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Investigation of exhaust emissions from the gasoline engine of a light duty vehicle in the Real Driving Emissions test

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Highlights

- The application of the Monte Carlo method to the results of empirical research in the RDE test turned out to be an effective way to determine the characteristics of pollutant emissions in the conditions of real car use.
- The scope of the article was to study the properties of a light duty vehicle combustion engine in conditions simulating its real operation.

Abstract

The article contains the research results and analysis of the processes that take place as part of a gasoline engine light duty vehicle Real Driving Emissions test. Dimensionless characteristics of exhaust emission and fuel mass consumption in the RDE test were also determined: emission intensity, particle number emission intensity, fuel mass consumption intensity. An algorithm for determining the characteristics specific distance pollutant emission, specific distance particle number and specific distance fuel mass consumption in the vehicle speed domain in the RDE test was presented using the Monte Carlo method. The determined characteristics were approximated by polynomial functions in the form of sets of points. These relationships were characterized by a large dispersion of values, which was primarily due to the fact that the random values of the averaging limits contain very different engine operating conditions.

Keywords
internal combustion engine, pollutant emission, RDE test, Monte Carlo method

1. Introduction

The scope of the article was to study the properties of a light duty vehicle combustion engine in conditions simulating its real operation. The RDE (Real Driving Emissions) test was developed as the official conditions simulating the real operation of a light duty vehicle. As a result of empirical studies, the emission intensity characteristics were recorded for: carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x) and carbon dioxide (CO_2), as well as the emission rate of the particle number (PN) and the fuel mass consumption intensity. Processing the recorded values made enabled calculating the zero-dimensional tailpipe emission and fuel consumption characteristics for the RDE test: mean specific distance pollutant emission, mean specific distance PN and mean specific distance fuel mass consumption. Another research goal was to determine the characteristics of the fuel mass consumption by the engine relative to the average velocity of the vehicle in the RDE test. For this purpose, the Monte Carlo method was used, randomly sampling the start and end points of averaging the vehicle velocity, emission and the PN values.

2. Literature review

Research on exhaust emission in real operating conditions of motor vehicles has been the subject of numerous research works in recent years. In [2], the travel speed curves and

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engine operating points in the RDE test [9] were analyzed, with each section considered individually – travel in urban, rural and highway sections. The engine operating points are described as the functions of the engine speed and relative torque. Available results indicate that the static engine operating states of the vehicle speed parameters had significantly lower impact than the dynamic ones. Finally, it was noted that the specific distance pollutant emissions in the test, which were a property of the tested objects, were most affected by traffic conditions on motorways.

The article [3] discusses testing methods of emission from an combustion engine operating in dynamic states in the RDE test. Zero-dimensional emission characteristics of individual exhaust gas components (average value, coefficient of variation) were determined for the assumed engine operating states. These states were analyzed for both positive and negative acceleration.

In [7], the current methods of testing, validation and development of methods for testing the emission from combustion engines of motor vehicles were reviewed. Discussing the new challenges and necessary adjustments to current approaches and illustrating that it is necessary to incorporate future regulatory requirements into current plans and actions. The article [12] analyzed the properties of a diesel engine of the Euro 6 emission category in dynamic conditions in the RDE test. An engine dynamometer was used to perform the tests, which simulated the conditions of a moving light truck's engine operation. The influence of dynamic states of engine operation on emission was analysed.

The paper [15] presented the results of emission results obtained in the RDE test on Polish roads. The coefficients of compliance for the vehicle engine emission were calculated, presented in the form of distance-specific emission during the type-approval test relative to the test results from the RDE test. In paper [18], specific distance emission of NOx, NO_2, CO, and CO_2 as well as the specific distance PN from a total of 19 Euro 6b, 6c and 6d-TEMP vehicles with gasoline engines (including those fueled with natural gas) and compression ignition engines were measured. The vehicles were tested in a variety of road conditions, also those beyond the requirements of RDE test conditions.

In [21], the engine emission of 13 Euro 6 light duty vehicles (8 with compression ignition engines and 5 with gasoline engines) was examined in the NEDC (New European Driving Cycle) [23], WLTC (Worldwide Harmonized Light Vehicles Test Cycle) [23] and RDE tests. The specific distance emission in the RDE test conditions have been significantly exceeded relative to the specific distance emission measured in both the NEDC and WLTC tests.

Article [22], discussed the impact of the processing method for the results of the RDE test (a type of measurement results averaging). The emission data was obtained from tests of 10 light trucks belonging to the Euro 6 category. It was found that the analyzed methods of averaging the results of empirical research did not lead to significantly different results. In the article [9], the impact of cold-starting engines and reaching a stabilized temperature on the measured exhaust emission was investigated.

In [24], the results of engine emission tests from three light duty vehicles were analyzed: a no-boost gasoline engine, a no-boost direct injection compression ignition engine and a boosted direct injection compression ignition engine. The tests were carried out in the WLTC, CLTC (China Light-duty Vehicle Test Cycle) and RDE tests. It was found that the CLTC test is more similar to the RDE test than the WLTC test due to the vehicle operating states: coordinates; velocity; acceleration. This paper presents the RDE test results for a light duty vehicle.

RDE tests belong to the category of tests based on time domain similarity. Driving tests can be created based on several types of similarities. Initially, driving tests were created mainly following the principle of the repeatability of zero-dimensional vehicle movement characteristics in real operation as well as in test conditions. Such characteristics included: the average vehicle velocity value, the maximum velocity value, velocity distribution, top acceleration values, etc. [4]. More complex characteristics were also considered, e.g. the mean absolute value of velocity times acceleration [4]. The NEDC test is an example of a test designed based on the similarity of the zero-dimensional characteristics of the vehicle motion in the conditions of real operation and in the test conditions. Since the FTP-72 (Federal Test Procedure) test [9], tests based on velocity similarity in the time domain have been created. An example of such a test is the current WLTC test. Driving cycle tests can also be designed based on the repeatability of the velocity process in the frequency domain. Such a method was presented in [6]. An additional feature of this method is the ability to generate the implementation of a random velocity process with the same spectral density by generating a pseudo-random phase of the frequency signal.

