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DRAFT CALCULATION OF FUEL CONSUMPTION AND EMISSION OF CO, HC AND NO_X BY A ENGINE CAR IN OPERATIONAL CONDITIONS

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Abstract

The study presents a draft calculation of fuel consumption and emission of CO_2, CO, HC and NO_x by a engine car used in real traffic conditions. In this project, the author was inspired by the results of his own studies and those of selected domestic and foreign research centres. The (static) engine performance maps including Brake Specific Fuel Consumption maps, g_e (CO_2), and maps of specific emission of CO, HC and NO_x,, serve as the basis for this study. Underlying such an approach are the disparate courses of fuel consumption and emission levels in the driving and non-driving modes of the engine.

For the study purposes, an adequate testing programme should be implemented, using a variable driving cycle [1]. A departure from the homologation cycles applied to this end allows covering, on an engine performance map, the area of engine operation being of interest to us with measuring points.

For calculations in operational conditions, the maps of changes of Δg_e, ΔCO_2, ΔCO, ΔHC and ΔNO_x for nonstationary operating conditions of the engine will be a complement to static engine performance maps. The author has already developed partial maps for the first two parameters. The development of the others requires the implementation of a costly research scheme in cooperation with a leading domestic research centre.

Keywords: *transport, combustion engines, fuel consumption, exhausts emissions*

1. Introduction

Over the past years, intensive work has been conducted in research centres to reduce the emission levels of toxic components of fuel and CO_2 in motor vehicles [1-6]. The work includes, above all, stand tests based on the homologation requirements, which to a large extent diverge from the real operating conditions of motor cars (Fig. 1).

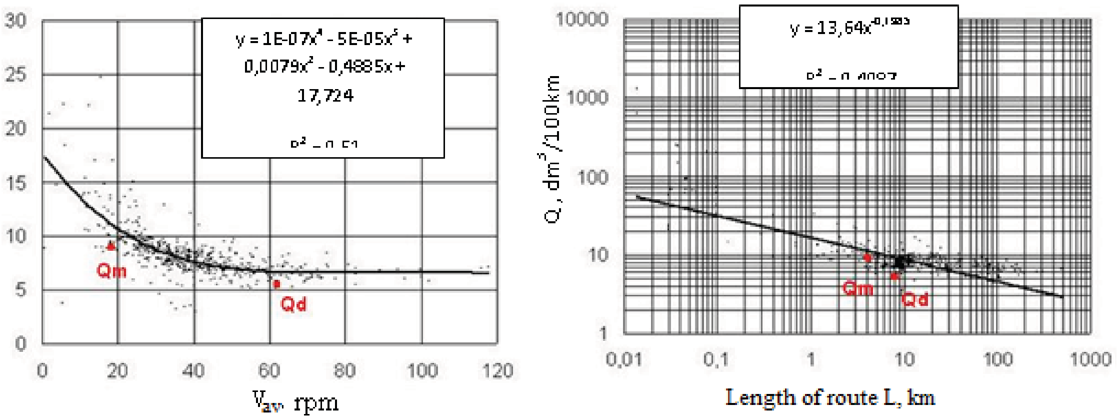

Fig. 1. Value of the real transient fuel consumption for a car, Q_{rz}, depending on v_{av} (on the left) and the distance travelled (on the right) [13]

It is possible to monitor fuel consumption in real-life operating conditions of a car using simple and cost-effective measuring methods. However, measurement of emission levels of selected fuel components (apart from CO_2) requires the application of expensive, portable or stationary, measuring apparatus [2]. Accurate identification of the conditions of fuel consumption by motor cars in real-life operating conditions enabled a more detailed characterisation of CO_2 emission and the emission of other components of fumes. This inspired the author's new approach to the issue of environmental pollution by the most popular means of transport.

Over the years, the examination methods regarding fuel consumption and emission of its toxic components have been undergoing changes, while taking into account the minimisation of the research cost criterion as the most important factor. Based on his own studies and those of other scientific centres, the author proposes to adopt a CO, HC and NO_x emission calculation method developed by himself, analogous to the calculation method of specific fuel consumption [8]. The main tool of the proposed method is a static map of specific emission of CO, HC and NO_x of an engine with isolines of constant emission in g/kW·h. In the author's opinion, it should be supplemented with characteristics of the influence of nonstationary conditions of engine operation on the specific emission of the above-mentioned components in "operation point" on the engine performance map.

