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ANALYSIS OF THE OPERATION STATES OF INTERNAL COMBUSTION ENGINE IN THE REAL DRIVING EMISSIONS TEST

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Abstract:

Internal combustion engines represent the largest share of motor vehicle propulsion types. Despite the introduction of alternative drives (hybrid and electric), combustion engines will continue to be the main factor in the development of transport. Therefore, work related to their technological development and reduction of their harmful effects on human health and the environment is required. The development of internal combustion engines can be seen in two directions: technological changes resulting in increased efficiency of such engines and the second direction connected with limitation of exhaust gas emission. The present work is included in the second direction of research interests and concerns the analysis of various operating conditions of internal combustion engines. The operating states, both static and dynamic, determine the operational properties of internal combustion engines, such as fuel and energy consumption as well as pollutant emissions. So far, such operating conditions have only been mapped on a chassis dynamometer in various homologation tests. The course of the type approval test was known and the conditions of measurement were also known, which made it impossible to introduce a random factor into such tests. Currently, these properties are determined in tests performed in real vehicle operating conditions – RDE (Real Driving Emissions). Such tests are representing real operating conditions of motor vehicles. Limitations for performing tests in real traffic conditions are, apart from formal requirements concerning the duration and distance of individual parts, the dynamic conditions of vehicles determined by the speed and acceleration of the vehicle. The study analyzed the properties of vehicle speed processes and engine operating states in the RDE test, taking into account its individual phases – driving in urban, rural and motorway conditions. Engine operation states are the processes of the engine rotational speed and its relative torque. It was found that the dynamic properties of the vehicle speed process are much more significant than the engine operating states. It was also found that the road emission of pollutants in the RDE test, which is the property of vehicles measured in the test, the motorway phase properties have greatest impact.

Keywords: *combustion engine, real driving emissions, engine operation states*

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1. Introduction

Driving tests of vehicle characteristics are usually designed to recreate the real operating conditions of the tested vehicles. Drive tests are mainly used for assessing the properties of light vehicles: passenger cars, light trucks, motorcycles, and mopeds. There are also drive tests for heavy vehicles: buses and trucks, for example SORT tests (Standardized On-Road Test Cycles) (UITP, 2017) for testing fuel consumption and energy consumption. The driving tests are defined by the vehicle speed characteristic, thus it can be stated that the vehicle driving conditions are described by the speed process. The concept of a process is more general than a cycle. Generally, a process is a state quantity defined on a certain normalized space (Chłopek, 2010; Chłopek 2015, Chłopek 2017). The domain in which the process is defined is most often time or a monotonic function of time (the process is then a function of time, or a time series) or the area of space (the process is then a field) (Chłopek, 2010; Chłopek 2015, Chłopek 2017). The concept of process as a function of time is the meaning used in article. If a process is indeterminate, then every possible realization is a cycle.

The most frequently studied properties of vehicles in driving tests are fuel consumption, energy consumption (especially in the case of electric cars) and the emission of pollutants from the internal combustion engine. Therefore, these properties are determined by the operating states of the engine. The operating states of the internal combustion engine, determining its properties, include (Chłopek, 2010; Chłopek 2015, Chłopek 2017):

– frequency of work cycles, described by rotational speed,
– engine load, described using useful power or – more often – with torque (since rotational speed is one of the states),
– the thermal state of the engine, described by the temperatures of individual parts, assemblies and engine consumables (mainly the engine coolant and engine oil).

Therefore, this article assumes that in a stabilized thermal state of an internal combustion engine, its operating state is determined by two processes: rotational speed and torque.

In stabilized vehicle motion conditions (meaning constant driving speed), the car's performance characteristics are determined by constant values of the rotational speed and torque processes of the engine. In unstable motion conditions, the engine operating states are determined by dynamic processes. Therefore, the operational properties of engines and – consequently – vehicles depend on the respective implementation of the engine rotational speed and torque processes. Therefore, it should be considered necessary to use drive tests simulating real operation of vehicles to test these properties.

The drive tests shall be developed according to the following criteria of similarity with the real conditions of the vehicle motion:

1. An accurate representation of the speed process based on the recorded data of this process in real vehicle driving conditions. Usually, it is not a directly applied result of empirical measurements, but rather results that have been processed, e.g. a combination of fragments of recorded process data with given properties, e.g. average speed. Examples of such tests include: FTP-75 (Federal Test Procedure) and WLTC (Worldwide Harmonized Light Vehicles Cycle) (Emission Test Cycles, 2021; Worldwide emission standards, 2021).
2. Synthesis of driving tests based on the similarity of non-dimensional characteristics of the speed process:
   – in the time domain, such as: mean value, minimum and maximum values, minimum and maximum acceleration values and many others (BUWAL, 1995),
   – in the process value domain, e.g. the share of zero speed value in the whole test.

   Examples of such tests include: NEDC (New European Driving Cycle) and Japanese 10-15 Mode (Emission Test Cycles, 2021; Worldwide emission standards, 2021).
3. Synthesis of drive tests based on the similarity of the speed process characteristics in the frequency domain (Chłopek, 2016).

The article uses engine operation states directly for the research of functional properties of heavy internal combustion engines to power: trucks and buses, as well as non-road vehicles and Non-Road Mobile Machinery as well as other objects and devices (Emission Test Cycles, 2021; Worldwide emission standards, 2022). These are both static tests, such as WHSC (World Harmonized Stationary Cycle), as well as dynamic tests, such as WHTC (World Harmonized Transient Cycle) (Emission Test Cycles, 2021; Worldwide emission standards, 2022).

Many papers present analysis of driving tests and operating states results for internal combustion engines. Paper (BUWAL, 1995) describes the procedure of creating single tests, used for things such as the development of INFRAS AG (INFRAS, 2014) software, which is used for the simulation of pollutant emissions. The methods used included, among others, a cluster analysis method for drive tests synthesis. The papers (André, 2004; André, 2006; André, 2009; André, 2020; Joumard, 1999) present the results of the CADC (The Common Artemis Driving Cycles) analysis obtained in driving tests. Very detailed drive tests results analysis can be found in (Barlows, 2009). The methodology of creating drive tests based on the similarity criteria of non-dimensional speed characteristics and accurate simulation in the time domain has been discussed in (Galgamuwa, 2015; Gamalath, 2012; Hung, 2007; Zhang, 2012). The papers (Merkisz, 2018; Pielecha, 2021) presents a comparison of driving tests with regard to their parameters. However, there is little work published regarding the operating states of engines in road tests. Articles (Barrios, 2012; Chłopek, 2010; Chłopek, 2015; Chłopek, 2017; Gis, 2021; Pielecha, 2020b) analyzed the impact dynamic states have on exhaust emissions in driving tests. Publications on RDE tests (Real Driving Emissions) can also be found (Andrych-Zalewska, 2019; Andrych-Zalewska, 2020; Andrych-Zalewska, 2021; Bebkiewicz, 2021; Pielecha, 2020; Skobiej 2021). A significant part of the considerations in these publications was devoted to the creation of these tests, however, there is no analysis of their properties.

