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DETERMINATION OF EXHAUST EMISSION CHARACTERISTICS IN THE RDE TEST USING THE MONTE CARLO METHOD

Monika ANDRYCH-ZALEWSKA[1], Zdzisław CHŁOPEK[2], Jerzy MERKISZ[3], Jacek PIELECHA[4]

[1] *Faculty of Mechanical Engineering, Wroclaw University of Science and Technology, Wroclaw, Poland*

[2] *Faculty of Automotive and Construction Machinery Engineering, Warsaw University of Technology, Warsaw, Poland*

[3, 4] *Faculty of Civil and Transport Engineering, Poznan University of Technology, Poznan, Poland*

Abstract:

The article presents a method of determining the characteristics of exhaust emissions and fuel mass consumption in real driving conditions based on a single test using the Monte Carlo method. The exhaust emission characteristics used are the relations between the emissions and the average vehicle speed, and the characteristic of the fuel mass consumption is the dependence of the fuel mass consumption at the average vehicle speed. The results of empirical research of a passenger car with a spark-ignition engine in the RDE test were used. The use of the Monte Carlo method made it possible to select the initial and final moments of averaging the process values, thanks to which it was possible to determine the discrete values of the characteristics for various values of average vehicle speeds. The determined discrete characteristics of the particulate mass and number emissions and fuel mass consumption relative to the average vehicle speed were approximated by polynomial functions of the second and third degree. The determined discrete characteristics, presented as sets of points, were characterized by a relatively small dispersion in relation to their polynomial approximations. The average relative deviation of the points of discrete characteristics from the value of the polynomial was in most cases small – less than 4%, only in the case of the number of particles emitted deviated from this, as the average relative deviation of the measured points from the determined polynomial was nearly 14%. Combined with the results of RDE empirical studies, the Monte Carlo method proved to be an effective method for determining the characteristics of exhaust emissions, measured in real vehicle operating conditions. The main advantage of the proposed method was a significant reduction in the actual workload necessary to carry out the empirical research –where it became possible to determine the characteristics in a large range of vehicle average speed values with just one drive test. Using standard methods of measuring this type of data, it would be necessary to conduct multiple tests, driving at different average vehicle speeds.

Keywords: *Monte Carlo method, RDE test, combustion engine, pollutant emission*

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Contact:
1) monika.andrych@pwr.edu.pl [https://orcid.org/0000-0001-6676-2508] – corresponding author; 2) zdzislaw.chlopek@pw.edu.pl [http://orcid.org/0000-0002-3499-2533]; 3) jerzy.merkisz@put.poznan.pl [http://orcid.org/0000-0002-1389-0503]; 4) jacek.pielecha@put.poznan.pl [http://orcid.org/0000-0001-7586-1989]

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1. Introduction

There exists a need to assess the impact of motorization on the natural environment, e.g. due to the emission of engine exhaust components. In order to achieve this an assessment of exhaust emissions can be carried out (COPERT; EEA/EMEP, 2019). For this purpose, it becomes necessary to know the exhaust emissions characteristics depending on the traffic conditions of road vehicles. Most often, the parameter used to characterize the vehicles operating conditions is their average driving speed (BUWAL, 1995; COPERT; EEA/EMEP, 2019). It should be noted that the lower average vehicle speed corresponds to greater traffic congestion and travel difficulty (BUWAL, 1995). The most useful characteristics for determining the exhaust emission intensity are the relative emissions of a given substance over the distance travelled, i.e. the derivative of exhaust emission in relation to the length of the road covered by the vehicle, and its average speed. Determining such characteristics requires various driving tests to be developed, which must correspond to the different types of vehicle traffic, such as in the Artemis research program (André, 2004). The exhaust emission characteristics are determined with driving tests done on a chassis dynamometer.

This method involves some bias due to the greater reproducibility of the driving conditions on a chassis dynamometer than it can be achieved in the actual operation of vehicles on roads. Since the advent of mobile equipment for exhaust emission testing from road vehicles (PEMS – Portable Emissions Measurement System) (Giechaskiel et al., 2016; PEMS Testing, 2020), which resulted from the introduction of the RDE (Real Driving Emissions) procedure in 2017 (Andrych-Zalewska et al., 2022; Semtech, 2010; TSI, 2008), it became possible to measure the exhaust emissions of vehicles in real driving conditions. However, the implementation of many tests, differing in the nature of the traffic experienced by the vehicle and, consequently, their average speed, carries its own problems. This paper is to propose the use of test results in one test to determine the characteristics of exhaust emissions for various vehicle traffic conditions by using the Monte Carlo method (Chłopek, 2009; Metropolis & Ulam, 1949) for random determination of the ranges of measurement sections. The Polish-American mathematician Stanisław Ulam - a representative of the famous Lviv school of mathematics centered around the world-famous mathematicians Hugo Steinhaus and Stefan Banach is considered to be the primary creator of the Monte Carlo method. Stanisław Ulam was an employee of Los Alamos National Laboratory and a member of the Manhattan Project during World War II. The co-creators of the Monte Carlo method are also considered to be collaborators of Stanisław Ulam at Los Alamos National Laboratory and the Manhattan Project: the American physicist of Greek origin Nicolas Metropolis and the Hungarian mathematician John von Neumann (originally: János Lajos Neumann).

The measured characteristics relate to exhaust emissions, particle number and fuel mass consumption. These are used to obtain the exhaust emission, emission of particle number and the road fuel mass consumption at an average vehicle speed. The paper presents discussion based on the results for passenger cars obtained in RDE test.

2. Literature review

The standard procedure in the existing literature presenting and discussing the results of exhaust emission and fuel consumption tests, was usually to assess the average properties in the entire test cycles. In recent years, there have been many publications on exhaust emission tests in conditions more similar to the real conditions of road vehicles operation. Such possibilities are provided by testing vehicles in the RDE (Real Driving Emissions) test (Andrych-Zalewska et al., 2022; Giechaskiel et al., 2016; Giechaskiel et al., 2021; Merkisz et al., 2019; Merkisz et al., 2020; Pielecha & Kurtyka, 2019; Woodburn et al., 2021).

Paper (Andrych-Zalewska et al., 2022) presents the analysis results of the car speed process and the operating states of the internal combustion engine measured in the RDE test conditions. The properties of vehicle speed processes and engine operation states in the RDE test were analysed, taking into account its individual phases – driving in urban, extra-urban and motorway conditions. The results of research in the time domain, process value and frequency were presented. The traffic conditions were found to have a significant impact on the power spectral density.

