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# Research of pollutant emissions from automotive internal combustion engines in conditions corresponding to the actual use of vehicles

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*The subject of the article is the study of pollutant emissions from automotive combustion engines that operate in conditions corresponding to the actual use of vehicles. Includes information on the properties of exhaust gas parameters characterizing the following features: energy, economic, environmental impact and serviceability, additional and constant. Reference was also made to the possibility of determining driving tests on the basis of the similarity of the frequency characteristics of the speed processes in both driving tests and in the real use of vehicles. The article presents the results of research on pollutant emissions from a passenger car during the RDE test. The emission of carbon monoxide, hydrocarbons, nitrogen oxides, particulate matter and carbon dioxide, as well as the number of particulate matter, were examined. The process of pollutant emission intensity and particle number intensity was presented. Tests were carried out on the statistical properties of the car speed, the intensity of pollutant emissions, and the intensity of the number of particulate matter. Correlation studies were carried out on the speed of the vehicle, the intensity of pollutant emissions, and the intensity of the number of particulate matter.*

Key words: *pollutant emission, vehicles, internal combustion engines*



## 1. Introduction

The article considers the problem of pollutant emissions from automotive internal combustion engines in conditions corresponding to the actual use of vehicles. The emission of pollutants from internal combustion engines is treated as one of their functional properties.

In order to be able to test the emission of pollutants from an internal combustion engine in conditions corresponding to its use in a vehicle, it is necessary to ensure the engine's operating states using the following methods [2, 3]:

– driving the vehicle in conditions corresponding to real use – such tests may be carried out either on a chassis dynamometer or in road conditions,
– simulating engine operating states in conditions corresponding to actual use in the vehicle – tests are carried out on an engine dynamometer.

For light vehicle engines (passenger cars, light trucks, minibuses and L-category vehicles – motorcycles, mopeds, quads and microcars), the tests may be carried out under comparable conditions on a chassis dynamometer. It is also possible to conduct tests in road conditions thanks to the use of the PEMS (Portable Emissions Measurement System) mobile emission testing system [16, 18, 19]. This type of research is carried out using type-approval tests of light vehicles in order to determine the emission of nitrogen oxides and the number of particulate matter [11, 20].

Heavy vehicles (trucks and buses) are mainly tested in road conditions. This is mainly due to the difficulty of accessing large-sized chassis dynamometers, of which there are very few. The tradition of testing heavy vehicles in road conditions is due to the fact that the operational fuel consumption of buses is determined using SORT (Standardized On-Road Test) and UITP (The International Association of Public Transport) tests [1].

In this work, the methods of creating driving tests that simulate the movement of vehicles have been systematized. The results of empirical tests of pollutant emissions from the internal combustion engine of a passenger car during the RDE (Real Driving Emissions) test in real driving conditions are also presented.

## 2. Performance characteristics of automotive internal combustion engines

The operational properties of internal combustion engines relate primarily to [2]:

– energy characteristics,
– economic features,
– impact on the environment,
– serviceability, reliability and durability.

Energy features are characterized primarily by useful power and dynamic properties – in the case of a car engine, it is the maximum speed and maximum acceleration of the vehicle. The economic features are characterized by the overall efficiency of the engine. Due to the impact on the environment, pollution and noise emissions are primarily considered.

These properties are strongly dependent on the operating states of internal combustion engines in both their static and dynamic states.

The following operating states of internal combustion engines are described in [2, 3, 5]:

– rotational speed,
– load,
– thermal state.

The measure of load is usually the engine's torque or net power. The thermal state is most often characterized by the temperature of operating factors: engine oil or engine coolant. In a stabilized thermal state of the engine, its operating states are therefore described by rotational speed and load.

In the case of car engines, the main factor determining engine operating states is the vehicle speed process [1–6]. For this reason, in order to simulate the operating states of car engines, they are tested in conditions corresponding to the movement of the vehicle.

## 3. Performance characteristics of automotive internal combustion engines

Driving tests are developed to simulate the operating states of internal combustion engines in conditions corresponding to the real use of road vehicles. Driving tests are processes of driving speed.