It should be noted that most of the research results published in the international literature focus on the emissions assessment and the averaged pollutant distance emission in the conditions of real operation of the vehicle. The essential elements of the scientific novelty contained in this article are:

- → study of the processes characterizing the vehicle speed, the operating states of the engine as well as the emission and fuel consumption in the time domain, and not only averaged processes,
- → correlation research of the examined processes characterizing vehicle velocity, engine operating states as well as emissions and fuel consumption,
- → the fuel consumption and emissions characteristics in conditions of vehicle motion in random RDE test conditions, calculated using the Monte Carlo method.

Due to the planned introduction of the Euro 7 standard, which drastically reduces the emission values, any research on these issues is and justly purposeful. This also applies to the interrelationships among the exhaust emissions. The research in question can be used to program the engine control unit and to develop an effective after-treatment system (selection of system parameters and catalysts).

3. Methodology of research

The research methodology includes: determining the average values in the RDE test of specific distance pollutant emission, specific distance PN and specific distance fuel mass consumption, as well as using the Monte Carlo method to calculate the RDE characteristics of the specific distance pollutant emission, specific distance PN and specific distance fuel mass consumption depending on the average vehicle velocity.

The specific distance pollutant emission in the RDE test (e) is express the exhaust emission measured – M divided by the vehicle travel distance – S.

$$e = \frac{M}{S} \tag{1}$$

The specific distance particulate emission – e_{PN} is expressed as the number of emitted particles measured – N_{PN} divided by the distance travelled by the vehicle.

$$e_{PN} = \frac{N_{PN}}{S} \tag{2}$$

The specific distance fuel consumption of the engine in the RDE test – FC is expressed as the mass of fuel consumed – M_{Fuel} divided by the distance traveled by the vehicle.

$$FC = \frac{M_{Fuel}}{S} \tag{3}$$

The RDE emission is the integral of the emission rate – EI.

$$m = \int_0^T EI(\tau)d\tau \tag{4}$$

where: τ – time, T – drive duration.

The PN in the RDE test – PN is the integral of the PN emission rate – EI_{PN}.

$$N_{PN} = \int_0^T EI_{PN}(\tau)d\tau \tag{5}$$

The fuel mass consumption in the test – M_{Fuel} is the integral of the fuel mass consumption intensity of the vehicle engine – EI_{Fuel}.

$$M_{Fuel} = \int_0^T EI_{Fuel}(\tau)d\tau \tag{6}$$

The distance travelled by the vehicle – S is the integral of vehicle velocity – V.

$$S = \int_0^T V(\tau)d\tau \tag{7}$$

The emission factor – EF is the ratio of specific distance pollutant emission and specific distance fuel mass consumption.

$$EF = \frac{e}{M_{Fuel}} \tag{8}$$

The PN factor – EF_{PN} is the ratio of the specific distance PN and the specific distance fuel mass consumed.

$$EF_{PN} = \frac{e_{PN}}{M_{Fuel}} \tag{9}$$

Monte Carlo method was used to determine the specific distance exhaust emission characteristics, the specific distance PN and the specific distance fuel mass consumption of the engine relative to the mean travel speed of the vehicle in the RDE test [5, 13]. Monte Carlo is one of the numerical methods used to solve very complex mathematical problems that are difficult to solve analytically or by using regular numerical methods, and – according to the concept of Chłopek [5] – to “create” a non-existent random reality. Research into this reality enables a significant improvement in the effectiveness of empirical research of the reality around us. In this work, the Monte Carlo method was used precisely in order to “create” a non-existent random reality.

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 credited as the main creator of the Monte Carlo method. Stanisław Ulam was an employee of Los Alamos National Laboratory and was involved in the Manhattan Project during WWII. 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). Stanisław Ulam and Nicolas Metropolis published the concept of the Monte Carlo method in a paper [13].

The name of the Monte Carlo method was derived from the use of pseudo-random numbers in the developed method, so the name of the numerical method refers to the world capital of gambling at the time.

In this paper the method to determine the combustion engine characteristics in terms of emission and fuel consumption was the Monte Carlo method, and it was used to randomize the times of the beginning and end of the research tests.

The points in time τ_a and τ_b, which are the limits of averaging emission, PN and engine fuel mass consumption, were determined by a pseudo-random number generator.

Specific distance pollutant emission – e in the time interval (τ_a, τ_b) is the ratio of emission in the time interval – M(τ_a, τ_b) and the distance travelled by the vehicle in the time interval – S(τ_a, τ_b).

$$e(\tau_a, \tau_b) = \frac{M(\tau_a,\tau_b)}{S(\tau_a,\tau_b)} \tag{10}$$

Specific distance PN in the time – e_{PN}(τ_a, τ_b) is determined as the value of the PN emitted – N_{PN}(t_1, τ_b) divided by the vehicle travel distance in time (τ_a, τ_b).

$$e_{PN}(\tau_a, \tau_b) = \frac{N_{PN}(\tau_a,\tau_b)}{L(\tau_a,\tau_b)} \tag{11}$$

Specific distance fuel mass consumption – FC(τ_a, τ_b) is determined as the value of the fuel mass consumption – M_{Fuel}(τ_a, τ_b) divided by the distance that the vehicle travelled in the time interval (τ_a, τ_b).

$$FC(\tau_a, \tau_b) = \frac{M_{Fuel}(\tau_a,\tau_b)}{S(t_1,t_2)} \tag{12}$$

Exhaust emission measured in time (τ_a, τ_b) is an integral of the emission rate – EI(τ_a, τ_b) in the same time span (τ_a, τ_b).

$$M(\tau_a, \tau_b) = \int_{\tau_a}^{\tau_b} EI(\tau)d\tau \tag{13}$$

The PN value (τ_a, τ_b) is an integral of the PN emission rate– EI_{PN}(τ_a, τ_b) in the time interval (τ_a, τ_b).

$$N_{PN}(\tau_a, \tau_b) = \int_{\tau_a}^{\tau_b} EI_{PN}(\tau)d\tau \tag{14}$$

Fuel mass consumption in the interval – M_{Fuel}(τ_a, τ_b) is an integral of the fuel mass consumption rate of the engine in the time interval – EI_{Fuel}(τ_a, τ_b).

$$M_{Fuel}(\tau_a, \tau_b) = \int_{\tau_a}^{\tau_b} EI_{Fuel}(\tau)d\tau \tag{15}$$

