ANALYSIS OF THE CORRELATION BETWEEN POLLUTANT EMISSIONS AND OPERATION STATES OF A COMPRESSION IGNITION ENGINE

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Summary

Results of research on the correlation between pollutant emission rates and the engine operation states that determine the pollutant emissions have been presented. The tests were carried out on a compression ignition (CI) engine Cummins 6C8.3 in the NRTC (Non-Road Transient Cycle) test conditions. At the tests, the speed, torque, and effective power of the engine under test were chosen as the main characteristics of the engine operation states that determine pollutant emissions. Correlation dependences of pollutant emission rates on engine operation states have been shown. Mathematic models of pollutant emission rates have been defined as second-degree polynomial functions of engine speed and torque. To analyse the correlation between the sets under investigation, the Pearson's linear correlation, Spearman's rank correlation, Kruskal's gamma correlation, and Kendall's tau correlation theories were used. It has been found statistically justifiable to treat the examined pairs of sets of physical quantities as strongly correlated. Moreover, the quantities defining the engine operation state have been found to have a similar impact on the carbon monoxide and hydrocarbons emission rates, while their impact on the nitrogen oxides emission rates has been found to be quite different. For the carbon monoxide and hydrocarbons emission rates, the engine speed has been found to be the factor of the strongest impact; as regards the nitrogen oxides emission rates, they were most strongly affected by the torque and effective power of the engine.

Keywords: internal combustion engines, dynamic tests, pollutant emissions, correlation analysis

1. Introduction

The operation of an internal combustion (IC) engine is described by the engine operation conditions and its operation state [5, 8].

The engine operation state is described by the quantities that characterize its operation in the conditions of typical engine use, i.e. the quantities that define the following [8, 9]:

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- engine energy properties related to engine's capacity to do work, such as effective power, torque, speed, brake mean effective pressure (BMEP), etc.;
- controllable processes that take place in the engine, especially the engine steering settings applied by the operator;
- fuel economy properties, such as effective efficiency, specific brake fuel consumption, etc.;
- engine properties that describe the processes accompanying the engine operation, including the ecological characteristics related to the pollutant emissions and noise emission, e.g. noise level or acoustic pressure.

The conditions of engine operations are determined by the following [8, 9]:

- ambient conditions having an impact on the resistance that must be overcome by a vehicle or machine when operating, including weather conditions;
- engine steering settings applied by the operator;
- resistance torque, depending on the nature of the work done by a vehicle or machine.

Among the quantities describing the IC engine operation state, we can mark out those determining its current performance characteristics. They include the quantities characterizing the intensity of the work being done by the engine, described by the effective power, and the thermal state of the engine, defined by the temperatures of engine components and systems [8, 9].

The quantities that characterize the intensity of work done by an engine are chiefly described by the engine torque, which defines the engine load, and crankshaft speed [8, 9]. Another measure of the engine load may also be the parameters of the engine steering settings applied by the operator [8, 9].

A function having numerical values, where the argument is either time or a monotonic function of time, is referred to as a "process" [24]. Consistently with the names adopted for the quantities that describe the operation of an IC engine, the processes of engine operation, engine operation conditions, and engine operation state may be discerned [5]. If such a process varies with time, it is referred to as "dynamic" [8]. Hence, the engine operation, engine operation conditions, and engine operation state may be considered as "dynamic processes". A similar approach is adopted to classify static processes in the description of engine operation. In consideration of the nomenclature traditionally used, and for the sake of reasonable terminological simplifications, it has become customary to use shortened forms "dynamic conditions of engine operation" and "dynamic states of engine operation" (or just "dynamic states") instead of "dynamic processes of engine operation conditions" and "dynamic processes of engine operation states", respectively. The nomenclature related to the static conditions and states is simplified similarly.

The three quantities used to describe the engine load, i.e. engine steering settings applied by the operator, torque, and speed, are interdependent. In static conditions, this is a functional dependence with numerical values; in dynamic conditions, however, it takes the form of an operational relation [8, 9].

In static conditions, the dependence of performance characteristics of IC engines on the states that determine the characteristics has the form of a functional relation, but in dynamic conditions, the performance characteristics of IC engines depend on the time histories of the said states [8, 9]. In this connection, the internal combustion engines in dynamic states have in general no immanent properties that would not depend on the current states of engine operation. Therefore, definite constraints in the form of comparable and repeatable conditions are imposed on the system under investigation to describe the performance characteristics of IC engines in dynamic conditions [8, 9]. This makes it possible to obtain averaged characteristics, e.g. specific distance pollutant emissions in vehicle driving tests, where a specific time history of vehicle speed determines the engine speed and torque [30].

