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ENGINE PERFORMANCE MAPS IN NONSTATIONARY OPERATING CONDITIONS OF CAR ENGINE

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Abstract

*A method is proposed in the paper to calculate effective efficiency of an engine in nonstationary operating conditions. A reference point for this method is the effective efficiency of the engine derived from its performance map. A research methodology has been developed to this end, the basis of which consists of measurements and calculations of the total energy efficiency of a car motion in a variable driving cycle. In order to determine the impact of the road grade, measurements were performed along a geodetically described road section in two traffic directions:"up" and "down". The adopted research scheme allows covering the area of the engine performance map being of interest to us with measuring points. The mean value or rotational speed and its change in unit of time were adopted as the leading parameters which have a dominating influence on, and result in a reduction of the effective efficiency of the engine. To improve the accuracy of calculations, the variable driving cycle consists of driving phases and idle running. The volume of fuel consumed, not accounted for in the driving phases, being the difference between the calculated and consumed fuel, is a measure of reduction of the effective efficiency of the engine, whilst the unit power of additional motion resistance of the vehicle (a*v) is a leading parameter in the analyses of the calculation results.*

Keywords: *B.S.F.C. map, specific fuel consumption, effective efficiency*

1. Introduction

In terms of the information characterizing the operation of the vehicle engine, its performance maps form the basic source of knowledge about the parameters of its operation field, such as the mean effective pressure and torque, brake horsepower and brake specific fuel consumption (BSFC), g_e [1, 2, 3, 4]. By using g_e, it is possible to calculate the effective efficiency and determine the course of economical and dynamic steering lines [5]. However, each of these parameters was determined for static conditions of the engine operation, later in the text called "stationary conditions". In fact, such a mode of engine operation in a car is rarely to be met with. The engine load performance for individual gear ratios of a B/K class car with a 1.6 SI engine in real motion is well illustrated in Fig. 1 [6].

The attempts made to identify the engine parameters in nonstationary operating conditions have not yielded any radical solutions, except for concepts such as "quasi-stationary" conditions of engine operation or the power reduction ratio, υ, in nonstationary operating conditions [7, 8, 9].

The first of the concepts, which the author attempted to define in paper [6], is connected with a very important identification of the scope of using the engine performance map to determine the effective efficiency of the engine. Its determination for very complex nonstationary conditions in real motion is extremely difficult without adopting some simplifications.

In practice, without special control instruments, there is no possibility to maintain the nonstationary operating conditions of the engine which depend on one of the two parameters: the rotational speed or load. While the rotational speed increases monotonically as the car accelerates, the load does not (Fig. 1).

The author has developed a research methodology and measurement technology which bring the problem nearer the solution. This gives us hope that an algorithm can be elaborated to calculate the effective efficiency of the engine in any operating conditions. The basis of the calculations consists of unconventional road tests regarding fuel consumption of a car in a variable driving cycle. In the calculations, the effective efficiency calculated on the basis of the engine performance map is used as the reference value. The author's scientific achievements in the scope of the applications of engine performance maps meet the general trend towards reducing research costs and performing tests on objects at their design stage.

