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ASSESSMENT OF THE IMPACT OF DYNAMIC STATES OF AN INTERNAL COMBUSTION ENGINE ON ITS OPERATIONAL PROPERTIES

OCENA WPŁYWU STANÓW DYNAMICZNYCH SILNIKA SPALINOWEGO NA JEGO WŁAŚCIWOŚCI UŻYTKOWE*

Internal combustion engines as systems described by non-linear models do not have any properties that would not depend on their current states. The paper presents results of testing an automotive engine in dynamic states determined by the vehicle acceleration sign in vehicle driving tests simulating the real operation of passenger cars. During the tests, pollutant emission rates and fuel flow rates averaged for specific vehicle states were examined. The processes under investigation were found to be highly sensitive both to the dynamic states and to the types of the vehicle driving tests.

***Keywords**: internal combustion engines, pollutant emissions, vehicle driving tests, dynamic states.*

Silniki spalinowe jako układy opisywane modelami nieliniowymi nie mają właściwości niezależnych od stanów, w jakich się znajdują. W pracy przedstawiono wyniki badań silnika samochodowego w stanach dynamicznych zdeterminowanych znakiem przyspieszenia pojazdu w testach jezdnych symulujących rzeczywistą eksploatację samochodów osobowych. Badano uśrednione w tych stanach: natężenie emisji zanieczyszczeń i natężenie przepływu paliwa. Stwierdzono znaczną wrażliwość badanych procesów zarówno na stany dynamiczne, jak i na rodzaje testów jezdnych.

***Słowa kluczowe**: silniki spalinowe, emisja zanieczyszczeń, testy jezdne, stany dynamiczne.*

1. Introduction

In general, real objects described by non-linear mathematical models considered satisfactorily consistent with the subject of modelling [9] have no properties that would be independent of the objects' states [8]. The objects of this kind include internal combustion (IC) engines. Therefore, the degree of generality of the IC engine research tasks must be limited. In particular, in the case of IC engines being in dynamic states, some constraints in the form of specific test procedures adopted, e.g. a definite class of the processes assumed as engine operation conditions or a special method of processing the test results, such as averaging within the range of process values, must be imposed on the system under investigation.

The operational properties of IC engines (for constant engine steering characteristics) are chiefly determined by the quantities that characterize the engine work intensity, described as the effective power output, and the thermal engine state defined by the temperatures of engine parts and systems [8]. The quantities characterizing the engine work intensity are usually described by engine torque output, representing the engine load, and engine crankshaft speed [8]. This description may also be supplemented with the current setting of engine steering as another engine load indicator. These three quantities, i.e. engine steering setting "s", engine torque output "M_e", and engine crankshaft speed "n", depend on each other. For static states, this interdependence is represented by an elementary function with numerical values:

$$F(s, M_e, n) = 0 \tag{1}$$

For dynamic states, it takes a form of an operational equation [2]:

$$\Im[s, M_e, n] = 0 \tag{2}$$

The load of an IC engine may also be described with the use of the resistance torque "M_o" instead of the engine torque output. For static states, the following equation obviously holds:

$$M_e = M_o \tag{3}$$

but for dynamic states, we have:

$$\frac{d}{dt}\left[J(t) \times n(t)\right] = M_e(t) - M_o(t) \tag{4}$$

where: t – time;
J – moment of inertia of the moving engine parts, reduced to the crankshaft axis.

Hence, the following functional equation with numerical values applies to static states:

$$F(s, M_o, n) = 0 \tag{5}$$

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** while for dynamic states, it takes the form of an operational equation:

$$\Re\left[s, M_o, n\right] = 0 \quad (6)$$

In dynamic conditions, the operational properties of IC engines depend not only on the values of the quantities that describe the state of engine operation but also on the processes of changes in these values (time histories) [8]. For this reason, the operational properties of IC engines in static and dynamic conditions may significantly differ from each other [8].