The objective of this study was to examine the dependences of ecological properties of a compression ignition (CI) engine, i.e. pollutant emission rates in this case, on the engine operation states determining these properties in the NRTC (Non-Road Transient Cycle) dynamic test [30]. The tests were carried out for the engine having been heated to a stable temperature of its normal operation; therefore, the engine speed, torque, and effective power could be adopted as the quantities that determine the ecological properties of the engine (for engine steering characteristics being constant in the test conditions). It was decided to examine the said dependences with the use of correlation theories, namely the Pearson's linear correlation theory [25] as well as the non-parametric Spearman's rank correlation [28], Kruskal's gamma correlation [22], and Kendall's tau correlation [20] theories. In this study, the author intentionally decided not to limit himself to the Pearson's theory, usually employed by most researchers, and there were two reasons for this fact. Firstly, the Pearson's theory is exclusively applicable to linear dependencies, while the other theories make it possible to analyse nonlinear dependencies as well. Secondly, the correlation estimation based on the Pearson's theory is very susceptible to the so-called "excess of outliers" [28]. The Spearman's idea of "ranking", i.e. substitution of "ranks", defined as the numbers of positions of successive observations in a sample put in order according to the value of one of the variables, for the original variable values, makes it possible to achieve far less susceptibility of the correlation estimation to outliers [28]. Similarly, other non-parametric theories are less susceptible to outliers as against the Pearson's correlation [20, 22, 28].

In the literature, examples can chiefly be met that describe the application of the Pearson's linear correlation theory to the investigations of the processes that take place in IC engines [2, 3, 6, 7, 11–19, 21, 23, 26, 29]; there are only quite few publications where the analysis is extended to include non-parametric correlation theories [2, 3, 6, 7, 11, 14, 19, 29]. In significant part, the publications concern correlation relationships between the properties of IC engines and the quantities that characterize the processes taking place in the engines or e.g. fuel properties. In [12], correlation relationships between specific distance emission limits specified in European regulations have been dealt with and the impact of the engineering solutions adopted on the ecological properties of IC engines, related to pollutant emissions, has been analysed. In the work presented in [10], the influence of thermal efficiency of an IC engine on nitrogen oxides emission was investigated for the fuels that contain esters of vegetable oils. Publication [21] describes investigations on the impact of combustion process parameters on the rate of formation of nitrogen oxides in engine cylinders. The subject of publication [17] was correlation models representing the relationships between the emission of particulate matter and the quantities characterizing the exhaust smoke density. Results of determining the relationships between pollutant emissions and exhaust gas recirculation coefficient have also been presented. The correlation relationship between specifications of fuels with biocomponent additives and parameters of the combustion process in a compression ignition (CI) engine was examined in the work reported in [15]; in that work, the impact of fuel specifications on specific brake fuel consumption and specific brake emissions was investigated as well. A correlation analysis of specific brake emissions from a CI engine subjected to an eight-phase static test [30] has been presented in [23]. The engine was powered with 12 fuel types. A correlation analysis of the specifications of fuels for CI engines has been carried out in the work described in [18], within which the susceptibility of pollutant emissions to fuel specifications was investigated in different areas of static engine operation states. Publication [16] presents an analysis of the properties of two CI engines designed to drive a generating set and a mower. The engines were powered with six fuel types obtained by recycling used vegetable oils. That work included a correlation analysis of the pollutant emission indicator. The work presented in [29] was dedicated to investigation on the correlation relationship between the specific distance emission of ammonia and other pollutant emissions from a CI engine provided with a system for selective catalytic reduction of nitrogen oxides with ammonia. The engine was tested in a motor vehicle on a chassis dynamometer in accordance with the NEDC test procedure. Interesting research results, i.e. results of an analysis of the emissions of fine particulate matter PM10 and nanoparticles (with aerodynamic particle diameters smaller than 100 nm) from a CI engine of a city bus, have been presented in publication [19]. The tests were carried out in the conditions of actual bus operation. In that report, results of investigation of the correlation dependence of the particulate matter emissions on *inter alia* engine operation states have been published. Report [11] comprises results of an analysis of relationships observed at different vehicle driving tests for specific distance emissions from IC engines of light trucks. Correlation between results of determining specific distance emissions on test beds and in actual vehicle operation has been estimated in paper [14]. Interesting research results, concerning correlation relationships for pollutant emissions from medium-speed marine IC engines, have been presented in [26]. Results of correlation investigations of the properties of a marine IC engine in static operation conditions and in dynamic states have been presented in publications [2] and [4], respectively.

Results of correlation investigations of pollutant emissions from a spark ignition engine and a compression ignition engine have been given in articles [7] and [6], respectively. Publication [4] deals with research on relationships between the rates of pollutant emissions from a compression ignition engine and the engine operation states determining the pollutant emissions, carried out with employing the function of intercorrelation between the processes under investigation.

The available literature publications dealing with results of correlation investigations dedicated to IC engine properties and to the engine operation states that determine the properties, covering both the dynamic and static conditions of engine operation, are rather few. This was the reason why this subject area was undertaken in this paper, with considering the correlation investigations on the dependence of IC engine properties on dynamic engine operation states as a way to acquire knowledge of the properties of such engines operating in dynamic conditions.

2. Research results

The specimen used for experimental tests was a six-cylinder compression ignition engine Cummins 6C8.3 of 8.3 dm3 capacity. The experiments were carried out within the project reported in [1]. The engine was tested on a test stand, whose test equipment included:

- electric dynamometer AFA-E 460/4,4-9 EU manufactured by AVL;
- digital tachometer and torque meter T10F manufactured by HBM;
- system of exhaust-gas analysers CEB II manufactured by AVL;
- particulate matter emission measuring system, including a partial-flow dilution tunnel Smart Sampler SPC 472 manufactured by AVL and a microbalance MT5 manufactured by Mettler Toledo;
- fuel consumption measuring system model 735 with a fuel temperature stabilization system, manufactured by AVL;
- air consumption measuring system Sensyflow P.