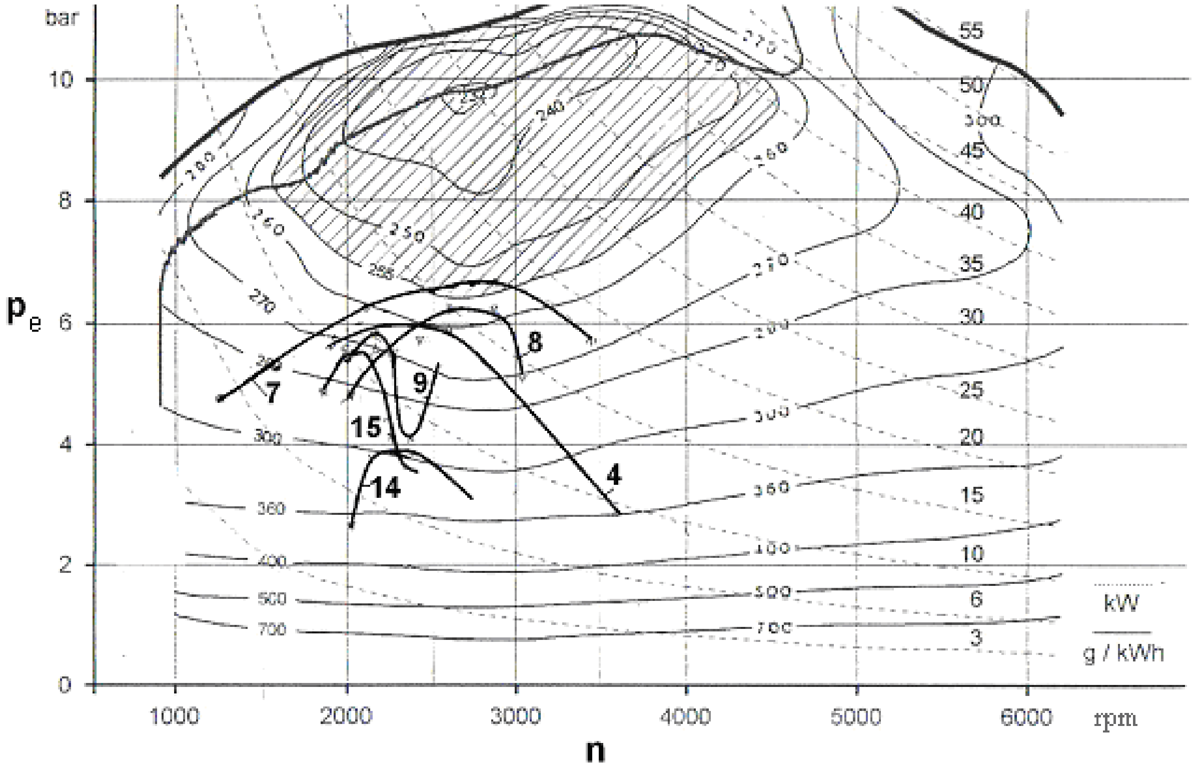

Fig. 1. Selected operation points of a 1.6 SI engine on a performance map during acceleration of a B/K class car in 1st (7), 2nd (4, 8, 14) and 3rd (9, 15) gears

2. Investigation program

Measurements taken during road tests in a variable driving cycle were an important chapter in the research on transient fuel consumption. The variable driving cycle simulated the traffic conditions in a built-up area. The purpose of the measurements made on two different, geodetically characterized, road sections (Fig. 2) was to optimise the car speed control techniques. The variable driving cycle is characterized by varied acceleration dynamics of the car (a*v) until a given speed. In the longest driving phase, '4', three techniques of speed control were applied: continuous drive, braking with engine and a drive in neutral gear.

The so conducted research scheme allows covering the engine performance map area being of interest to us with measuring points and eliminates the characteristic fluctuation of the speed profile in the range imposed by homologation requirements.

Owing to the research method developed it was possible to apply the author's method of optimising the transient fuel consumption in a variable driving cycle and in the longest transient phase "4", depending on the unit power of additional motion resistance - (a*v), where $a^* = (a \cdot \delta + g \cdot \sin\alpha)$ [10, 11].

However, the greatest achievement of the testing technology developed is the method to calculate the reduction of effective efficiency of an engine in nonstationary operating conditions. This method enables determination of the effective efficiency of the engine depending on the changes

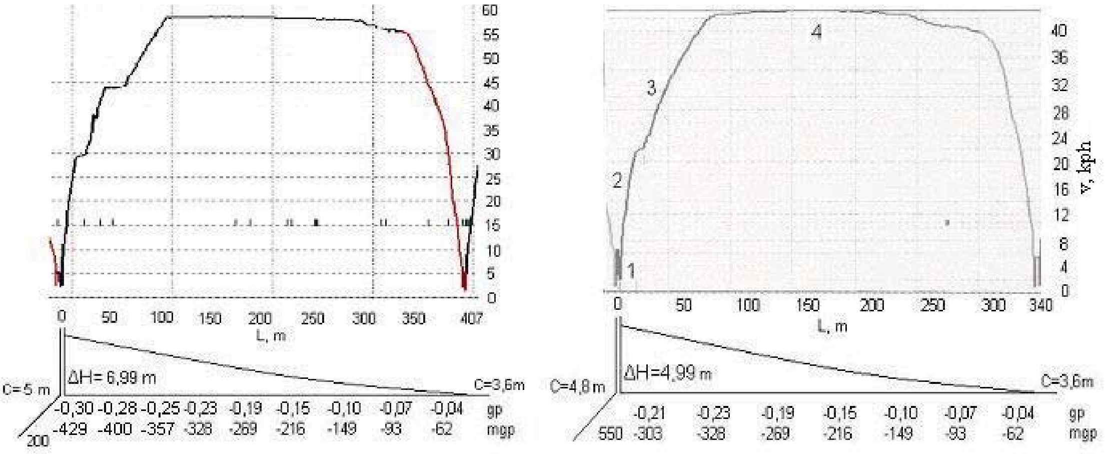

Fig. 2. Speed profile in a variable driving cycle realised on measuring section 'H'using 3 speed control techniques in transient phase '4'

in the engine speed, ν_n, and load, ν_M. In the calculations, the effective efficiency calculated on the basis of the original engine performance map is used as the reference value.