A process is a state quantity defined on a certain normed space. The domain in which the process is defined is usually time or a monotonic function of time (process – time function, time series) or an area of space (process – field). In this article, a process is treated as a numerical function whose argument is time or a monotonic function time. The zero-dimensional characteristic of the process is the functional of this process, e.g. the mean value of the process, standard deviation of the process, extreme values of the process relative to speed, etc.

There are two basic ways to create driving tests. The first method of developing driving tests involves simulating the speed process in the time domain [1, 6–8]. On the basis of empirical tests of vehicles in real traffic conditions, speed processes are recorded. Then, the registered velocity processes are analyzed in terms of their selected properties, e.g. the average value, the average value of the absolute value of the product of velocity and acceleration, or the probability density. There are two options for developing driving tests in this way. The first option is to adopt the selected recorded speed process as the driving test, with the second being to create the driving test as a combination of fragments of recorded processes. Examples of tests created on the basis of simulating the time domain are the homologation FTP-75 (Federal Test Procedure) and WLTC (Worldwide Harmonized Light Vehicles Test Cycle) [11, 20] tests, as well as special tests for simulating traffic conditions in traffic jams – Stop&Go, or for traffic on motorways and expressways – Autobahn [6].

Tests created on the basis of simulating the time domain can be treated as stochastic processes in the form of a set of realizations [15].

The second method of developing driving tests is the arbitrary adoption of the speed process, and then the selection of the parameters of this process in accordance with the principle of the similarity of these parameters with the parameters of the processes recorded in the conditions of the actual use of vehicles. The arbitrary adoption of the speed process consists in adopting the character of the process similar due to certain properties to the speed processes actually occurring in the use of vehicles. Such parameters are, for example, the average speed value, the maximum speed value, or extreme acceleration values. Examples of such tests are the following homologation tests: NEDC (New European Driving Cycle), which consists of both driving tests in cities – UDC (Urban Driving Cycle) and driving tests outside cities – EUDC (Extra Urban Driving Cycle) or Japanese 10-15 Mode [11, 20].

It is also possible to create driving tests based on the similarity of frequency characteristics [9].

The developed tests are used for the following purposes:

– testing the compliance of the properties of light vehicles; tested on a chassis dynamometer and in road conditions using the RDE test. There are applicable legal acts in approval procedures – the evaluation criterion is the emission of pollutants and the number of particulate matter [11, 20];
– an inventory of pollutant emissions carried out over the course of 1 year – the result is the national annual pollutant emission [5, 12];
– forecasting the state of environmental pollution by determining the intensity of pollutant emissions and, by modeling the spread of pollutants, determining the concentration of pollutants.

While the conditions of vehicle movement in the approval procedures are strictly defined, in the other two applications, driving tests must simulate different traffic conditions. Traffic models are usually distinguished: in traffic jams, in cities (no traffic jams), outside cities, and on motorways and expressways [5, 10]. Numerous tests have been developed for these purposes as part of extensive research programs. For example, under the ARTEMIS (Assessment and Reliability of Transport Emission Models and Inventory Systems) program, numerous CADC (Common Artemis Driving Cycles) tests [1] have been developed, which correspond to the movement of vehicles in driving conditions in cities, outside cities, and on highways and expressways.

Thanks to the study of pollutant emissions and fuel consumption using various tests, it was possible to develop software that allows the emission of pollutants and the number of particulate matter for various vehicle traffic conditions to be determined. This software contains, for elementary and cumulative vehicle categories, formulas for the emission of pollutants and the number of particulates with regards to the average speed.

A category is a class of objects that have specific characteristics and which are related to each other. Categories of road vehicles are determined according to the following criteria: application, contractual size, construction properties, fuel, and technical level [10].

The elementary category of road vehicles includes vehicles with all the same criteria. The cumulative category of motor vehicles includes vehicles with not all the same criteria.

