Article citation info:
ANDRYCH-ZALEWSKA, M., CHŁOPEK, Z., MERKISZ, J. et al. Determination of characteristics of pollutant emission from a vehicle engine under traffic conditions in the engine. *Combustion Engines*. 2022, **191**(4), 58-65. https://doi.org/10.19206/CE-147327

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Determination of characteristics of pollutant emission from a vehicle engine under traffic conditions in the engine test

ARTICLE INFO

Received: 8 February 2022
Revised: 6 March 2022
Accepted: 13 March 2022
Available online: 13 March 2022

The paper describes the method of determination of exhaust emission characteristics from a vehicle engine based on the results obtained in a driving test simulated on an engine dynamometer. These characteristics are the relations between the specific distance emissions and the zero-dimensional characteristics of the process of vehicle velocity: the average velocity value and the average value of the absolute value of the product of vehicle velocity and acceleration. The exhaust emission characteristics are used to simulate the emissions from vehicles operating in different types of traffic conditions. The engine operating states in the engine dynamometer tests were determined by the operating conditions of the vehicle during the test. The authors applied the Monte Carlo method in order to determine the characteristics of different values of the zero-dimensional characteristics of the vehicle velocity process. This enabled the determination of the characteristics based on the test results from a single realization of the process of vehicle velocity. Additionally, the developed method allowed a replacement of the empirical research on the chassis dynamometer with the one performed on the engine dynamometer. The obtained exhaust emission characteristics are in line with the characteristics obtained on the chassis dynamometer in multiple tests.

Key words: *combustion engine, pollutant emission, driving test, engine test, characteristics of pollutant emission, the Monte Carlo method*

1. Introduction

Engineers need to know the motor vehicle exhaust emission characteristics that allow a simulation of the specific distance exhaust emissions, particularly if changes in the traffic organization or the structure of the vehicles in use occur [3, 7, 9–11, 15, 16]. There exists a serious problem with the development of a method of assessment of the driving properties of motor vehicles that characterize their environmental impact. The simplest and most frequently applied quantity characterizing the vehicles in motion is the average vehicle velocity [3, 7–11]. It is, therefore, necessary to know the exhaust emissions for the categories of individual motor vehicles under different traffic conditions [3, 7, 9–11, 21].

Category (from Greek: κατηγορείν – to assert), in philosophy is a term introducing a structure: a class of objects possessing certain characteristics related with one another.

Vehicle categories are divided in terms of their different criteria, particularly [3, 7, 9–11]:

- designation,
- conventional size of the vehicles and their engines,
- properties of motor vehicles and their engines in terms of their engine cycle and detailed technological solutions as well as their usable properties (exhaust emissions in particular),
- engine fuels,
- technical level of advancement of the vehicles and their engines.

The elementary category of motor vehicles [7] are the ones of the same criteria-related characteristic features such as passenger vehicles fitted with diesel engines of the displacement not exceeding 2 dm^3 of the Euro 6 emission standard, fueled with diesel fuel.

The accumulated category of motor vehicles [7] are vehicles not having the same criteria-related characteristic features such as passenger vehicles fitted with spark ignition engines.

The most accumulated vehicle category of motor vehicles is all motor vehicles.

In order to determine the exhaust emission characteristics of vehicles from individual categories, it is necessary to carry out empirical research in driving tests corresponding to the actual operating conditions of the tested object [1, 2, 4, 5, 12, 13, 20, 22]. Information on such properties is contained in a variety of databases such as INFRAS AG [11] or COPERT [9]. Figure 1 presents the example relation between the average specific distance emission of carbon monoxide and the average vehicle velocity for passenger vehicles fitted with spark ignition engines of the displacement range 1.4–2 dm^3 and the emission category of Euro 5 according to INFAS AG [11].

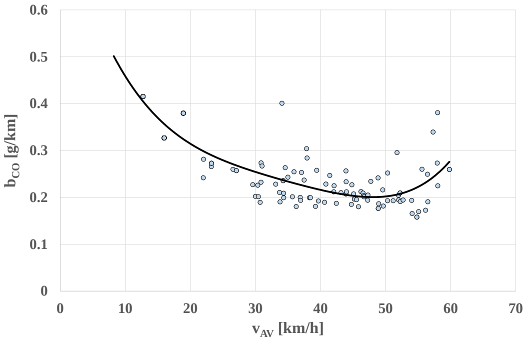

Fig. 1. Example characteristics of exhaust emissions – relation between the average specific distance emission of carbon monoxide and the average vehicle velocity

One can observe specific properties of the characteristics: high average emission of carbon monoxide for low average vehicle velocity, typical of non-stable vehicle motion and an increasing average emission of carbon monoxide for high vehicle load and increasing average velocity.