The calculations where conducted using the total energy efficiency of motion for variable driving cycles, with engine driving phases and engine operation phases during idle running, with the main share of drive in neutral gear. Constant load of the engine in the driving phases of successive driving cycles was determined through changing the maximum inclination angle of the acceleration pedal.

In order to obtain credible results, each measurement was repeated several times. The tests were conducted in a realistic range of values of the unit power of additional motion resistance: beginning from a value at which in third gear, it was possible to slightly accelerate the car when driving "uphill", to a maximum value at which the engine operation was still stable when starting up in first gear [12].

In order to determine the influence of the range of the rotational speed used on a reduction of effective efficiency of the engine, measurements were made for two values of the mean rotational speed for each gear ratio of a transmission: 1800 and 2300 rpm (Table 1).

Table 1. Acceleration ranges of a B/K class car in a variable driving cycle

Nr	Series of measurements	v	$n_{śr}$	Vehicle velocity kph		
		kph	rpm	I	II	III
0	1	2	3	4	5	6
1	$1^{1)}$	0-58	2300	0-25	25-40	40-58
2	$2^{2)}$	0-45	2200	0-20	20-45	-
3	$3^{1)}$	0-58	1800	0-15	15-35	35-58

$^{1)}$ -full driving cycle, $^{2)}$- not a 3rd gear ratios phase

3.Calculation method

For the calculation of efficiency loss of an SI engine in nonstationary operating conditions, variable driving cycles were used where the engine work is limited to two phase types: driving and non-driving phases (idle running, with the main share of neutral gear in phase '4'. A balancing method was applied for the calculations with taking into account the calculated and the measured fuel consumption. A leading parameter in the analyses is the unit power of additional motion resistance (a*v) which characterizes the acceleration dynamics of the car [13, 14].

As the acceleration dynamics of the car grew, an increase was observed in the consumed fuel volume 'not accounted for' in the driving phases above the reference value $G_{ir,ref}$, which is visible in Fig. 3. The flow rate of the fuel consumed, ΔG_{ir}, per unit (a*v), not accounted for in the calculation method of the total energy efficiency of motion, is called the sensitivity coefficient of transient fuel consumption to nonstationary operating conditions of the engine and denoted as $G_{\eta e}$:

$$G_{\eta e} = \frac{\Delta G_{ir}}{\Delta\left(a^* \cdot v\right)}, \quad \frac{cm^3 \cdot kg}{s \cdot W} . \tag{1}$$

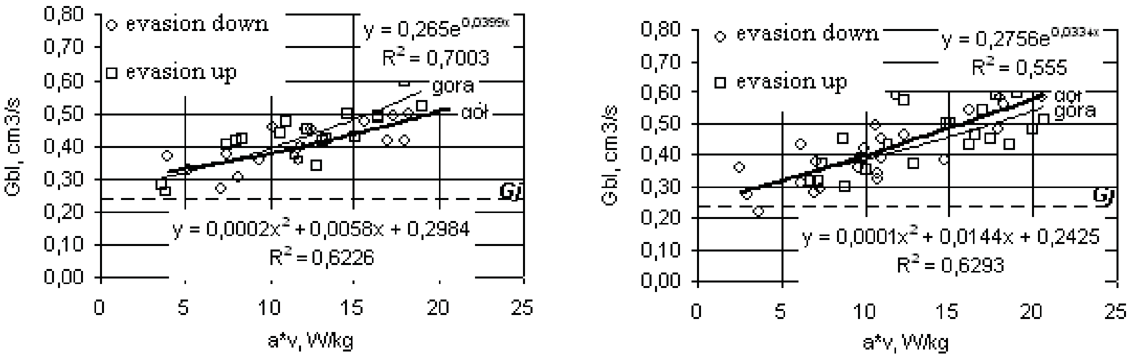

Fig. 3. Characteristics of transient fuel consumption in non-driving phases of a variable driving cycle ($G_{bl} = G_{ir}$, $G_j = G_{ir,ref}$)