When the thermal state of the IC engine is stable, the engine properties in its dynamic states are determined by the engine torque and crankshaft speed processes. In this connection, the operational properties of an IC engine in its dynamic states cannot be, in general, unequivocally evaluated. However, there is a possibility of considering the operational properties of an IC engine in certain dynamic states that may be assumed as elementary states. As one of the possible criteria of qualifying to the elementary dynamic states of an IC engine, the signs (positive or negative) of derivatives of the states with respect to time in the whole range of engine operation parameters may be considered. Thus, the following elementary states of engine operation are possible as combinations of engine controls setting, resistance torque, and engine crankshaft speed:

$$\frac{ds}{dt} > 0 \wedge \frac{dM_o}{dt} > 0 \;; \quad \Rightarrow \quad \frac{dn}{dt} > 0 \quad (7)$$

$$\frac{ds}{dt} > 0 \wedge \frac{dM_o}{dt} > 0 \;; \quad \Rightarrow \quad \frac{dn}{dt} < 0 \quad (8)$$

$$\frac{ds}{dt} > 0 \wedge \frac{dM_o}{dt} < 0 \;; \quad \Rightarrow \quad \frac{dn}{dt} > 0 \quad (9)$$

$$\frac{ds}{dt} < 0 \wedge \frac{dM_o}{dt} > 0 \;; \quad \Rightarrow \quad \frac{dn}{dt} < 0 \quad (10)$$

$$\frac{ds}{dt} < 0 \wedge \frac{dM_o}{dt} < 0 \;; \quad \Rightarrow \quad \frac{dn}{dt} < 0 \quad (11)$$

$$\frac{ds}{dt} < 0 \wedge \frac{dM_o}{dt} < 0 \;; \quad \Rightarrow \quad \frac{dn}{dt} > 0 \quad (12)$$

In turn, if the engine torque output is to be taken into account in the said combinations in place of the resistance torque, then the possible elementary states of engine operation may be defined as follows:

$$\frac{ds}{dt} > 0 \wedge \frac{dM_e}{dt} > 0 \;; \quad \Rightarrow \quad \frac{dn}{dt} > 0 \quad (13)$$

$$\frac{ds}{dt} > 0 \wedge \frac{dM_e}{dt} > 0 \;; \quad \Rightarrow \quad \frac{dn}{dt} < 0 \quad (14)$$

$$\frac{ds}{dt} > 0 \wedge \frac{dM_e}{dt} < 0 \;; \quad \Rightarrow \quad \frac{dn}{dt} > 0 \quad (15)$$

$$\frac{ds}{dt} < 0 \wedge \frac{dM_e}{dt} > 0 \;; \quad \Rightarrow \quad \frac{dn}{dt} < 0 \quad (16)$$

$$\frac{ds}{dt} < 0 \wedge \frac{dM_e}{dt} < 0 \;; \quad \Rightarrow \quad \frac{dn}{dt} < 0 \quad (17)$$

$$\frac{ds}{dt} < 0 \wedge \frac{dM_e}{dt} < 0 \;; \quad \Rightarrow \quad \frac{dn}{dt} > 0 \quad (18)$$

The use of descriptions (7–12) and (13–18) may also be considered with respect to the assumed ranges of values of individual processes. Moreover, there is a possibility of taking into account combinations of engine operation conditions and states defined by the ranges of values of individual processes, signs of derivatives of the processes with respect to time, and zero values of the time derivatives with tolerance ranges appropriately defined (constant-value processes), e.g.:

$$\frac{ds}{dt} > 0 \;; \qquad \frac{dM_e}{dt} \in \left[\delta_{M_e} - \frac{\varepsilon_{\delta M_e}}{2} ; \delta_{M_e} + \frac{\varepsilon_{\delta M_e}}{2}\right] \quad (19)$$

for

$$s \in \left[s_{min} ; s_{max}\right] \quad n \in \left[n_{min} ; n_{max}\right] \quad M_e \in \left[M_{e\,min} ; M_{e\,max}\right] \quad (20)$$

In the conditions of stable thermal state of an IC engine, the state of an automotive engine in the conditions of engine operation in a moving vehicle is determined by the vehicle speed process [8]. Therefore, vehicle driving tests may be used to examine the operational properties of automotive IC engines. Such tests are commonly carried out within type-approval tests [25, 26] and special tests where special vehicle traffic conditions are simulated, e.g. those prevailing in urban traffic congestions (the "Stop-and-Go" test [5]) or in the traffic on motorways and fast roads (the "Autobahn" test [5]). Obviously, the results of examination of the operational properties of engines in the dynamic states that occur at various test procedures will differ from each other.

The need to examine the operational properties of engines in dynamic states has existed for many years. Many publications with reports of works on this subject are issued [1, 3, 4, 6–8, 10–19, 21–24] but, in principle, there are no standards so far for tests of this type; only the methods of examining the averaged properties of IC engines in dynamic states, such as those used at type-approval tests, may be considered as standards [25, 26].

