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CORRELATION STUDIES OF PROCESSES: VEHICLE VELOCITY, POLLUTANT EMISSIONS, AND VEHICLE FUEL CONSUMPTION IN THE WORLD-WIDE LIGHT-DUTY TEST CYCLE

Summary. The article presents the worldwide harmonized light-duty test cycle results of a diesel engine passenger vehicle carried out on a chassis dynamometer. Pollutant emissions from exhaust and fuel consumption were measured. Vehicle velocity was treated as a variable determining pollutant emissions and fuel consumption because the engine operating states depend on engine velocity and load during engine operation, and these states in turn affect pollutant emissions and fuel consumption. Actions taken to reduce pollutant emissions and consumption of fuel are often in opposition to each other. Therefore, there is a need to optimize these activities. There is also a need to know the relationship between the effects of taking specific actions that serve to achieve individual goals in order to rationalize actions aimed at reducing pollutant emissions and fuel use. The originality of the article lies in the use of the correlation theory between pollutant emission and fuel consumption as well as the processes that determine them, primarily vehicle velocity, to rationalize these activities. Pearson's linear correlation theory was used to assess the relationships between individual variables. Significant differences were found in the correlation coefficients between individual variables, which confirmed the need to take integrated actions to reduce pollutant emissions and fuel consumption.

1. INTRODUCTION

Among the operation properties of combustion engines, the most significant are their ecological properties, primarily due to the pollutant emission, as well as economic properties, determined by the overall efficiency of the engines and, consequently, fuel consumption. The goal of reducing pollutant emissions is to reduce combustion engines' harmful environmental impact, with a primary focus on protecting the health and life of living beings. Reducing fuel consumption may contribute to reducing the depletion rate of natural resources, and in the case of fossil fuels, to reducing CO_2 emissions, the main greenhouse gas in terms of overall pollutant emissions.

Other properties of combustion engines, such as durability, reliability, and maintainability, have been largely improved to a high degree of perfection.

Currently, pollutant emissions can be considered a basic characteristic defining the development of combustion engines. This is confirmed by the constantly tightening environmental protection regulations regarding the use of combustion engines. Paper [9] describes a proposal to introduce regulations regarding pollutant emissions from light vehicle engines at the Euro 7 level. Paper [25]

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describes a proposal for Euro 7 regulations for light trucks. Complete information on pollutant emission testing methods and limits characterizing these emissions can be found on website [12]. Similar information was included in the guide [25]. This summary confirms the dynamic increase in requirements regarding pollutant emissions from combustion engines. In [16] trends in regulations regarding specific distance emissions from combustion engines of trucks and buses were described. Meanwhile, [23] concerns the reduction of greenhouse gas emissions from internal combustion engines of road vehicles.

Actions taken to reduce pollutant emissions and reduce fuel use are often contradictory. Therefore, there is a need to optimize these activities. Therefore, this paper intends to evaluate the relationship of pollutant emissions with fuel consumption as well as with the values that determine these parameters.

The quantities that determine pollutant emissions and fuel consumption are engine operating states, which mostly consist of engine speed, engine load, which can be measured by torque, and the engine's thermal state. For road vehicle engines, the parameters determining the engine operating states include vehicle velocity and motion resistance. These values also influence the time it takes for the engine to heat up to a stabilized thermal state [7, 8].

In laboratory conditions on a chassis dynamometer, when the motion resistances are repeatable, the variable that determines the operating states of the engine is the vehicle velocity.

The quantities characterizing pollutant emissions and fuel consumption depend on the engine operating states and, therefore, on vehicle velocity, not in the form of functions with numerical values but in the form of a functional; in particular, these quantities are velocity functionals [7, 8]. Therefore, the possibility of examining the interdependence of values characterizing and determining pollutant emissions and fuel use represents specific classes of engine operating states. In this article, this is achieved by using repeated tests on a chassis dynamometer in the research. Of course, it is also possible to study the interdependence of pollutant emissions and fuel use, along with the processes that determine these properties in random conditions, including in the conditions present with real driving on the roads. However, this makes it necessary to study the dependencies of variables in the domains of their values to study the probability density and the multidimensional probability density of variables [5, 17, 18].

2. LITERATURE REVIEW

The late 19th and early 20th century were a period of increased interest in the statistical relationships between random variables in many fields. Francis Galton developed the theoretical concept of correlation and regression to the mean, and Karl Pearson developed the theory of linear correlation.

The creators of non-parametric correlation theories were Maurice George Kendall, a British statistician; Charles Spearman, a British psychologist; Wilson Allen Wallis, an American statistician and economist; Steven Goodman, an American physician; William Henry Kruskal, an American statistician and mathematician; and Robert Hough Somers, an American sociologist and statistician.

There are many papers on vehicle testing in the worldwide harmonized light-duty test cycle (WLTC) test. These articles concern both the results of pollutant emissions tests in the entire test and in its fragments corresponding to the different nature of vehicle movement.

This is the test currently in force in the European Union in the approval procedure for light vehicles (passenger cars, light duty vehicles, and minibuses) at the Euro 6 regulation level. At present, work is being carried out to introduce regulations at the Euro 7 level [9].

In the article [1], the effect of the thermal state of the compression ignition engine of a passenger car on emissions was analyzed. In the paper [4], the influence of the thermal condition of internal combustion engines on the results of road vehicle emissions inventories was examined. The paper [3], in turn, considered the risks associated with particulate matter emissions and presented the results of an emission inventory of particulate matter size fractions.

The work [22] compared the results of air pollutant emissions inventory from road vehicles of different cumulative categories: passenger cars, light-duty vehicles, heavy-duty vehicles, buses, motorbikes, and mopeds. In the emissions inventory, there are very different engine operating states corresponding to the operation of vehicles under different conditions, mainly dynamic conditions.

The operating states of internal combustion engines considered in the emissions inventory significantly exceed the diversity of engine operating states in type approval tests.

The paper [6] presents the results of a comparative study of carbon dioxide emissions in WLTC [11, 25] and new European driving cycles (NEDC) tests [11, 25]. In the paper [13], the results of tests on emissions of other pollutants in WLTC and NEDC tests are compared. There are only a few publications on the correlation relationships of pollutant emission test results. Only in [2] the topic of correlation dependencies of the studied variables was discussed. This article described the outcomes of a study of vehicle velocity processes and variables characterizing pollutant emissions and fuel consumption. The statistical characteristics of the variables and their histograms were examined.