Examples of emission simulation software are: COPERT (Computer Program to Calculate Emissions From Road Transport) [10], normally used for pollutant inventory [5, 12], and HBEFA (Handbook Emission Factors for Road Transport) INFRAS AG (Infrastructure, Umwelt- und Wirtschaftsberatung) [13].

## 4. Empirical studies of pollutant emissions from an internal combustion engine in conditions corresponding to the actual use of vehicles

Empirical studies of pollutant emissions from an internal combustion engine in conditions corresponding to the actual use of vehicles were carried out using the RDE test.

The subject of the research was a passenger car with a spark-ignition engine, which was equipped with an automatic gearbox at the Euro 6 level due to road emissions. The car was tested for pollutant emissions and fuel consumption using the RDE test. The test is performed with a cold engine start-up. The PEMS mobile pollutant emission testing system was used in the research [16]. The Semtech DS analyzer [18] and the TSI 3090 EPSS™ (Engine Exhaust Particle Sizer™ Spectometer) analyzer [19] were used for the pollutant emission tests.

The recorded processes were subjected to low-pass filtration using the second-order Savitzky-Golay filter [17] in order to reduce the share of high-frequency noise in the signals.

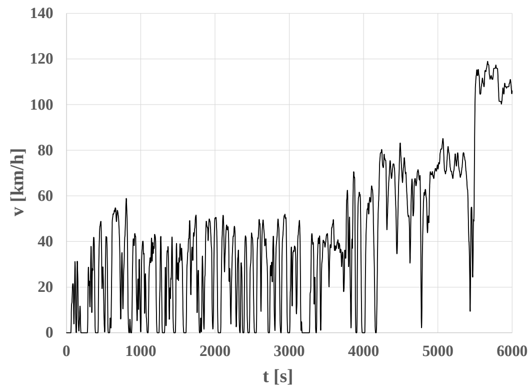


Fig. 1. Car speed process – v during the RDE test

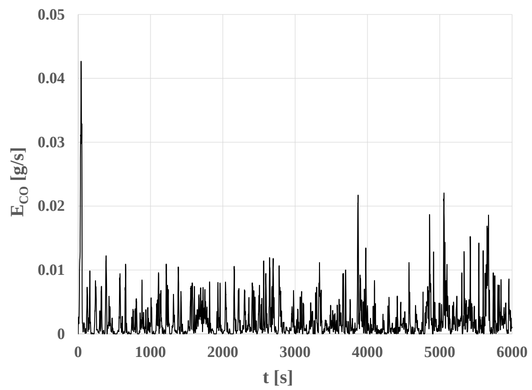


Fig. 2. The process of carbon monoxide emission intensity – $E_{CO}$ from the car engine during the RDE test

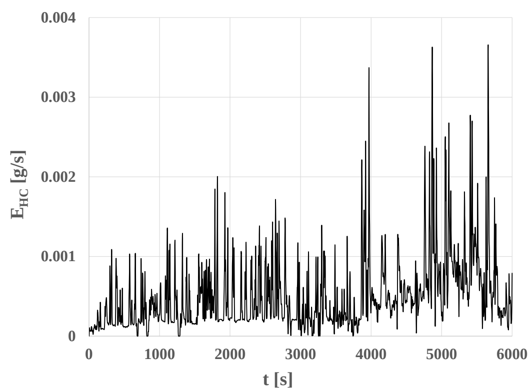


Fig. 3. The process of hydrocarbon emission intensity – $E_{HC}$ from the car engine during the RDE test

Figure 1 shows the car speed process during the RDE test. Figures 2–5 show the processes of the emission intensity of pollutants: carbon monoxide, hydrocarbons, nitrogen oxides and carbon dioxide from the car engine during the RDE test.