Most of the works concern the controlling of IC engines with taking into account dynamic states [4, 12, 14, 17, 23]. In publication [4], a mathematical model used to simulate the injector operation in a common rail engine fuelling system has been presented. Monograph [12], prepared at ETH in Zürich, shows the present-day state of knowledge regarding the modelling of working processes in IC engines in respect of the use of such processes in engine control systems. Publication [14] is dedicated to the use of a mathematical model of the processes taking place in the IC engine to control the processes in an HCCI (Homogenous Charge Compression Ignition) engine. A multidimensional model used for developing IC engine control algorithms with the application of fuzzy logic has been shown in publication [17]. Results of examination of the parameters of controlling an automotive engine in real operation conditions have been presented in paper [23].

The properties of automotive IC engines in specific working conditions prevailing during real vehicle operation are examined as well [15, 16, 19], where e.g. mobile measurement systems PEMS (Portable Emissions Measurement System) are used. Results of the examination of pollutant emissions from non-road and automotive engines have been presented in publications [15] and [16], respectively. The impact of passenger car motion parameters on fuel consumption and pollutant emissions during real vehicle operation in urban traffic conditions has been analysed in publication [19].

Some of the works are dedicated to research on the processes of flows, air-fuel mixture formation, combustion, and formation of individual exhaust gas components in IC engines being in dynamic states [22, 24].

Most of the publications deal with motor vehicle engines; however, results of the examination of pollutant emissions from a marine IC piston engine during engine start-up and from an agricultural tractor engine have been presented in papers [13] and [15], respectively.

At this work, a decision was made to carry out tests with the use of the test procedures named as "PIMOT tests", developed by the authors during the work described in publication [7]. A unique concept of defining appropriate test procedures for the simulation of real conditions of driving a passenger car [6] was adopted. The vehicle velocity recorded in comparable traffic conditions (i.e. in the street congestion, urban, extra-urban, and high-speed traffic conditions) were treated as individual realizations of stochastic processes of vehicle velocity in the traffic conditions under consideration. Based on an analysis of the stochastic processes, several velocity processes were selected for each of the types of vehicle motion conditions, with treating individual realizations of a stochastic process as a vehicle driving test for each of the types of the traffic conditions under consideration. Individual realizations of the vehicle speed process were defined in conformity with the criterion of faithful simulation in the time domain. The vehicle driving tests were defined based on the similarity of zero-dimensional characteristics of the stochastic processes of speed in real vehicle operation and in the tests, i.e. the expected values, extreme values, and variance, taken as a criterion for comparisons.

Figs. 1–4 show the PIMOT vehicle driving tests, with each of them consisting of four realizations of the stochastic processes of vehicle velocity that characterize the vehicle motion in the following conditions:

- urban traffic congestions (denoted by "CT");
- urban traffic without congestions (denoted by "UT");
- extra-urban ("rural") traffic (denoted by "RT");
- high-speed traffic (on motorways and fast roads, denoted by "HT").

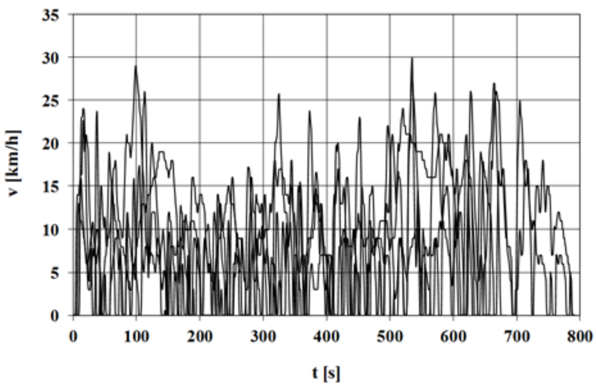

Fig. 1. The vehicle velocity – v for test drives in urban traffic congestions – the driving tests CT

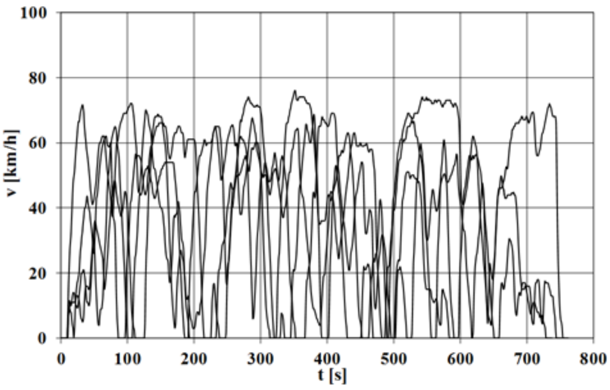

Fig. 2. The vehicle velocity – v for test drives in urban traffic – the driving tests UT