A measure of worsening of the effective efficiency of an engine is the value of increase in the transient fuel consumption, G_{ir}, above the reference value $G_{ir,ref}$ = 0.28 cm^3/s. With correct assumptions and calculations, it should take on a form of an asymptote of the maps from Fig. 3. Hence:

$$\Delta G_{ir} = (G_{ir} - G_{ir,ref}) \text{ , } cm^3/s \text{ ,} \tag{2}$$

where:
$(a^*\cdot v)_{av}$ – the average unit power of additional motion resistance of the car, [W/kg],
t_{ir} – duration of non-driving phases, [s],
$G_{ir,ref}$ – transient fuel consumption for reference idle running, [cm^3/s (G_j)],
G_{ir} – transient fuel consumption when idle running, calculated from the driving cycle balance, [cm^3/s(G_{bl})],
$G_{\eta e}$ – coefficient of transient fuel consumption sensitivity to nonstationary operating conditions (as a function of engine speed), [$cm^3\cdot kg/(s\cdot W)$].

The fuel volume, not accounted for as a result of a reduction of the engine effective efficiency in the driving phases with defined acceleration dynamics $(a^*\cdot v)_{av}$ can be calculated from two equations:

$$\Delta V_{\eta e} = (a^*\cdot v)_{av} \cdot t_{ir} \cdot G_{\eta e} \text{ , } cm^3 \text{ ,} \tag{3}$$

or from the definition of the consumed fuel volume ‘not accounted for’:

$$\Delta V_{\eta e} = \Delta G_{ir}\cdot t_{ir} = (G_{ir} - G_{ir,ref})\cdot t_{ir} \text{ , } cm^3 \text{ .} \tag{4}$$

A definition of nonstationary operating conditions of the engine has also been introduced:

$$v_n = \frac{n_k - n_p}{t_k - t_p} \text{ , } \frac{rpm}{s} \text{ ,} \tag{5}$$

where:

n_i, n_f –engine speed at the beginning (initial) and at the end (final) of the driving phase considered, in a given gear, [rpm],

t_i , t_f – time of the beginning and end of the car driving phase examined, [s].

The rightness of the adopted assumptions and of the method to calculate the reduction of engine effective efficiency in nonstationary operating conditions is confirmed by the asymptotic shape of $G_{ir,ref}$ in relation to $G_{\mathbf{ir}}$ maps in Fig. 3.

4. Calculation results

Calculations of fuel consumption for driving phases were made using a numerical method. The rectilinear course of corrective maps of Δg_e was determined from Fig. 4 using the method of calculation error minimisation (column 12, Table 2) of the fuel volume not accounted for, $\Delta V_{\eta e}$, calculated on the basis of individual values for each gear (col. 13) and average values (col. 2) for each cycle (a*v). The dependence of the coefficient of nonstationary operating conditions of the engine, ν_n, on the unit power of additional motion resistance of the car in individual “gears” is presented in Fig. 5. The impact of longitudinal road slope is well visible. For gear 3, the map of $\nu_n = f(a*v)$ was introduced for a horizontal road section in the form of a broken line.

*Table 2. Calculation of the engine effective efficiency reduction for varied unit power of additional motion resistance of a car (a*v)*