Such an approach to the problem discussed will contribute to an increased interest in the performance maps of motor car engines using their characteristics in the vehicle/engine system already in the designing stage. In addition, the research cost will be significantly reduced, and so will its duration. However, reaching this stage of the research requires engagement of considerable funds.

As regards engines operating in non-driving phases and in transient thermal states, the author proposes a separate course of calculations, beyond the scope of this study.

2. Theoretical assumptions

The operation statuses of the motor car engine in real operating conditions can be divided into two groups: driving and non-driving. In any conditions of real operation of a car, these may be assigned to each phase of the speed profile. The course of the profile depends on the mutual relations between the total force of motion resistance and the driving force acting on the drive wheels in a car.

Calculations of the transient fuel consumption of a car using the method of total energy efficiency and carbon balance, based on emission maps of selected components, show considerable discrepancies in the assumptions made in both methods [9, 10]. These discrepancies, in turn, affect the accuracy of calculation of fuel consumption and, probably, of the emission of selected compounds. There are various reasons for significant errors in the calculation of transient fuel consumption of a vehicle driven by an SI engine using the carbon balance method based on emission maps of selected compounds. The principal reasons include the lack of a sufficient number of measuring points in the area investigated, a hardly accurate interpolation of the points of constant emission with 3rd degree polynomials and a lack of a boundary, both on the maps and in the analysis made, between the driving and non-driving phases. In the non-driving phases, there is a considerable variety of operating conditions of the engine which, in extreme cases, may affect the operating conditions of the engine in its driving phases.

In real operation of a car, three principal types of the engine operation conditions can be distinguished:

- continuous drive (a special case with engine load close to zero),
- drive in neutral gear,
- braking with the engine.

All these engine operating conditions require an extensive analysis, as it is inadmissible to accept on their boundaries continuity of emission of toxic compounds and fuel consumption. In order to separate these processes in the above-mentioned conditions of the car speed profile control, it is necessary to adopt general BSFC and emission maps as a basis for the calculations to be made in the engine driving phases.

3. Emission of toxins in engine driving phases

The driving phases in the course of engine operation are strictly connected with the load resulting from the car motion resistance in the consecutive phases of the speed profile in real-life operating conditions. The driving phases of an engine should be considered separately for a motor car at thermally steady and transient states. The engine performance maps are customarily prepared for the operating conditions present in a steady thermal state. They characterise, by means of isolines of specific fuel consumption, g_e, and emission of CO_2, CO, HC and NO_x (g/kW·h), the effective efficiency of the engine and the specific emission in driving phases, in the entire operation field. Examples of such maps are presented in Fig. 2 [11].