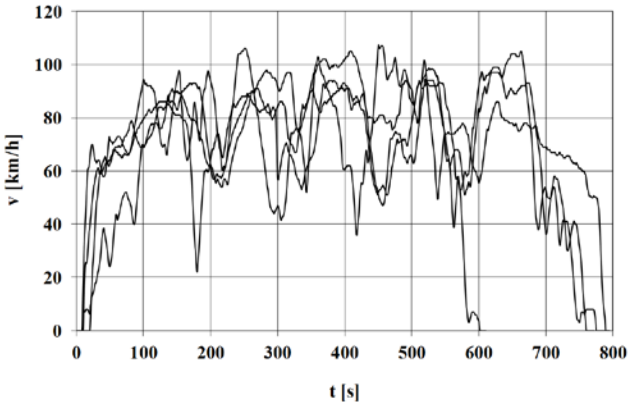

Fig. 3. The vehicle velocity – v for test drives in extra-urban traffic – the driving tests RT

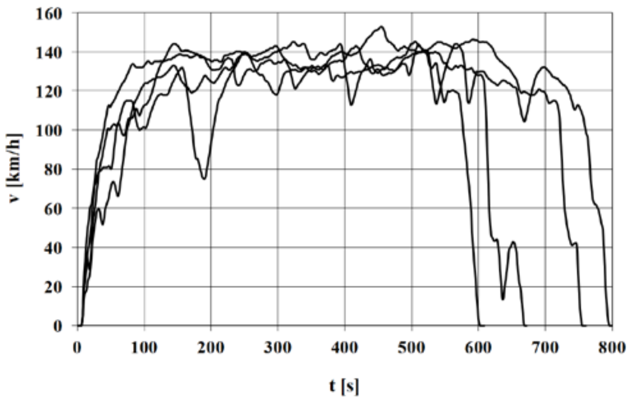

Fig. 4. The vehicle velocity – v for test drives in high-speed traffic – the driving tests HT

2. Methods, object, and results of testing

To assess the impact of dynamic states of an IC engine on its properties, a research work was done, which was based on tests carried out in conditions corresponding to negative and positive accelerations of the vehicle tested. During the tests, pollutant emissions and fuel consumption were examined. The said impact of dynamic states was assessed in the conditions of engine operation in a motor vehicle subjected to PIMOT tests.

The test specimen was a Honda Civic passenger car provided with a spark-ignition engine of 1 396 cm^3 displacement volume.

The vehicle tests were carried out on a Schenck-Komeg vehicle chassis dynamometer EMDY 48. The pollutant emissions were examined with the use of an exhaust gas analysing test stand which incorporates a Horiba Mexa 7200 system provided with the following analysers:

- AIA–721A (carbon monoxide concentration);
- AIA–722 (carbon dioxide concentration);
- MPA–720 (oxygen concentration);
- CLA–755A (nitrogen oxides concentration);
- FIA–725A (hydrocarbon concentration).

The processes subjected to investigation included the intensity of flow of the fuel consumed by the engine and the pollutant emission intensity. The signals were synchronized at the location where the exhaust gas was taken off, downstream of the multifunctional catalytic reactor; the delays in individual signals related to the exhaust gas analysis process were taken into account and the fuel flow intensity was determined from the balance of carbon mass in the signals of exhaust gas component emission intensity. The signals under investigation were pre-processed for gross errors to be eliminated and for the share of high-frequency interference to be reduced. The measurement results were sampled with a frequency of 10 Hz and then averaged for 10 subsequent samples. Thus, the sampling interval for the signals processed was equal to 1 s. The gross errors were identified by the method of analysing the current variance of measurement results. For the share of high-frequency noise in the signals to be reduced, a Golay-Savitzky low-pass filter [20] was used, where both-side approximation from two data points on each side to a polynomial of degree 2 was applied.

Let sets $\mathbf{E_{CO}}$, $\mathbf{E_{HC}}$, $\mathbf{E_{NOx}}$, $\mathbf{E_{CO2}}$ and $\mathbf{G_f}$ contain digitized values of pollutant emission intensity, fuel flow intensity, and vehicle acceleration for each of the test realizations with a sampling frequency of 1 Hz. The power of each of the sets is N. Each of the sets may be presented in the form of a sum of sets consisting of elements characterized by such a feature that the vehicle acceleration is either positive or negative:

$$\mathbf{X} = \mathbf{X_{(a<0)}} \cup \mathbf{X_{(a>0)}} \tag{21}$$

where: $\mathbf{X = E_{CO}, E_{HC}, E_{NOx}, E_{CO2}, G_f}$.