Within this work, the processes of pollutant emission rates, speed, torque, and effective power of the engine were subjected to measurements. The measurement signals were synchronized with taking into account the exhaust gas tap-off location in the engine exhaust system (the delays in individual signals, related to the exhaust gas analysis, were taken into account). The measurement signals were processed to eliminate gross errors and to reduce the high-frequency interference contribution. The measurement sampling frequency was 10 Hz. The gross errors were identified by continuously analysing the variance of measurement results. To reduce the contribution of high-frequency noise to the signals, a Golay-Savitzky low-pass filter [27] was used, with both-side approximation from 5 data points on each side to a polynomial of degree 2 being applied.

The tests were carried out in accordance with the NRTC dynamic test procedure designed for IC engines of non-road machines, with the engine having been heated to a stable temperature of its typical operation. Figs. 1 and 2 show time histories of the engine speed and torque, respectively, recorded during the NRTC test.

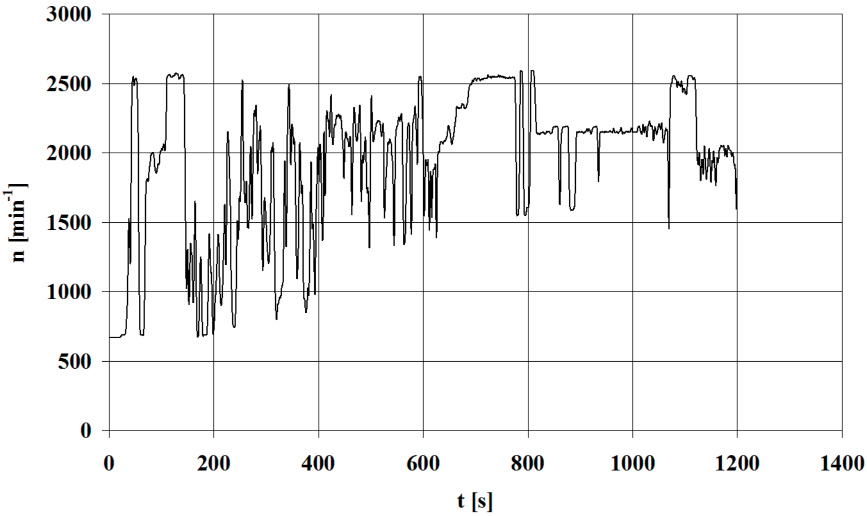

Fig. 1. Engine speed (n) vs. time (t) curve, recorded during the NRTC test

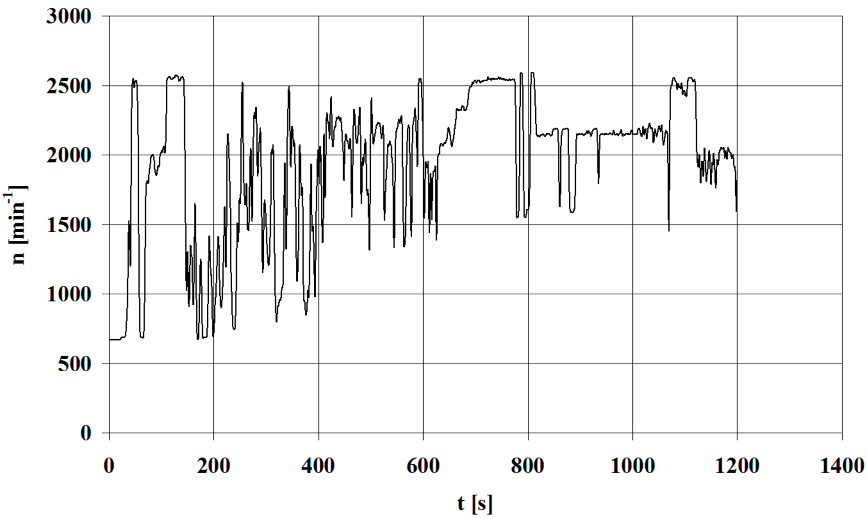

Fig. 2. Engine torque (M_e) vs. time (t) curve, recorded during the NRTC test

The graph shown in Fig. 3 represents the set of the IC engine operation states during the NRTC test against the background of the full-load torque vs. speed curve. A point of coordinates (average speed, average torque) determined for the test has been marked on the graph as well.