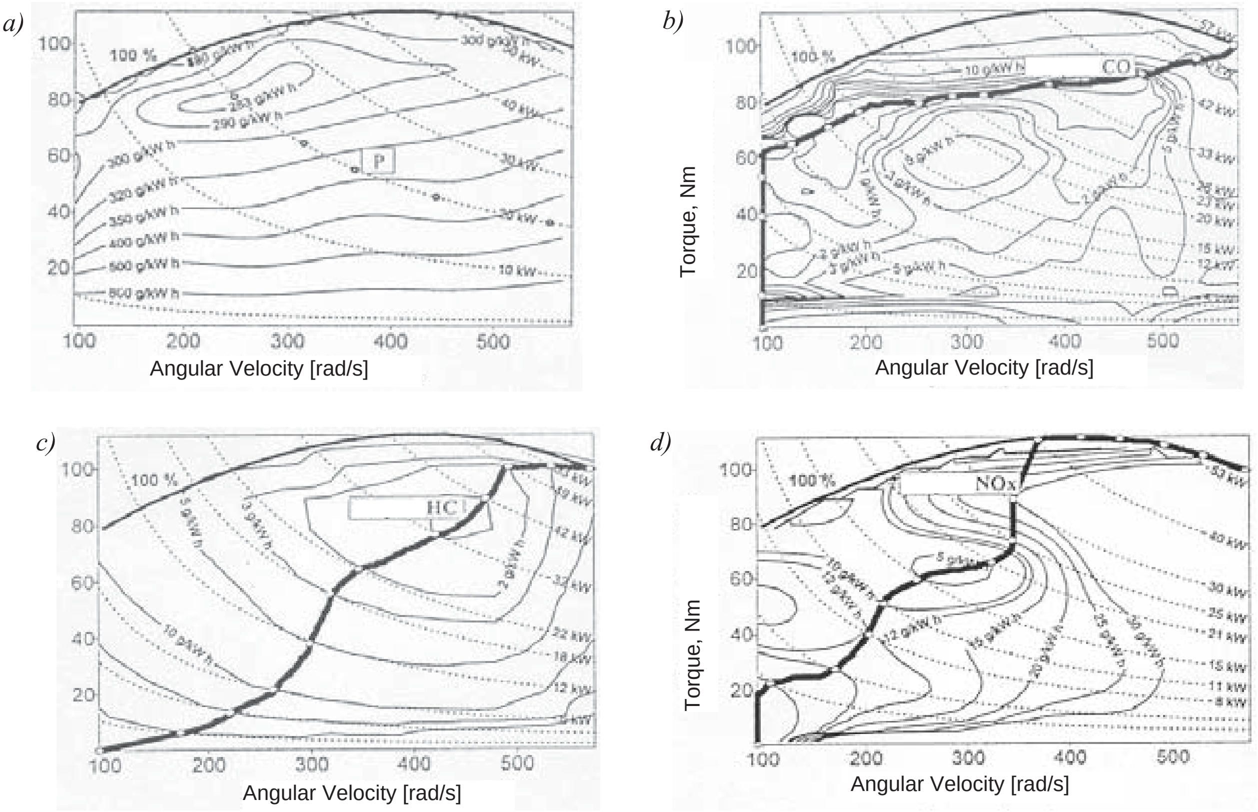

Fig. 2. Engine performance maps with isolines of brake specific fuel consumption, g_e, and specific emission of CO_2, CO, HC and NO_x (g/kW·h) [11]

In paper [12, 13], the author presented a method, elaborated by himself, to plot engine performance maps for nonstationary operating conditions by means of the existing (static) maps. It is possible to determine on their basis identical maps for the emission of CO_2 in static conditions and, as their complement, corrective maps for dynamic operating conditions, $\Delta CO_2 = f(\nu_n, n_{śr})$, which is presented in Fig. 3.

Non-stationary operating conditions, dependent on rotational speed, are characterised by coefficient ν_n defining the change of rotational speed of the engine in unit of time (min^{-1}/s). In the calculation method of transient fuel consumption using the carbon balance method for a car produced in 2004, the taking into account the carbon included in carbon oxide and hydrocarbons has practically no influence on the result. The only component that affects the result is the emission of CO_2. The relations between transient fuel consumption and carbon dioxide emission are expressed by the dependence:

$$1.0\ \text{dm}^3/100\ \text{km of petrol used} \sim 24.5\ \text{g emission of } CO_2/\text{km}. \tag{1}$$

Today, there are two complementary methods known in the country to calculate transient fuel consumption of a car: the original calculation method of total energy efficiency of motion, whose foundations were developed by Prof. W. Siłka [14], and the carbon balance method, the basis for which are the dynamic emission maps elaborated for CO_2, CO, HC and NO_x [15, 16] by Prof. K. Romaniszyn. Due to the adopted measuring methodology, each of these methods has different prerequisites. In the first of them, studies were conducted in traffic conditions, with measurements of the average fuel consumption and speed profile taken with a Motograph in a variable driving cycle. They were performed along a geodetically dimensioned section of road in a two-direction traffic [13].