The travel distance – S(τ_a, τ_b) is an integral of the vehicle velocity in the same time interval – V(τ_a, τ_b).

$$S(\tau_a, \tau_b) = \int_{\tau_a}^{\tau_b} V(\tau)d\tau \tag{16}$$

The average vehicle travel velocity – V_{Avg}(τ_a, τ_b) is determined as the ratio of the vehicle distance travelled in the time interval (τ_a, τ_b) and the duration of the interval τ_b – τ_a.

$$V_{Avg}(\tau_a, \tau_b) = \frac{S(\tau_a,\tau_b)}{\tau_a - \tau_b} \tag{17}$$

4. Measured data

A light duty vehicle with a gasoline engine and an automatic gearbox (emission category of Euro 6) was the test object in the conducted research based on specific distance emission. The vehicle was subject to an RDE test for emissions and fuel consumption, in accordance with the applicable steps in the approval procedure. The PEMS (portable emission measurement system) was used [14]. A Semtech DS analyzer [17] and a TSI 3090 (Engine Exhaust Particle Sizer™ Spectrometer) analyzer [20] were each used to measure the exhaust emissions.

The data recorded by the device was filtered by a Savitzky-Golay filter [16] as a way of reducing the high-frequency noise in the measured values.

Vehicle speed in the test was measured (Fig. 1).

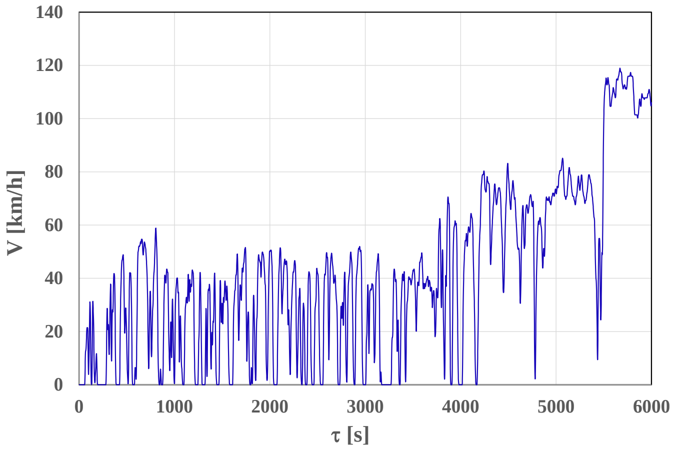

Fig. 1. Vehicle velocity process – V in the RDE test.

The vehicle speed corresponds to driving in traffic conditions inside cities, outside of a city, and on highways and expressways. Figure 2 shows the vehicle throttle position control process in the RDE test. This process corresponds to a significant variation in vehicle velocity. The concept of throttle control is a quantity characterizing the operator's influence on the engine. In the case of a vehicle engine, it is the angle of opening the accelerator pedal. Figure 3 shows the vehicle engine speed in the test.

A clearly visible difference exists in the nature of vehicle motion in the subsequent sections of the RDE test, corresponding to the specific traffic conditions in urban areas, in the outskirts of urban areas and on highways and expressways. As a result of these differences other differences occur in the engine operating states, which was confirmed by the test results presented in Figures 2–5.

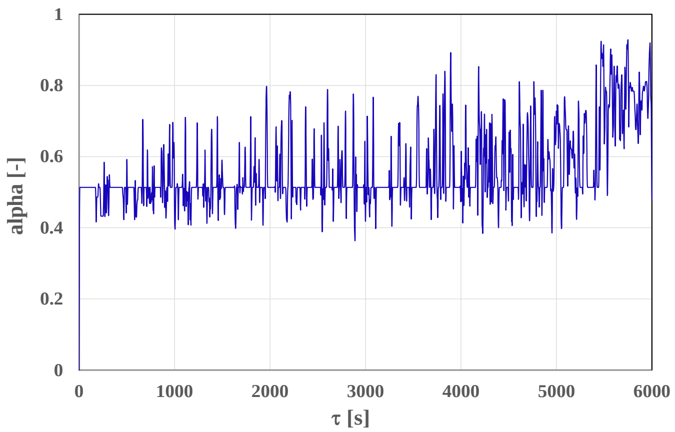

Fig. 2. Throttle position – alpha in the RDE test.

The throttle control values in every RDE phase differed slightly. The smallest variability of the throttle control occurred in urban traffic conditions, the largest in traffic conditions on highways and expressways.

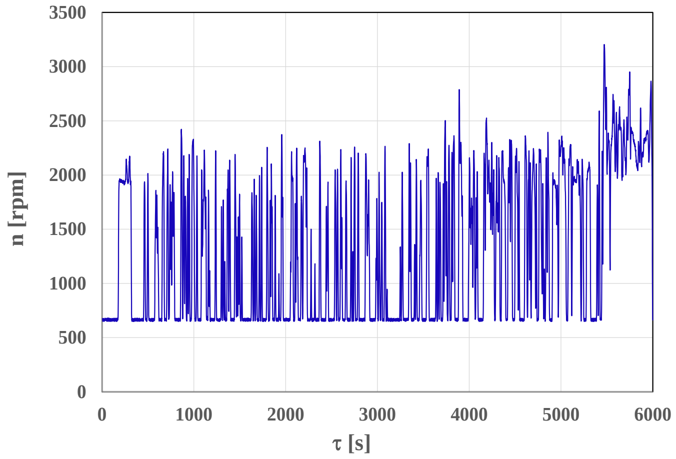

Fig. 3. Engine speed – n in the RDE test.

The nature of the engine speed changes in real driving conditions inside and outside cities was similar, only in motorway and expressway traffic conditions the mean speed value and variability were clearly higher. There was a significant share of the zero engine speed value, which was the result of the ASG system operation (Automatic Stop and Go).

Figure 4 shows the relative engine torque. The relative torque was scaled relative to the maximum value.

Figure 5 shows the relative effective engine power. The relative effective power was scaled relative to its maximum value.