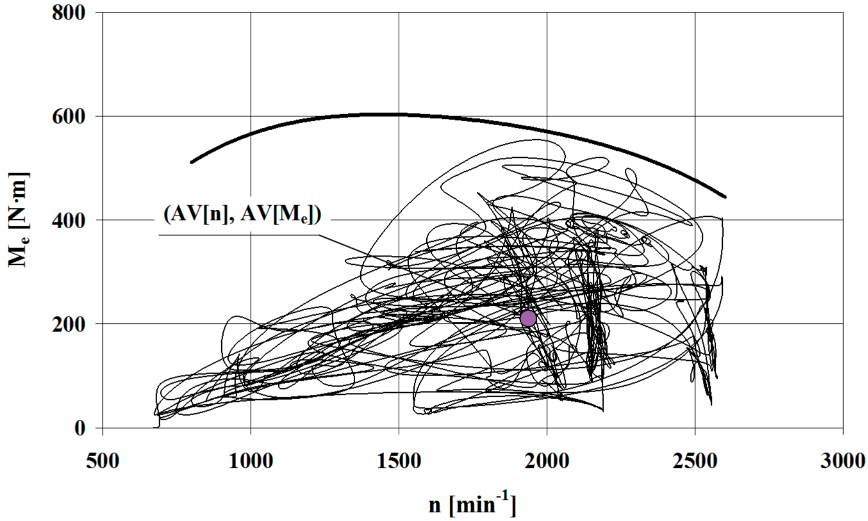

Fig. 3. The set of the IC engine operation states during the NRTC test against the background of the full-load torque vs. speed curve: n – engine speed; AV[n] – average value of the engine speed; AV[M_e] – average value of the engine torque

The correlation relationships between pollutant emission rates and engine speed, torque, and effective power have been shown in Figs. 4–6, Figs. 7–9, and Figs. 10–12, respectively.

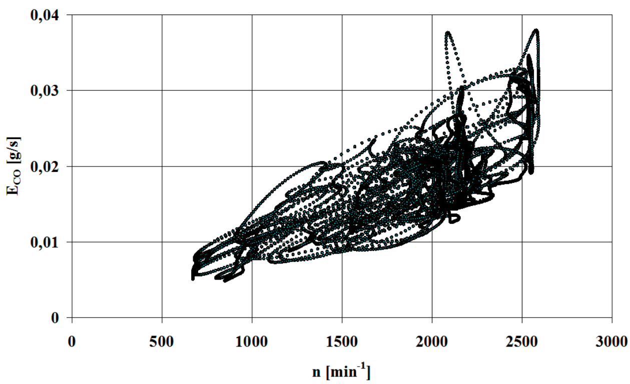

Fig. 4. Correlation relationship between carbon monoxide emission rate (E_{CO}) and engine speed (n) in the NRTC test

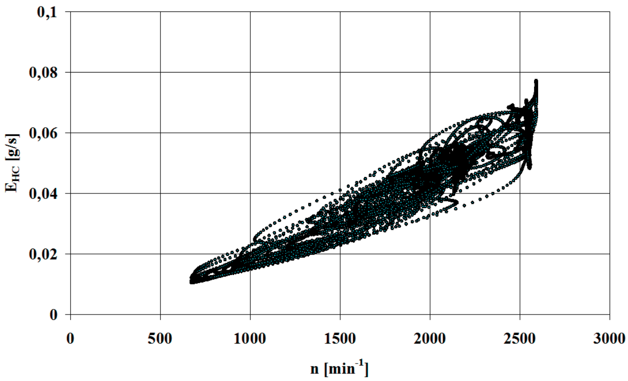

Fig. 5. Correlation relationship between hydrocarbons emission rate (E_{HC}) and engine speed (n) in the NRTC test

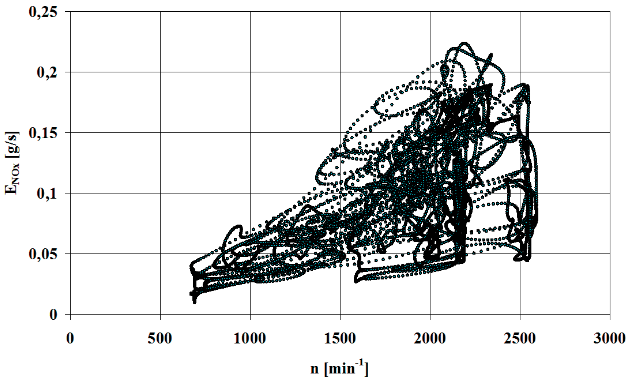

Fig. 6. Correlation relationship between nitrogen oxides emission rate (E_{NOx}) and engine speed (n) in the NRTC test

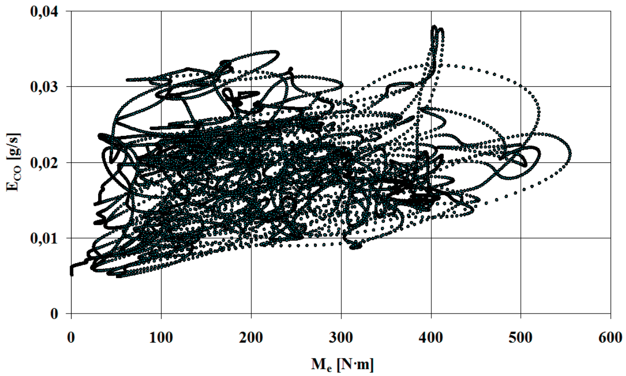

Fig. 7. Correlation relationship between carbon monoxide emission rate (E_{CO}) and engine torque (M_e) in the NRTC test