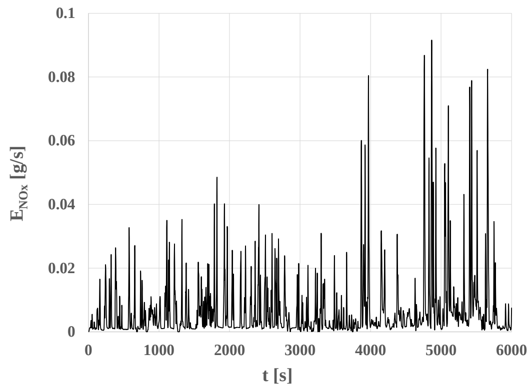


Fig. 4. The process of nitrogen oxide emission intensity – $E_{NOx}$ from the car engine during the RDE test

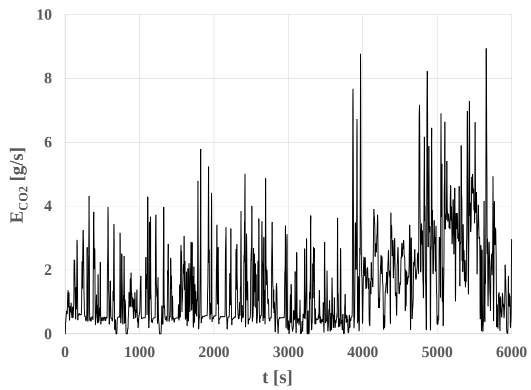


Fig. 5. The process of carbon dioxide emission intensity – $E_{CO2}$ from the car engine during the RDE test

Figure 6 shows the particle number intensity process during the RDE test.

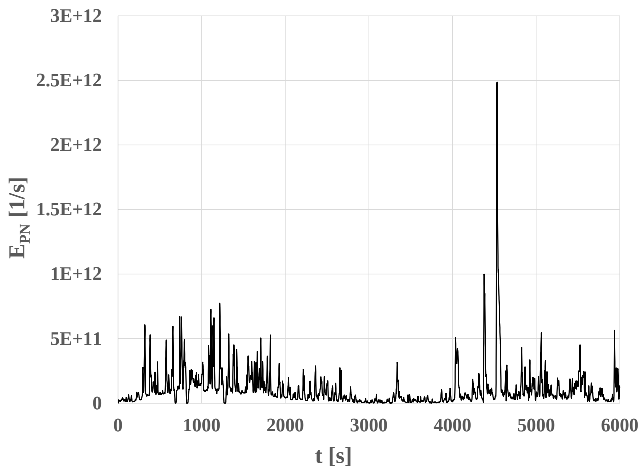


Fig. 6. Process of particle number intensity – $E_{PN}$ from the car engine during the RDE test

The statistical properties [14] of the velocity process and the processes of pollutant emission intensity and parti-

cle number intensity were also tested. The following were designated:
- minimum value – Min,
- maximum value – Max,
- range – R,
- average value – AV,
- median – M,
- standard deviation – D,
- coefficient of variation – W.

Figure 7 shows the zero-dimensional statistical characteristics of the car speed process, Fig. 8–11 – the processes of pollutant emission intensity, and Fig. 12 – the particle number intensity process.

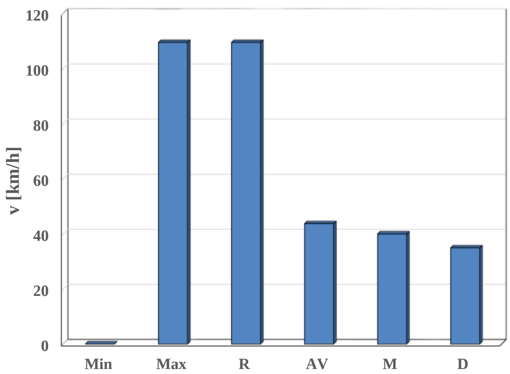


Fig. 7. Statistical characteristics of the car speed process – v

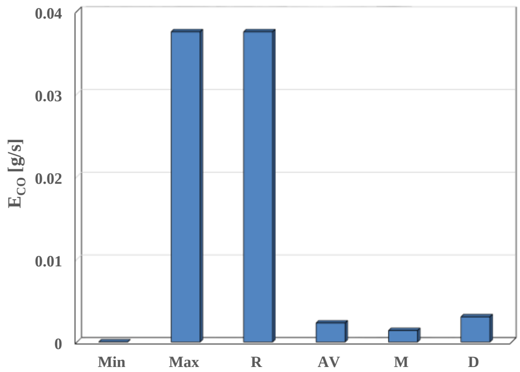


Fig. 8. Statistical characteristics of the carbon monoxide emission intensity process – $E_{CO}$