The paper (Giechaskiel et al., 2016) presents the research results of an RDE test. Six stages of the procedure were described in detail: vehicle selection, vehicle preparation, route design, drive execution,

route verification and exhaust emissions calculation. Of these steps, the preparation of the vehicle and the execution of the test drive were described in more detail. Examples of route verification and emission calculations were also provided.
Citation (Giechaskiel et al., 2021) is the JCR (Journal Citation Reports) technical report from 2021, developed for the European Commission. This study is considered as scientific support for the European policy-making process. The report concerns research methodology in RDE tests.
Publication (Merkisz et al., 2019) presents the results of research on the impact of a cold engine start in the RDE test. The tests were carried out on a passenger car with a spark-ignition engine with direct fuel injection; the vehicle complied with the Euro 6c emission standard. It was found that the impact of cold engine start on exhaust emissions was not too great, which resulted primarily from the long distance travelled in the test, which was about 48 km.
Authors of (Merkisz et al., 2020) presented the exhaust emission test results from a hybrid car engine in the WLTC (Worldwide Harmonized Light Vehicles Cycle) and RDE tests. A very low emission value and road number of particulates was found in both tests in comparison with the limits outlined in the homologation procedures.
The article (Pielecha & Kurtyka, 2019) presents the RDE test results of two cars with spark-ignition engines. The tests were carried out on the same test route, which includes urban, rural and motorway sections. The obtained results were subjected to analysis in line with the requirements of the RDE procedure and the Euro 6c toxicity standard. The dynamic properties of both tests were also compared based on the average product value of the vehicle speed and its positive acceleration.
The test results of two passenger cars with plug-in hybrid drive meeting the requirements of Euro 6d were shown in (Woodburn et al., 2021). The tests were performed both in the WLTC test on a chassis dynamometer and in the RDE test. It was found that the battery state of charge had a noticeable effect on exhaust emissions, and even more so on fuel consumption.
The Monte Carlo method is used in engine research mainly to simulate engine processes (Hölz et al., 2019; Probst et al., 2019) and to develop control algorithms (Mourat et al., 2021; Probst et al., 2019; Zhang et al., 2021).
Paper (Hölz et al., 2019) presents the application of the Monte Carlo method to simulate processes related to thermal processes and the flow of cooling liquid in a turbocharged spark-ignition engine.
Article (Probst et al., 2019) concerns the use of the Monte Carlo method for the simulation of fluid flow in internal combustion engines. The results of the research were used to optimize the combustion engine's control algorithms.
The application of the Monte Carlo method for the purposes of stochastic optimization of the control algorithms, taking into account the system uncertainty was discussed in (Mourat et al., 2021).
While in (Sun & Ertz, 2020) the Monte Carlo method and the LCA (Life Cycle Assessment) method were used to assess the environmental benefits of supplying engines of heavy vehicles with liquefied natural gas (LCA).
In (Zhang et al., 2021) the Monte Carlo method was also used, in this case to optimize the control algorithms of an aircraft piston engine.
The use of the Monte Carlo method for research procedures in internal combustion engines is mainly the focus of a group of authors associated with articles (Chłopek, 2009; Laskowski et al., 2019) and the authors of article (Huertas et al., 2019) for the assessment of exhaust emissions and fuel consumption by road vehicles. The developed methods were used to simulate the tests of 15 buses.
Article (Huertas et al., 2019) presents the comparison of three ways of using the Monte Carlo method to create driving tests. For this purpose, four regions were selected and simultaneously monitored the speed, fuel consumption and pollutant emissions of a fleet of 15 buses with the same level of pollutant emissions over eight months of normal operation.
In (Chłopek, 2009) a comprehensive interpretation was presented of the application of the Monte Carlo method for the purpose of learning about determinate and random properties of the explored reality. An example of the application of the Monte Carlo method to simulate a dynamic test for testing internal combustion engines based on a static test was shown.
The results of simulations of organic compounds emissions from internal combustion engines of road vehicles for the purpose of assessing the impact of these emissions on the concentration of pollutants in the atmospheric air were provided in (Laskowski et al., 2019). The emission characteristics of organic

compounds determined by the Monte Carlo method were used for this purpose. The test results presented in this article fall into the category of Monte Carlo method applications for determining the characteristics of exhaust emissions and fuel consumption in the conditions of real vehicle operation.

3. Empirical test results

The processes recorded in the research were processed with the Savitzky-Golay filter (Savitzky & Golay, 1964) in order to reduce the share of high-frequency noise in the obtained signals.

Figures 1–11 display the results of empirical tests of a passenger car with a direct injection spark-ignition engine in the RDE test. Figure 1 is the vehicle speed profile obtained in the RDE test.

Figure 2 shows the engine control system's operation recorded in the RDE test.

Figure 3 shows the engine rotational speed throughout the RDE test.