This article focuses on the analysis of the internal combustion engine operating states and the speed process in the RDE test. The research methodology employed is original, namely tests in various domains, including in the frequency domain.

2. Aim and research plan

The aim of the research was to test the vehicle speed process properties in the RDE test along with the operating states of the internal combustion engine. The research was carried out for both static and dynamic process states. Conducting comprehensive tests for vehicle movement in various conditions, ranging from the city center to the highway, made it possible to formulate original conclusions on the impact that the properties of these driving conditions have on the operating conditions of the internal combustion engine, determining the exhaust emission and fuel consumption.

The test object was a Fiat Idea passenger car with the Fiat 1.3 JTD inline four-cylinder turbocharged diesel engine, with a displacement of 1300 cm^3. The rated power of the engine was 51 kW at 4100 rpm, the maximum torque of 180 Nm was achieved at 1750 rpm.

The drive tests were carried out in accordance to the RDE test method in and around the city of Poznan, including sections of the S11 expressway and the A2 motorway. The total length of the test drive was over 72 km. The tests were carried out after the engine reached a stable thermal state.

The PEMS (Portable Emission Measurement System) was used for measuring the exhaust emission values (PEMS, 2020). Semtech DS analyzer (Semtech, 2010) and a TSI 3090 EEPS™ (Engine Exhaust Particle Sizer™ Spectrometer) analyzer (TSI, 2008) were the equipment used for the exhaust emission tests. Similar studies have been described in detail in the authors' previous publications (Andrych-Zalewska, 2021; Pielecha, 2020a).

Measured quantities in tests done in dynamic driving conditions were recorded with a frequency of 10 Hz and then filtered using a second-degree Savitzky-Golay filter in order to reduce the presence of high-frequency noise in the signals (Savitzky, 1964).

3. Research method

The research methodology concerns processes in the time domain – t:

– vehicle speed – v(t),
– engine speed – n(t),
– relative torque – $M_{er}(t)$.

Relative torque is defined as:

$$M_{er}(n) = \frac{M_e(n)}{M_{eext}(n)} \quad (1)$$

where:
n – engine speed,
M_e – engine torque,
$M_{e\,ext}$ – torque at engine peak value (on engine speed characteristic).

The following methods of assessing the tested processes have been considered (Andrych-Zalewska, 2019; Pielecha, 2020a):

– for urban driving– designation – U,
– for rural driving – designation – R,
– for motorway driving – designation – H.

Tests were carried out in the domains of (Chłopek, 2016; Chłopek, 2017):
– time – these include non-dimensional characteristics of processes, such as e.g. mean value, standard deviation, coefficient of variation,
– process values – namely histograms,
– frequency – the spectra power density.

4. Research results

Figures 1–3 show the vehicle speed, engine speed and relative torque measured in the RDE test. The graphs show the individual phases of the test: urban (U), rural (R) and motorway (H).

The urban driving phase lasted 3,794 seconds, the distance traveled by the vehicle was 22.710 km. The rural phase lasted 956 seconds, the distance traveled by the vehicle in this phase was 19.117 km. In the 1250 s motorway phase, the vehicle traveled 30.876 km. The total test time was 6,000 seconds and the distance traveled by the vehicle was 72.703 km. The minimum vehicle speed was in the following phases: urban – 0 km/h, rural – 0 km/h and motorway – 20.9 km/h. The maximum vehicle speed for the three test phases was: urban – 78.9 km/h, rural – 86.9 km/h and motorway – 109.48 km/h. The fractional share of the urban phase in the entire test for distance and duration was: time – 0.623, distance – 0.312. These share values were: for rural driving 0.159 and 0.263; and for motorway travel 0.208 and 0.425, for the share of time and distance respectively.

The maximum value of the engine rotational speed was about 3670 rpm, the lowest rotational speed – apart from the start-up phase – was about 770 rpm.

Figures 4-6 show the histograms of the processes of: vehicle speed, engine speed and relative engine torque in the RDE test and its phases. Histograms show frequency (numerical share) in intervals with central values presented on the axis of the independent variable. The central value of the velocity in each value interval is the mean of the extreme values of that interval.

In the speed process histogram for the entire test, the highest rate of occurrence could be observed for speeds less than 5 km/h. This was related to the high share of operating phases where the vehicle was not moving (speed of 0 km/h) throughout the entire test – the share of time in the RDE test of car standstill equals 0.177. In addition, the share of speed values was similar throughout the range – less than 0.1, the highest for the central speed value of 40 km/h, a similar value for the central speed of 50 km/h, and then 80 km/h, which was related to the high rate with which this rural speed occurred. In the urban phase, the highest speed rate – about 0.33 was found for speed values below 5 km/h, which is a result of the large share of time the vehicle spent stationary in the urban driving phase – the overall share of time spent in the urban phase was 0.273. For a higher speed, the distribution was even – the rate was within the range of 0.12–0.15, the rate value was lower than 0.05 only for the central speed value equal to 60 km/h. In the rural phase, the shares of speed were dominated by the central speed value equal to 70 km/h and 80 km/h. In motorway phase, the dominant speed was for the central speed value equal to 100 km/h and 110 km/h.

There is a significant difference in the engine speed and relative torque histograms versus the vehicle speed histogram. This is largely due to the reduction of the rotational speed and torque amplitudes as a result of using a drive system with a variable transmission ratio which was selected depending on the driving speed. In the entire test, as well as in its individual phases, the highest rate of the engine rotational speed was observed for the central value 1000–2000 rpm. In the case of relative torque, the highest rate was found within the range of the central value of 0.2–0.5.

The study of vehicle speed processes in the domains of process values showed a large range of their distribution throughout the test as well as in its individual phases. In the case of relative rotational speed and relative torque, this spread was smaller. The significant share of the combustion engine operation at a relatively low rotational speed, less than 2000 rpm and with a small average load, in the order of 0.2–0.5, should be noted.