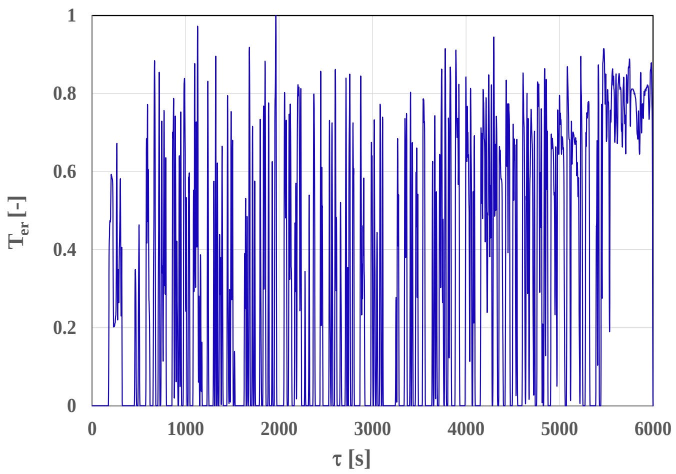

Fig. 4. Relative engine torque – T_{er} in the RDE test.

The engine torque characteristic was similar in all test phases, both in terms of value and its variability.

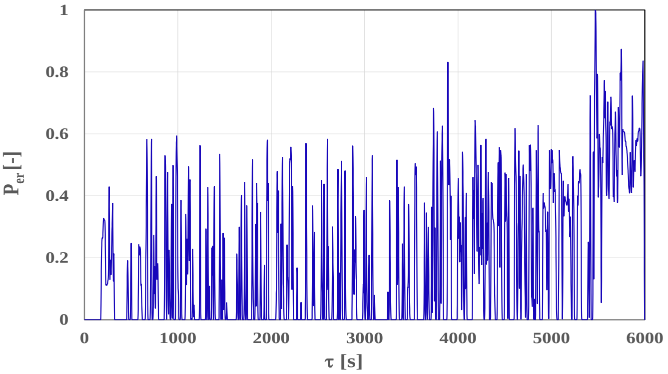

Fig. 5. Relative effective power process – P_{er} in the RDE test.

The differences in the engine effective power values was primarily in the fact that they were greater for driving in non-urban conditions, and above all in motorway and expressway conditions, which was caused by greater motion resistance at higher driving speeds.

Figures 6–9 were used to show the emission rate processes of: CO, HC, NOx and CO_2 from the vehicle engine as obtained from the test.

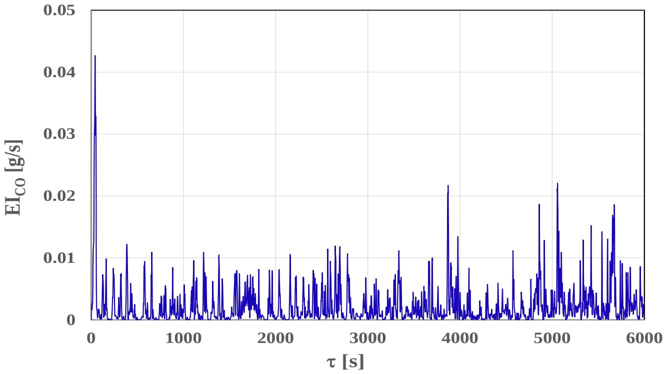

Fig. 6. CO exhaust emission process – EI_{CO} from the vehicle engine in the RDE test.

The CO emission intensity characteristics were defined by the fact that the local maxima were the highest in the motorway and highway driving phase, with the exception of the engine cold start.

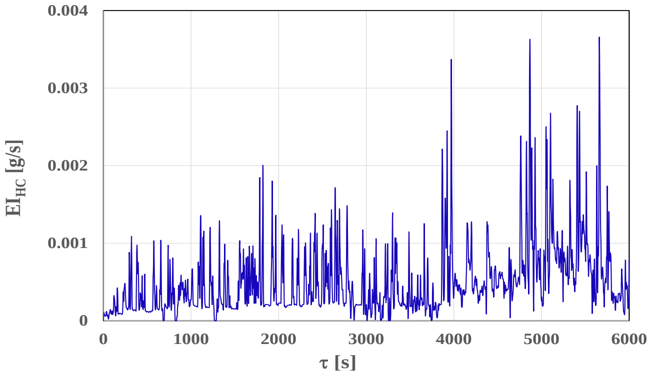

Fig. 7. Hydrocarbon exhaust emission process – EI_{HC} from the engine in the RDE test.

Also, hydrocarbon emission rate was clearly higher in motorway and expressway traffic conditions than other test phases.

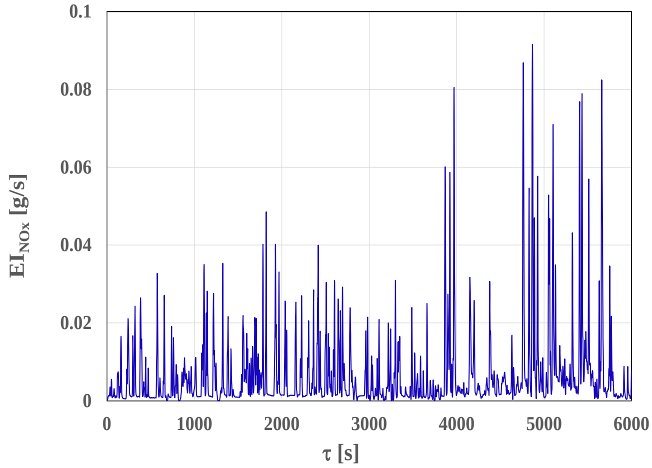

Fig. 8. NOx exhaust emission process – EI_{NOx} from the car engine in the RDE test.

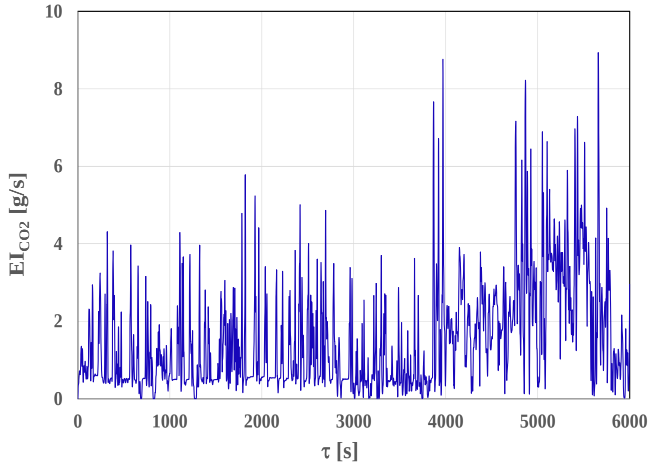

Fig. 9. CO_2 exhaust emission process – EI_{CO2} from the vehicle engine in the RDE test.

