emission and PN intensity, as well as on the basis of the results of process research in the field of their values, it was found that the process distributions are flattened and right-side asymmetric. Negative flattening characterizes distributions of vehicle speed and engine speed. For the other processes, the flattening is positive. The characteristics of the probability density of the engine operating state processes show some similarity. The same applies to the probability density of exhaust emission and PN intensity processes.
4. On the basis of research in the frequency domain, various dynamic properties of the considered processes of car speed and engine speed, as well as on CO emission intensity, were found. The weakest dynamic properties are for the useful power process and NO_x intensity.

The obtained results of the analysis of car speed processes, engine operating states, and the intensity of exhaust emission and PN are difficult to generalize. The main reason for this state of affairs is the fact that these are the results obtained for one implementation of stochastic processes (Papoulis et al., 2002), which should be treated as processes in the conditions of real vehicle use. It is advisable to carry out such analyzes for many implementations of the vehicle speed process, but this will be very laborious and costly research – the authors have such plans in the future. It would be particularly valuable to determine the probabilistic characteristics of the properties of the studied processes when treated as stochastic processes.

Nomenclature

AV – average value,
CO – carbon oxide,
CO_2 – carbon dioxide,
CS– catalityc stripper,
D – standard deviation,
E – pollutant (exhaust) emission/ particle number intensity,
E_{CO2s} – standarized carbon dioxide emission intensity,
E_{COs} – standarized carbon oxide emission intensity,
E_{HCs} – standarized hydrocarbon emission intensity,
E_{NOxs} – standarized nidrogen oxides emission intensity,
E_{PNs} – standarized particle number intensity,
EPSS™ – Engine Exhaust Particle Sizer™ Spectometer,
f – frequency,
FFT – Fast Fourier Transformation,
G – power spectral density,
g – probability density,
H – histogram frequency,
HC – hydrocarbons,
HDV – Heavy Duty Vehicle,
K – kurtosis,
LDV – Light Duty Vehicle,
M – median,
Max – maximum value,
M_{er} – relative engine torque,
M_{es} – standarized engine torque,
Min – minimum value,
n – engine speed,
n – engine speed,
N_{er} – relative engine effective power,
N_{es} – standarized engine effective power,
NO_x – nitrogen oxides,
n_s – standarized engine speed,
PC – Passenger Cars,

PEMS – Portable Emissions Measurement System,
PN – particle number,
R – range,
RDE – Real Driving Emissions,
S – skewness,
T – time,
v – vehile velocity,
v_s – standarized vehile velocity,
W – coefficient of variation.

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