Let the power of the sets $\mathbf{X_{(a<0)}}$ be $N_{(a<0)}$ and the power of the sets $\mathbf{X_{(a>0)}}$ be $N_{(a>0)}$. The average value of elements of the sets $\mathbf{X_{(a<0)}}$ is:

$$X_{(a<0)AV} = \frac{1}{N_{(a<0)}} \sum_{i=1}^{N_{(a<0)}} X_{(a<0)i} \tag{22}$$

For the sets $\mathbf{X_{(a>0)}}$, this average value is:

$$X_{(a>0)AV} = \frac{1}{N_{(a>0)}} \sum_{i=1}^{N_{(a>0)}} X_{(a>0)i} \tag{23}$$

where: $X_{(a<0)AV} = E_{CO(a<0)j}, E_{HC(a<0)j}, E_{NOx(a<0)j}, E_{CO2(a<0)}, G_{f(a<0)j}$;
$X_{(a>0)AV} = E_{CO(a>0)j}, E_{HC(a>0)j}, E_{NOx(a>0)j}, E_{CO2(a>0)}, G_{f(a>0)j}$;
j = 1, 2, 3, 4 – item number of a realization of each of the tests.

Example test results for specific traffic types have been presented in illustrations as specified below:

- for the CT test, in Figs. 5 and 6;
- for the UT test, in Figs. 7 and 8;
- for the RT test, in Figs. 9 and 10;
- for the HT test, in Figs. 11 and 12.

The graphs shown in the said illustrations represent the average values and the relative ranges of the average fuel flow intensity and average pollutant emission intensity for the test results for negative and positive vehicle accelerations in specific test realizations.

The average value of the average pollutant emission intensity for the realizations of each of the tests is:

$$E_{x(a>0)} = \frac{1}{4} \sum_{j=1}^{4} E_{x(a>0)j} \tag{24}$$

where: x = CO, HC, NOx, CO_2.

Similarly, the average value of the average fuel flow intensity is defined as follows:

$$G_{f(a>0)} = \frac{1}{4} \sum_{j=1}^{4} G_{f(a>0)j} \tag{25}$$

The relative range is defined as the ratio of the absolute value of range R to the average value AV:

$$\delta = \frac{|R|}{AV} \tag{26}$$

where: $AV = E_{x(a<0)}, E_{x(a>0)}, G_{f(a<0)}, G_{f(a>0)}$, and

$$R = \max(y) - \min(y) \tag{27}$$

where: $y = E_{x(a<0)}, E_{x(a>0)}, G_{f(a<0)}, G_{f(a>0)}$;
max – operator of the maximum value of the elements of a set;
min – operator of the minimum value of the elements of a set.

In the graphs below, the indices (a<0) and (a>0) have been referred to in the legends.

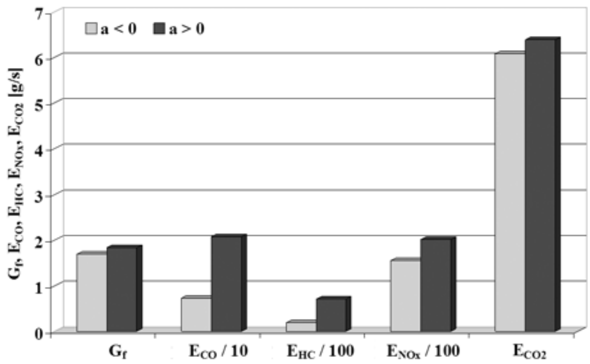

Fig. 5. Average values of the average fuel flow intensity (G_f) and of the average intensity of emission of carbon monoxide (E_{CO}), hydrocarbons (E_{HC}), nitrogen oxides (E_{NOx}), and carbon dioxide (E_{CO2}) for negative (a < 0) and positive (a > 0) vehicle accelerations in the CT test