The work [12] shows the results of empirical research in the WLTC test on a passenger vehicle with a compression-ignition engine and a modified power supply system enabling the addition of liquefied petroleum gas fuel. The study examined not only the pollutant emissions but also the engine indication and the rate of heat released from the engine cylinder.

The paper [19] assessed the differences in the pollutant emissions results in the WLTC test and real driving conditions in a city setting. It was estimated that the greatest difference was in the mean specific distance CO emission – over 150% of the value under actual driving conditions. In the case of hydrocarbons (HC) and nitrogen oxides (NO_x), this difference was over 60%.

Paper [21] compared the results of pollutant emissions from six vehicles in the WLTC, New European Driving Cycle (NEDC), and common Artemis driving cycle (CADC) tests. A significant level of sensitivity of pollutant emissions to the specific conditions of the used driving tests was observed. Paper [7] presents the results of vehicle engine research in dynamic states characterized by vehicle acceleration under real driving conditions. The investigated variables were very sensitive to the dynamic states, as well as to the type of driving tests used.

Paper [8] presents a systemic approach to the issues of combustion engine dynamics. The concepts of internal combustion engine operating variables, operating conditions, and engine operating states were formalized. An axiomatic classification of the engine operation was proposed to be a static and dynamic process. Pollutant emissions were studied under the following conditions: the entire test, increasing the engine velocity, reducing the engine velocity, and engine velocity above idle. The average emission intensity was highly sensitive to the types of dynamic states discussed.

Paper [10] presents the test results of 40 Indian auto-rickshaws with three different fuel and engine combinations, operating in the Indian driving cycle test. Intensity levels of CO, HC, NOx, PM2.5, and CO_2 emissions were recorded. Models of specific distance pollutant emission and specific distance fuel consumption were developed to allow these values to be simulated. Russian and European emission and dispersion models were analyzed in [14], which assessed road transport-related air pollution at the scale of a street and a region, using the example of St. Petersburg in Russia. Based on the results of empirical studies of pollutant concentrations, a method of adapting the COPERT IV model was designed, enabling the determination of the road vehicles' pollutant emissions characteristics.

Paper [15] presents the results of using several models that describe pollutant emissions and the dispersion of pollutants to assess the air quality. These models were Caline4 (California Department of Transportation), Hiway-2 (United States Environmental Protection Agency), Mobile5b (United States Environmental Protection Agency), and COPERT III (European Environmental Protection Agency).

In [20], the results of research carried out as part of the DECADE project, implemented under the European Commission's 5th Framework Program (The DECADE (2000–2003) project, carried out under the European 5th Framework Programme) were presented. As a result of this research, software was created to forecast the fuel consumption and pollutant emissions of vehicles for a specific type of traffic. The outcomes of empirical tests of combustion engines and vehicles on an engine dynamometer and a chassis dynamometer (on a training ground and in real road traffic) were used for this purpose.

3. RESEARCH METHOD

The method of assessing the relationships between pollutant emissions and fuel consumption values of the vehicle and the variables determining the engine operating states included the following activities:

1. Carrying out empirical vehicle tests on a chassis dynamometer in the homologation test and recording the test results.
2. Processing the test results to mitigate the contribution of high-frequency noise in the signals.
3. Determining the linear correlation coefficients between the studied variables.
4. Evaluating the analysis results of the determined linear correlation coefficients between the examined variables.

The article concerns the dynamic processes. Generally, a changing variable in the mathematical sense can be defined as a quantity defined in a normalized range. The normalized range is a linear range within which the concept of a norm is defined, which is a generalization of the concept of the length (modulus) of a vector in Euclidean space.

The dimension where the variable is described is usually:

- time or a monotonic time function (the variable is a time function or time series),
- area range (the variable is a field).

Variables can be classified based on the degree of uncertainty [17, 18] into:

- causal – determined,
- random – stochastic, statistical.

A stochastic process is a set of process implementations [12, 13]. Due to their dependence on time, they can be distinguished into [7, 8]:

- static – constant in the time domain,
- dynamic – varying in the time domain.

The variables studied in this article were considered dynamic because they were not periodic [3, 4].

Empirical tests were carried out on a passenger vehicle with a four-cylinder compression-ignition engine and a displacement of 1.5 dm^3, rated power of 96 kW, and Euro 6 AP pollutant emission class. The tests were performed using an apparatus that fulfilled the legal obligations of type-approval procedures.

The tests were undertaken under the WLTC test conditions – Class 3b, in line with the worldwide harmonized light vehicles test procedure (WLTP) [11, 25].

The following variables were recorded digitally:

- vehicle velocity,
- carbon monoxide emission intensity,
- nitrogen oxide emission intensity,
- hydrocarbon emission intensity,
- methane hydrocarbon emission intensity,
- carbon monoxide emission intensity,
- fuel mass consumption intensity.

To mitigate the proportion of high-frequency noise in the recorded digital signals with n points, we processed the test results using a digital non-recursive low-pass filter with a number of averaging points (N) [5]. For points with numbers N ÷ (n – N), the filter had the form

$$x_i = \frac{1}{2\cdot N+1}\sum_{j=i-N}^{j=i+N} z_j \tag{1}$$

where: z_i – points of the original recorded signal,
x_i – points of the filtered signal,
i = 1 ÷ n – number of the signal point.

For points numbered 1 ÷ (N – 1), the filter took the form of

$$x_i = \frac{1}{i}\sum_{i=0}^{i=N-1} z_i \tag{2}$$

For points numbered (n – N + 1) ÷ n, the filter took the form of

$$x_i = \frac{1}{n-i+1}\sum_{i=n-N+1}^{i=n} z_i \tag{3}$$

From the tests conducted, the number of signal-averaging points was selected to equal nine, which then means that N = 4.

The correlation theory was adopted to assess the interdependence of the studied variables.

This choice was determined by the fact that the conducted study, according to this theory, concerns linear correlation.

The estimator of the Pearson linear correlation coefficient of random variables x_i and y_i is

$$r_{x,y} = \frac{\sum_{i=1}^{n}(x_i - AV[x])\cdot(y_i - AV[y])}{\sqrt{\sum_{i=1}^{n}(x_i - AV[x])^2\cdot(y_i - AV[y])^2}} \tag{4}$$

where: AV – mean value operator.