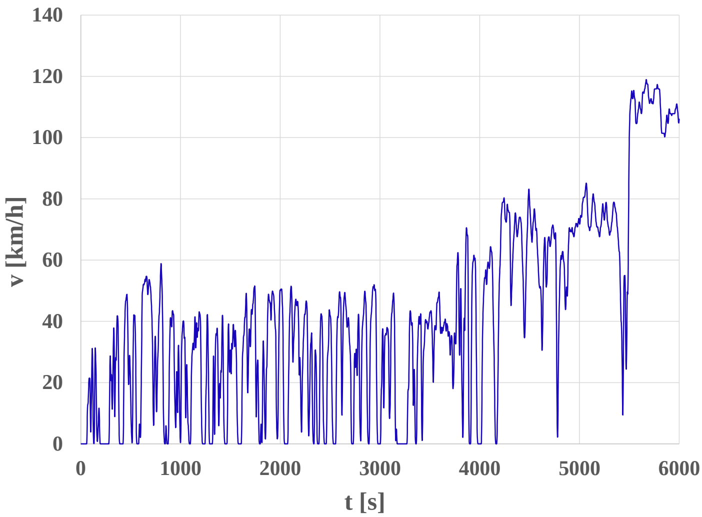

Fig. 1. Vehicle speed profile obtained in the RDE test

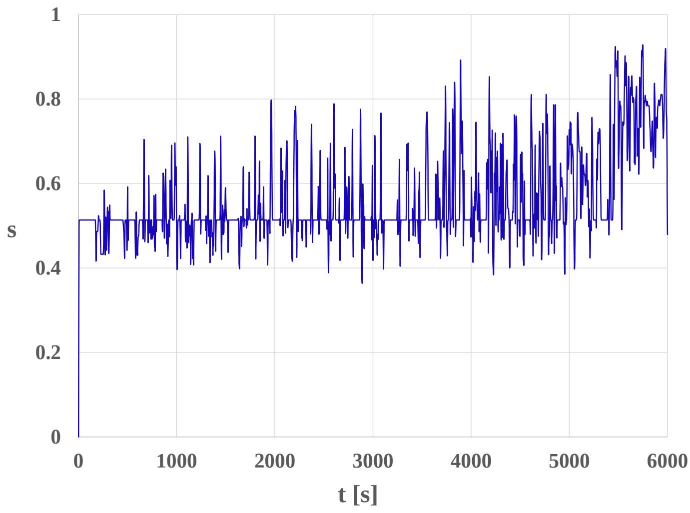

Fig. 2. Engine control system's operation in the RDE test

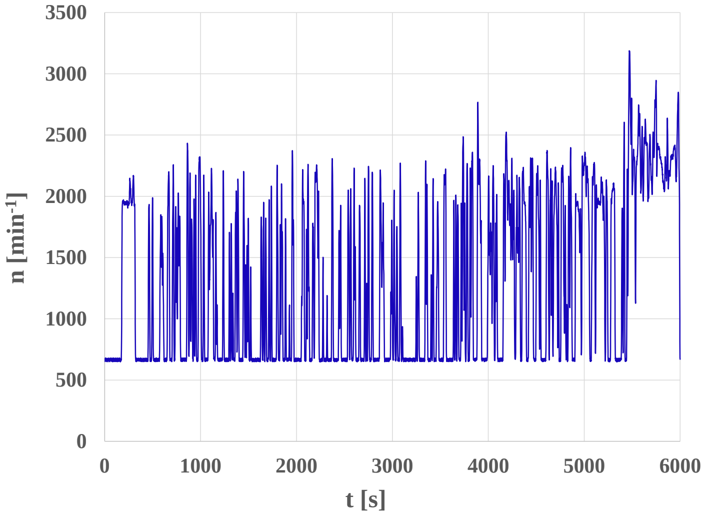

Fig. 3. Engine rotational speed throughout the RDE test

Figure 4 shows the relative engine torque during the RDE test. Relative torque was defined by the equation:

$$M_{er}(n) = \frac{M_e(n)}{M_{e\,ext}(n)} \quad (1)$$

where: n – engine speed, M_e – engine torque, $M_{e\,ext}$ – nominal engine torque (on the engine speed and torque curve).

Figure 5 shows the engine relative net power for a vehicle in the RDE test. Relative net power is then compared to the maximum net power obtained in the test.

Figures 6–9 provide a visualization of the exhaust emission intensity characteristics of: carbon monoxide, hydrocarbons, nitrogen oxides and carbon dioxide.

Figure 10 is a representation of the exhaust emission intensity of the number of particles in an RDE test.