Kod	$(a^*\cdot v)_{av}$ W/kg	ΔV_n cm^3	$\Delta V_{\eta e}$ 1) cm^3	1st gear		2nd		3rd		$\Sigma\Delta V_n$ cm^3	$\frac{(4)-(11)}{(4)}$ %	$(a^*\cdot v)_{1,2,3}$ W/kg
				$\Delta g_{e,3}$ g/kWh	$\Delta\eta_{e,śr}$ %	$\Delta g_{e,3}$ g/kWh	$\Delta\eta_{e,śr}$ %	$\Delta g_{e,3}$ g/kWh	$\Delta\eta_{e,śr}$ %			
1	2	3	4	5	6	7	8	9	10	11	12	13
2a	17.9	21.8	5.1	130	12.2	62	7.9	26	3.7	4.8	7.7	16/20.4/17
2b	18.6	28.5	6.5	126	12.5	48	6.2	21	3.2	5.5	15.4	18.2/19/18.3
4a	14.8	21.5	5.7	63	9.7	63	8.0	25	2.1	4.0	30.0	10.5/20/14
4b	16.2	28.4	5.7	110	10.6	44	5.7	20	2.9	4.8	15.8	14/17.7/17
6a	9.9	22.2	2.8	84	7.4	43	4.8	18	2.1	2.8	0	9.2/11/9.3
6b	10.0	35.5	2.3	80	7.1	32	3.7	12	1.5	3.4	-48.0	9/11/10
10a	18.1	21.9	5.1	144	13.8	58	5.0	31	4.4	4.7	7.8	18/18.2/18
10b	20.8	26.9	6.5	150	14.7	50	6.5	25	3.5	6.4	1.5	21.3/19.5/20
14a	9.5	21.1	2.3	87	7.4	38	4.0	16	2.0	2.7	-17.4	8.5/9.8/10
14b	11.4	32.6	2.8	82	8.5	32	3.7	11	1.5	3.8	-35.7	13.4/11/9.5
17a	6.9	22.4	1.7	58	4.7	44	3.9	14	1.5	2.3	-35.3	6.4/7.5/6.8
17b	8.7	29.1	2.2	70	6.7	27	3.0	12	1.4	2.3	-4.5	8.3/8.7/9.1
18a	7.3	22.34	1.8	60	4.8	34	3.3	17	1.9	2.2	-22.0	6/7.6/8.3
18b	7.2	30.7	1.6	56	4.7	24	2.4	6	0.6	1.8	-12.5	6.4/7.3/7.2
19a	7.0	21.2	1.7	56	3.3	28	2.5	15	1.6	1.6	6.0	4.9/6/6.3
19b	6.7	32.6	1.4	60	4.1	19	1.6	9	1.0	3.3	-118	6.4/7.8/7.8

1)– the “not accounted for” fuel volume $\Delta V_{\eta e}$ calculated on the basis of the coefficient of sensitivity, $G_{\eta e}$ to an increase in the unit power of additional motion resistance $G_{\eta e} = 0.011$ cm^3 ·kg/s/W

Based on the BSFC maps in Fig. 4 and 5, it is possible to determine the maps of effective efficiency reduction of the engine, $\Delta\eta_e$ depending on the unit power of additional motion resistance (a*v).

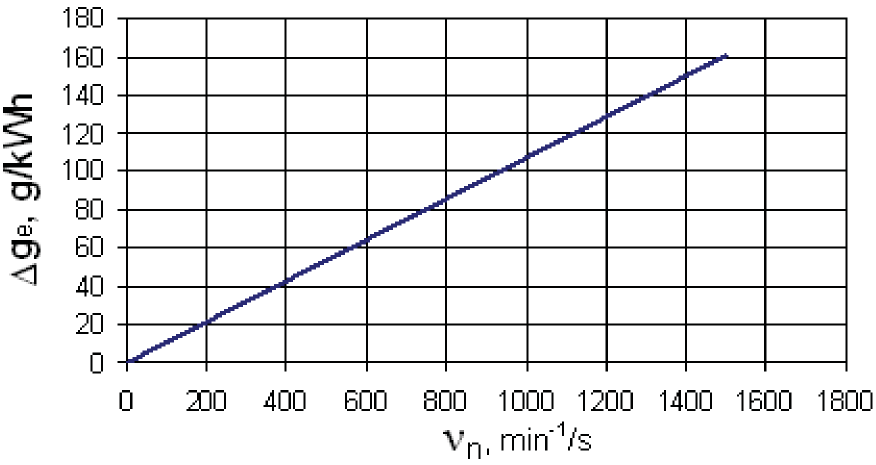

Fig. 4. Maps of BSFC increase, Δg_e depending on the factor of non-stationary operating conditions of the engine, ν_n (n_{av} = 2300 rpm (=min^{-1}))

The grey areas in Fig. 6 were determined for an analogical variable driving cycle, but with the car accelerating up to 45 kph in first two gears only (on a road section "H" shortened to 340 m). The performance maps for the lowest gear ratios were calculated based on the falling trend in engine efficiency in subsequent gear ratios. A transient form of the maps of the effective efficiency reduction in nonstationary operating conditions from Fig. 6 consists of the maps obtained based on the calculation results from Table 2, presented for two gears in Fig. 7.