It is, however, difficult to validate these characteristics. In such a case, it is necessary to carry out time-consuming empirical research in laboratories that are generally hardly accessible. These are laboratories equipped with chassis dynamometers and laboratory equipment for exhaust emission analysis. It is, therefore, purposeful to develop simpler methods of determination of the exhaust emission characteristics for motor vehicles under different conditions of their operation.

Literature does not provide many examples regarding alternative methods of determination of exhaust emission characteristics from motor vehicles. Conventional methods are described in detail in [3, 10].

Much more materials one can find in literature as regards the results of research carried out in driving tests. In [2, 4, 5, 7, 12, 13] the authors describe the influence of the dynamic properties on the exhaust emissions from motor vehicles. Majority of the works treats on the exhaust emission results from driving tests [1, 2, 5, 7, 12, 13], including actual traffic conditions.

In [6] the application of the Monte Carlo method used for the determination of the exhaust emission characteristics under quasi-random conditions was first described. The Monte Carlo method was also used in the synthesis of the driving tests to investigate the properties of motor vehicles operated in quasi-random conditions [8].

In this paper, the authors present the results that are a validation of the developed methodology of determination of exhaust emission characteristics from motor vehicles based on the results of empirical research performed on a combustion engine on an engine dynamometer in a test simulating the engine operating states in a driving test.

2. Research aim, object, program and equipment

The aim of the investigations was the development of the method of determination of exhaust emission characteristics corresponding to the varied conditions of operation of a motor vehicle based on the tests performed on an engine dynamometer in a single dynamic test without the necessity of performing multiple tests on a chassis dynamometer.

For the determination of the exhaust emission characteristics, the authors used the results of empirical research described in detail in [1, 2].

The object of the research was a Fiat 1.3 JTD MultiJet diesel engine fitted in Fiat Idea. This is a four-cylinder, straight, turbocharged engine of the displacement of 1300 cm^3. The engine fueling system uses a common rail solution with a direct injection of the maximum injection pressure of 140 MPa. The engine power output is 51 kW at 4100 min^{-1}. The engine's mean effective pressure under nominal conditions is 1.15 MPa, therefore the engine does not have a high power/displacement ratio even though it is a turbocharged one. Under the conditions of maximum torque (180 N·m at 1750 min^{-1}) the mean effective pressure amounts to 1.74 MPa.

The engine exhaust system is fitted with an oxidation catalyst but it does not have a diesel particulate filter. The investigated vehicle falls in the emission category of Euro 4.

The program of the research included a performance of an engine dynamometer test developed based on the engine parameters recorded in a separate driving test.

To this end, the authors used a special test designed at Poznan University of Technology and carried out in the streets of Poznan in actual traffic. The test was named 'The Malta test' referring to Lake Malta, around which the test route extended. The test route (Fig. 2) was selected in such a way as to make the vehicle driving conditions as close to the NEDC (New European Driving Cycle) test conditions as possible. The route profile was varied in terms of elevation above the sea level and the maximum difference was 25.2 m.

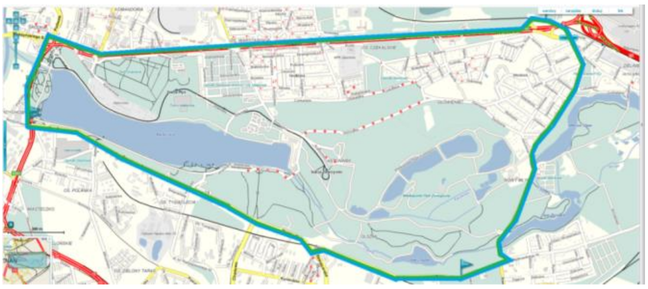

Fig. 2. The Malta test route

During the test drive the following were recorded: the vehicle velocity (Fig. 3) and the engine speed and load.

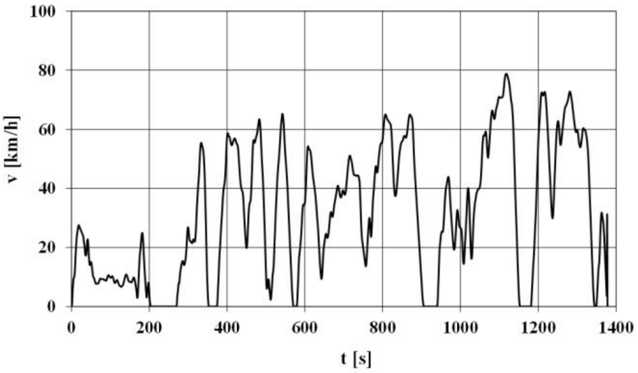

Fig. 3. The process of vehicle velocity in the Malta test

During the Fig. 4 and 5 present the engine speed and relative torque.