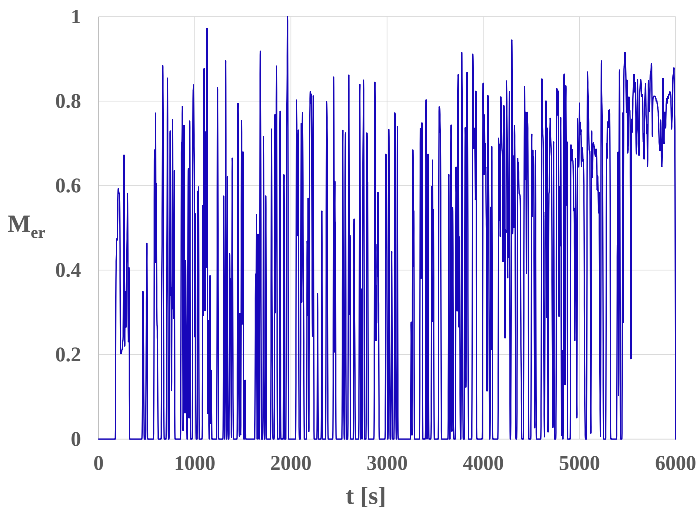

Fig. 4. Relative engine torque during the RDE test

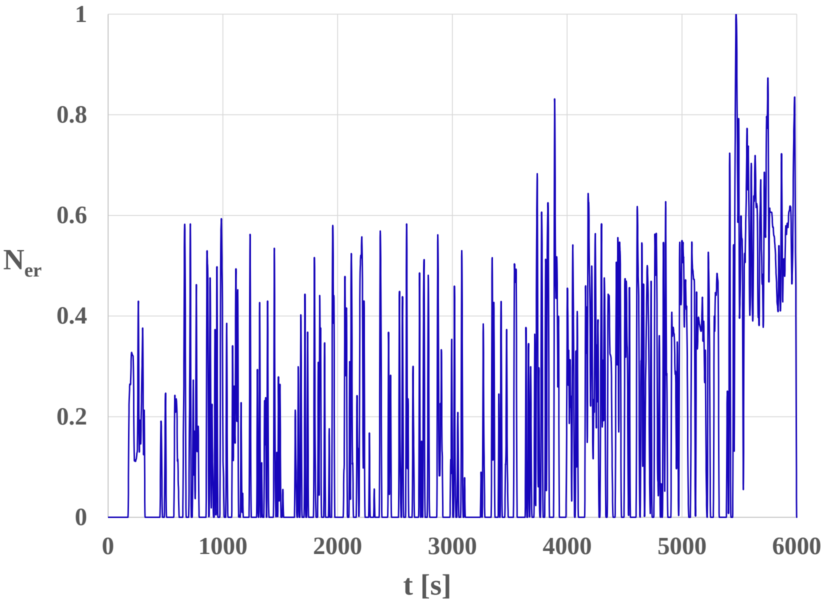

Fig. 5. The relative net power characteristic for a vehicle in RDE test

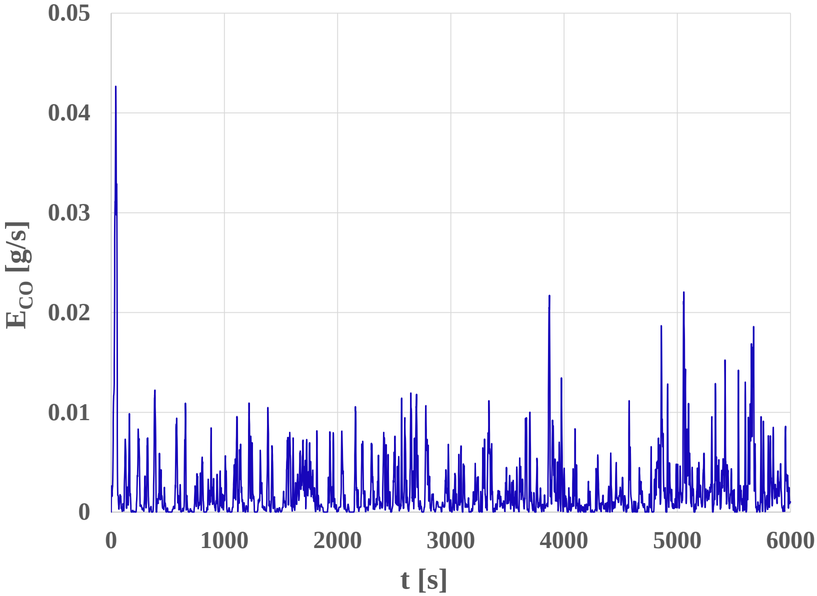

Fig. 6. Carbon monoxide exhaust emission intensity measured in the RDE test

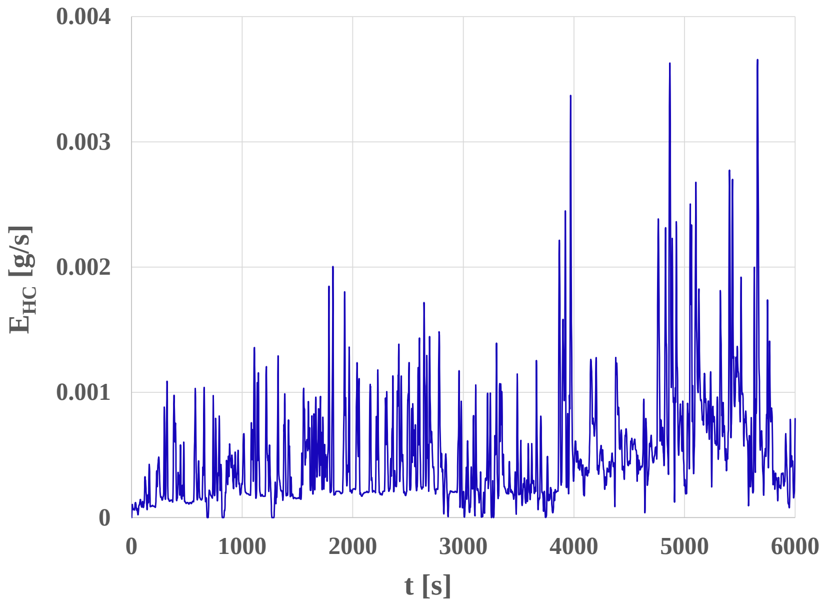

Fig. 7. Hydrocarbons exhaust emission intensity measured in the RDE test

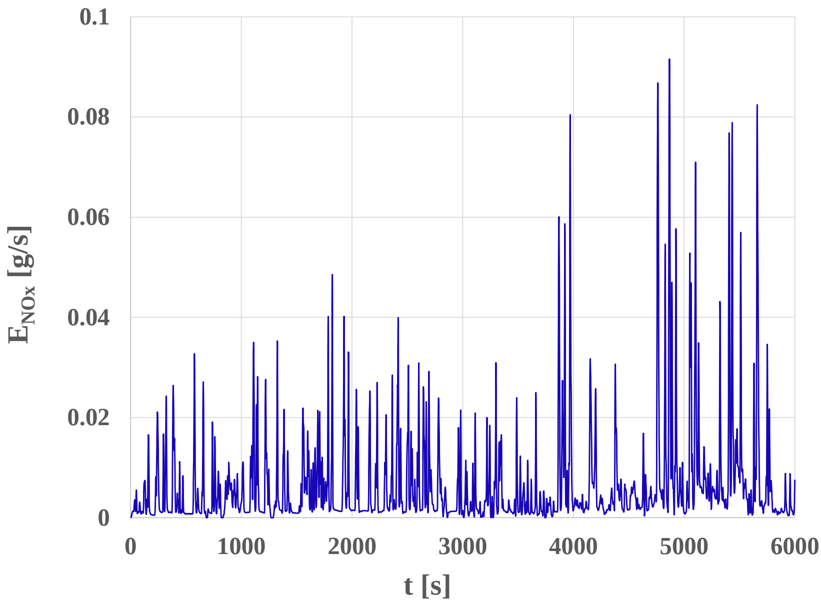

Fig. 8. Nitrogen oxides exhaust emission intensity measured in the RDE test

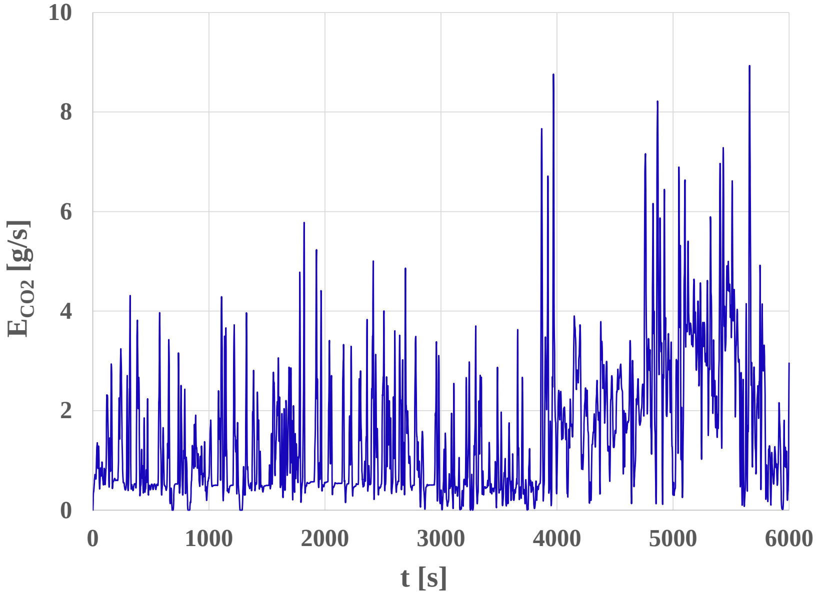

Fig. 9. Carbon dioxide exhaust emission intensity measured in the RDE test

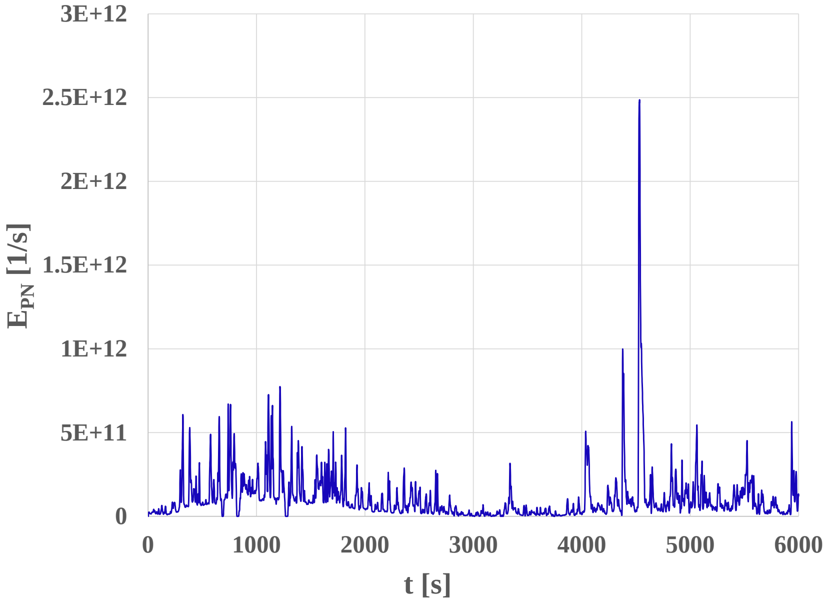

Fig. 10. Particle number exhaust emission intensity measured in the RDE test

Figure 11 shows the fuel mass consumption intensity for the engine of the vehicle tested in RDE.

4. Results of data analysis

Figures 12–15 show the relationships between the operating states of the engine in an RDE test. RDE tests of engine and vehicle operating states were conducted in order to assess the parameter ranges of these states in the perspective of how representable