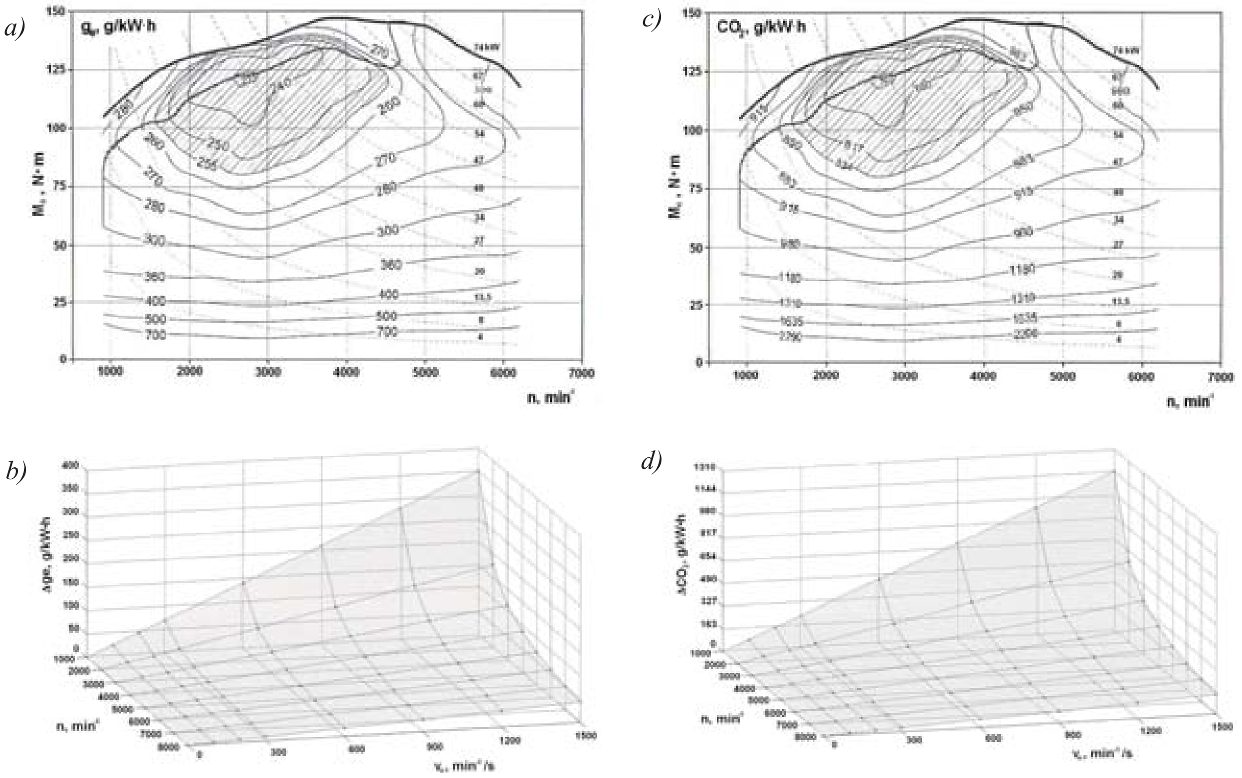

Fig. 3. BSFC and emission maps of an SI engine, 1.4 dm^3 cc, with isolines of g_e and CO_2, and with maps of Δg_e and ΔCO_2 correction to nonstationary operating conditions (min^{-1} = rpm)

In the other method, fuel consumption and emission of selected compounds were measured in real time for a car in homologation driving cycles, NEDC and FTP-75, on an engine test bench. What these two methods have in common is that they consider the measurement results for a car working in steady thermal conditions.

The real transient fuel consumption of a car designated with the letter C, driven by an SI engine of cubic capacity of 1.6 dm^3 [16], is a test of accuracy of transient fuel consumption calculations made by means of each of the methods discussed. The difference between the transient fuel consumption calculated on the basis of static and dynamic maps is comparable for the two driving cycles: urban and extra-urban, which is presented in Tab. 1. It amounts to 0.50 (0.51) and 0.05 (0.06) dm^3/100 km, respectively. The convergence of the results testifies to a comparable, in the both methods, influence of nonstationary conditions of engine operation on the transient fuel consumption calculated in homologation driving cycles.