The engine relative torque was defined as:

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

where: n – engine speed, $\mathrm{M_e}$ – engine torque, $\mathrm{M_{e\,ext}}$ – engine torque at full throttle.

Figure 6 presents the collective engine operating states in the Malta test in the following coordinates: engine speed–relative engine torque. In the graph, the following points were marked: average engine speed (AV[n]) and average value of the relative torque (AV[$\mathrm{M_{er}}$]). As we can see, the average engine load is not high – approx. 20% at a moderate engine speed of approx. 1500 min^{-1}.

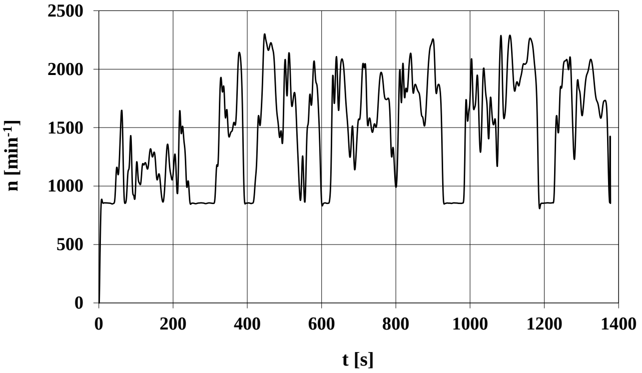

Fig. 4. The process of engine speed in the Malta test

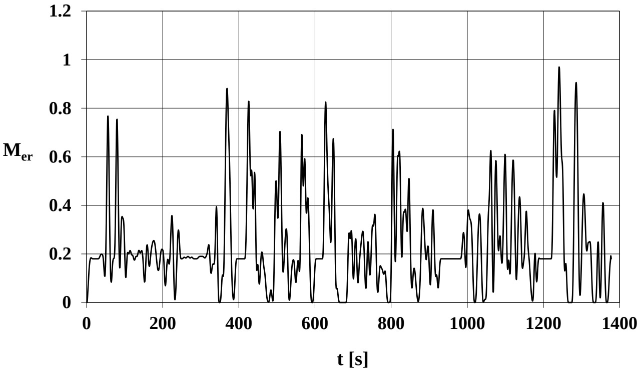

Fig. 5. The process of relative engine torque in the Malta test

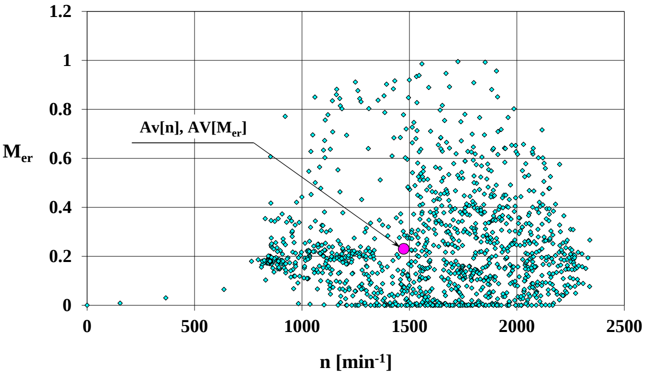

Fig. 6. Set of engine operating states in the Malta test

The engine tests in the Malta test performed on an engine dynamometer were carried out for a thermally stabilized engine.

The tests were carried out on Dynoroad 120 kW by AVL that enables the recording of parameters in a wide range of measurement resolutions while maintaining the high sampling quality (10 Hz).

For the testing of the exhaust emissions under dynamic engine states, the Semtech DS analyzer was applied with the following modules [18]:

- Flame Ionization Detector (FID) determining the concentration of hydrocarbons,
- Non-Dispersive Ultraviolet (NDUV) module utilizing ultraviolet radiation for the measurement of nitrogen monoxide and nitrogen dioxide,
- Non-Dispersive Infrared (NDIR) module utilizing infrared radiation for the measurement of the concentration of carbon monoxide and carbon dioxide,
- an electrochemical analyzer for the determination of the concentration of oxygen,
- an exhaust flow measurement module.

For the measurement of the particle number, the TSI 3090 EPSS™ (Engine Exhaust Particle Sizer™ Spectrometer) was applied [19]. The TSI 3090 EPSS™ analyzer measures the particle size distribution in the diameter range of 5.6 nm to 560 nm.

The measurement quantities in the dynamic conditions were recorded with the frequency of 10 Hz and then filtered using the second order Savitzky-Golay filter to reduce the share of noise in the high frequency signals [17].

3. Methodology

The subject of the research presented in this paper was the exhaust emission characteristics under the conditions corresponding to actual engine operation in a vehicle.

As the values characterizing the exhaust emissions, the specific distance exhaust emissions and the specific distance particle number were adopted.