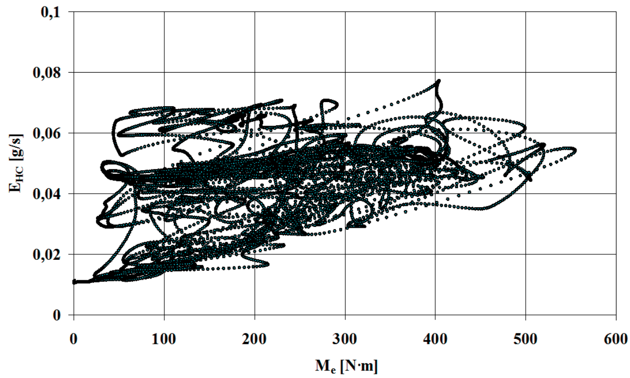

Fig. 8. Correlation relationship between hydrocarbons emission rate (E_{HC}) and engine torque (M_e) in the NRTC test

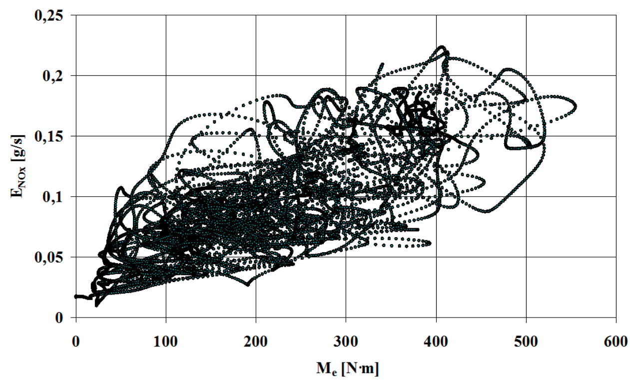

Fig. 9. Correlation relationship between nitrogen oxides emission rate (E_{NOx}) and engine torque (M_e) in the NRTC test

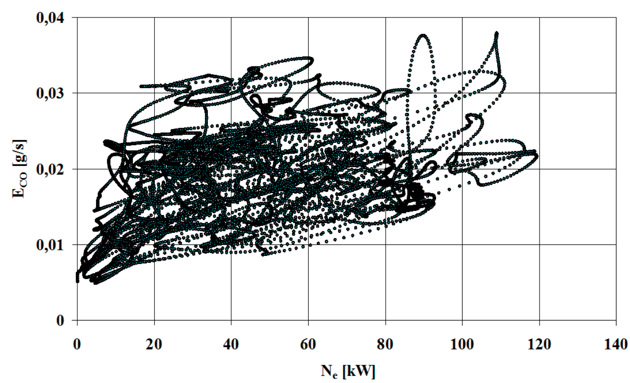

Fig. 10. Correlation relationship between carbon monoxide emission rate (E_{CO}) and effective power (N_e) of the engine in the NRTC test

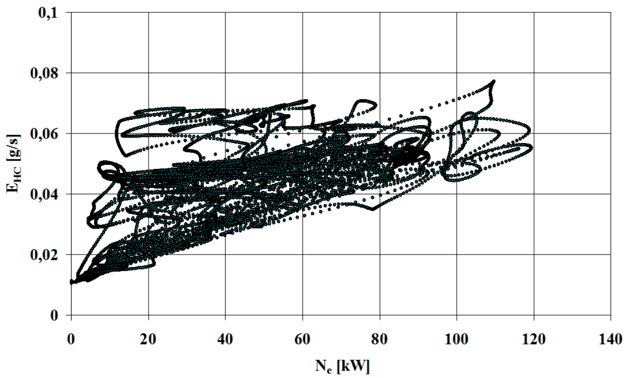

Fig. 11. Correlation relationship between hydrocarbons emission rate (E_{HC}) and effective power (N_e) of the engine in the NRTC test

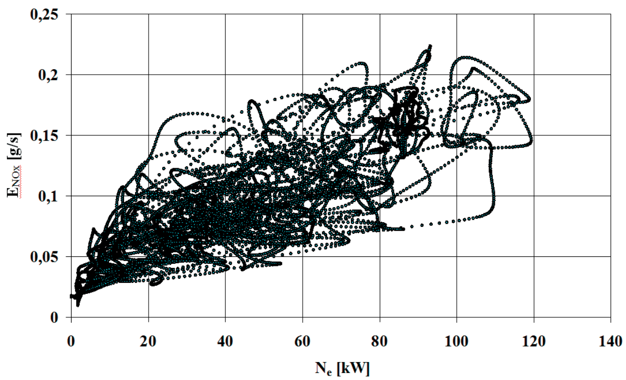

Fig. 12. Correlation relationship between nitrogen oxides emission rate (E_{NOx}) and effective power (N_e) of the engine in the NRTC test

To estimate the trends in the dependences of pollutant emission rates on engine speed and torque, these dependences on the variables chosen as arguments were approximated by second-degree polynomial functions. In consequence, mathematical models of pollutant emission rates were obtained as shown below.