Linear correlation coefficients were determined between the recorded and filtered signals using estimator (4).

4. EMPIRICAL TEST RESULTS

Figs. 1 – 8 present the filtered variable curves that were obtained from the WLTC test of the vehicle. Fig. 1 shows the vehicle speed process in the test.

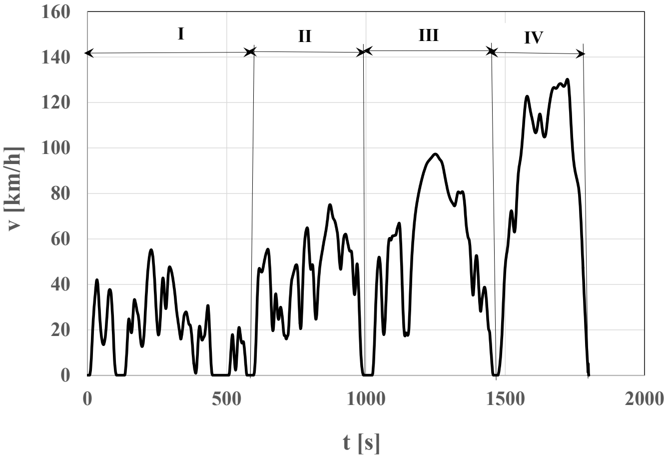


Fig. 1. Vehicle speed process in the WLTC

The test included four phases that were distinguished by the values of the driving velocity:

- I – Low,
- II – Medium,
- III – High,
- IV – Extra High.

For each phase, the duration was as follows: I – 586 s, II – 423 s, III – 458 s, and IV – 333 s. The entire WLTC test lasted 1800 s.

In each phase, the vehicle traveled the following distances: Phase I – 3.09 km, Phase II – 4.76 km, Phase III – 7.16 km, and Phase IV – 8.25 km. During the entire WLTC test, the vehicle traveled a total distance of 23.27 km.

In Phase I, the average vehicle velocity was 19.01 km/h and the maximum value was 54.64 km/h. In Phase II, the average vehicle velocity was 40.48 km/h and the maximum value was 74.49 km/h. In Phase III, the average vehicle velocity was 56.29 km/h and the maximum value was 97.23 km/h. In Phase IV, the average vehicle velocity was 89.23 km/h and the maximum value was 129.71 km/h.

The mean vehicle speed in the WLTC test as a whole was 46.53 km/h.

The coefficient of variation of vehicle speed was as follows: Phase I – 0.77, Phase II – 0.49, Phase III – 0.52, Phase IV – 0.43, and entire test – 0.77. Therefore, the strongest vehicle speed dynamic properties occurred in Phase I, the weakest occurred in Phase IV, and they were similar in phases II and III.

Figs. 2-7 present the intensity of emission of the tested exhaust components.

The highest intensity of CO emissions (both the maximum value and the average value) was found in Phase I, followed by Phase IV. This high pollutant emission intensity of CO in Phase I resulted from the significant instability of the engine operating states and low engine load; meanwhile, in Phase IV, the main factor was the significant load of the engine caused by the high vehicle speed. The least dynamic variable was found in Phase II, and the most dynamic was found in Phase I.

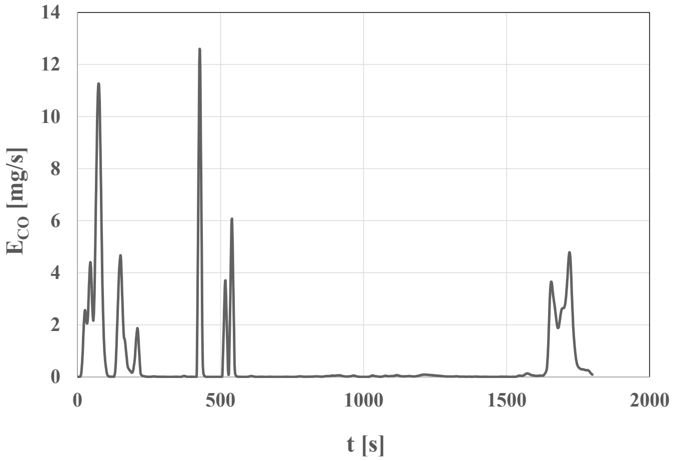


Fig. 2. Intensity of CO emissions in the WLTC test

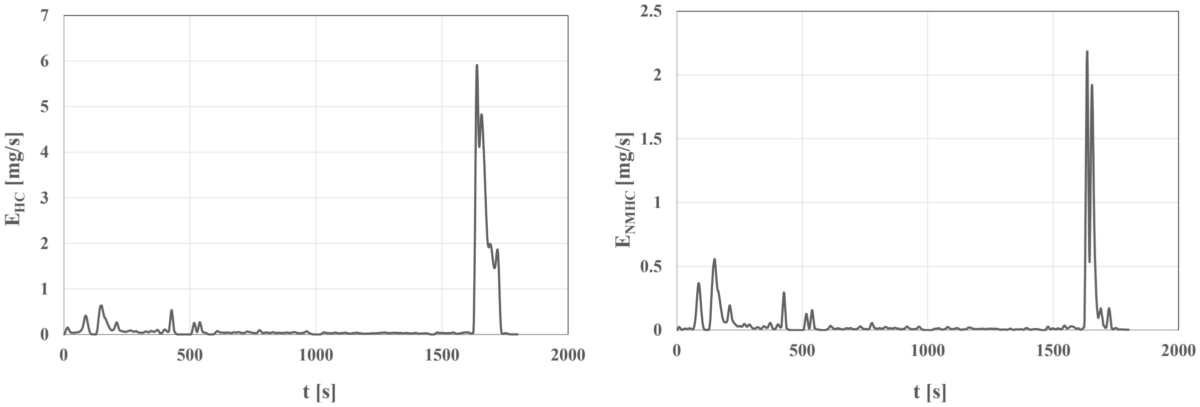


Fig. 3. Intensity of HC emissions in the WLTC test (left)
Fig. 4. Intensity of NMHC emissions in the WLTC test (right)

Regarding the intensity of hydrocarbon exhaust emissions, the highest maximum value by far was in Phase IV along with the average value. Phase IV also showed the most dynamic properties of the measured variables.