Figures 7–10 show the set of engine states in the RDE test and in its phases. The graphs show a point in red which has the following coordinates: mean value of the engine speed – mean value of the relative engine torque.

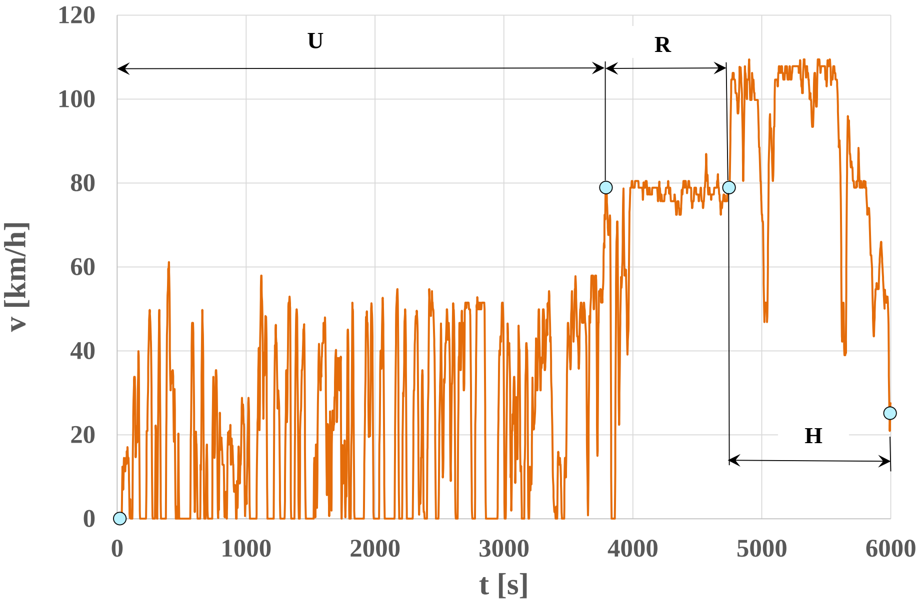

Fig. 1. Vehicle velocity in the RDE test as a function of time

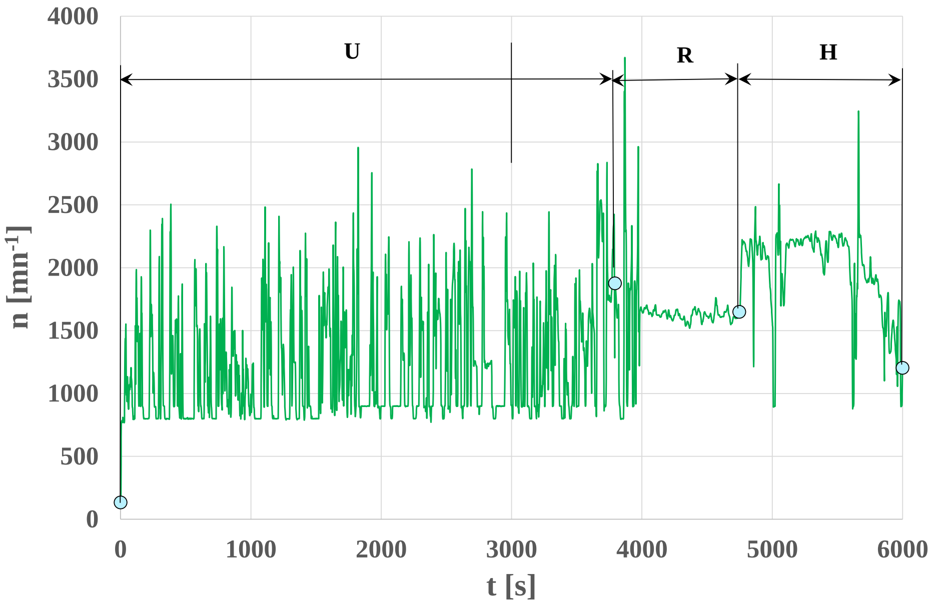

Fig. 2. Engine speed in the RDE test as a function of time

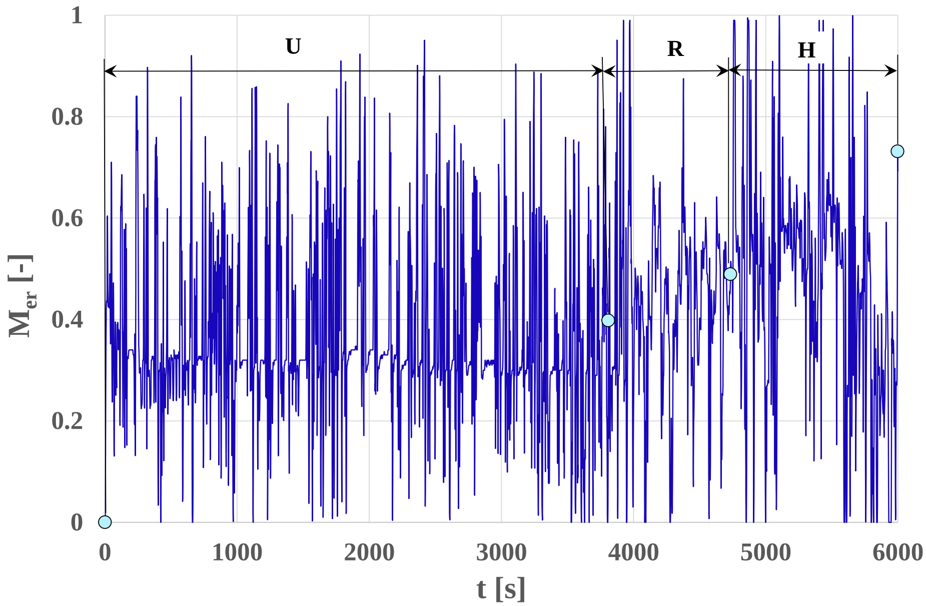

Fig. 3. Relative engine torque in the RDE test as a function of time

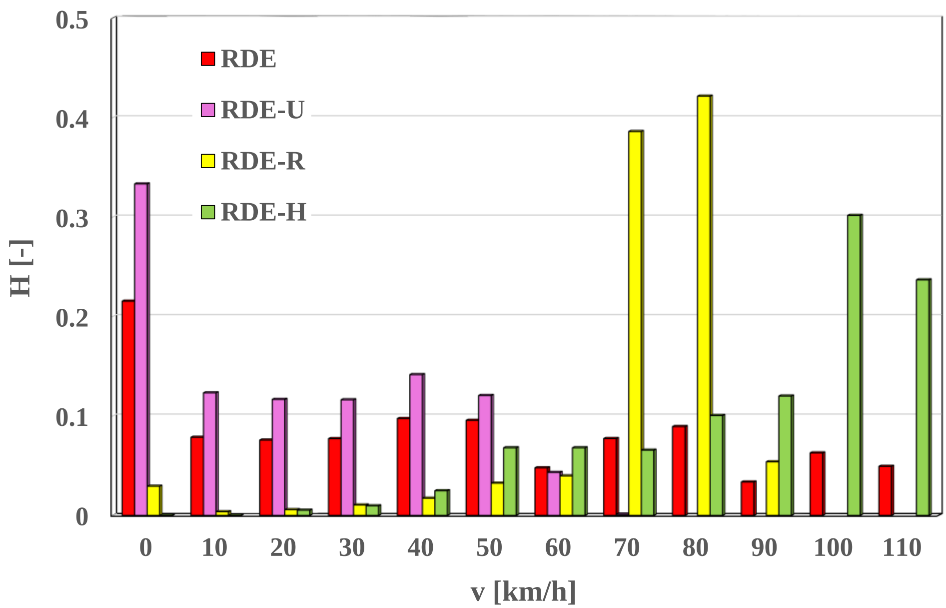

Fig. 4. Histogram of vehicle velocity in the RDE test and in its phases

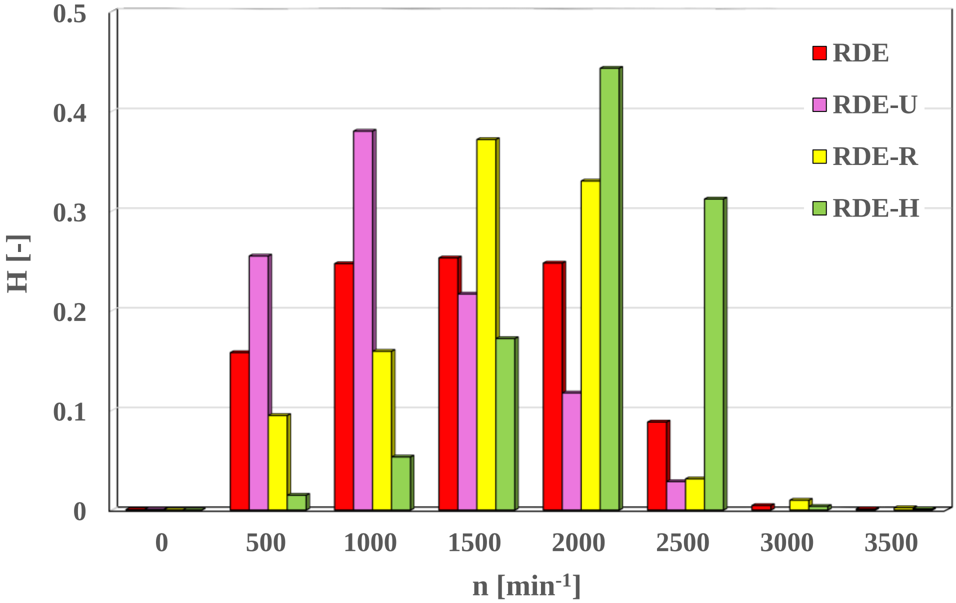

Fig. 5. Histogram of engine speed in the RDE test and in its phases

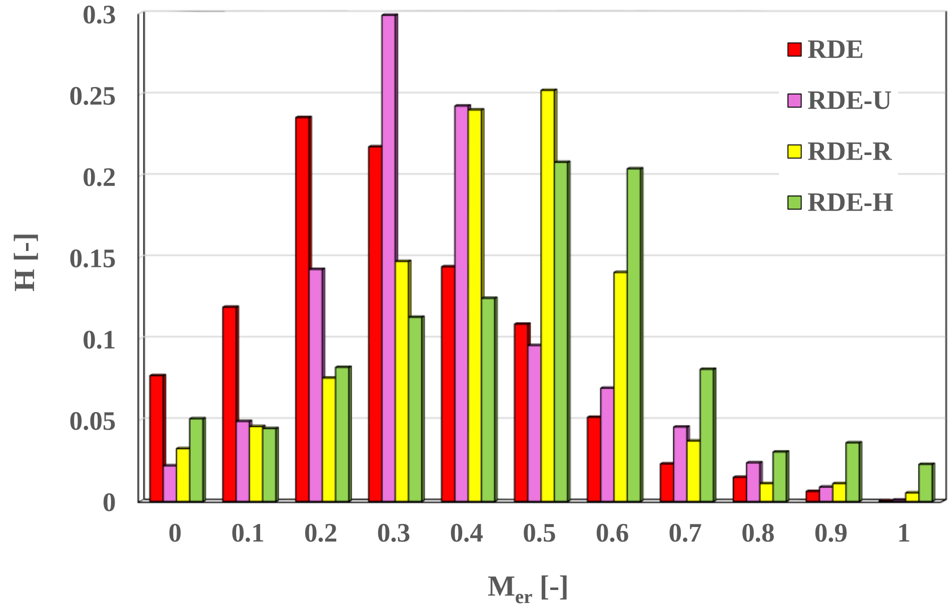