The specific distance exhaust emissions (b) are a derivative of the exhaust emissions against the distance covered by the vehicle [7]:

$$\hat{b}_i = \frac{m_i}{ds} \tag{2}$$

where: m_i – emission of an exhaust component, s – distance covered by the vehicle, i = CO (carbon monoxide), i = HC (hydrocarbons), i = NO_x (nitrogen oxides), i = CO_2 (carbon dioxide).

The specific distance particle number (b_{PN}) is a derivative of the particle number (PN) against the distance covered by the vehicle:

$$\hat{b}_{PN} = \frac{PN}{ds} \tag{3}$$

The following independent variables of the exhaust emission characteristics were adopted:

- average vehicle velocity

$$v_{AV} = AV[v(t)] = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} v(t)\,dt \tag{4}$$

where: AV – average value operator, v – vehicle velocity, t – time, t_1 – start time of averaging, t_2 – end time of averaging; $t_2 > t_1$,

- average value of the absolute value of the product of vehicle velocity and acceleration

$$A = AV\big[Abs[v(t) \cdot a(t)]\big] = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} |v(t) \cdot a(t)|\,dt \tag{5}$$

where: Abs – absolute value operator, a – vehicle acceleration.

The interpretation of the average vehicle velocity as the characteristics of the process of vehicle velocity is obvious. This quantity characterizes the vehicle engine load [3, 7, 10]. The interpretation of the average value of the absolute value of the product of vehicle velocity and acceleration characterizes the engine load under dynamic states [3, 7].

For the determination of the average specific distance exhaust emissions and the average specific distance particle number, the recorded tracings of the following were used:

- exhaust emission intensity (carbon monoxide – E_{CO}, hydrocarbons – E_{HC}, nitrogen oxides – E_{NOx}, carbon dioxide – E_{CO2}),
- intensity of particle number (E_{PN}).

The average specific distance exhaust emissions and the average specific distance particle number was determined from the formulas:

$$b_i = AV[\hat{b}_i] = \frac{1}{s(t_1,t_2)} \cdot \frac{1}{t_2-t_1} \int_{t_1}^{t_2} E_i(t) \quad (6)$$

where: $s(t_1, t_2)$ – distance covered by the vehicle in time between t_1 and t_2.

$$s(t_1,t_2) = \int_{t_1}^{t_2} v(t)\,dt \quad (7)$$

For the determination of the exhaust emission characteristics, the authors applied the Monte Carlo method [14] generating the realization of the processes of vehicle velocity and acceleration as well as the exhaust emission intensities and the particle number intensities as fragments of tracings recorded in the empirical research of random values of the start and end time. If, in formulas (3)–(6), we assume the value of time t_1 and t_2 as quasi-random values, we obtain the average values of specific distance emissions of pollutants and the average value of specific distance particle number as quasi-random. Similarly, the independent variables of the characteristics are also quasi-random ones.

The values of time t1 and t2 are obtained as:

$$t_1 = rnd \cdot t_{max} \quad (8)$$

$$t_2 = rnd \cdot t_{max} \quad (9)$$

where: t_{max} – test duration, rnd – quasi-random number from the 0, 1 interval of even distribution.

Thanks to the application of the Monte Carlo method in determination of the exhaust emission characteristics it is possible to determine these characteristics based on the results from a single test rather than multiple tests with varied average velocities, as applied in conventional empirical research.

4. Research results and discussion

Figures 7–11 present the exhaust emission intensities and the intensities of particle emissions.