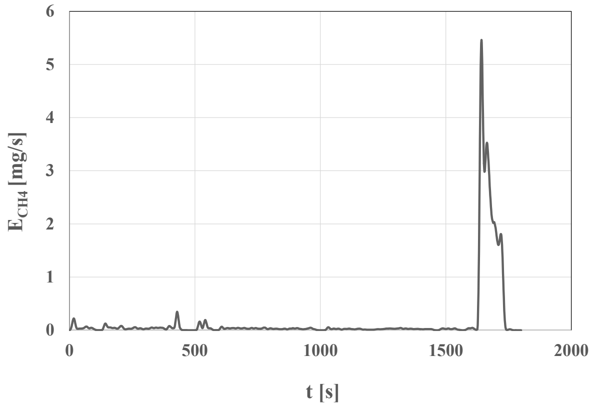
Similar to the hydrocarbon emission intensity, the properties of the emission intensity of the considered organic compounds were very similar.

The properties of the intensity of NO_x emissions differed significantly from the CO emission intensity and organic compound emission intensity. The highest exhaust emission intensity of NO_x was observed in Phase I, followed by Phase II. Similarly, the process properties were the strongest in Phase I, followed by Phase II.

In the case of carbon dioxide (CO_2) emission intensity, the value was determined by the engine load, which resulted from the vehicle velocity. The highest CO_2 emission intensity was found in Phase IV. The dynamic properties of the CO_2 emission intensity values were similar in all test phases.

Fig. 8 shows the vehicle fuel consumption curve.

The intensity of CO_2 emissions was approximately linearly correlated with the intensity of the vehicle's fuel consumption.



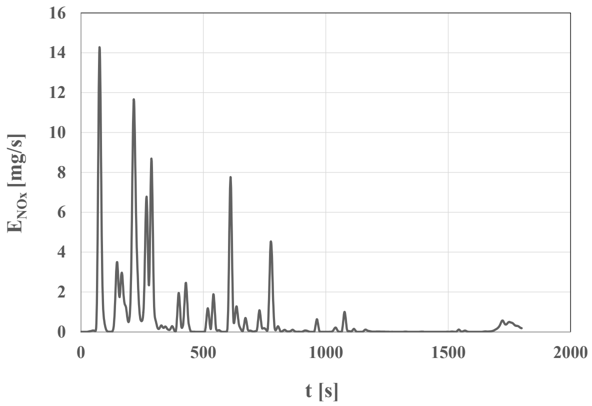
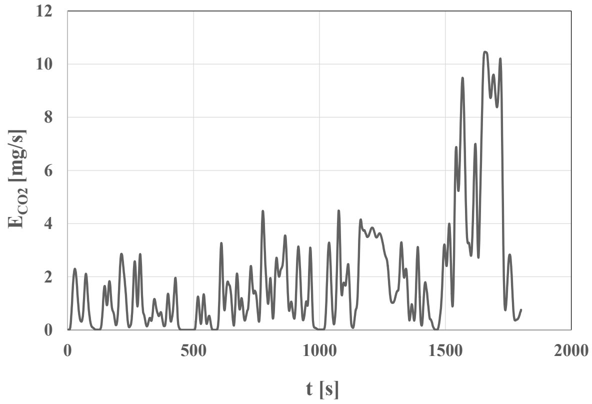


Fig. 5. Intensity of (methane) CH_4 emissions in the WLTC test (left)
Fig. 6. Intensity of NO_x emissions in the WLTC test (right)



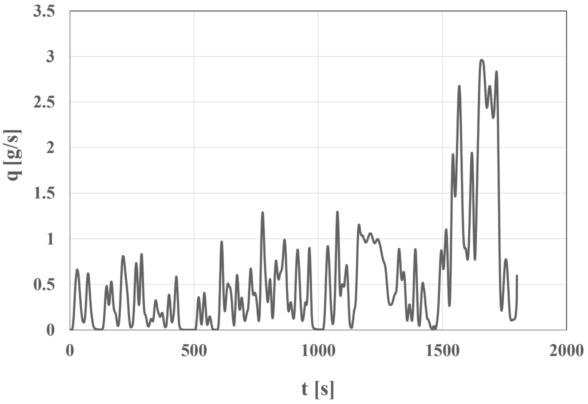
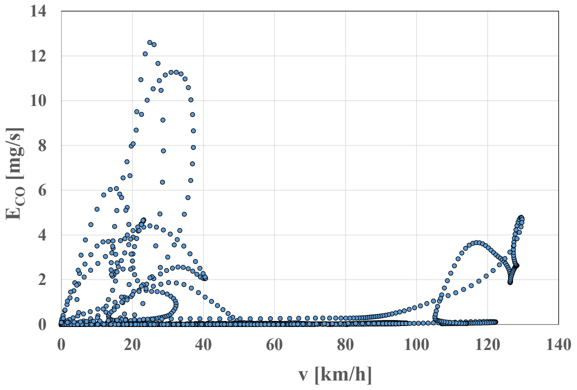


Fig. 7. Intensity of CO_2 emissions in the WLTC test (left)
Fig. 8. Fuel mass consumption in the WLTC test (right)

5. RESULTS ANALYSIS

Figs. 9–12 present examples of correlations between the studied variables.



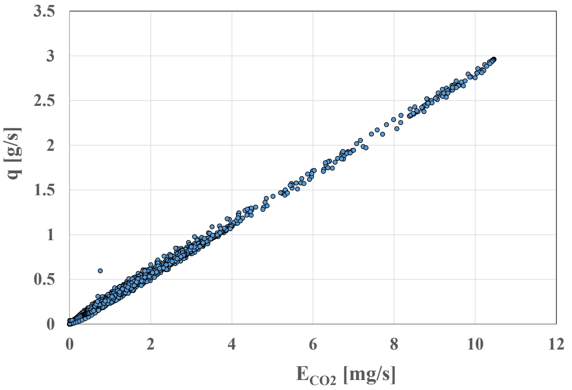
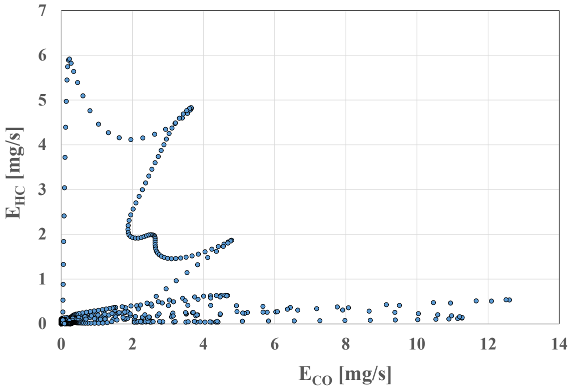


Fig. 9. Correlation between CO emission intensity and vehicle speed in the WLTC test (left)
Fig. 10. Correlation between vehicle's fuel mass consumption intensity and CO_2 emission intensity in the WLTC test (right)

The CO emission intensity and vehicle velocity were weakly correlated in the WLTC test outcomes. However, there was a very strong correlation between the vehicle's fuel mass consumption intensity and CO_2 emission intensity (Fig. 10).