was the obtained exhaust emission data. Additional points with coordinates determined by the center of mass of all the other points in each set were marked on the charts. Figure 12 shows the relationship between the vehicle speed and the engine control in the RDE test.

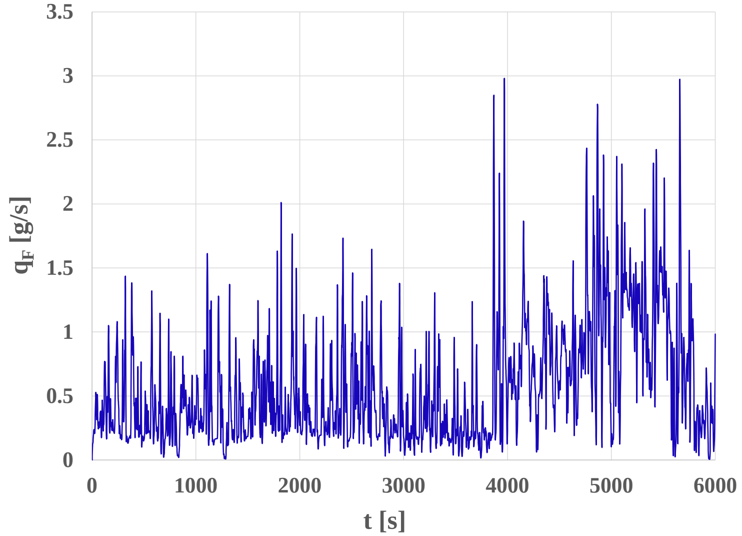

Fig. 11. Fuel mass consumption intensity measured in the RDE test

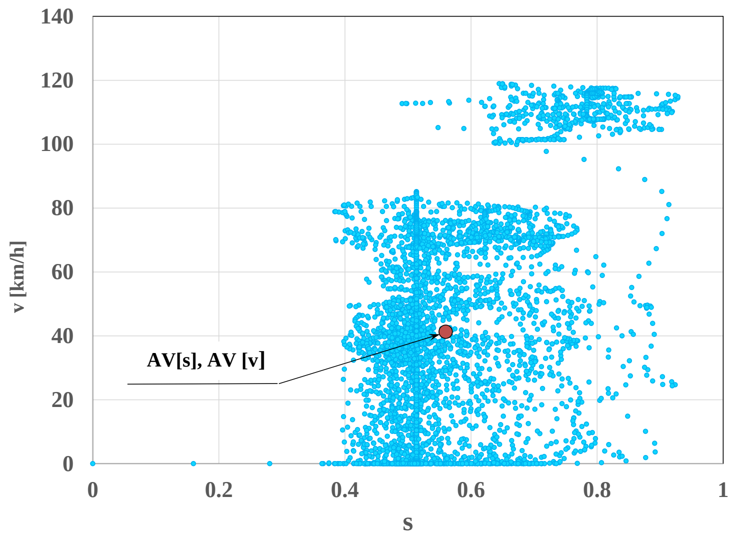

Fig. 12. The relationship between the vehicle speed and the engine control in the RDE test

Engine control was mainly in the range of values greater than 0.4. The average control value was less than 0.6 and the average speed was around 40 km/h. Figure 13 shows the relationship between engine control and engine rotational speed in the RDE test. The maximum rotational speed was greater than 3000 rpm. The average value of the engine rotational speed was close to 1300 rpm. The relationship between the relative engine torque and its rotational speed in the RDE test was illustrated in Figure 14. The mean relative torque value was approximately 0.3. Figure 15 shows the relationship between the engine relative net power and its rotational speed in the RDE test.