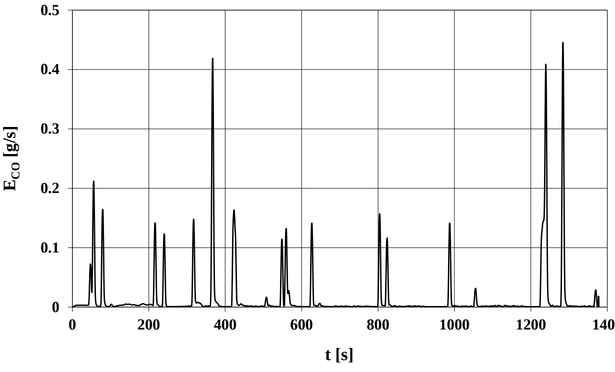

Fig. 7. The process of carbon monoxide emission intensity in the Malta test

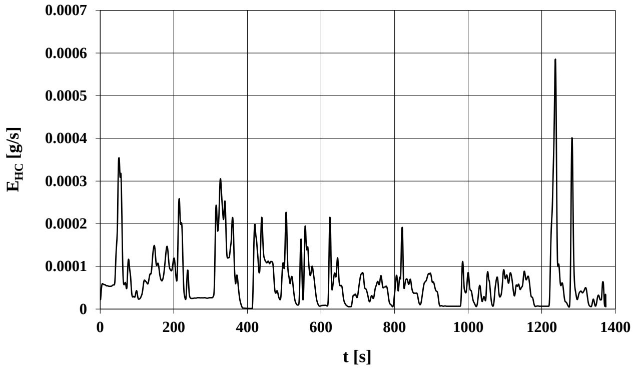

Fig. 8. The process of hydrocarbons emission intensity in the Malta test

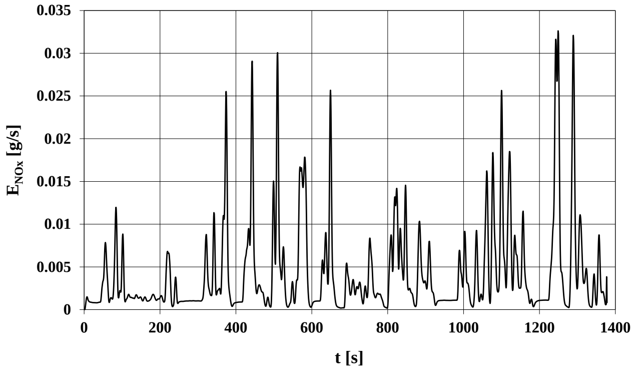

Fig. 9. The process of nitrogen oxides emission intensity in the Malta test

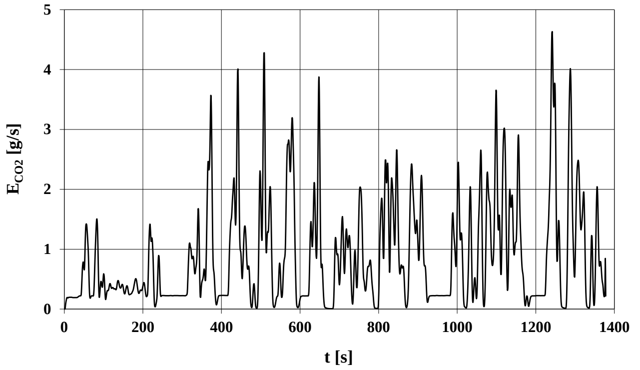

Fig. 10. The process of carbon dioxide emission intensity in the Malta test

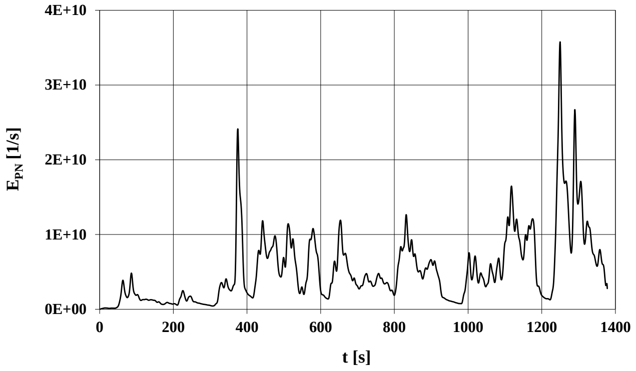

Fig. 11. The process of particle number intensity in the Malta test

Figure 12 presents the example realizations of the process of vehicle velocity in the portions of the Malta test used to determine the exhaust emission characteristics.

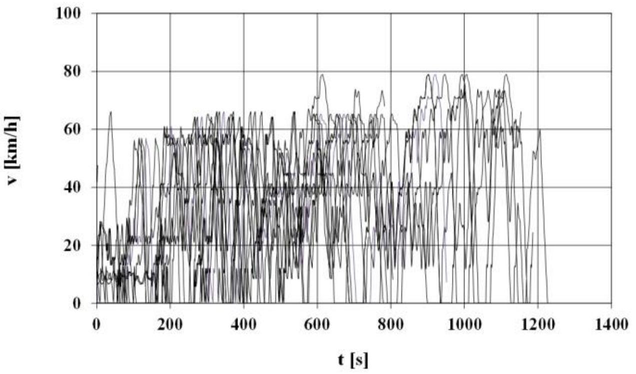

Fig. 12. Examples of vehicle velocity processes in fragments of the Malta test

Figures 13–17 present the exhaust emission characteristics in the form of a dependence of the average specific distance exhaust emissions and the average specific distance particle number on the average vehicle velocity in the Malta test.

The obtained characteristics were approximated with polynomial functions of the maximum degree lower than 7.