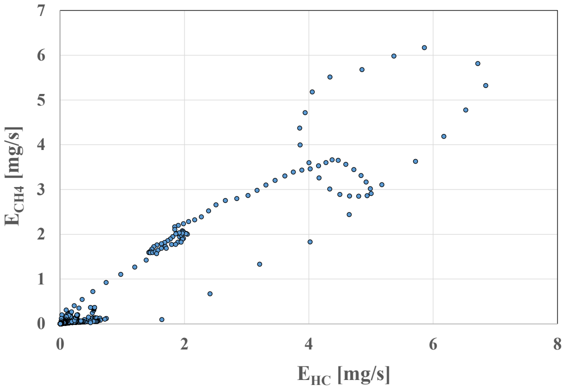


Fig. 11. Correlation between CO emission intensity and HC emission intensity in the WLTC test (left)
Fig. 12. Correlation between methane emission intensity and HC emission intensity in the WLTC test (right)

The CO emission intensity and hydrocarbon emission intensity were not significantly correlated.

The correlation between the emissions of organic compounds: HC and CH_4 was stronger than that between the emissions of other pollutants (e.g., between the emission of CO and the emission of HC (Fig. 11).

In general, the correlations among exhaust emission rates, fuel mass consumption, and vehicle speed vary. Naturally, this article presents only selected relationships for brevity. Presenting the full results of the study of correlations between the considered quantities would be possible only in a research report. However, it was possible to present the full research results in the form of a set of Pearson's linear correlation coefficients for the studied quantities.

Table 1 shows the Pearson's linear correlation coefficients of vehicle travel velocity, the pollutant emission intensities of measured exhaust components, and fuel mass consumption intensity.

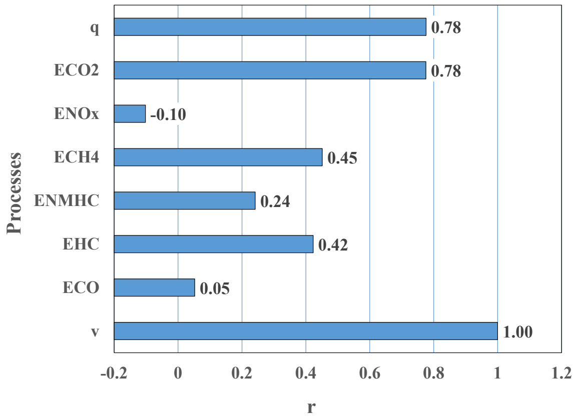
Table 1

Pearson's linear correlation coefficients of vehicle velocity, pollutant emission intensities of flue gas components, and fuel mass consumption intensity

		v	E_{CO}	E_{HC}	E_{NMHC}	E_{CH4}	E_{NOx}	E_{CO2}	q
		[km/h]	[mg/s]	[mg/s]	[mg/s]	[mg/s]	[mg/s]	[mg/s]	[g/s]
v	[km/h]	1.000	0.052	0.423	0.241	0.451	-0.102	0.776	0.776
E_{CO}	[mg/s]	0.052	1.000	0.290	0.274	0.267	0.411	0.217	0.222
E_{HC}	[mg/s]	0.423	0.290	1.000	0.840	0.973	-0.023	0.622	0.627
E_{NMHC}	[mg/s]	0.241	0.274	0.840	1.000	0.700	0.079	0.371	0.378
E_{CH4}	[mg/s]	0.451	0.267	0.973	0.700	1.000	-0.060	0.655	0.658
E_{NOx}	[mg/s]	-0.102	0.411	-0.023	0.079	-0.060	1.000	0.008	0.018
E_{CO2}	[mg/s]	0.776	0.217	0.622	0.371	0.655	0.008	1.000	0.999
q	[g/s]	0.776	0.222	0.627	0.378	0.658	0.018	0.999	1.000

Figs. 13-20 show the Pearson's linear correlation coefficients between the studied variables.

Fig. 13 presents the Pearson's linear correlation coefficient between the study variables and vehicle travel velocity.



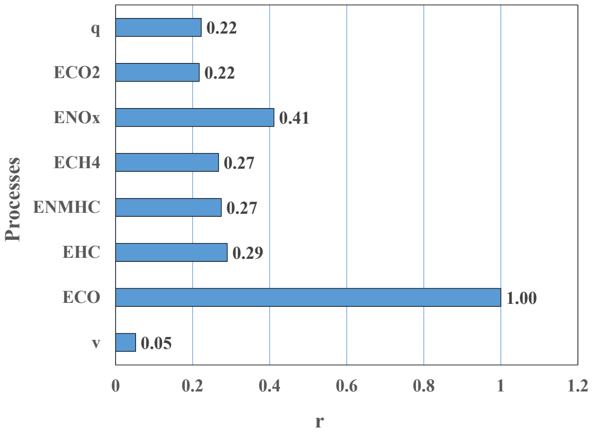
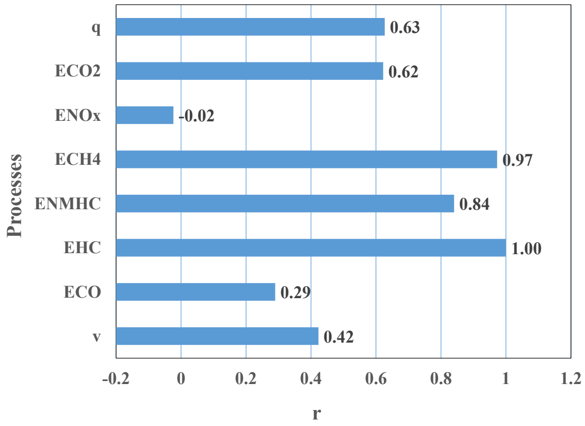