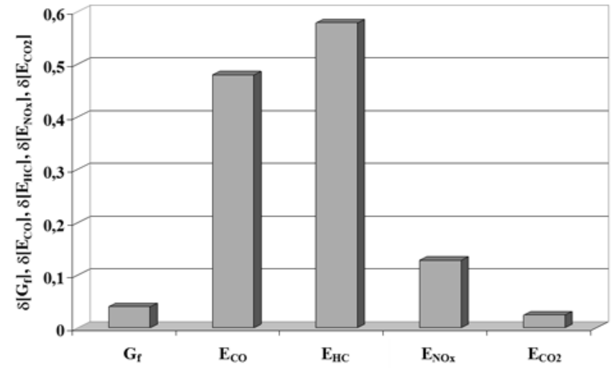

Fig. 6. Relative ranges of the average fuel flow intensity (G_f) and of the average intensity of emission of carbon monoxide (E_{CO}), hydrocarbons (E_{HC}), nitrogen oxides (E_{NOx}), and carbon dioxide (E_{CO2}) for negative and positive vehicle accelerations in the CT test

A vehicle driven in urban traffic congestions is subject to very special conditions of motion, characterized by low absolute values of vehicle acceleration. This explains the fact that the carbon dioxide emission intensity and fuel flow intensity, determined for the vehicle acceleration phase, do not significantly differ from the corresponding values measured for the deceleration phase, especially if the "averaging" properties of the exhaust gas sampling system are taken into consideration. In contrast, significant increase can be clearly seen in the intensity of emission of hydrocarbons and, in second rank, carbon monoxide.

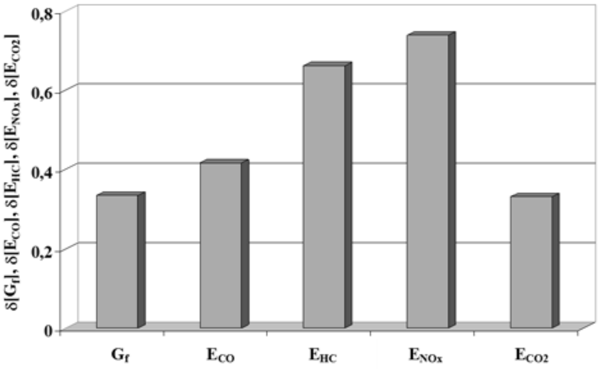

Fig. 7. Average values of the average fuel flow intensity (G_f) and of the average intensity of the emission of carbon monoxide (E_{CO}), hydrocarbons (E_{HC}), nitrogen oxides (E_{NOx}), and carbon dioxide (E_{CO2}) for negative (a < 0) and positive (a > 0) vehicle accelerations in the UT test

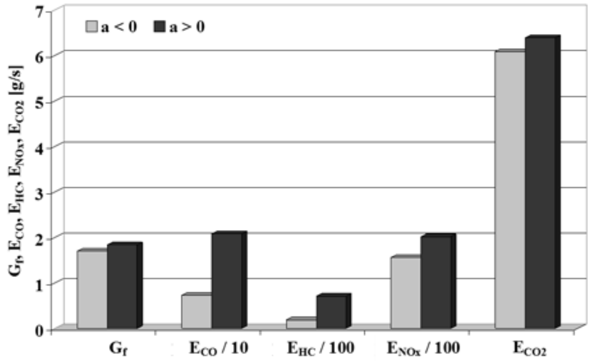

Fig. 8. Relative ranges of the average fuel flow intensity (G_f) and of the average intensity of the emission of carbon monoxide (E_{CO}), hydrocarbons (E_{HC}), nitrogen oxides (E_{NOx}), and carbon dioxide (E_{CO2}) for negative and positive vehicle accelerations in the UT test

For the vehicle driven in urban traffic conditions (exclusive of traffic congestions), the differences in pollutant emission intensity and fuel intensity rates for the phases of accelerated and decelerated vehicle motion are much bigger than those recorded for vehicle drives in urban traffic congestions. A particularly high relative range (exceeding 50%) can be noticed for the nitrogen oxides emission intensity; this is related to high engine load occurring when the vehicle is accelerating.

The relations observed in the conditions of extra-urban traffic are similar to those recorded for the urban traffic conditions, except for the fact that the impact of vehicle accelerations on the increase in pollutant emission intensity and fuel flow intensity is even more clearly visible.