It was similar for NOx emission intensity characteristic – and in this case, a much higher value of NOx emission was associated with a higher engine load, i.e. in driving conditions on motorways and expressways.

For CO_2 emission intensity, its value was clearly higher for vehicle moving at a high speed, so in driving conditions on motorways and expressways, fuel consumption increased.

There is a significant difference between the results of CO emission intensity and HC, NOx and CO_2. For the emission rate of CO, NOx and HC, the highest values appeared for high engine load at high vehicle velocity.

Figure 10 shows the particle emission rate in the RDE test.

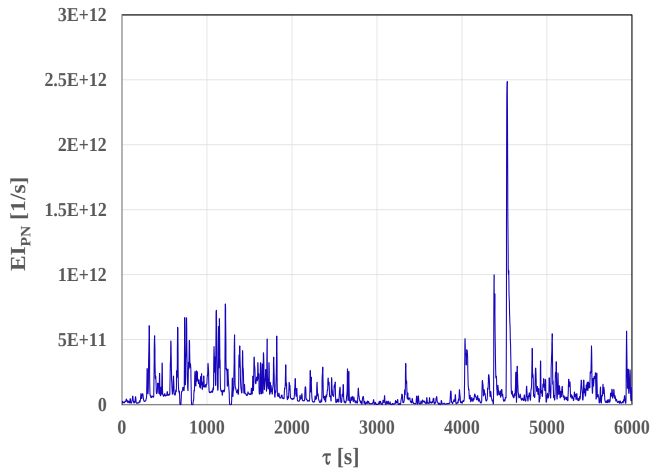

Fig. 10. PN intensity process – EI_{PN} from the engine in the RDE test.

PN emission intensity was less consistent. The emission rate was stable, except for in the case of motorways and expressways driving conditions where a very high local maximum could be observed. The PN intensity was found to have a wide range of values. Particularly high value of PN intensity coincided with a rapid increase of throttle control process.

Figure 11 shows the process of fuel mass consumption for the vehicle engine in the RDE test.

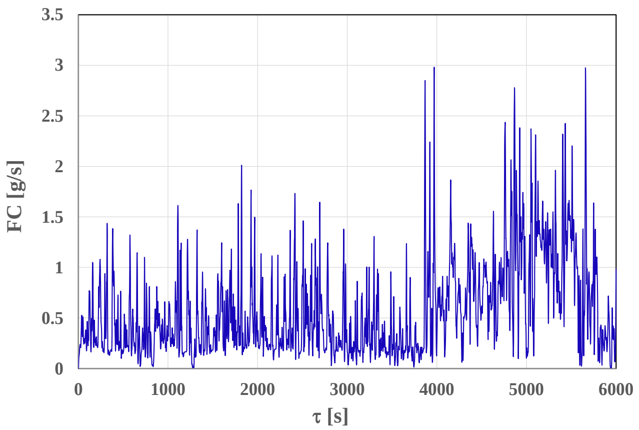

Fig. 11. Vehicle engine's fuel mass consumption process – FC in the RDE test.

There is naturally a clear correlation of the engine fuel mass consumption and the vehicle velocity values and, consequently, the corresponding engine load. A clear relationship between the mass fuel consumption intensity and the intensity of CO_2 emissions is also apparent.

5. Results and discussion

Table 1 was used to show the dimensionless characteristics of emission and fuel consumption in the test.

Table 1. Zero-dimensional emission and fuel consumption in the RDE test

CO	HC	NOx	CO_2	PN	FC
e [g/km]				e_{PN} [1/km]	[g/km]
0.199	0.0439	0.580	131.2	9.50E+12	49.4
EF				EF_{PN} [1/g]	
0.00404	0.000890	0.0117	2.65	1.90E+11	

The relative specific distance emission values determined in the test were presented as a fraction of the Euro 6 exhaust emission limits, and resulted in values as follows: for CO – 0.199, for HC – 0.439, for NOx – 9.661, for PN – 15.833.

Figure 12 is the set of vehicle and RDE engine operating points in the coordinates of throttle control and vehicle velocity.

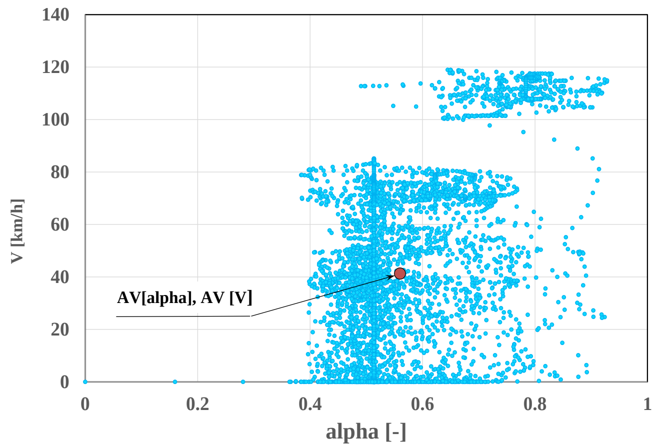

Fig. 12. The vehicle operating points from the RDE test in the throttle control – alpha and vehicle velocity – V coordinates.

A point representing the averaged central coordinate values has been marked on the chart in red.

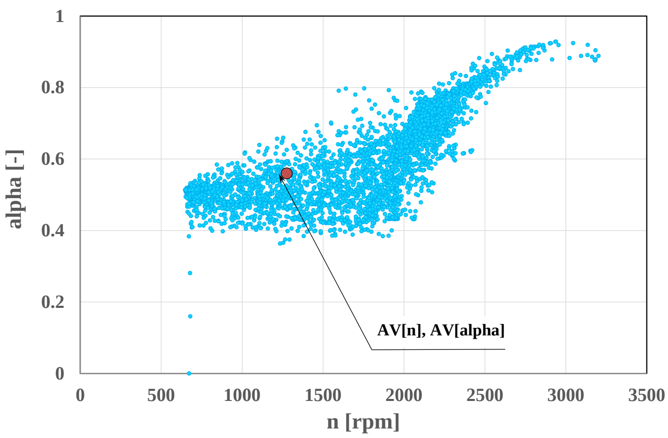

Fig. 13. The set of vehicle engine operating points in the RDE test in the engine speed – n and throttle control – alpha coordinates.