Fig. 13. Pearson's linear correlation coefficient between the vehicle velocity and the following variables: vehicle velocity, intensity of CO emissions, intensity of HC emissions, intensity of nonmethane hydrocarbon (NMHC) emissions, intensity of CH_4 emissions, intensity of NO_X emissions, intensity of CO_2 emissions, and intensity of vehicle fuel use in the test WLTC (left)

Fig. 14. Pearson's linear correlation coefficient between the intensity of CO emissions and the following variables: vehicle velocity, intensity of CO emissions, intensity of HC emissions, intensity of NMHC emissions, intensity of CH_4 emissions, intensity of NO_X emissions, intensity of CO_2 emissions, and intensity of vehicle fuel use in the test WLTC (right)

Among the variables, CO_2 emissions and fuel use of the vehicle showed the strongest correlation with vehicle speed. The variable least correlated with the vehicle speed was the nitrogen oxide emission intensity, for which the correlation coefficient was negative.

The correlation coefficient of pollutant emission intensities with the CO emission intensity ranged from 0.22–0.41. The highest correlation was found with the intensity of nitrogen oxide emission. The correlation coefficient of CO emission intensity with the vehicle velocity was the smallest.



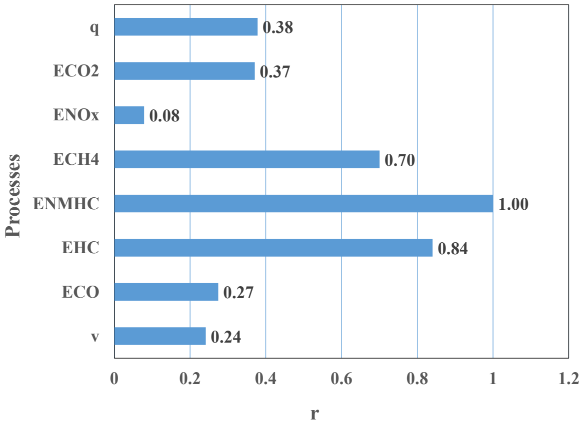
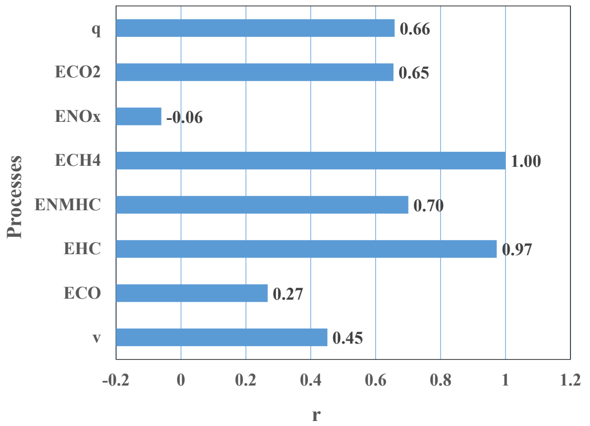


Fig. 15. Pearson's linear correlation coefficient between the intensity of HC emissions and the following variables: vehicle velocity, intensity of CO emissions, intensity of HC emissions, intensity of NMHC emissions, intensity of CH_4 emissions, intensity of NO_X emissions, intensity of CO_2 emissions, and intensity of vehicle fuel use in the test WLTC (left)

Fig. 16. Pearson's linear correlation coefficient between the intensity of NMHC emissions and the following variables: vehicle velocity, intensity of CO emissions, intensity of HC emissions, intensity of NMHC emissions, intensity of CH_4 emissions, intensity of NO_X emissions, intensity of CO_2 emissions, and intensity of vehicle fuel use in the test WLTC (right)

The correlation coefficient of hydrocarbon emission intensity with CH_4 emission intensity was the highest (0.97). The lowest, slightly negative, correlation coefficient was noticed with the intensity of NO_X emissions.

The highest linear correlation coefficients between the intensity of non-methane hydrocarbon emissions and the emission intensity of other substances were observed for HC and CH_4. The smallest was found for NO_x.



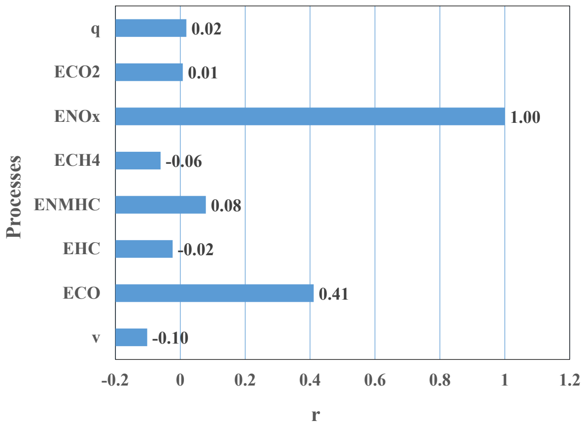


Fig. 17. Pearson's linear correlation coefficient between the intensity of CH_4 emissions and the following variables: vehicle velocity, intensity of CO emissions, intensity of HC emissions, intensity of NMHC emissions, intensity of CH_4 emissions, intensity of NO_X emissions, intensity of CO_2 emissions, and intensity of vehicle fuel use in the test WLTC (left)

Fig. 18. Pearson's linear correlation coefficient between the intensity of NO_x emissions and the following variables: vehicle velocity, intensity of CO emissions, intensity of HC emissions, intensity of NMHC emissions, intensity of CH_4 emissions, intensity of NO_X emissions, intensity of CO_2 emissions, and intensity of vehicle fuel use in the test WLTC (right)

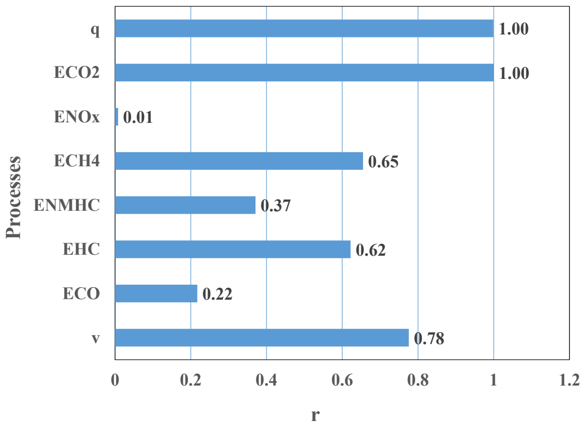
The methane and hydrocarbon emission intensities had the highest correlation coefficient, followed by methane and non-methane hydrocarbon emission intensities. The smallest, slightly negative, correlation coefficient was found between methane and nitrogen oxide emission intensities.