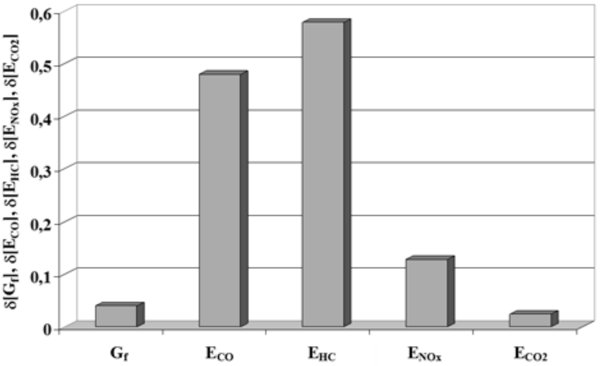

Fig. 9. Average values of the average fuel flow intensity (G_f) and of the average intensity of the emission of carbon monoxide (E_{CO}), hydrocarbons (E_{HC}), nitrogen oxides (E_{NOx}), and carbon dioxide (E_{CO2}) for negative (a < 0) and positive (a > 0) vehicle accelerations in the RT test

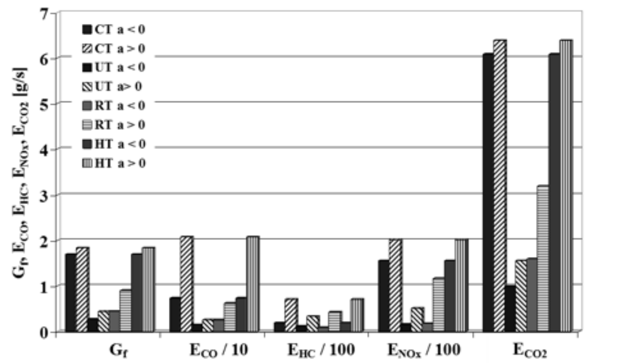

Fig. 10. Relative ranges of the average fuel flow intensity (G_f) and of the average intensity of the emission of carbon monoxide (E_{CO}), hydrocarbons (E_{HC}), nitrogen oxides (E_{NOx}), and carbon dioxide (E_{CO2}) for negative and positive vehicle accelerations in the RT test

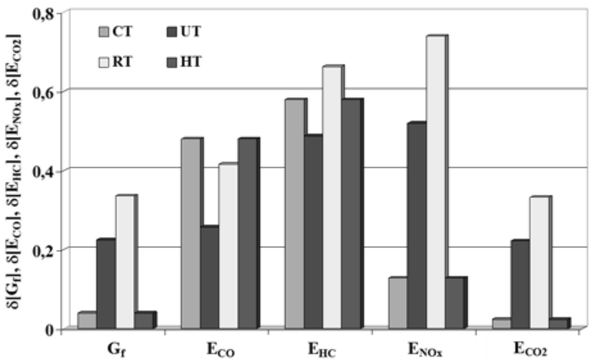

Fig. 11. Average values of the average fuel flow intensity (G_f) and of the average intensity of the emission of carbon monoxide (E_{CO}), hydrocarbons (E_{HC}), nitrogen oxides (E_{NOx}), and carbon dioxide (E_{CO2}) for negative (a < 0) and positive (a > 0) vehicle accelerations in the HT test

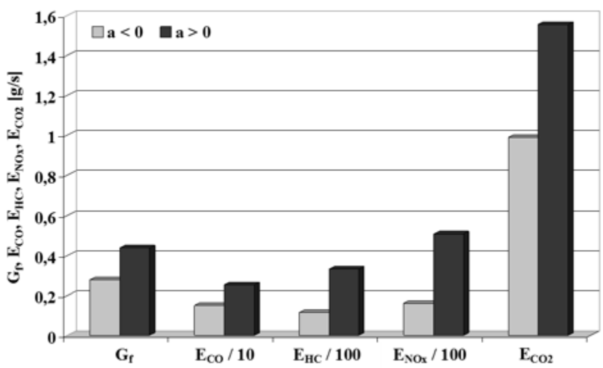

Fig. 12. Relative ranges of the average fuel flow intensity (G_f) and of the average intensity of the emission of carbon monoxide (E_{CO}), hydrocarbons (E_{HC}), nitrogen oxides (E_{NOx}), and carbon dioxide (E_{CO2}) for negative and positive vehicle accelerations in the HT test

During vehicle drives on motorways and fast roads, the absolute vehicle acceleration values are low. In this connection, no significant differences can be seen in fuel flow intensity and carbon dioxide emission intensity for the phases of vehicle acceleration and deceleration. A similar finding may be formulated for the nitrogen oxides emission intensity. Differences occur, however, for the carbon monoxide and hydrocarbons emission intensity.

An overall graph of the average fuel flow intensity and average pollutant emission intensity for the negative and positive vehicle accelerations in the PIMOT tests has been presented in Fig. 13.