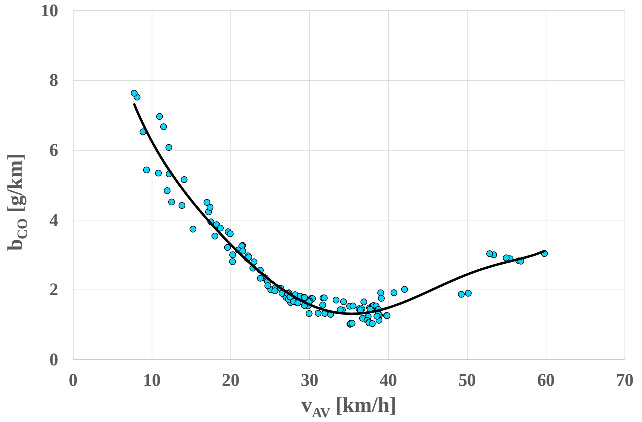

Fig. 13. Dependence of the average specific distance emission of carbon monoxide on the average vehicle velocity in the Malta tes

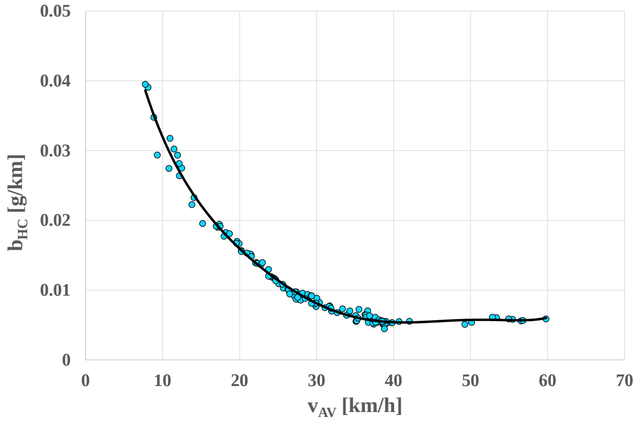

Fig. 14. Dependence of the average specific distance emission of hydro carbons on the average vehicle velocity in the Malta test

The quality of the approximation is characterized by the coefficient of determination. In the case of the determined characteristics, the highest value had the coefficient of determination for the characteristics of the emission of hydrocarbons (0.9897). For the outstanding exhaust components, the value of the coefficient of determination was also high – the lowest occurred for the nitrogen oxides (0.8793). The spread of the determined points for the characteristics of the particle number was much higher – the coefficient of determination was only 0.3742.

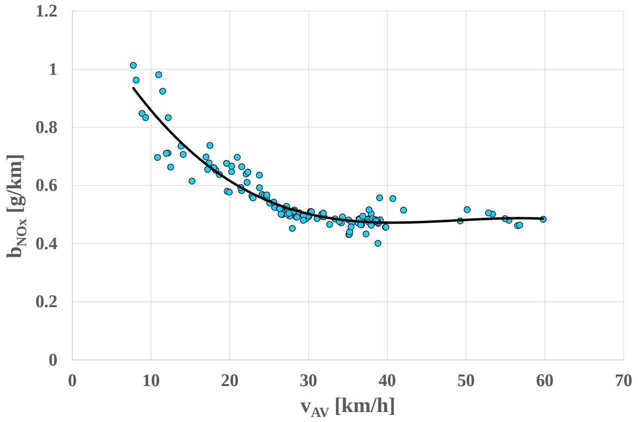

Fig. 15. Dependence of the average specific distance emission of nitrogen oxides on the average vehicle velocity in the Malta test

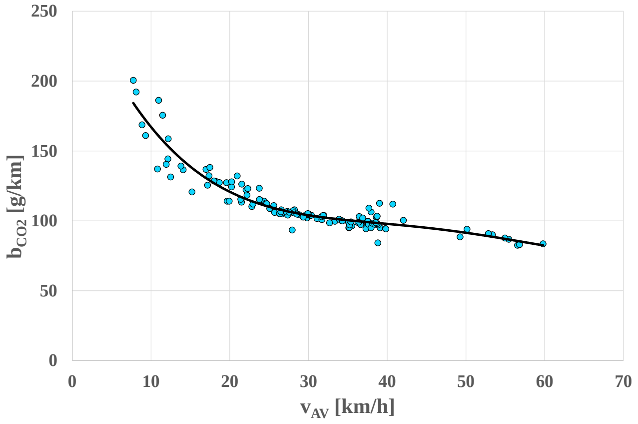

Fig. 16. Dependence of the average specific distance emission of carbon dioxide on the average vehicle velocity in the Malta test

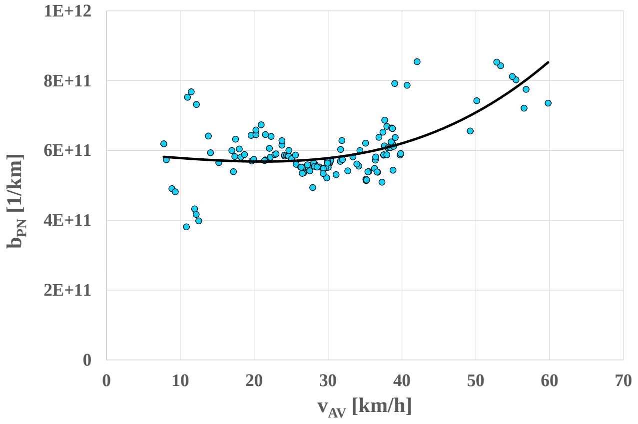

Fig. 17. Dependence of the average specific distance particle number on the average vehicle velocity in the Malta test

The obtained characteristics indicate a high level of regularity and compliance with the experiments [3, 6, 7, 9–11].