The average vehicle speed was measured to be about 41 km/h, and the average throttle control value was slightly above 0.55.

Figure 13 is the set of vehicle operation points in the RDE test in the following coordinates: engine speed – throttle control. A point representing the averaged central coordinate values has been marked on the chart in red.

The average engine speed was about 610 rpm. The relatively low average engine speed value was caused by a large share of the zero engine speed due to the operation of the ASG system.

Figure 14 is the set of vehicle operation points in the RDE test in the following coordinates: engine speed – relative engine torque. A point representing the averaged central coordinate values has been marked on the chart in red.

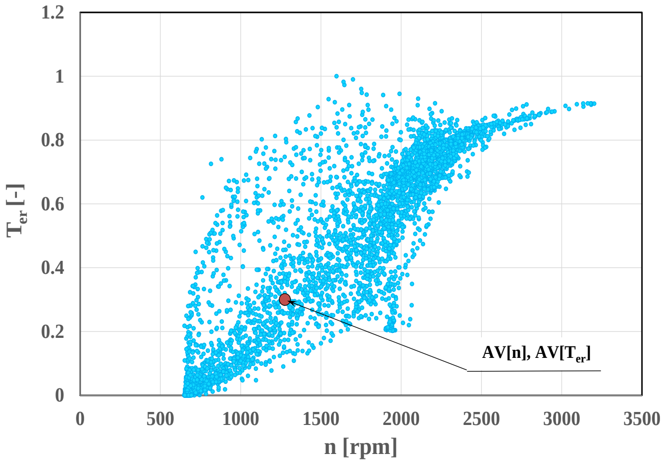

Fig. 14. The set of vehicle engine operating points in the RDE test in engine speed – n and relative engine torque – T_{er} coordinates.

The average value of the relative engine torque was about 0.3.

Figure 15 is the set of vehicle operation points in the following coordinates: engine speed – relative effective power. A point representing the averaged central coordinate values has been marked on the chart in red.

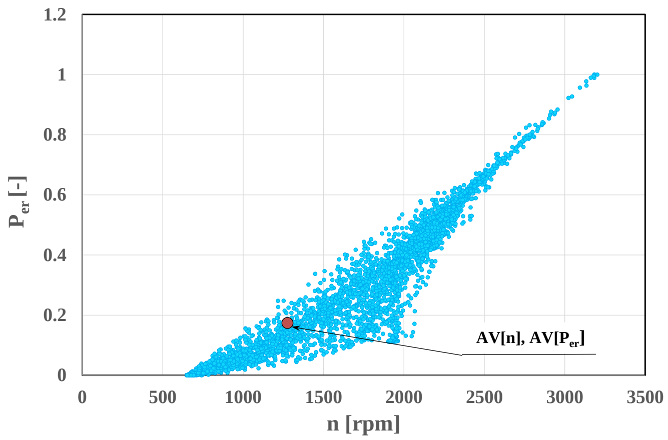

Fig. 15. The set of vehicle engine operating points in the RDE test in engine speed – n and relative effective power – P_{er} coordinates.

The relative effective power value reached approx. 0.17. All these variables were characterized by a large dispersion of measured values. The smallest dispersion was found for the throttle control data points.

Correlation studies of the obtained data were performed. The coefficients of determination between the obtained value sets were calculated (Table 2).

Table 2. Coefficient of determination – R^2 for the examined processes in the RDE test

	V	alpha	n	T_{er}	P_{er}	EI_{CO}	EI_{HC}	EI_{NOx}	EI_{CO2}	EI_{PN}
alpha	0.245									
n	0.155	0.540								
T_{er}	0.142	0.528	0.876							
P_{er}	0.199	0.742	0.923	0.888						
EI_{CO}	0.00110	0.00310	0.000300	0.000300	1.00E-05					
EI_{HC}	0.0639	0.0317	0.0230	0.0252	0.02920	0.143				
EI_{NOx}	0.0063	0.0044	0.0021	0.0028	0.0029	0.134	0.836			
EI_{CO2}	0.0903	0.0381	0.0380	0.0361	0.0423	0.10260	0.857	0.653		
EI_{PN}	0.00430	0.00430	0.000400	2.00E-05	1.00E-05	0.0115	0.0723	0.0646	0.0926	
FC	0.0751	0.0238	0.0259	0.0259	0.0302	0.0877	0.817	0.624	0.961	0.0921

In most cases, the examined processes were not found to be correlated with each other. The strongest correlation was observed between the fuel mass consumption intensity and the CO_2 and hydrocarbon emission intensity, followed by its correlation with NOx emission intensity. Due to the nature of combustion engine operation the values of engine speed, relative engine torque and relative effective power were strongly correlated. A strong correlation was found between the throttle control and the relative effective power, followed by the values of engine speed and relative engine torque.

The engine operation states could be seen to be more strongly correlated with the vehicle travel velocity data, than to the values of exhaust emission or fuel consumption. The emission intensity values were relatively weakly correlated with each other, especially with the PN emission intensity. Only the emission intensity values of HC, NOx and CO_2 were strongly correlated. It should be noted that the characteristics of emission intensity and the PN intensity were poorly correlated with the engine operating states, such as: engine speed, relative engine torque and relative effective power. The data points determined as described by the set of equations (10) – (17) were approximated by a 2nd degree polynomial in the following coordinates: specific distance pollutant emission, specific distance PN and specific distance fuel mass consumption – average vehicle velocity.

Figures 16–19 show the specific distance pollutant emission characteristics relative to the mean vehicle speed.