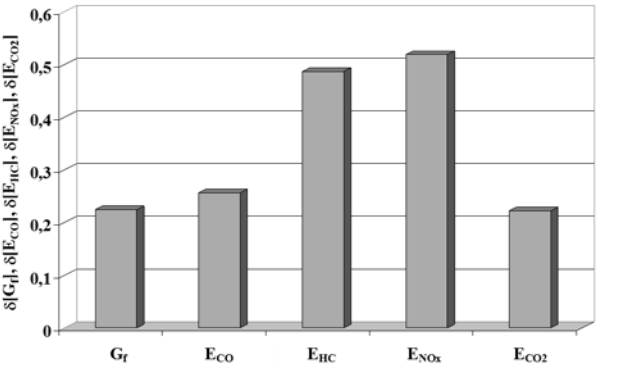

Fig. 13. Average values of the average fuel flow intensity (G_f) and of the average intensity of the emission of carbon monoxide (E_{CO}), hydrocarbons (E_{HC}), nitrogen oxides (E_{NOx}), and carbon dioxide (E_{CO2}) for negative ($a < 0$) and positive ($a > 0$) vehicle accelerations in the PIMOT tests

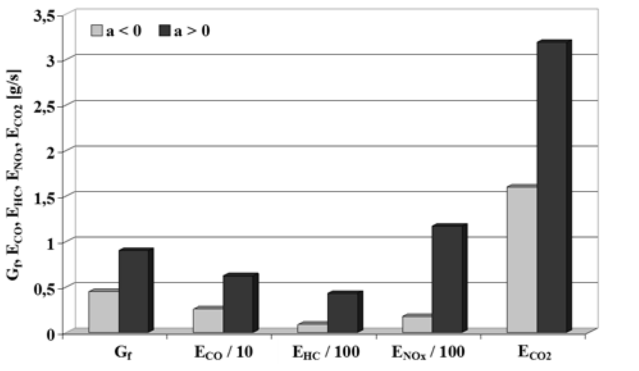

Fig. 14. Relative ranges of the average fuel flow intensity (G_f) and of the average intensity of the emission of carbon monoxide (E_{CO}), hydrocarbons (E_{HC}), nitrogen oxides (E_{NOx}), and carbon dioxide (E_{CO2}) for negative and positive vehicle accelerations in the PIMOT tests

An overall graph of the relative ranges of fuel flow intensity and pollutant emission intensity for negative and positive vehicle accelerations in the PIMOT tests has been shown in Fig. 14.

3. Conclusions

Based on the tests carried out for dynamic states of an IC engine, the following conclusions may be formulated.

1) It has been unequivocally ascertained that the values of pollutant emission intensity and fuel flow intensity in the conditions of vehicle acceleration are higher than those determined when the vehicle motion is decelerated. The values of these differences are significantly diversified depending on the quantities examined and the conditions of vehicle motion, determined by the test types adopted. The relative range of the average pollutant emission intensity and of the fuel flow intensity varies within limits from 0.024 to 0.739, where the lowest and the highest value were obtained for the carbon dioxide emission intensity in the conditions of vehicle motion in urban congestion traffic and for the nitrogen oxides emission intensity in the conditions of vehicle motion in extra-urban traffic, respectively.
2) No unequivocal interrelations have been found to exist between the increase in pollutant emission intensity and fuel flow intensity as determined for vehicle acceleration on the one hand and those determined for vehicle deceleration on the other hand, at different test types. As an example, when the vehicle was operated in the conditions of urban congestion traffic and traffic on motorways and fast roads, the quantity found to be most sensitive to the dynamic states under consideration was the hydrocarbons emission intensity; in the conditions of urban and extra-urban traffic, the highest sensitivity was observed for the nitrogen oxides emission intensity.
3) The highest values of the relative ranges of pollutant emission intensity and fuel flow intensity were recorded in the conditions of extra-urban traffic; the values of these relative ranges were on the lowest level for the conditions of urban congestion traffic.
4) The relative range of pollutant emission intensity in the vehicle acceleration phase reached the highest value for the hydrocarbons emission while the lowest values of this relative range were recorded for the carbon dioxide emission intensity and for the fuel flow intensity.

In general, a statement may be made that in the states of IC engine operation when the vehicle acceleration sign is positive, the average intensity of flow of the fuel consumed and the average pollutant emission intensity are higher than those corresponding to negative vehicle acceleration. In some cases, this difference is very big, i.e. the relative range of these quantities even exceeds 70%.

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