Figures 18–22 present the exhaust emission characteristics in the form of dependence of the average specific distance exhaust emissions and the average specific distance particle number on the average value of the absolute value of the product of velocity and acceleration of the vehicle in the Malta test.

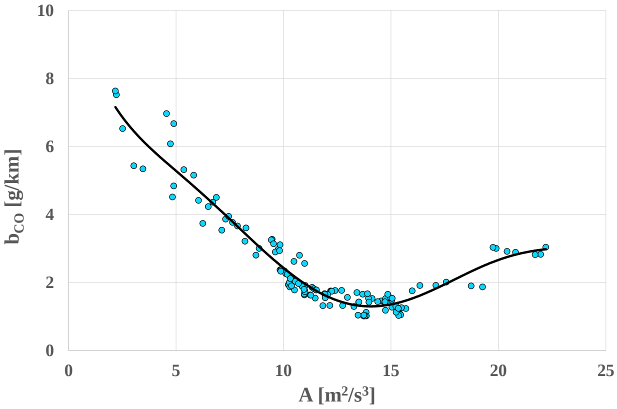

Fig. 18. Dependence of the average specific distance emission of carbon monoxide on the average value of the absolute value of the product of vehicle velocity and acceleration in the Malta test

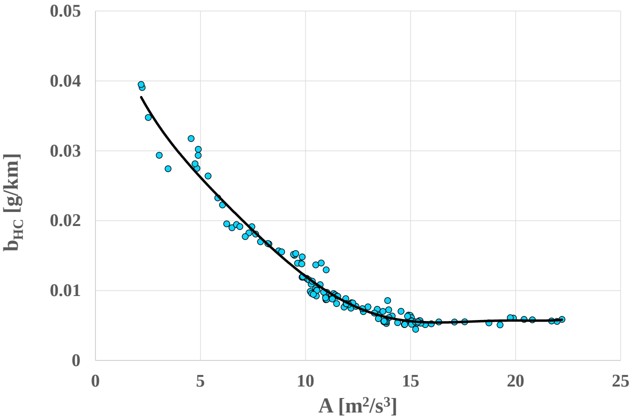

Fig. 19. Dependence of the average specific distance emission of hydrocarbons on the average value of the absolute value of the product of vehicle velocity and acceleration in the Malta test

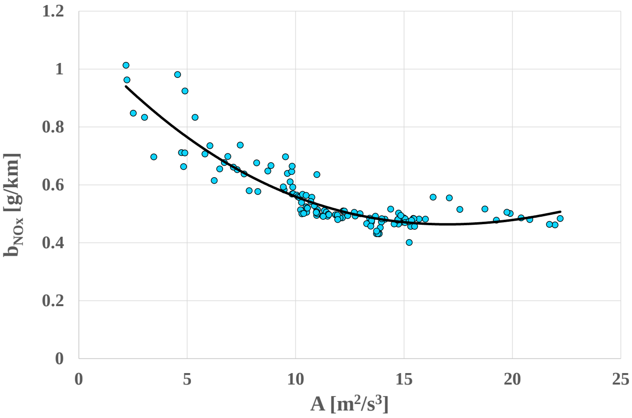

Fig. 20. Dependence of the average specific distance emission of nitrogen oxides on the average value of the absolute value of the product of vehicle velocity and acceleration in the Malta test

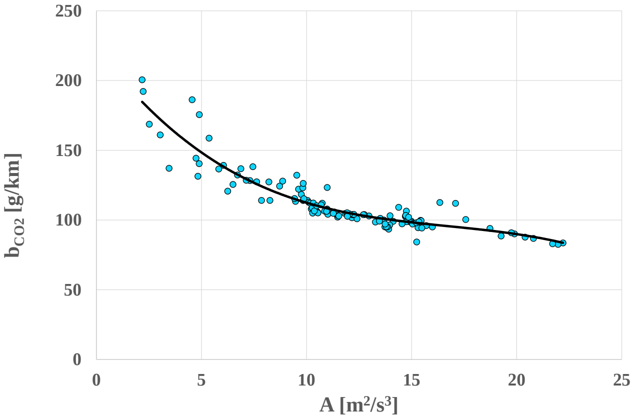

Fig. 21. Dependence of the average specific distance emissions of carbon dioxide on the average value of the absolute value of the product of vehicle velocity and acceleration in the Malta test