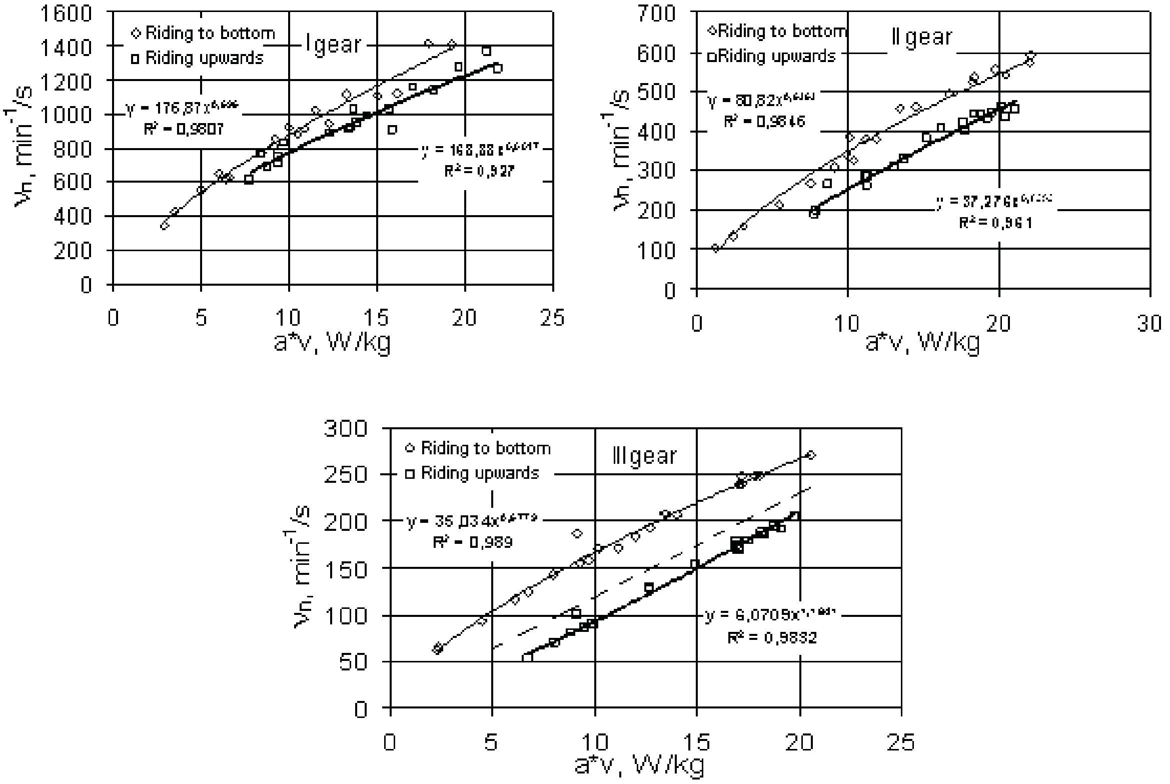

Fig. 5. The dependence of the coefficient of nonstationary operating conditions of the engine, ν_n, on the unit power of additional motion resistance of the car in individual "gears" (n_{av} = 2300 rpm (= min^{-1}))