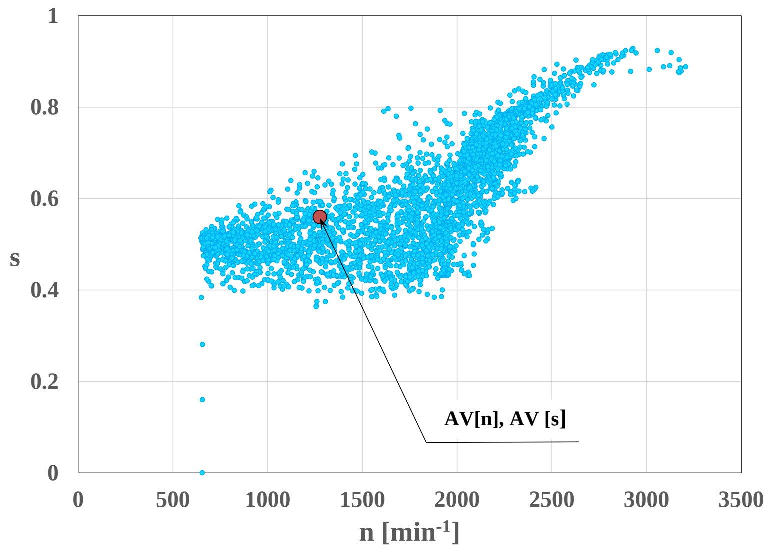

Fig. 13. The relationship between the engine control and the engine rotational speed in the RDE test

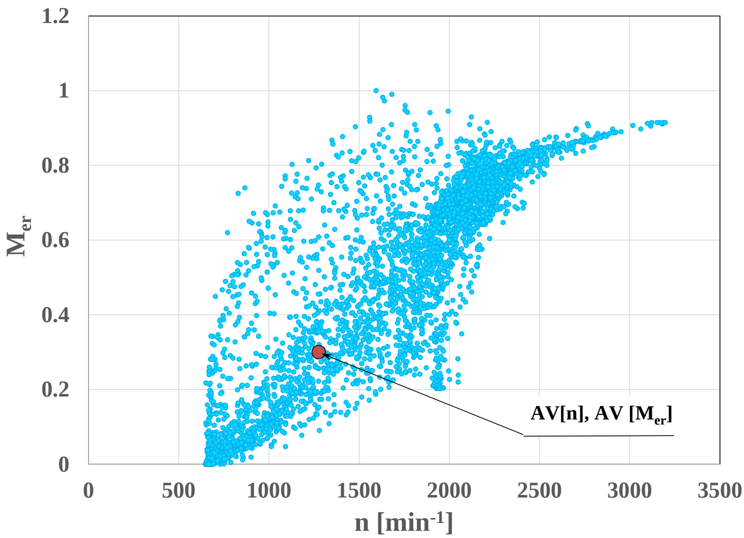

Fig. 14. The relationship between the relative engine torque and the engine rotational speed in the RDE test

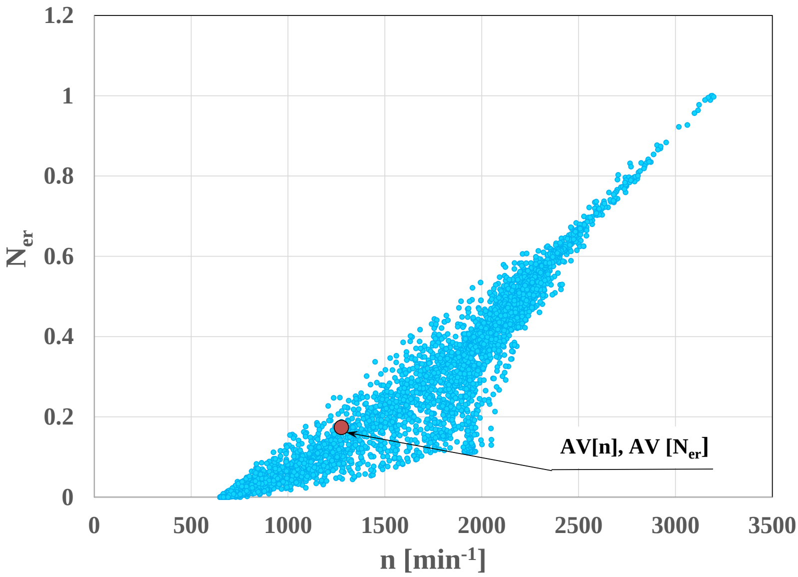

Fig. 15. The relationship between the engine relative net power and the engine rotational speed in the RDE test

The average relative net power value was below 0.2. Figures 16–21 contain the characteristics of exhaust emissions, particle number and fuel mass consumption determined in the RDE test using the Monte Carlo method. The average values of the exhaust emission intensity, the particle number emission intensity and the fuel mass consumption rate within the time limits (t_1, t_2) selected using the pseudo-random number generator were:

$$E_{AV}(t_1, t_2) = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} E(t) dt \quad (2)$$

The mean vehicle travel speed in the time range (t_1, t_2) was:

$$v_{AV}(t_1, t_2) = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} v(t) dt \quad (3)$$

While the mean road exhaust emission value, the mean number of emitted particles and the mean fuel mass consumption rate in the time range (t_1, t_2) equal:

$$b(t_1, t_2) = \frac{E_{AV}(t_1, t_2)}{v_{AV}(t_1, t_2)} \quad (4)$$

Figures 16–19 show the characteristics of exhaust emission, the number of emitted particles was presented in Figure 20 – while the fuel mass consumption characteristic can be seen on Figure 21. The sets of points determined by the Monte Carlo method were approximated by polynomial functions of the second and third degree.
The determined discrete characteristics presented as sets of points were characterized by a relatively small dispersion in relation to their polynomial approximations. Figure 22 shows the average relative deviation of the points of the discrete characteristics from the values of the polynomial approximations:

$$d = AV\left[2 \frac{|b - b_{apr}|}{b + b_{apr}}\right] \quad (5)$$

The average relative points deviation of discrete characteristics from the polynomial values was small in most cases – less than 4%, only in the case of the road number of particles emitted the average relative deviation of the points from the determined polynomial was almost equal to 14%.