– For carbon monoxide:

$$E_{CO} = 4{,}8 \cdot 10^{-3} - 7{,}5527 \cdot 10^{-7} \cdot n + 3{,}5754 \cdot 10^{-5} \cdot M_e + 4{,}1752 \cdot 10^{-9} \cdot n^2 - 2{,}1174 \cdot 10^{-8} \cdot n \cdot M_e + 6{,}0097 \cdot 10^{-9} \cdot M_e^2 \qquad (1)$$

– For hydrocarbons:

$$E_{HC} = 2{,}7 \cdot 10^{-3} + 7{,}7325 \cdot 10^{-6} \cdot n + 1{,}5361 \cdot 10^{-5} \cdot M_e + 6{,}0363 \cdot 10^{-9} \cdot n^2 - 1{,}0246 \cdot 10^{-8} \cdot n \cdot M_e + 4{,}9663 \cdot 10^{-8} \cdot M_e^2 \qquad (2)$$

– For nitrogen oxides:

$$E_{NOx} = -1{,}68 \cdot 10^{-2} + 7{,}1256 \cdot 10^{-5} \cdot n - 1 \cdot 10^{-4} \cdot M_e - 1{,}9456 \cdot 10^{-8} \cdot n^2 + 1{,}6266 \cdot 10^{-7} \cdot n \cdot M_e + 5{,}7869 \cdot 10^{-8} \cdot M_e^2 \qquad (3)$$

Graphs illustrating the mathematical models of pollutant emission rates as functions of engine speed and torque have been presented in Figs. 13–15.

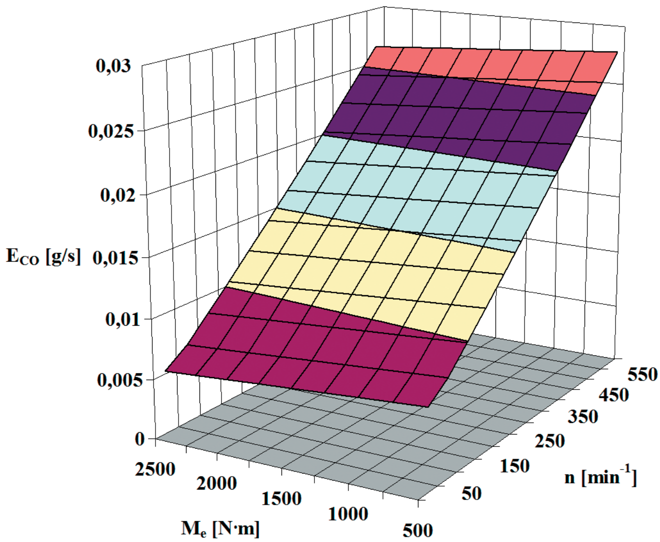

Fig. 13. Graph representing the second-degree polynomial function that approximates the dependence of carbon monoxide emission rate (E_{CO}) on engine speed (n) and torque (M_e)

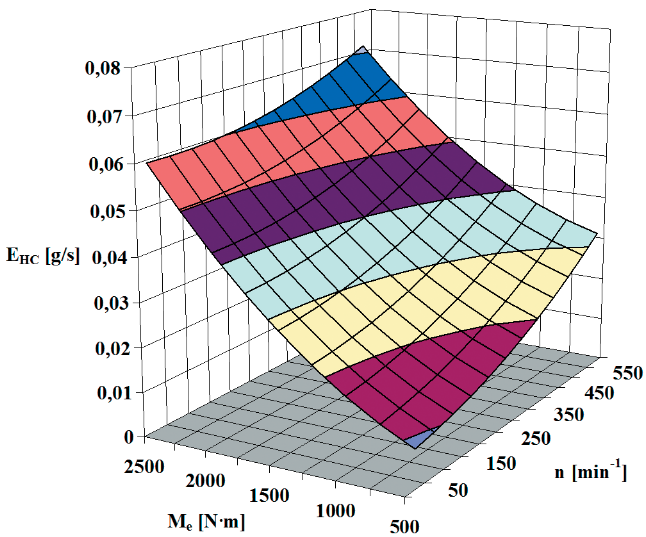

Fig. 14. Graph representing the second-degree polynomial function that approximates the dependence of hydrocarbons emission rate (E_{HC}) on engine speed (n) and torque (M_e)

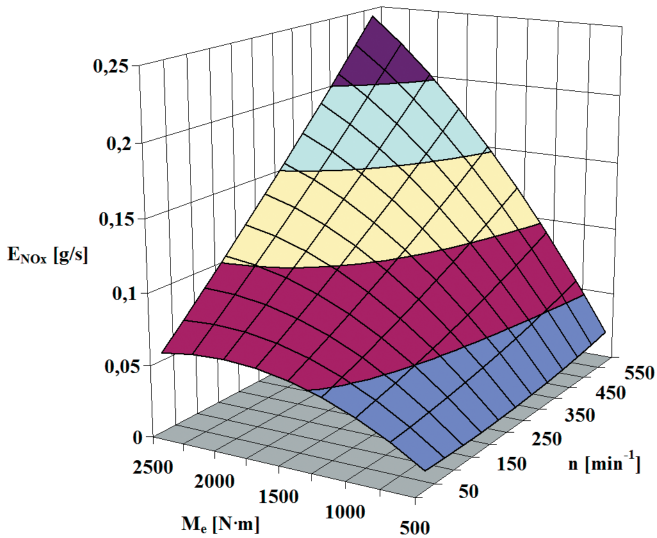

Fig. 15. Graph representing the second-degree polynomial function that approximates the dependence of nitrogen oxides emission rate (E_{NOx}) on engine speed (n) and torque (M_e)

The trends in the pollutant emission rates as functions of individual arguments are similar to each other. All the emission rates (except carbon monoxide emission rate, which is a decreasing function of engine torque) are increasing functions of the arguments chosen, but the susceptibility of rates of emission of individual pollutants to the engine speed and torque varies significantly.