Fig. 6. Histogram of relative engine torque in the RDE test and in its phases

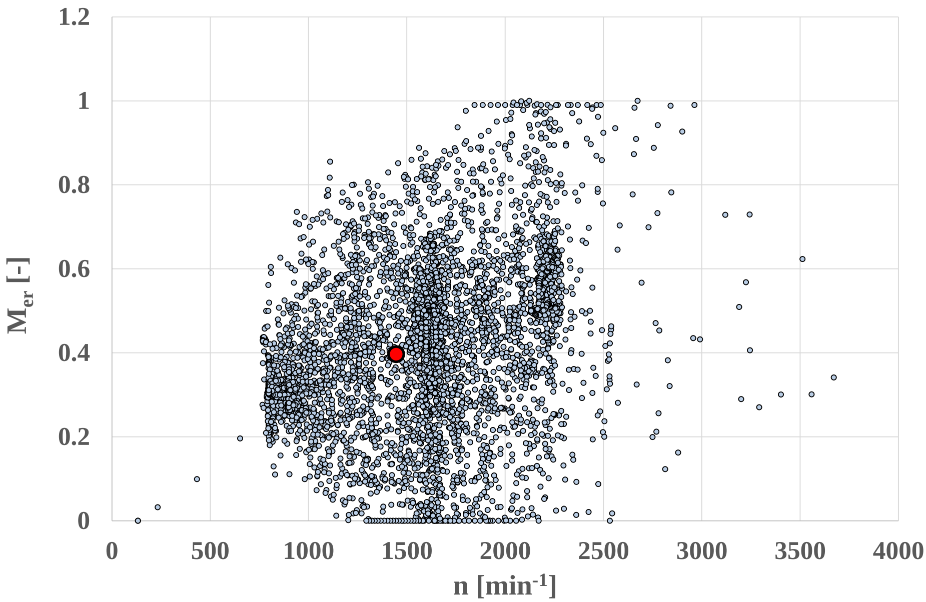

Fig. 7. Set of engine states in the RDE test

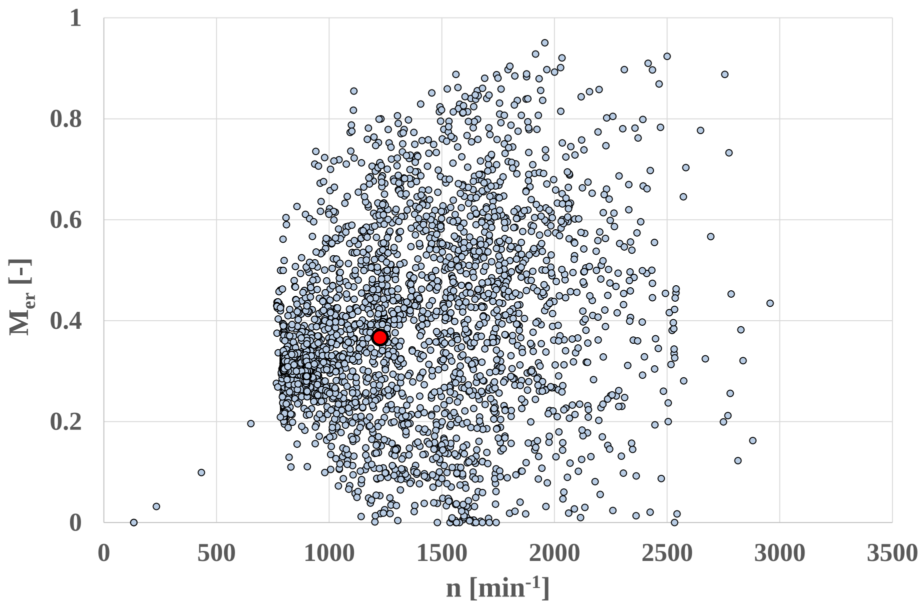

Fig. 8. Set of engine states in the urban phase of the RDE test

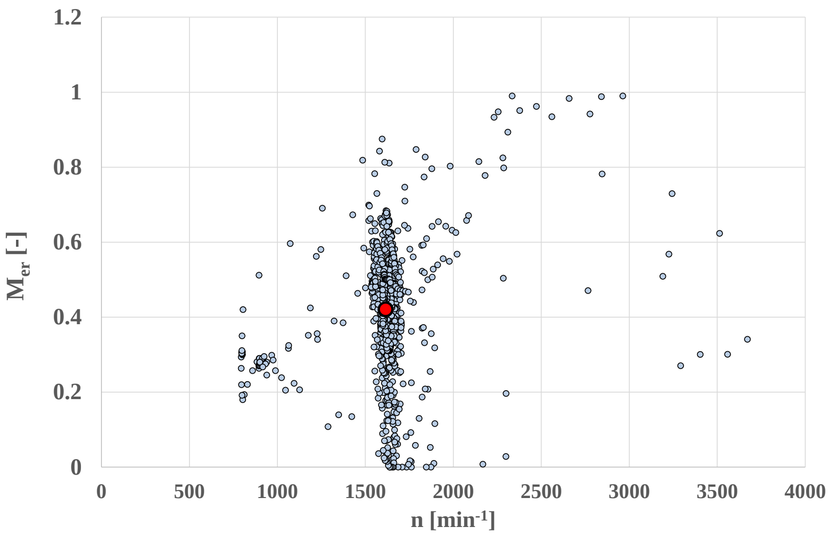

Fig. 9. Set of engine states in the rural phase of the RDE test

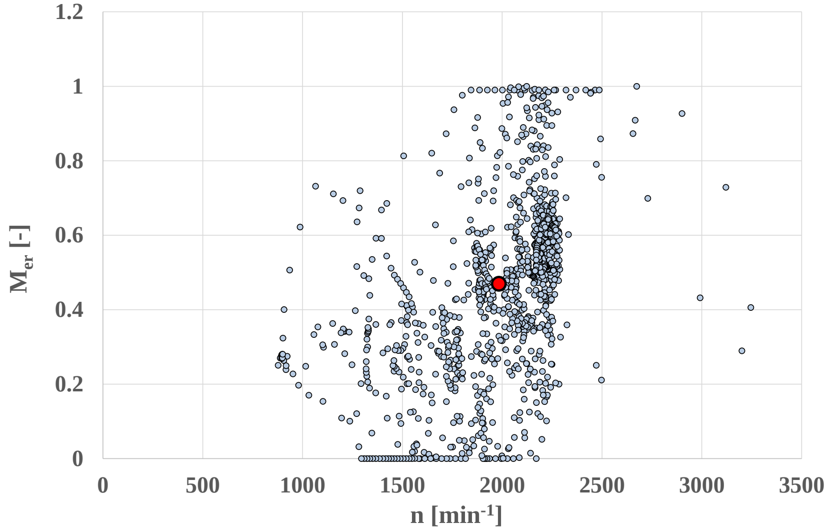

Fig. 10. Set of engine states in the highway phase of the RDE test

The spread of individual points indicates the variability of the processes of the engine rotational speed and its relative torque. The lowest variability of the processes of engine operation states occurred for rural driving.

Figure 11 shows a comparison of the mean value of the engine states in the RDE test and in its constituent phases.

The highest average engine load occurred for motorway driving phase, and the lowest for urban driving phase. The average engine load throughout the test was lower than in the rural phase. The engine average relative useful power (as a linear relation between the product of the engine rotational speed and its relative torque) was: for the entire test – 0.208, for the urban phase – 0.161, for the rural phase –

0.236, and for the motorway phase – 0.330. Thus, the average relative net power of the engine in the motorway phase was almost 60% higher than in the test as a whole.

Figures 12–14 show the processes average value for: vehicle speed, engine speed and relative engine torque in the RDE test and in its phases.