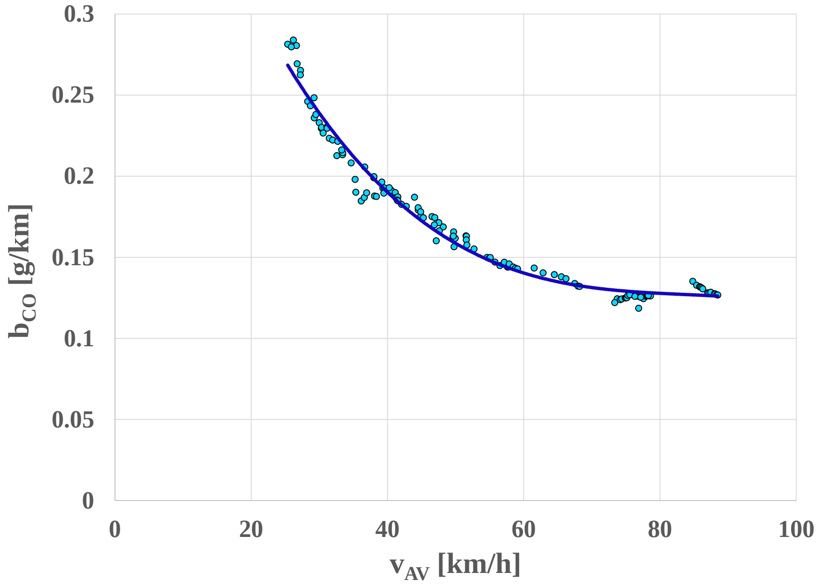

Fig. 16. Carbon monoxide exhaust emission characteristic from the engine of a vehicle in the RDE test

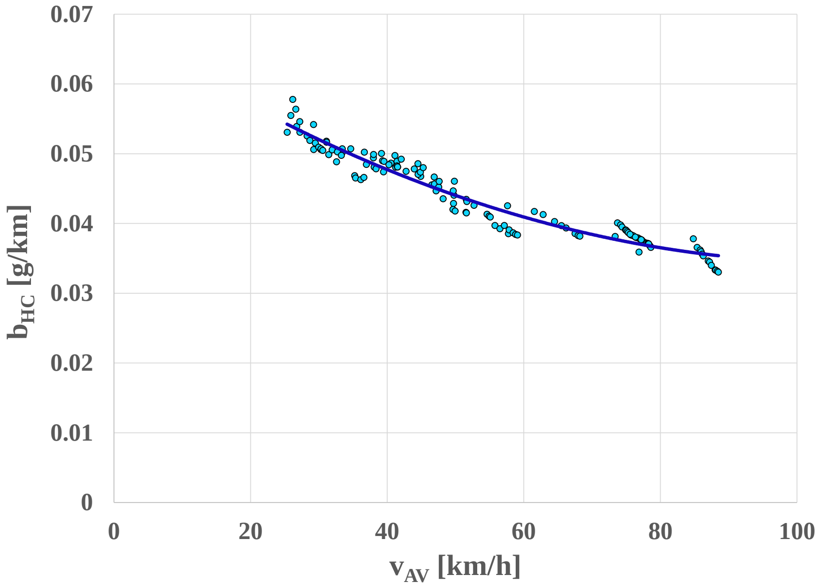

Fig. 17. Hydrocarbons exhaust emission characteristic from the engine of a vehicle in the RDE test

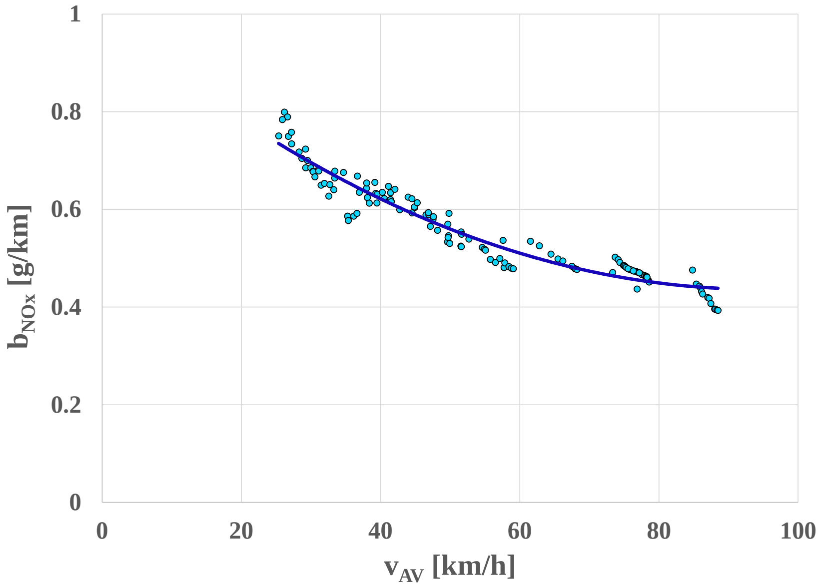

Fig. 18. Nitrogen oxides exhaust emission characteristic from the engine of a vehicle in the RDE test

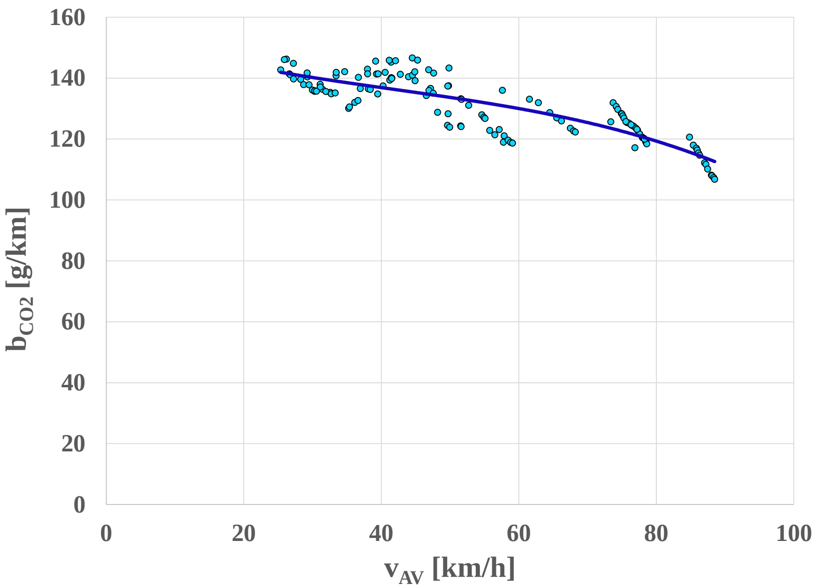

Fig. 19. Carbon dioxide exhaust emission characteristic from the engine of a vehicle in the RDE test