Figs. 16–18 shows coefficients of Pearson's linear correlation, Spearman's rank correlation, Kruskal's gamma correlation, and Kendall's tau correlation between pollutant emission rates and speed, torque and effective power of the engine under test. The presentation of the quantities observed has been so arranged that the coefficients of correlation between the rates of emission of individual pollutants and all the quantities characterizing the engine operation state that determine the pollutant emissions can be easily compared with each other.

Although the correlation coefficient values are widely diversified, as they range from 0.13 to 0.95, the probability that the hypothesis of absence of a correlation would not be rejected was below 0.01 in all the cases analysed. This can be explained by a very big size of the sets under investigation [13], which consist of about 12 000 elements each.

Fundamental differences could be observed, depending on the arguments chosen, i.e. the carbon monoxide and hydrocarbons emission rates on the one hand and the nitrogen oxide emission rates on the other hand. The correlation coefficients for carbon monoxide and hydrocarbons emission rates have markedly higher values if the correlation is taken in relation to engine speed; conversely, the correlation coefficients determined for nitrogen

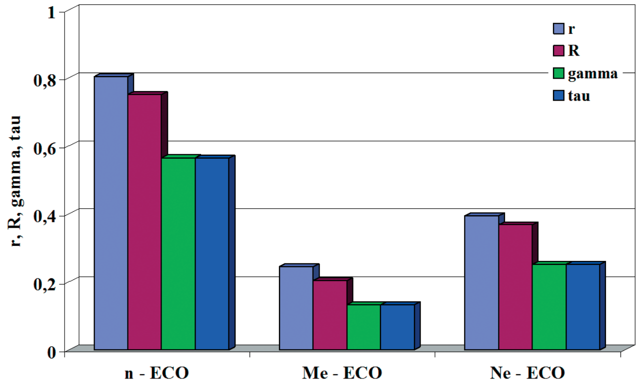

Fig. 16. Coefficients of Pearson's linear correlation (r), Spearman's rank correlation (R), Kruskal's gamma correlation (gamma), and Kendall's tau correlation (tau) between carbon monoxide emission rate (ECO) and speed (n), torque (Me), and effective power (Ne) of the engine under test

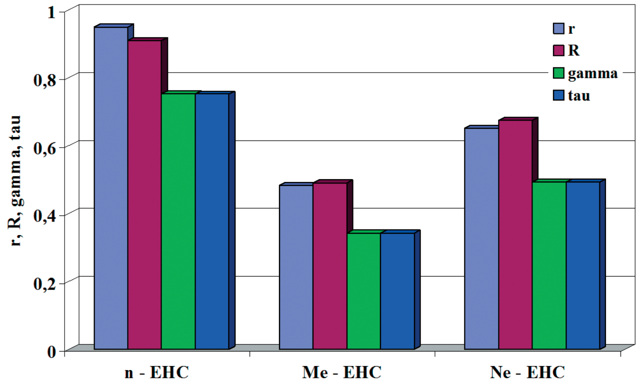

Fig. 17. Coefficients of Pearson's linear correlation (r), Spearman's rank correlation (R), Kruskal's gamma correlation (gamma), and Kendall's tau correlation (tau) between hydrocarbons emission rate (EHC) and speed (n), torque (Me), and effective power (Ne) of the engine under test

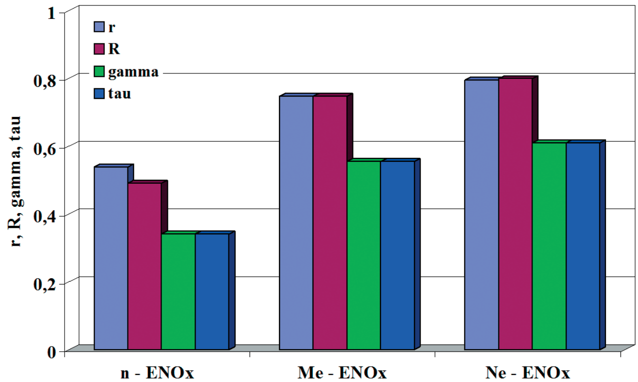

Fig. 18. Coefficients of Pearson's linear correlation (r), Spearman's rank correlation (R), Kruskal's gamma correlation (gamma), and Kendall's tau correlation (tau) between nitrogen oxides emission rate (ENOx) and speed (n), torque (Me), and effective power (Ne) of the engine under test

oxides emission rate predominate when the correlation is taken in relation to engine torque and effective power. This finding is consistent with expectations, because the nitrogen oxides emission is chiefly induced by the temperature of gases inside engine cylinders and this temperature rises with increasing engine load.

Figs. 19–21 present the coefficients of Pearson's linear correlation, Spearman's rank correlation, Kruskal's gamma correlation, and Kendall's tau correlation between pollutant emission rates and speed (Fig. 19), torque (Fig. 20), and effective power (Fig. 21) of the engine. The presentation of the quantities observed has been arranged as shown so that the coefficients of correlation between the rates of emission of individual pollutants and all the quantities characterizing the engine operation state that determine the pollutant emissions can be compared with each other.