The highest correlation coefficient was observed between the intensities of NO_X emissions and CO emissions. For the emission intensity of other substances and the fuel use of the vehicle and the vehicle speed, the correlation was weak. For velocity, methane, and non-methane hydrocarbons, the correlation was slightly negative.

The intensity of CO_2 emissions was practically linearly dependent on the fuel use intensity. The CO_2 emission intensity was closely related to vehicle speed and organic compound emission intensity. The weakest correlation was found between the intensity of CO_2 emissions and NO_X emissions.

As expected, the correlation of the vehicle fuel mass consumption intensity with other values was similar to that of CO_2 emission intensity.

Pearson's linear correlation coefficients between the studied quantities varied greatly, which corresponds to the correlation relationships presented as an example. As expected, the linear correlation between the carbon dioxide emissions rate and the fuel mass consumption rate was the strongest; the Pearson linear correlation coefficient was 1.00 (accurate to two decimal places). The smallest Pearson's linear correlation coefficient was found between the emission rate of organic compounds and the emission rate of nitrogen oxides; the coefficient value was negative.



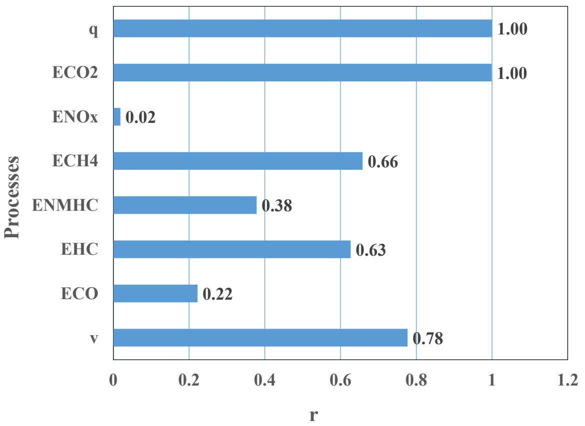


Fig. 19. Pearson's linear correlation coefficient between the intensity of CO_2 emissions and the following variables: vehicle velocity, intensity of CO emissions, intensity of HC emissions, intensity of NMHC emissions, intensity of CH_4 emissions, intensity of NO_X emissions, intensity of CO_2 emissions, and intensity of vehicle fuel use in the test WLTC (left)

Fig. 20. Pearson's linear correlation coefficient between the vehicle fuel use intensity and the following variables: vehicle velocity, intensity of CO emissions, intensity of HC emissions, intensity of NMHC emissions, intensity of CH_4 emissions, intensity of NO_X emissions, intensity of CO_2 emissions, and intensity of vehicle fuel use in the test WLTC (right)

6. CONCLUSIONS

Based on the conducted tests, it can be concluded that vehicle speed, the emissions of pollutants, fuel consumption in the WLTC test, and the properties of the variables and the relationships between them varied.

In addition, the following conclusions have been drawn:

1. The intensity of CO_2 emissions was practically linearly dependent on the fuel mass consumption of the vehicle. Therefore, the properties of both variables were practically identical.
2. The pollutant emission intensities of organic processes (HC, non-methane hydrocarbons, and methane) were similar.
3. The maximum value and the average value of the emission intensities varied for different substances:
   - For CO, the emission intensity was the highest in Phase I of the test, followed by Phase IV.
   - For the organic compound emission intensities, the highest maximum value and average value were observed in Phase IV.
   - The highest intensity of nitrogen oxide emissions was recorded in Phase I, followed by Phase II.
   - The intensity of CO_2 emissions was determined by the engine load resulting from the vehicle velocity. The highest CO_2 emission intensity was found in Phase IV.
4. The dynamic properties of pollutant emission intensities varied for different substances:
   - For CO, the least dynamic intensity of emission was seen in Phase II, and the most dynamic was seen in Phase I.
   - The most dynamic organic compound emission intensities were present in Phase IV.
   - The intensity of NO_X emissions was the highest in Phase I, followed by Phase II.
   - The dynamic properties of CO_2 emission intensity were similar in all test phases.
5. The variables most highly correlated with the vehicle speed were CO_2 emission intensity (correlation coefficient of 0.78) and the intensity of fuel use of the vehicle (correlation coefficient of 0.78). The NO_X emission intensity was the least correlated, with a correlation coefficient of -0.10. The emission intensity of organic compounds was much more correlated (correlation

coefficients between 0.24 and 0.45). The correlation with the CO emissions intensity was also weak (correlation coefficient of 0.05).

6. The correlation coefficient of pollutant emission intensities with the CO emission intensity were all in the range of 0.22–0.41; the highest was for the intensity of NO_X emissions. The correlation coefficient of CO emission intensity with the vehicle velocity was the least significant.
7. The correlation coefficients between the intensity of organic compound emissions and the emission intensity of other organic compounds were among the highest, while the smallest, slightly negative, correlation coefficient occurred for their relationship with the emission intensity of NO_x.
8. The correlation coefficient between NO_X emission intensity and CO emission intensity was the highest. For the emission intensities of other substances, the correlation was weak.
9. The CO_2 emission intensity was strongly correlated with the vehicle velocity and with the organic compound emission intensities. The weakest correlation was found between the intensity of CO_2 emissions and the intensity of NO_X emissions.

This research confirms that the factors determining the emissions of organic compounds and NO_x were the most varied and unrelated to each other, followed by the factors involved in CO and NO_x emissions. This highlights the need to take coordinated actions to reduce emissions of CO and organic compounds on the one hand, and NO_x on the other, with separate strategies for each.

The study of pollutant emissions, not just of the dimensionless characteristics of pollutants (primarily the specific distance emission of pollutants and the specific distance number of particulate matter in tests on a chassis dynamometer, and in engine tests – the specific emission of pollutants and the specific number of particulate matter), was also advisable for the intensity of particulate emissions and the particle number emission intensity.