Tab. 1. Juxtaposition of the results of calculation of Q_U and Q_{EU} based on static and dynamic maps of g_e and CO_2

Item	Calculated methods of mileage fuel consumption*) Q_U and Q_{EU}	Q_U = 12.64 dm^3/100 km		Q_{EU} = 7.93 dm^3/100 km	
		Calculated Q_U and Q_{EU} from maps			
		Static	Dynamics	Static	Dynamics
1	Absorptive of energy E_c	11.5	12.0	7.73	7.78
2	ΔQ	0.50		0.05	
3	Carbon balance – maps CO_2	12.23	12.75	6.38	6.44
4	ΔQ	0.51		0.06	
5	Correct maps CO_2 & ΔCO_2	–	13.4	–	7.75

*) notes: Q_U, Q_{EU} - mileage fuel consumption in UDC and EUDC cycle, respectively

4. Research planning

Determination of the maps of influence of nonstationary conditions of engine operation, ν_n, on the change in specific emission of CO, HC and NO_x, requires making tests at a test stand for a continuous analysis of their emission in unit of time. The starting point will be here such maps of specific emission of the above-mentioned toxic compounds as those presented in Fig. 2. There has been no method developed so far to adapt those maps for engines with similar ecology related properties (meeting the requirements of a given standard, an analogous model of adaptive fuel injection control, cubic capacity, etc.).

Next, using a portable or stationary measurement system of fuel consumption and fume contamination, real-time tests should be carried out in a variable driving cycle. The variable driving cycle is characterised by varied acceleration dynamics of a car until a given speed.

In the author's opinion, the acceleration dynamics of a car is best characterised by unit power of additional motion resistance (a*v). In the product of a* and vehicle velocity "v", a* is the sum of acceleration of car "a" and acceleration of gravity "g", corrected by the rotating mass factor δ and road grade "p". The calculations are more accurate when conducted in a variable driving cycle limited to driving phases and idle running, with a main share of the latter. An example of a so realised driving cycle is presented in Fig. 4a.

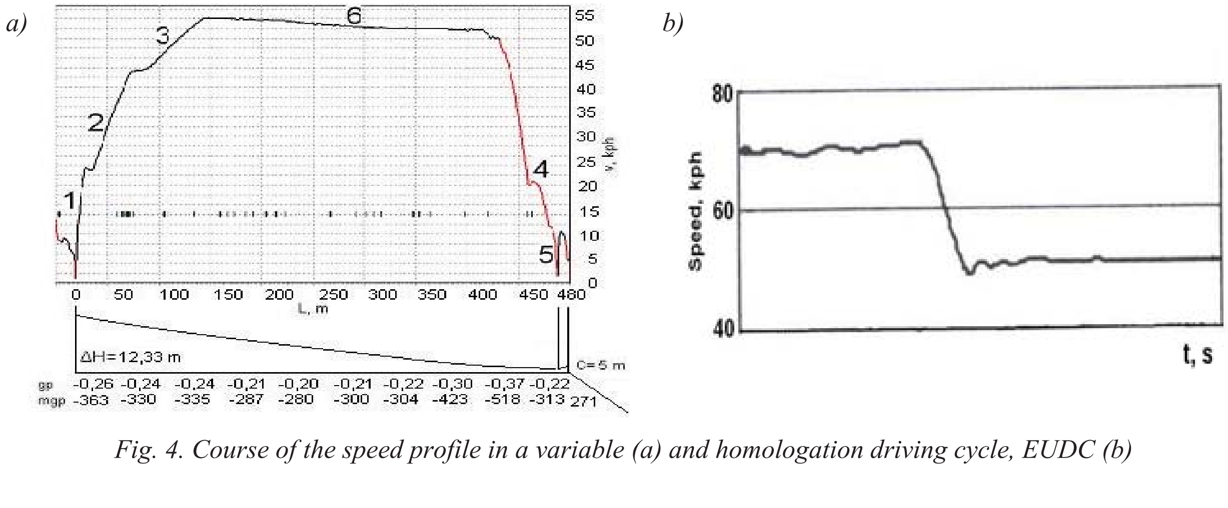

Fig. 4. Course of the speed profile in a variable (a) and homologation driving cycle, EUDC (b)

To obtain credible results, every measurement should be repeated several times on the engine performance map in the area of engine operation being the object of our interest. It is worth emphasising that with the so realised research scheme, the characteristic fluctuation of the speed profile in the range imposed by homologation requirements is eliminated, which, based on an example of a speed profile section from EUDC (Extra-Urban Driving Cycle), is presented in Fig. 4b.