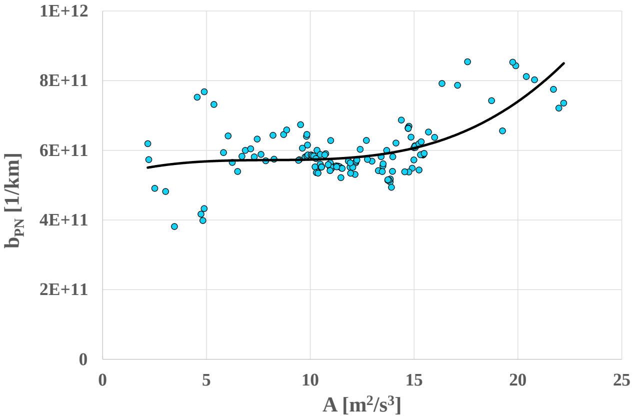

Fig. 22. Dependence of the average specific distance particle number on the average value of the absolute value of the product of vehicle velocity and acceleration in the Malta test

The obtained characteristics were approximated with polynomial functions of the maximum degree lower than 7.

The quality of the approximation of the determined characteristics was similar in nature to the characteristics in the domain of average values. The best matching quality of the approximating function occurred for the characteristics of hydrocarbons – the coefficient of determination was 0.9725. For the outstanding exhaust components, the coefficient of determination was greater than 0.82 (the lowest value occurred for nitrogen oxides – 0.8242).

Similarly to the characteristics in the domain of average values of velocity, the greatest spread occurred for the characteristics of particle number – the coefficient of determination was 0.3888.

The obtained characteristics show a significant regularity and compliance with the experiments [3, 7].

Therefore, one can assess that the expectation was met that it is possible to practically use the obtained characteristics to simulate the exhaust emissions under different vehicle operating conditions.

5. Conclusions

The paper As a result of the performed investigations the following conclusions can be drawn:

1. The possibility of the application of the Monte Carlo method for the determination of the exhaust emission char-

acteristics based on the results of empirical research carried out in a single test is hereby confirmed. This is an obvious benefit since, in conventional methods, multiple tests of different properties have to be carried out and these are tests that are costly, time-consuming and difficult to complete.

2. The authors have confirmed the possibility of application of the results of the engine tests on an engine dynamometer (rather than on the chassis dynamometer) for the determination of the exhaust emission characteristics. This is an important feature of the proposed method because we know that tests on chassis dynamometers are much more difficult to carry out and less cost-efficient compared to the tests performed on an engine dynamometer. Besides, ensuring greater accuracy and repeatability is simpler to obtain on an engine dynamometer compared to a chassis dynamometer. Another advantage is the fact that in the tests simulated on the engine dynamometer, engineers can investigate heavy-duty vehicle engines: heavy-duty trucks and buses as well as heavy machinery. The performance of tests of heavy-duty vehicles on chassis dynamometers is extremely limited by the access to such laboratories. For example, in Europe there are only a few laboratories having such equipment designed for scientific research of heavy-duty trucks. Obviously, for heavy non-road machinery, load simulation on chassis dynamometers is impossible.

3. The obtained characteristics are congruent with the current state of knowledge, which confirms the possibility of their practical application.

The investigations presented in this paper can be continued. It is possible to consider the two-dimensional exhaust emission characteristics in the domain of vehicle average velocity and the average value of the absolute value of the product of vehicle velocity and acceleration as well as multidimensional characteristics in the domain of other zero-dimensional characteristics of the vehicle velocity process [3, 7].

Nomenclature

A	average value of the absolute value of the product of vehicle velocity and acceleration
a	vehicle acceleration
Abs	absolute value operator
AV	average value
b_i	specific distance emission of the i-th pollutant
CO	carbon monoxide
CO_2	carbon dioxide
E_i	emission intensity of the i-th pollutant
E_{PN}	emission intensity of particle number
EPSS™	Engine Exhaust Particle Sizer™ Spectrometer
FID	flame ionization detector
HC	hydrocarbons
$M_{e\ ext}$	engine torque at maximum engine throttle position
M_e	engine torque
M_{er}	relative engine torque
n	engine speed
NDUV	non-dispersive ultraviolet
NIDR	non-dispersive infrared
NO_x	nitrogen oxides
PEMS	portable emissions measurement system
PN	particle number
t	time
t_1	start time of averaging
t_2	end time of averaging
v	vehicle velocity
v_{AV}	average vehicle velocity

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