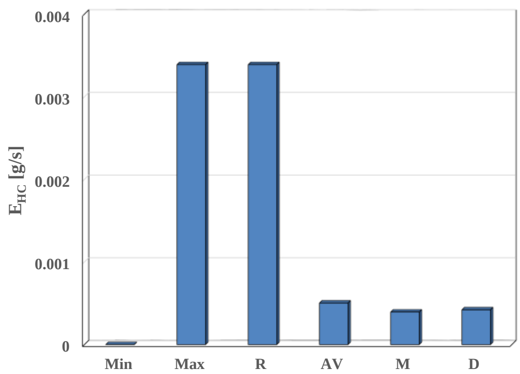


Fig. 9. Statistical characteristics of the hydrocarbon emission intensity process – $E_{HC}$

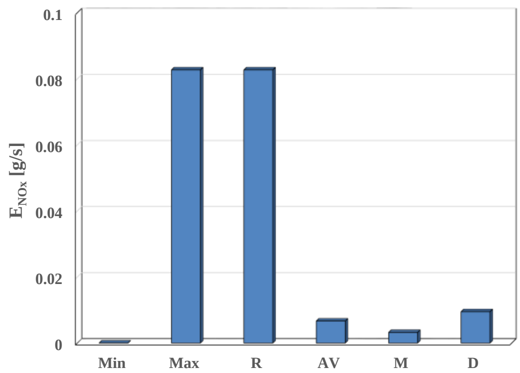


Fig. 10. Statistical characteristics of the nitrogen oxide emission intensity process – $E_{NOx}$

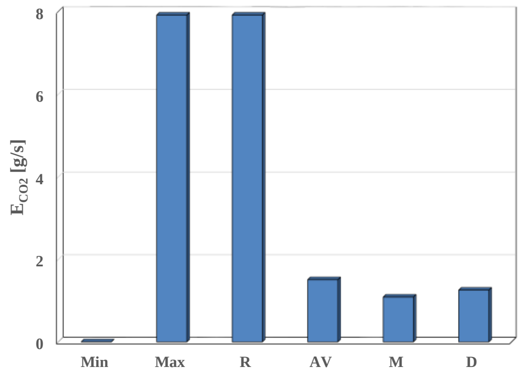


Fig. 11. Statistical characteristics of the process of carbon dioxide emission intensity – $E_{CO2}$

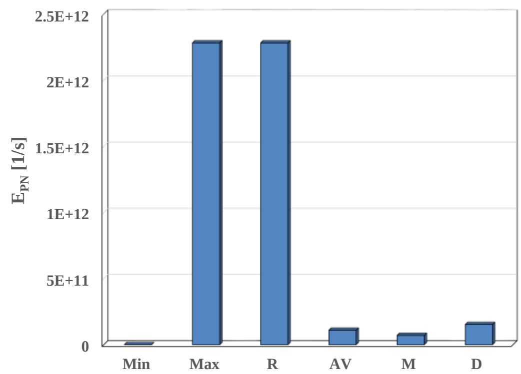


Fig. 12. Statistical characteristics of the particle number intensity process – $E_{PN}$

For all the processes, the average value is greater than the median.

Figure 13 shows the coefficient of variation of the examined processes.

The coefficient of variation characterizes the dynamic properties of processes [14]. The processes of carbon monoxide and nitrogen oxide emission intensity, as well as the intensity of the number of particulate matter, are characterized by the strongest dynamic properties.

Correlation studies [14] of the following processes were carried out: pollutant emission intensity and particle number intensity – the test results are presented in Table 1.