”Manual” control of the car speed within the range specified by homologation requirements contributes to expanding the nonstationary conditions of engine operation (oscillation of constant speed). This causes an increase of transient fuel consumption in car C with an SI engine of 1.6 cc (m_c = 1760 kg) in NEDC (New European Driving Cycle) by ca. 0.25 dm^3/100 km. A comparable increase of Q was obtained using the calculation methods of carbon balance and total motion energy efficiency.

To determine the influence of the range of the engine rotational speed used on a reduction or increase of specific fuel consumption and specific emission of selected compounds, measurements must be made for several ranges of rotational speed for each gear ratio of a transmission [8]. For each range of speed, it is necessary to take at least 70-90 measurements at a thermally steady state on a 350-450 m long road section, in order to record the impact of road grade, preferably in two-direction traffic: ”up” and “down”.

Constant load of the engine in the driving phases of successive driving cycles can be determined through changing the maximum inclination angle of the acceleration pedal.

5. Discussion of research results

Analogically to the situation of determining the influence of nonstationary conditions of engine operation on the increase of specific fuel consumption g_e from an engine performance map, also here the measure of the influence will consist of a change in specific emission of a given toxic compound in relation to a reference value, read out from the (static) engine performance map in Fig. 2.

The real possibilities of obtaining dynamic maps of specific emission in the form of correction maps of ΔCO, ΔHC and ΔNO_x (g/kW·h) for static specific emission maps are corroborated by the correction maps of ΔCO, … (g/s) generated by the author. The maps presented in Fig. 5 have been determined based on the emission maps included in papers [16, 17], developed for car C with an SI engine of 1.6 dm^3 cc.

The maps in Fig. 5 have been generated based on emission maps of carbon oxide, hydrocarbons and nitrogen oxides for a positive angular acceleration of the engine. This allows acquiring maps for an engine in a driving mode at a thermally steady state, intact with emission perturbations in transient operating conditions. It must be remembered, however, that we have to deal with driving phases in real conditions as well as on an engine test bench, at negative accelerations higher than the coasting acceleration a_w, which most often, is a negative value [14, 18, 19].

Any irregularities in their course may result from approximation of the isolines of constant emission of the compounds discussed with 3rd degree polynomials in the engine operation area not fully covered by measuring points. This refers in particular to the range of engine load above the rotational speed $n_{av} > 3800$ rpm. The maps generated show an increase of effective efficiency of the engine as a function of of increase of the nonstationary operational conditions factor, ν_n (e.g. the map of $\Delta CO_2 = f(\nu_n)$ for $n_{av} = 4300\ min^{-1}$ visible in Fig. 5a.

In the author’s opinion, their more accurate course can be obtained by using the direction of their increasing trend for three maps encumbered with the least approximation error [16]. They are the maps for n = 1911, 2400 and 2870 rpm. Taking into account the principle of adaptive control of fuel injection in SI engines, all the maps of $\Delta CO_2 = f(\nu_n)$ can be generated for n_{av} = const. by using the equation [12]:

$$\Delta CO_2 = A \cdot \nu_n / n_{av}\ [g/s], \tag{2}$$

where A = 4.33 g - factor of proportionality for the engine discussed.

Their new courses are denoted in Fig. 5a by bold lines. The course of the ΔCO and ΔHC curves obtained on the basis of their emission maps does not show any decrease of the combustion air factor in a fuel blend with air in nonstationary engine operation conditions.