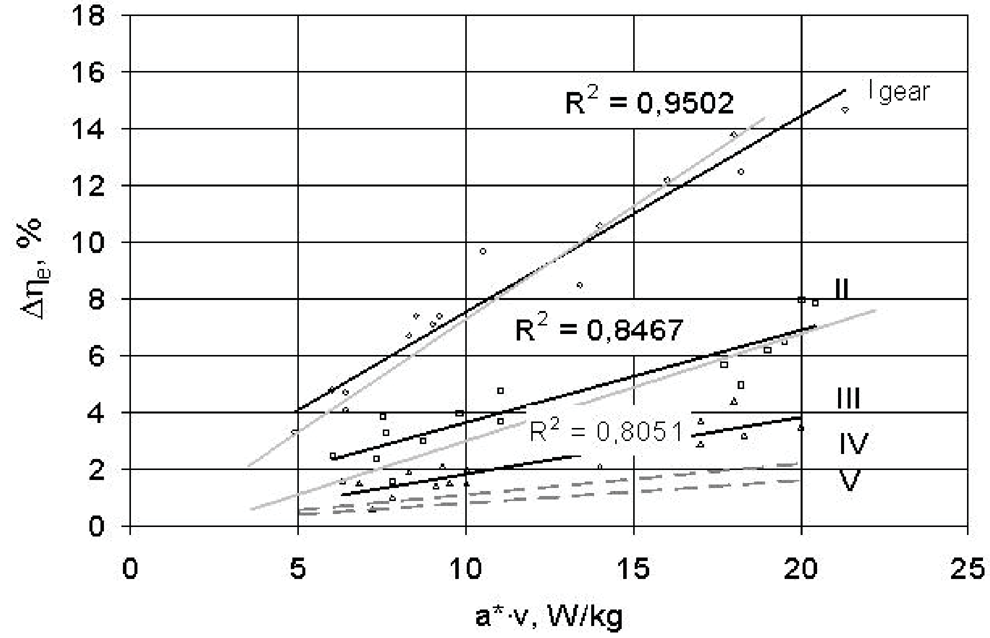

*Fig. 6. The characteristics of effective efficiency reduction of the engine, Δ η_e depending on the unit power of additional motion resistance (a*v)*

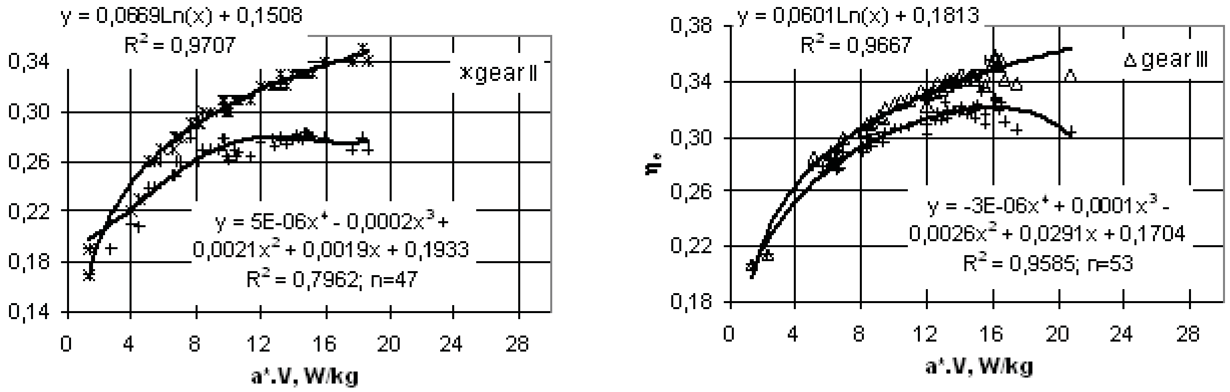

Fig. 7. A transient form of the maps of the effective efficiency reduction in nonstationary operating conditions from Fig. 6 consists of the maps obtained based on the calculation results from Table 2

A 2% deviation of the calculated effective efficiency from its value resulting from the engine performance map was accepted as permissible. This range allowed defining the engine operation conditions at a boundary of stationary and nonstationary modes of operation. In the paper, this range is defined as quasi-stationary conditions of engine operation [7].

Analogical measurements and calculations in individual gears were conducted in a variable driving cycle for an engine operating at a lower average speed (1800 rpm). Maps of Δg_e increase for both speeds are presented in Fig. 8.

Their course confirms the principle of adaptive control of fuel injection, according to which the engine speed is a leading control parameter: a reduction of the engine speed slows down the operation time of adaptive control of fuel injection, the task of which is to bring the fuel blend composition to a stoichiometric value in the shortest time possible [15, 16]. The above two maps perfectly inscribe into a map of Δg_e increment in the tested range of SI engine operation. This increase is defined by equation (6), visualised in Fig. 8.