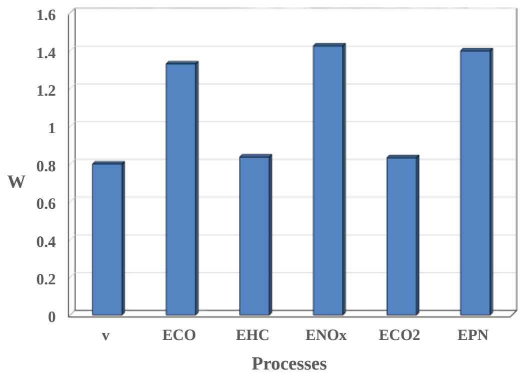


Fig. 13. Coefficient of variation of the examined processes – W

Table 1. Coefficient of determination – $R^2$ between the tested processes during the RDE test

| | v | $E_{CO}$ | $E_{HC}$ | $E_{NOx}$ | $E_{CO2}$ | $E_{PN}$ |
|---|---|---|---|---|---|---|
| $E_{CO}$ | 0.0011 | | | | | |
| $E_{HC}$ | 0.0639 | 0.1428 | | | | |
| $E_{NOx}$ | 0.0063 | 0.1339 | 0.8360 | | | |
| $E_{CO2}$ | 0.0903 | 0.1026 | 0.8573 | 0.6534 | | |
| $E_{PN}$ | 0.0043 | 0.0115 | 0.0723 | 0.0646 | 0.0926 | |

The processes of the pollutant emission intensity and the intensity of the number of particulate matter are weakly correlated with the process of car speed – the weakest in the case of carbon monoxide emission intensity, and the strongest in the case of carbon dioxide emission. This results from the fact that with increasing speed, fuel consumption also increases, and consequently carbon dioxide emissions.

The process of particle number intensity is the least correlated with all the pollutant emission intensity processes. The most strongly correlated is the intensity of hydrocarbon emissions with the intensity of emissions of carbon dioxide and nitrogen oxides.

An exemplary correlation relationship between pollutant emission intensity processes during the RDE test is shown in Fig. 14.

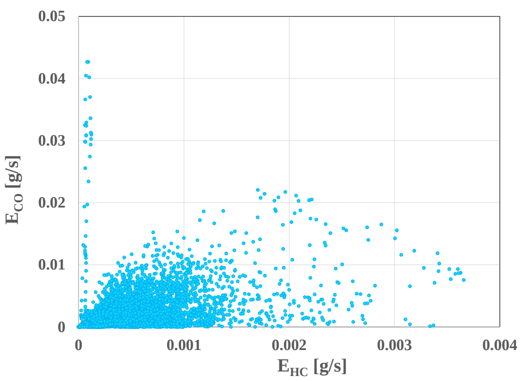


Fig. 14. Correlation relationship between the carbon monoxide emission intensity – $E_{CO}$ and the hydrocarbon emission intensity – $E_{HC}$ during the RDE test

On the basis of the recorded pollutant emission intensity and particle number rate, as well as the vehicle speed process, the average values during the RDE test were determined: emission of pollutants and number of particulate matter.

The average emission – b of pollutants during the RDE test is the ratio of the emission of pollutants in the test – m and the length of the road covered by the car in the test – L.

$$b = m/L \tag{1}$$

The mean particle number during the RDE test – b_PN is the ratio of the number of particles in the test – PN and the distance traveled by the car in the test.

$$b\_PN = PN/L \tag{2}$$

The pollutant emission during the RDE test is the integral of the pollutant emission intensity – E.

$$m = \int_0^T E(t)dt \tag{3}$$

where: t – time, T – test duration.

The particulate number during the RDE-PN test is the integral of the particulate number intensity – EPN.

$$PN = \int_0^T E_{PN}(t)dt \tag{4}$$

The length of the road covered by the car during the RDE test – L is the integral of the car's speed – v.

$$L = \int_0^T v(t)dt \tag{5}$$

Table 2 presents the zero-dimensional pollutant emission characteristics during the RDE test.