The average vehicle speed in the test was 43.6 km/h, which in the urban phase was – 21.5 km/h, in rural phase – 72 km/h, and in the motorway phase – 109.5 km/h. There was a large relative difference in the mean speeds in the individual test phases – the value of the mean vehicle speed variation in the individual test phases was 0.470.

Compared to the vehicle speed, the variation of the average engine speed in individual test phases was much lower. In this case, the coefficient of variation of the average engine speed value in individual test phases was 0.193.

The variability of the relative engine torque in individual test phases was even smaller in relation to the values for vehicle speed and engine rotational speed. The coefficient of variation of the mean relative engine torque value in the individual test phases was 0.100.

Figure 15 shows the coefficient of variation of the processes of: vehicle speed, engine speed and relative engine torque in the RDE test and in its phases. Of the determined coefficients of variation the highest coefficient value was found for the vehicle speed process in the urban driving phase and in the entire test, but in the phases in which the vehicle speed was more stable: such as the rural and motorway driving phases, the coefficients of variation of the relative torque reached the highest values. In general, however, both the relative engine torque process and, especially, the engine speed process were less dynamic than the vehicle speed process due to the use of variable gear ratios in the drive system. This fact was confirmed by the results presented in Figure 16 – the standard deviation of the sets of process variability coefficient values for: vehicle speed, engine rotational speed and relative engine torque.

Figures 17–19 show the power spectral density of the following processes: vehicle speed, engine rotational speed and relative engine torque in the RDE test and in its phases.

The procedure of determining the power spectral density for the measured processes was carried out for a set of 4096 discrete values of the processes.

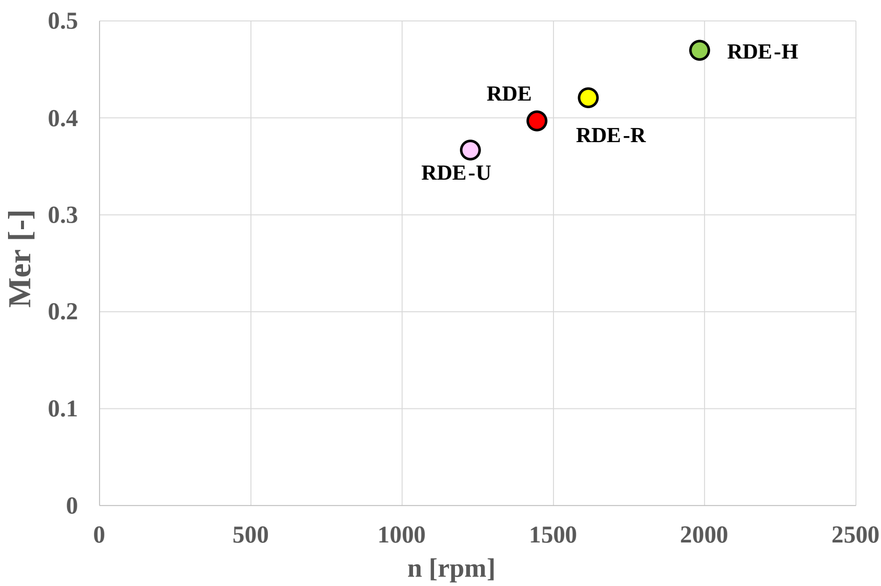

Fig. 11. Average values of engine states in the RDE test and in its phases

The procedure of determining the processes power spectral density included the following operations:
– standardization of the values of discrete processes (Bendat, 2011),
– removing the linear trend,
– using the Hamming time window (Hamming, 1962),
– using a fast Fourier transform to determine the power spectral density (Bendat, 2011),
– segment averaging of the widened estimator of the power spectral density of processes using a symmetrical filter with a width of 21 values (Bendat, 2011).

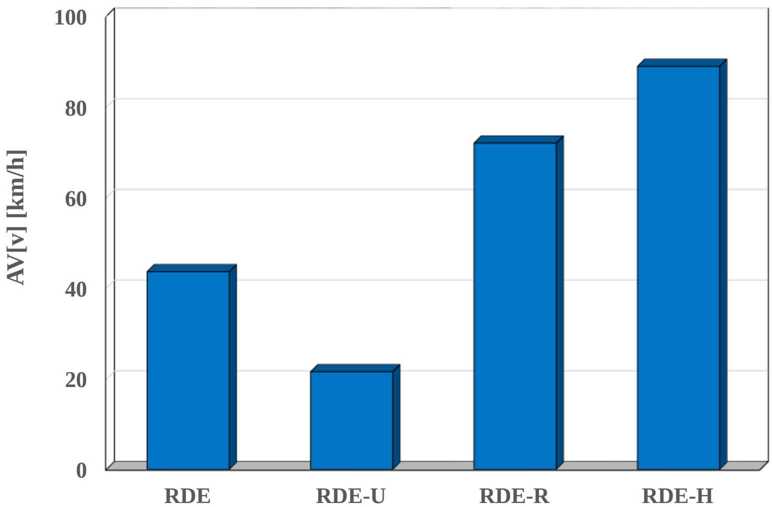

Fig. 12. Average value of vehicle velocity process in the RDE test and in its phases