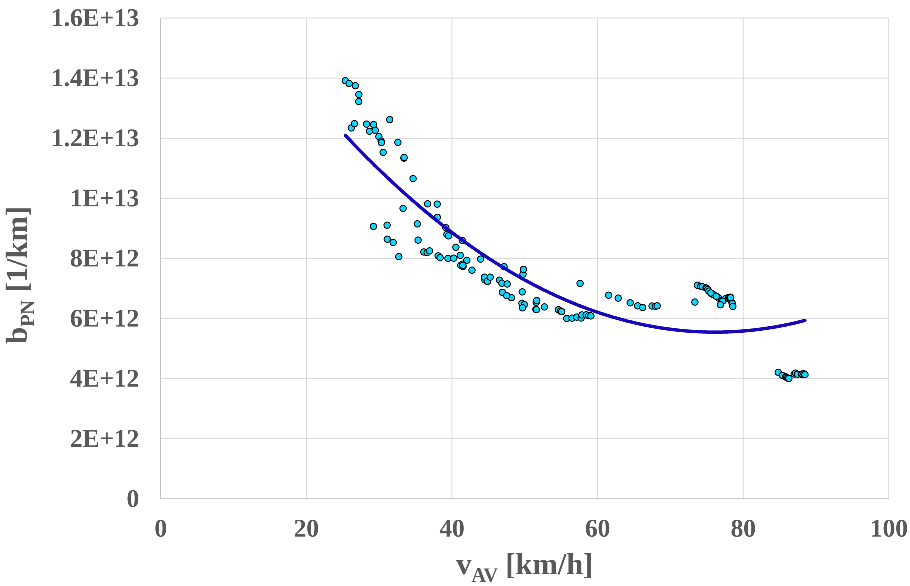

Fig. 20. Particle number exhaust emission characteristic from the engine of a vehicle in the RDE test

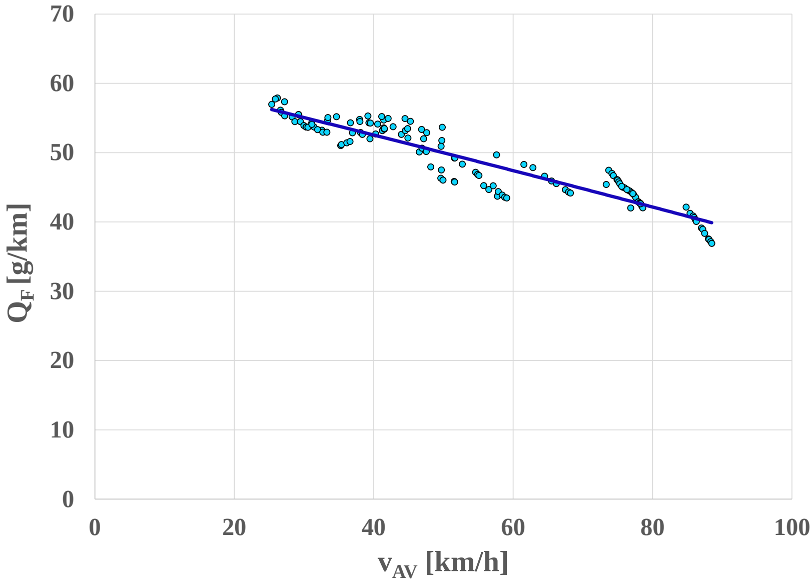

Fig. 21. Fuel mass consumption characteristic from the engine of a vehicle in the RDE test

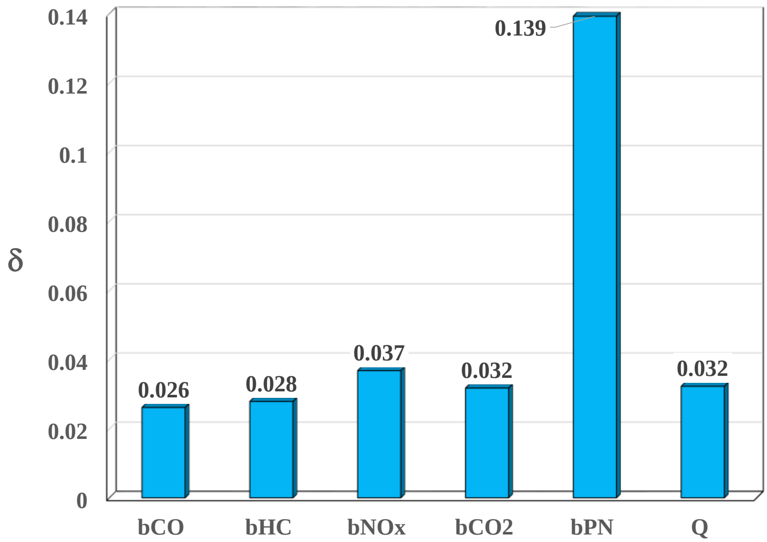

Fig. 22. The average relative points deviation of discrete characteristic from the polynomial approximation values

5. Conclusion

When used with empirical RDE test results the Monte Carlo method turned out to be an effective method to determine the characteristics of exhaust emission, particle number emissions and fuel mass consumption, as measured in real operating conditions of the vehicle. The method provided very reproducible results. The main advantage of the proposed method was a significant reduction in the actual labor necessary to conduct the empirical research – using just one test it became possible to determine the characteristics in a large range of mean vehicle speed values. It would have been necessary to carry out multiple tests, driving with different mean vehicle speeds, when using standard methods of measuring this type of data. Another important advantage was the fact that the determined characteristics correspond well to the real conditions of the vehicle's movement.

Nomenclature

AV – average value operator
b – specific distance pollutant emission/specific distance particulate number
CO – carbon oxide
CO_2 – carbon dioxide
E – pollutant emission intensity/particle number intensity
EPSS™ – Engine Exhaust Particle Sizer™ Spectometer
HC – hydrocarbons
M_{er} – relative engine torque
n – engine speed
N_{er} – relative engine effective power
NO_x – nitrogen oxides
PEMS – Portable Emissions Measurement System
PN – particle number
Q – specific distance fuel mass consumption
q_F – fuel mass consumption intensity
RDE – Real Driving Emissions
s – engine control
t – time
v – vehicle velocity

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