It would be worth extending this research to other types of driving tests, primarily those done in real traffic conditions (e.g., in the real driving emissions test) and in real random traffic conditions. In such a case, it would be advisable to develop the measurement results in a probabilistic manner.

References

1. Adamiak, B. & et al. *An analysis of emissions at low ambient temperature from diesel passenger cars using the WLTP test procedure*. SAE Powertrains, Fuels & Lubricants. 2020. DOI: 10.4271/2020-01-2186.
2. Andrych-Zalewska, M. Investigation of processes in the WLTC test of a passenger car with a diesel engine. *Combustion Engines*. 2023. Vol. 62(3). DOI: 10.19206/CE-168328.
3. Bebkiewicz, K. & et al. Assessment of environmental risks of particulate matter emissions from road transport based on the emission inventory. *Applied Sciences*. 2021. Vol. 11(13). No. 6123. DOI: 10.3390/app11136123.
4. Bebkiewicz, K. & et al. Influence of the thermal state of vehicle combustion engines on the results of the national inventory of pollutant emissions. *Applied Sciences*. 2021. Vol. 11(19). No. 9084. DOI: 10.3390/app11199084.
5. Bendat, J.S. & Palo, P.A. *Practical techniques for nonlinear system analysis and identification. sound and vibration.* Bay Village. OH, June 1990.
6. Bielaczyc, P. & Szczotka, A. & Woodburn, J. Carbon dioxide emissions and fuel consumption from passenger cars tested over the NEDC and WLTC – an overview and experimental results from market-representative vehicles. In: *2nd International Conference on the Sustainable Energy and Environmental Development*. 2019. *IOP Conf. Series: Earth and Environmental Science*. 2019. Vol. 214. No. 012136. DOI: 10.1088/1755-1315/214/1/012136.
7. Chłopek, Z. & et al. Assessment of the impact of dynamic states of an internal combustion engine on its operational properties. *Eksploatacja i Niezawodnosc – Maintenance and Reliability*. 2015. Vol. 17(1). P. 35-41.
8. Chłopek, Z. Some remarks on engine testing in dynamic states. *Silniki Spalinowe – Combustion Engines*. 2010. Vol. 4(143). P. 60-72.

9. *Euro 7 New proposal for vehicle emissions type approval in Europe.* Commission European. Presentation at GRPE 87. 12/01/2023.
10. Grieshop, A.P. & et al. Modeling air pollutant emissions from Indian auto-rickshaws: Model development and implications for fleet emission rate estimates. *Atmospheric Environment*. Vol. April 2012. Vol. 50. P. 148-156. DOI: 10.1016/j.atmosenv.2011.12.046.
11. *ISO 8178*. Available at: https://dieselnet.com/standards/cycles/iso8178.php.
12. Kneba, Z. & et. al: Numerical methodology for evaluation the combustion and emissions characteristics on WLTP in the light duty dual-fuel diesel vehicle. *Combustion Engines*. 2022. Vol. 189(2). P. 94-102. DOI:10.19206/CE-143334.
13. Koszałka, G. & Szczotka, A. & Suchecki, A. Comparison of fuel consumption and exhaust emissions in WLTP and NEDC procedures. *Combustion Engines*. 2019. Vol. 179(4). P. 186-191. DOI: 10.19206/CE-2019-431.
14. Lozhkina, O.V. & Lozhkin, V.N. Estimation of road transport related air pollution in Saint Petersburg using European and Russian calculation models. *Transportation Research Part D: Transport and Environment*. May 2015. Vol. 36. P. 178-189. DOI:10.1016/j.trd.2015.02.013.
15. Marmur, A. & Mamane, Y. Comparison and evaluation of several mobile-source and line-source models in Israel. *Transportation Research Part D: Transport and Environment*. July, 2003. Vol. 8. No. 4. P. 249-265. DOI: 10.1016/S1361-9209(03)00002-6.
16. Merkisz, J. & et al. European Union Emission Standard Euro V and Euro VI Technology (New Trends in Emission Control in the European Union; published in Chinese). *Chemical Industry Press*. 2016. Vol. 1. ISBN 978-7-122-25424-5. Beijing 2016, China.
17. Papoulis, A. *Probability, random variables, and stochastic processes*. McGraw-Hill Kogakusha, Tokyo 1965. 9th edition. ISBN: 0-07-119981-0.
18. Parzen, E. On estimation of a probability density function and mode. *Annals of mathematical statistics*. 1962. Vol. 33(3). P. 1065-1076. DOI: 10.1214/aoms/1177704472. JSTOR 2237880.
19. Pathak, S.K. & et al. Real world vehicle emissions: Their correlation with driving parameters. *Transportation Research Part D: Transport and Environment*. May 2016. Vol. 44. P. 157-176. DOI: 10.1016/j.trd.2016.02.001.
20. Pelkmans, L. & Debal, P. Comparison of on-road emissions with emissions measured on chassis dynamometer test cycles. *Transportation Research Part D: Transport and Environment*. July, 2006. Vol. 11. No. 4. P. 233-241. DOI: 10.1016/j.trd.2006.04.001.
21. Sileghem, L. & et al. Analysis of vehicle emission measurements on the new WLTC, the NEDC and the CADC. *Transportation Research Part D: Transport and Environment*. October 2014. Vol. 32. P. 70-85. DOI: 10.1016/j.trd.2014.07.008.
22. Szczepański, K. & Chłopek, Z. & Bebkiewicz, K. & Sar, H. Assessment of pollutant emission in Poland from various categories of transport. *Environmental Protection and Natural Resources*. 2022. Vol. 33(3). P. 1-9. DOI: 10.2478/oszn-2022-0008.
23. *Decarbonizing Combustion Vehicles: A Portfolio Approach to GHG Reductions*. Transportation Energy Institute. July 2023.
24. Valverde, V. & et al. Measurement of gaseous exhaust emissions of light-duty vehicles in preparation for Euro 7: a comparison of portable and laboratory instrumentation. *Energies.* 2023. Vol. 16. No. 2561. DOI: 10.3390/en16062561.
25. Worldwide emission standards. Passenger cars and light duty vehicles. Delphi. *Innovation for the real world*. 2020/2021.

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