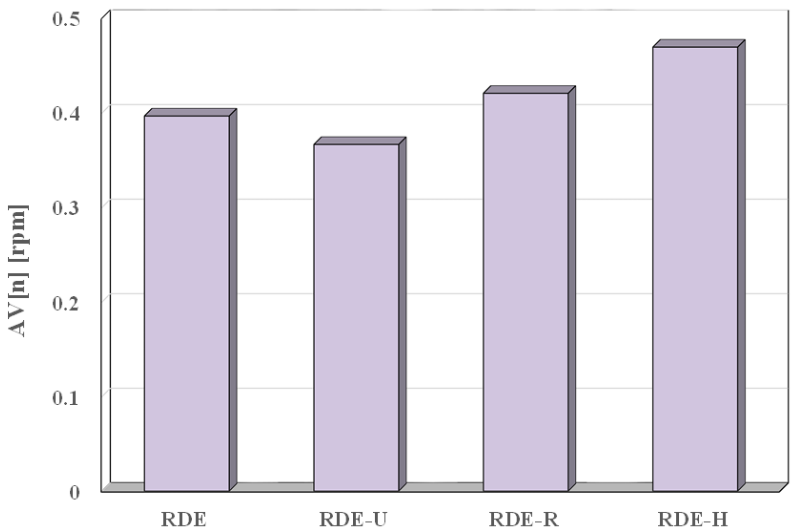

Fig. 13. Average value of engine speed process in the RDE test and in its phases

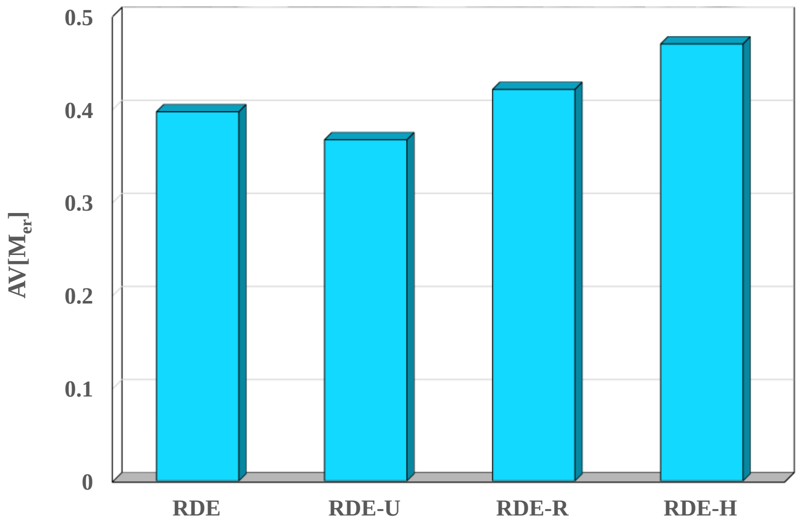

Fig. 14. Average value of relative engine torque process in the RDE test and in its phases

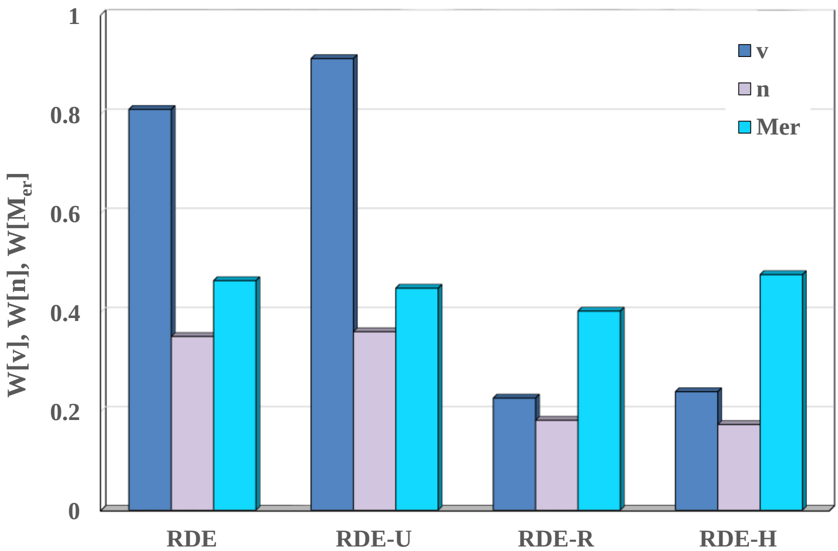

Fig. 15. Coefficient of variation for the processes: vehicle speed, engine speed and relative engine torque

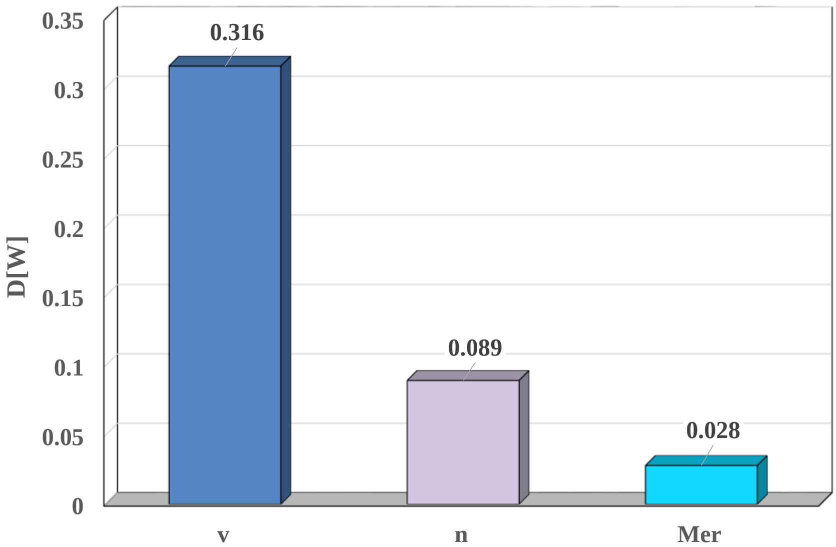

Fig. 16. Standard deviation of sets of coefficients of variation for the processes: vehicle velocity, engine speed and relative engine torque

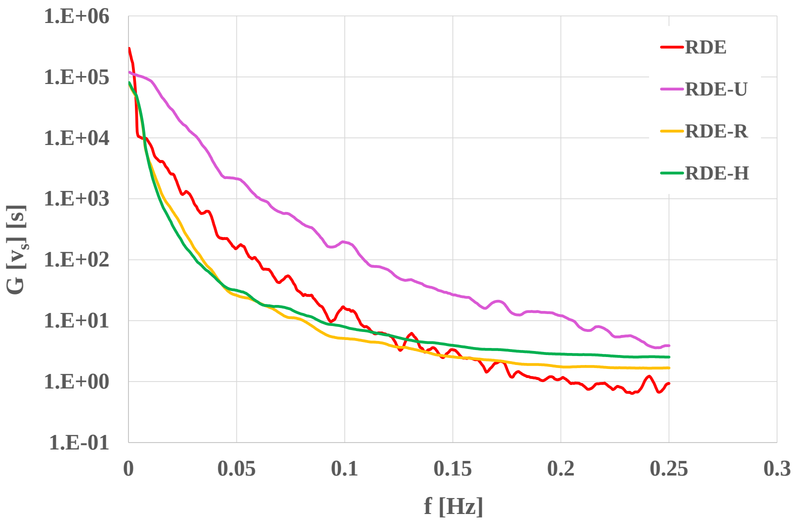

Fig. 17. Power spectral density of vehicle velocity in the RDE test and in its phases