Table 2. Zero-dimensional characteristics of pollutant emissions and fuel consumption during the RDE test

| $b_{CO}$ | $b_{HC}$ | $b_{NOx}$ | $b_{CO2}$ | $b_{PN}$ |
|---|---|---|---|---|
| g/km | | | | 1/km |
| 0.1994 | 0.04387 | 0.5796 | 131.2 | 9.500E+12 |

In relation to the emission limits of pollutants and the number of particulate matter at the Euro 6 level, the relative values of the emission determined during the RDE test are as follows: for carbon monoxide – 0.199, for hydrocarbons – 0.439, for nitrogen oxides – 9.66, for the number of particles – 15.8.

## 5. Conclusions

Based on the conducted research, the following conclusions can be drawn:

1. The processes characterizing the emission of pollutants are mostly poorly correlated with each other. These processes are also weakly correlated with the car speed process. The most strongly correlated is the intensity of hydrocarbon emissions with the intensity of emissions of carbon dioxide and nitrogen oxides.
2. For all the examined processes, the average value is greater than the median.
3. In relation to the emission limits of pollutants and the number of particulate matter at the Euro 6 level, the relative values of the emission determined during the RDE test are as follows: for carbon monoxide – 0.199, for

hydrocarbons – 0.439, for nitrogen oxides – 9.66, for the number of particles – 15.8.

4. The strongest dynamic properties, assessed on the basis of the coefficient of variation, are characterized by the processes of carbon monoxide and nitrogen oxide emission intensity and the intensity of the number of particulate matter.
5. The processes of pollutant emission intensity and the process of particle number intensity are characterized by strong maxima for small process values.

It is expedient to continue working in the following directions:

1. It is advisable to treat the stages of the car velocity process, and consequently the operating states and the internal combustion engine during the RDE test, as stochastic processes that are represented by sets of realizations. Empirical studies that are performed for many implementations of the car speed process during the RDE test enable the waveforms of the engine's operating states, which are actually the processes of these states, to be obtained. Conducting empirical research in individual implementations of stochastic processes enables research results to be statistically elaborated.
2. It is advisable to conduct separate tests for each phase of the RDE test. The test results would enable the assessment of the specificity of the car's traffic conditions on the engine operating states and, consequently, on the intensity of pollutant emissions and the intensity of the number of particulate matter.
3. It is interesting to compare the impact of the technical level of cars in terms of pollutant emissions with the results of the RDE test.
4. It is useful to compare the test results of the same car during the RDE test and the WLTC test.

**Acknowledgements**

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## Nomenclature

| | |
|---|---|
| CI | compression ignition |
| CNG | compressed natural gas |
| DI | direct injection |
| LPG | liquified petrolum gas |
| SI | spark ignition |
| ARTEMIS | Assessment and Reliability of Transport Emission Models and Inventory Systems |
| Autobahn | driving test on highways and expressways |
| AV | average value |
| b | average road emission of the pollutant/average road number of particulates |
| CADC | Common Artemis Driving Cycles |
| CO | carbon monoxide |
| CO2 | carbon dioxide |
| COPERT | Computer Programme to Calculate Emissions From Road Transport |
| D | standard deviation |
| E | pollutant emission intensity/particle number intensity |
| EPSS™ | Engine Exhaust Particle Sizer™ Spectometer |
| EUDC | Extra Urban Driving Cycle |
| FTP | Federal Test Procedure |
| HBEFA | Handbook Emission Factors for Road Transport |
| HC | hydrocarbons |
| Japanese 10-15 Mode | homologation test in Japan |
| L | distance traveled by the car |
| m | emission of pollution |
| M | median |
| Max | maximum value |
| Min | minimum value |
| NEDC | New European Driving Cycle |
| NOx | nitrogen oxides |
| PEMS | Portable Emissions Measurement System – portable emission testing system |
| PN | particle number |
| R | range |
| RDE | Real Driving Emissions – test in the conditions of real use of the road vehicle |
| SORT | Standardised On-Road Test |
| Stop&Go | driving test in traffic jams |
| t | time |
| UDC | Urban Driving Cycle |
| UITP | The International Association of Public Transport |
| v | vehile velocity |
| W | coefficient of variation |
| WLTC | Worldwide Harmonized Light Vehicles Test Cycle |

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