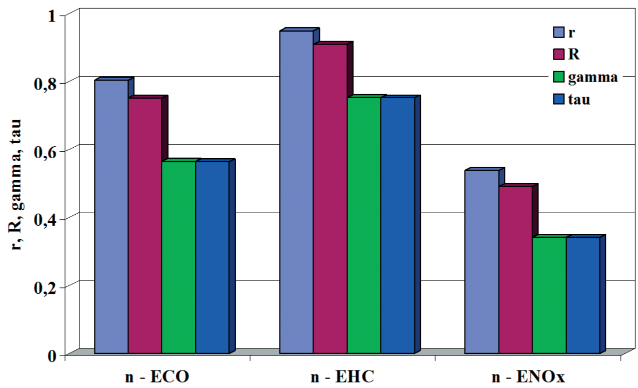

Fig. 19. Coefficients of Pearson's linear correlation (r), Spearman's rank correlation (R), Kruskal's gamma correlation (gamma), and Kendall's tau correlation (tau) of carbon monoxide emission rate (ECO), hydrocarbons emission rate (EHC), and nitrogen oxides emission rate (ENOx) with engine speed (n)

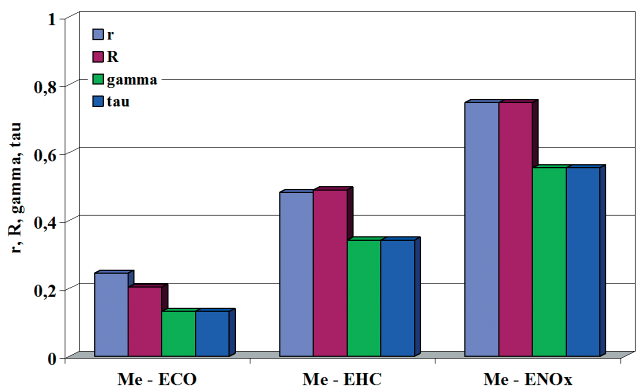

Fig. 20. Coefficients of Pearson's linear correlation (r), Spearman's rank correlation (R), Kruskal's gamma correlation (gamma), and Kendall's tau correlation (tau) of carbon monoxide emission rate (ECO), hydrocarbons emission rate (EHC), and nitrogen oxides emission rate (ENOx) with engine torque (Me)

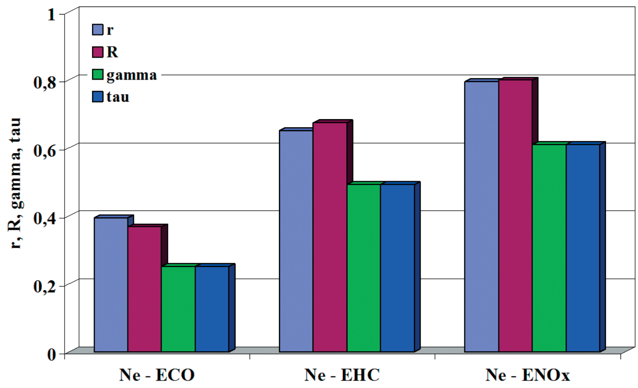

Fig. 21. Coefficients of Pearson's linear correlation (r), Spearman's rank correlation (R), Kruskal's gamma correlation (gamma), and Kendall's tau correlation (tau) of carbon monoxide emission rate (ECO), hydrocarbons emission rate (EHC), and nitrogen oxides emission rate (ENOx) with effective power (Ne) of the engine under test

The engine speed is most strongly correlated with the hydrocarbons emission rate and, on a slightly lower level, with the monoxide emission rate. In the case of the torque and effective power, the strongest and weakest correlation can be observed for nitrogen oxides emission rate and carbon monoxide emission rate, respectively.

3. Recapitulation

The research work having been carried out may be recapitulated by formulating the following conclusions concerning the dependences, observed in the NRTC test conditions, of the pollutant emission rates on the quantities characterizing the engine operation state that determine the pollutant emissions:

1. In spite of wide differences between correlation coefficient values (which varied from 0.13 to 0.95), it is statistically justifiable to treat the examined pairs of sets of physical quantities as strongly correlated, as the probability that the hypothesis of absence of a correlation would not be rejected was below 0.01 in all the cases analysed.

2. Although different tests were used to estimate the correlation, the trends observed in the results of calculation of correlation coefficients are similar to each other in qualitative terms.

3. The quantities characterizing the engine operation state have the strongest impact on the carbon monoxide and hydrocarbon emission rates, as opposed to the nitrogen oxides emission rate. The carbon monoxide and hydrocarbon emission rates are most strongly affected by the engine speed, unlike the nitrogen oxides emission rate, which predominantly depends on the torque and effective power of the engine.

The research results presented here have been obtained from tests carried out according to the NRTC test procedure, i.e. both in definite static states of engine operation and for definite properties of dynamic engine operation states. Therefore, it would be reasonable to extend the scope of the research program to cover other test conditions, both those to be observed at type-approval procedures and those set at special tests.

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