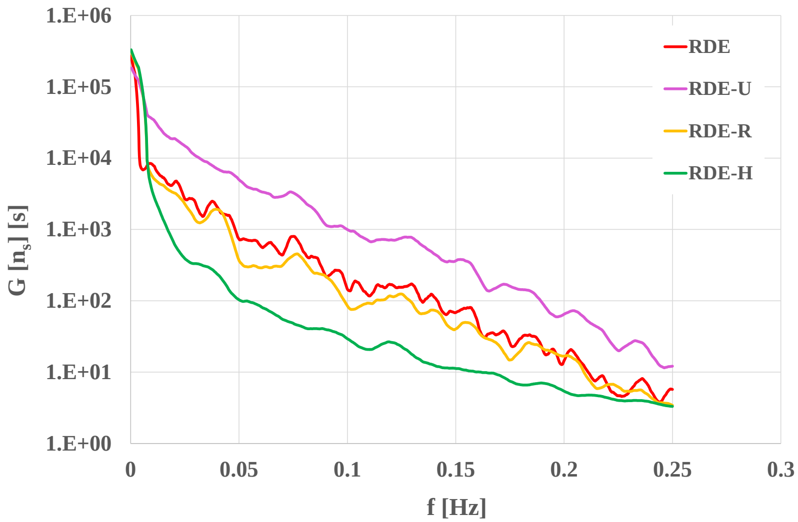

Fig. 18. Power spectral density of engine speed in the RDE test and in its phases

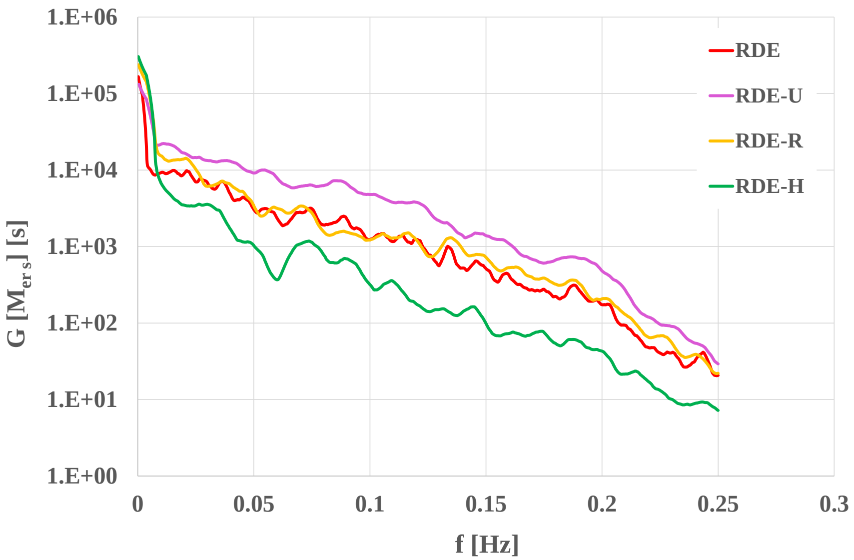

Fig. 19. Power spectral density of relative torque engine in the RDE test and in its phases

The highest power spectral density value of the analyzed processes for the urban phase of the test is clearly visible. This was confirmed by the results of the mean value of the power spectral process of the vehicle speed in the RDE test and in its phases – Figure 20.

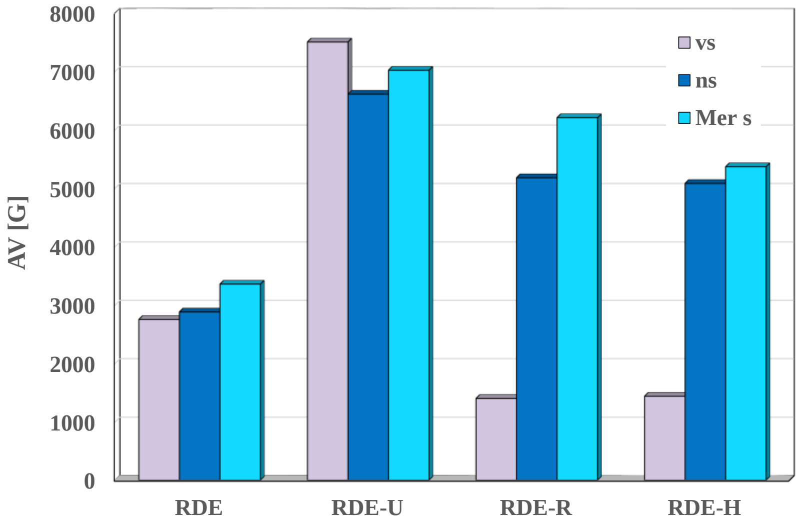

Fig. 20. Average value of power spectral density of the processes: vehicle velocity, engine speed and relative engine torque in the RDE test and in its phases.

5. Conclusions

The performed research and testing has made it possible to formulate the following two most important general conclusions:

1. The dynamic properties of the vehicle speed process in the RDE test were the most responsive in relation to the engine operating states. These properties were not significantly different in the individual phases of the RDE test. The properties of the speed process in the rural phase were the least dynamic, but in the motorway phase they were similar to those in the urban phase.
2. The processes of the engine speed and the relative torque of the engine were much less dynamic than the processes of the vehicle speed. However, it should be noted that the dynamic properties of the engine operating states in the motorway phase were similar to those in the urban driving phase. At the same time, however, the fact that the engine load was much higher in the motorway phase than in the urban driving phase can also be considered significant.

Due to the fact that the share of the distance traveled by the vehicle in the RDE test in the motorway phase was the largest (it amounted to as much as about 0.425 of the whole test), the significant share of exhaust emissions and fuel consumption values for that driving phase had a decisive impact on the overall results. These results include: road exhaust emissions (mainly: carbon monoxide, non-methane hydrocarbons, methane, nitrogen oxides, particulate matter and carbon dioxide), road exhaust emission of the number of solid particles as well as the fuel consumption or mileage (or alternatively road energy consumption). This means that in order to meet the increasingly more restrictive exhaust emission requirements, as well as fuel consumption and energy consumption limits, the optimization of control algorithms for working processes in internal combustion engines in dynamic states in conditions of high engine load play the most important role (Guzzella, 2004).

Nomenclature

AV	average value
D	standard deviation
EEPS™	Engine Exhaust Particle Sizer™ Spectrometer
f	frequency
G	power spectral density
H	histogram frequency

$M_{e\ ext}$	engine torque at maximum motor control setting
M_e	engine torque
$M_{er\ s}$	standarized relative engine torque
M_{er}	relative engine torque
n	engine speed
n_s	standarized engine speed
PEMS	Portable Emissions Measurement System
t	time
v	vehicle velocity
v_s	standarized vehicle velocity
W	coefficient of variation

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