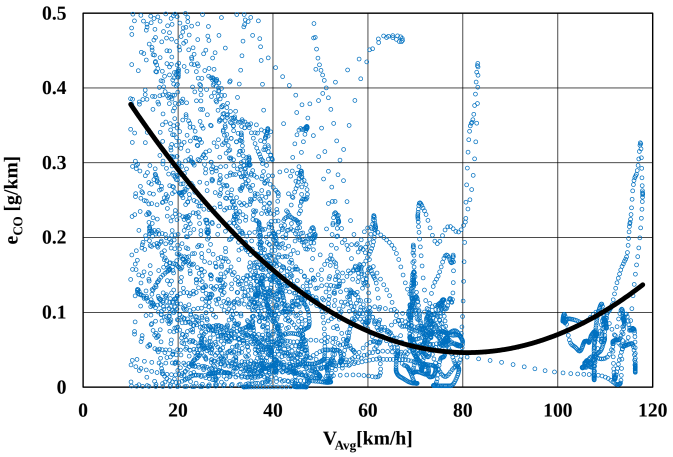

Fig. 16. Specific distance emission of CO – e_{CO} as a function of the average vehicle velocity – V_{Avg} in the RDE test.

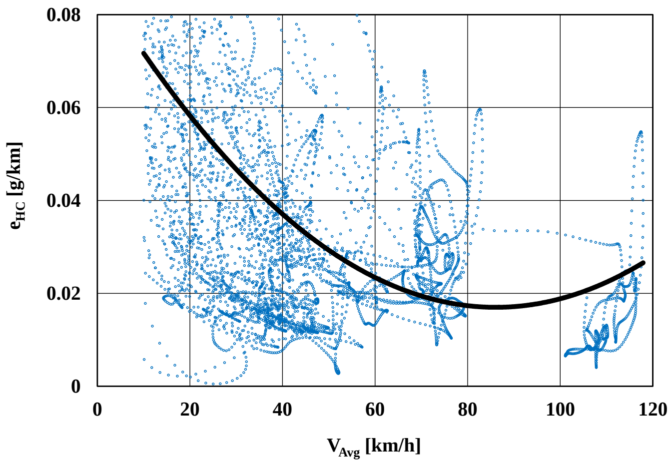

Fig. 17. Specific distance emission of HC – e_{HC} as a function of the average vehicle velocity – V_{Avg} in the RDE test.

The obtained impact of the average vehicle velocity on the CO specific distance emission was consistent with the characteristics determined as a result of many drive tests with different average vehicle velocities. Data obtained from such tests is included in software used for emissions simulation from motor vehicles, e.g. [4, 8, 11]. However, it should be emphasized that the characteristics determined using the Monte Carlo method were based on the results obtained in one test, and not in multiple tests.

As in the case of CO, the HC specific distance emissions were consistent with past experience.

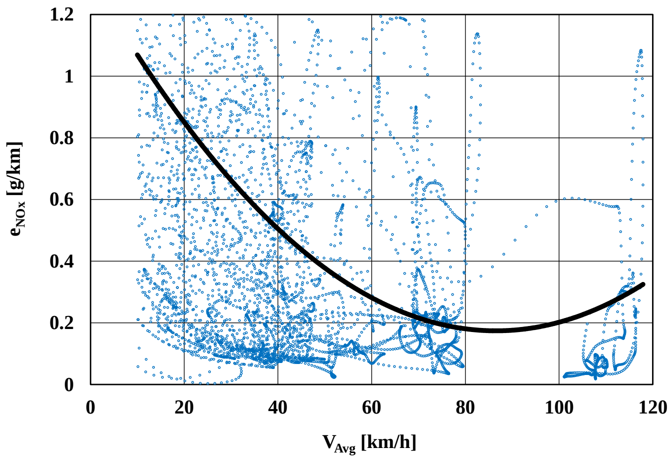

Fig. 18. Specific distance emission of NOx – e_{NOx} as a function of the average vehicle velocity – v_{Avg} in the RDE test.

Also, the relationship between the NOx specific distance emission on the average vehicle velocity was consistent with the characteristics determined using other test results from multiple tests.

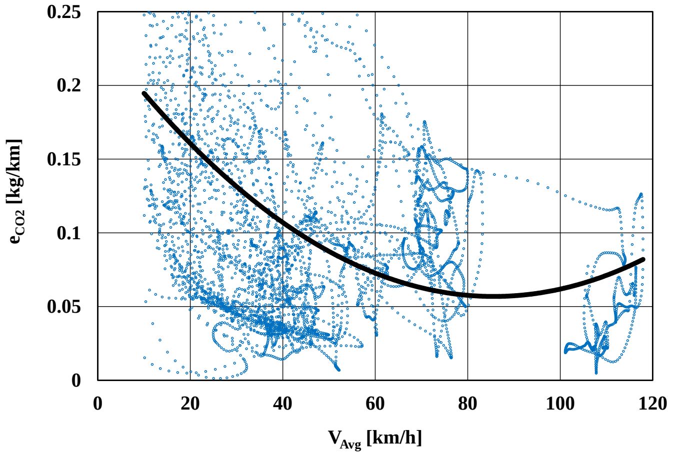

Fig. 19. Specific distance emission of CO_2 – e_{CO2} as a function of the average vehicle velocity – V_{Avg} in the RDE test.

It is also typical for CO_2 specific distance emissions that higher values were found for lower average driving velocity, i.e. in conditions of heavy traffic. Specific distance emissions of CO_2 also increased at high average travel velocity at heavy engine load, which was accompanied by an expected increase in fuel consumption.

Figure 20 presents the characteristics of the specific distance PN relative to the vehicle average velocity in the test.

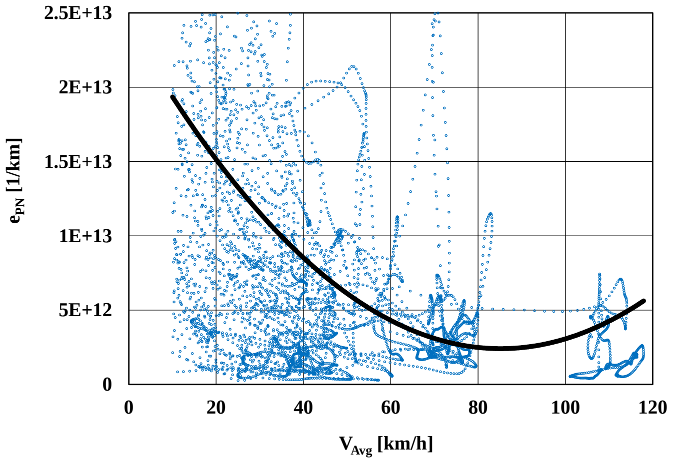

Fig. 20. Specific distance PN – e_{PN} as a function of the average vehicle velocity – V_{Avg} in the RDE test.