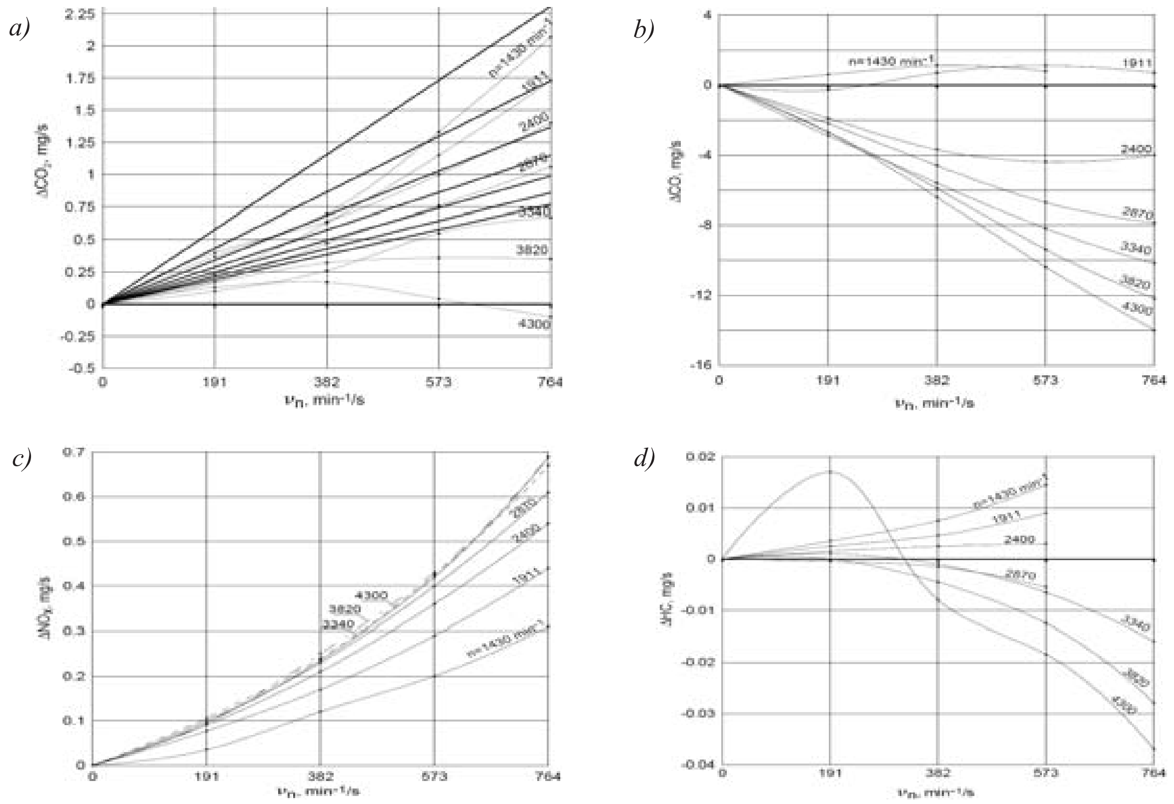

Fig. 5. Maps of changes in the emission of CO, HC and NO$_x$ resulting from nonstationary operational conditions as a function of rotational speed, ν_n, and average rotational speed of the engine, n_{av} (developed based on [15]) min^{-1} = rpm

6. Conclusions

Based on the presented findings, the following conclusions can be formulated:

1. The method developed to determine the effective efficiency of the SI engine in operational conditions requires taking into account the nonstationary conditions of engine operation, depending on the load. As results from the pilot research programme developed, their influence is significant for low gear ratios of a transmission, i.e. in the area where the nonstationary conditions dependent on the rotational speed ν_n are in a majority of cases negligible (quasi-stationary conditions of engine operation) [17].
2. The main advantage of the method developed is that the general static map including a map of isolines of specific fuel consumption, g_e, and specific emission of CO, HC and NO$_x$ (g/kW·h), can be used as the reference area for the calculations.
3. Based on the dynamic maps of emission of CO, HC and NO$_x$ (g/s) [16], through analogy to the solutions adopted for the specific fuel consumption g_e, it has been shown that it is possible to develop dynamic maps of specific emission of CO, HC and NO$_x$ (g/(kW·h)) being complementary to the static maps (b), (c) and (d) in Fig. 2.
4. The generating of dynamic maps of specific emission of harmful substances by a car in operational conditions requires carrying out an appropriate programme of stand tests or road tests with a stationary or mobile laboratory for fuel analysis.

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