The high variability of the vehicle velocity when driving slowly caused frequent accelerations, and these were conditions conducive to increased particulate matter emissions. On the other hand, the increase in the PN specific distance at high average vehicle velocity resulted from the high engine load.

The specific distance fuel mass consumption of the engine was shown in Figure 21, related to the vehicle average velocity in the test.

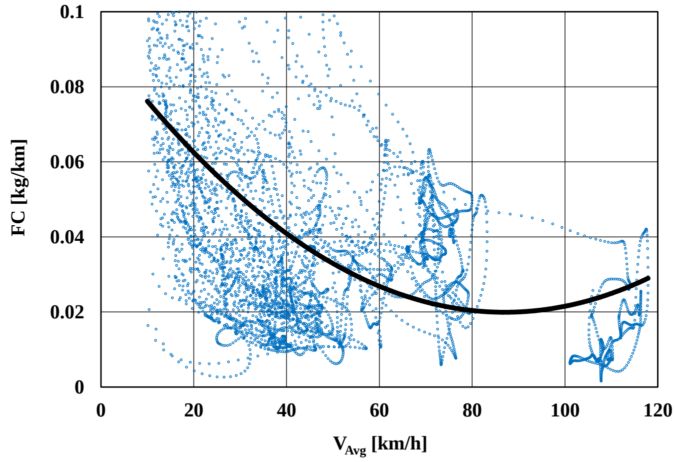

Fig. 21. Specific distance fuel mass consumption of the engine – FC as a function of the average vehicle velocity – V_{Avg} in the RDE test.

The fuel consumption characteristics were consistent with the determined fuel consumption characteristics.

The measured specific distance emission values were characterized by a very large dispersion of values, which was understood to be the result of the random averaging limits values that contain very different combustion engine operating conditions. However, the sets of values approximated by a polynomial of the second degree determined the relationship between the specific distance emission values, specific distance PN and specific distance fuel mass consumption as well as the vehicle average velocity that were consistent with these same relationships as determined for many driving tests with different average driving velocity, see: [4, 5, 1, 8, 10, 11, 19]. For the engine tailpipe emission characteristics, the specific distance PN and fuel mass consumption, it was typical that for a lower average vehicle velocity the characteristics reached high values. This was due to the fact that a low average velocity corresponds with significant traffic difficulties and congestion, which leads to a high variability in the engine operating states.

6. Conclusions

The conducted research can be summarized with the following conclusions:

1. The values of the average specific distance emission determined in the RDE test conditions were compared with the limit values for Euro 6 vehicles powered by gasoline engines. Compared to the Euro 6 emission limits, the relative

specific distance emission values determined in the RDE test were as follows: for CO – 0.199, for HC – 0.439, for NOx – 9.661, the PN – 15.833.

2. The sets of vehicle and engine operating points in the RDE test were analyzed in the coordinates as listed:

- throttle control – vehicle velocity;
- engine speed – throttle control;
- engine speed – relative engine torque;
- engine speed – relative effective power.

The average values of the analyzed variables in the RDE test were approximately: for vehicle velocity – 41 km/h, for throttle control – 0.55, for engine speed – 610 rpm, for relative engine torque – 0.3, for relative effective power – 0.17.

All the measured variables were characterized by a large dispersion of values. The smallest dispersion was found for the throttle control values.

3. Based on the conducted correlation studies of the considered variables of the vehicle and its engine operating states, as well as the values of emission intensity, the PN emission rate and the fuel mass consumption rate, it was found that in most cases the examined variables were not notably correlated with each other. The correlation between these variables and the engine operating states was also not observed. A strong correlation, on the other hand, was found for the values of fuel mass consumption rate and the CO_2 emission rate as well as the engine speed, relative engine torque and relative effective power, which resulted from the mutual relationships binding these variables through the combustion process.

4. The specific distance emission characteristics, PN emission and fuel mass consumption, which were determined using the Monte Carlo method, relative to the vehicle average velocity, corresponded to the engine operating states for the vehicle in the RDE test. The value of these variables were characterized by a large dispersion, which resulted primarily from the fact that the random values of the averaging limits contained very different engine operating conditions, but the sets of values approximated by the polynomial of the second degree were consistent with the relationships determined for many driving tests at different average velocities. For the determined characteristics it was typical that for the low average velocity the variables had high values. This is due to the fact that a low average velocity value corresponds to significant traffic difficulties and congestion, which resulted in high variability of the engine operating states.

It is advisable to continue research work in two directions. The first direction is testing the sensitivity of the determined characteristics to various implementations of the Monte Carlo procedure. These studies were possible based on the results of previous empirical research, and therefore require only an input of intellectual work.

The second direction is conducting such research for various implementations of the RDE test. Such studies, being both costly and labor-intensive, require considerable effort. The authors believe, however, that the continuation of research in this direction is necessary in order to objectively assess the operational properties of combustion engines of road cars in conditions corresponding to their real operation.

Abbreviations

Avg	average value
e	specific distance pollutant emission/specific distance particulate number
CLTC	China Light-duty Vehicle Test Cycle
CO	carbon monoxide
CO_2	carbon dioxide
EI	pollutant emission intensity/particle number intensity
EPSS™	Engine Exhaust Particle Sizer™ Spectrometer
FTP	Federal Test Procedure
HC	hydrocarbons
S	vehicle distance

M	pollutant mass
T_{er}	relative engine torque
M_{Fuel}	mass fuel consumption
n	engine speed
NEDC	New European Driving Cycle
P_{er}	relative effective power
NO_x	nitrogen oxides
PEMS	Portable Emissions Measurement System
PN	particle number
FC	specific distance fuel mass consumption
EI_{Fuel}	fuel mass consumption intensity
R^2	coefficient of determination
RDE	Real Driving Emissions
T	time
V	vehicle velocity
V_{Avg}	average vehicle velocity
WLTC	Worldwide Harmonized Light Vehicles Test Cycle

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