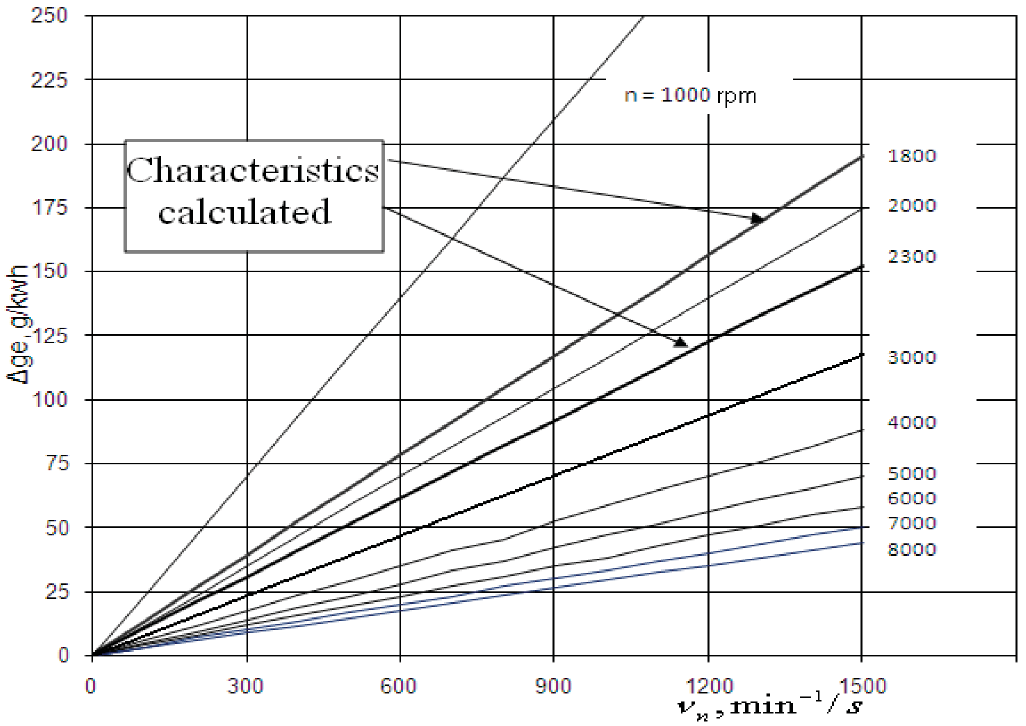

Fig. 8. Map of increase in the specific fuel consumption Δg_e from the performance map of the 1.6 SI engine from Fig.4 in nonstationary operating conditions (min^{-1} = rpm)

Equation (1) has the following general form:

$$\Delta g_e = A\cdot \nu_n/n, \tag{6}$$

which is the effect of the assumption that:

$$\Delta g_e\cdot n_{av} = const., \tag{7}$$

where:

A = 233 (g·s)/(kW·h) – proportionality factor for the SI engine tested,
ν_n – coefficient of nonstationary conditions of engine operation depending on the engine speed, [rpm/s],
$n_{śr}$ – average engine speed, [rpm].

The proportionality factor A has physical significance in the equation. If the units of time are reduced in the numerator and denominator, the result is:

$$A = 0.065 \text{ g/kW}. \tag{8}$$

For a 1.6 dm^3 SI engine it expresses the increase in fuel consumption per unit of brake horsepower, caused by adaptive control of fuel injection in nonstationary operating conditions.

5. Conclusions

1. The concept of studies adopted, based on the calculation of the total energy efficiency of car motion in selected and variable driving cycles on the basis of original or adapted engine performance maps, has proven legitimacy of the method developed to calculate the effective efficiency of the engine in real operating conditions of a car.
2. The development of a method for measuring and calculating the mutual dependence between the effective efficiency of the engine and the coefficient of nonstationary operating conditions

adopted in the considerations has the greatest scientific value. In addition, a mutual dependence between the effective efficiency of the engine and its average speed has been proven.

3. High accuracy of the test results was verified using statistical methods.
4. The author’s scientific achievements meet the general trend for reducing research costs and performing tests on objects at their design stage. The work done by the author allowed making use of engine performance maps to plot a map of the impact of nonstationary operating conditions on the effective efficiency of the engine. Moreover, the method developed may be applied and used widely.

References

[1] Mysłowski, J., *Doładowanie silników*. WKŁ, Warszawa 2002.

[2] Siłka, W., *Energochłonność ruchu samochodu*, WNT, Warszawa 1997.

[3] Romaniszyn, K., *Ocena różnic w określaniu zużycia paliwa samochodu na podstawie charakterystyki uniwersalnej i dynamicznej*, Silniki Spalinowe, No 2, pp. 48-54, 2004.

[4] Ubysz, A., *Method of generating B.S.F.C. map of car engines*. Kongres PTNSS–2009–SC–147, Combustion Engine 2009-SC1, pp. 323-330, Opole 2009.

[5] Jantos, J., *Ekologizacja samochodu przez zastosowanie sterownika momentu obrotowego,* III Ogólnopolska Konferencja Naukowo-Techniczna „Pojazd a Środowisko”, pp. 175-182, Radom 2001.

[6] Ubysz, A., *Wyznaczanie kwazistacjonarnych warunków pracy silnika ZI w samochodzie,* Czasopismo Techniczne Mechanika z. 8-M, pp. 123-131, 2008.

[7] Arczyński, S., *Mechanika ruchu samochodu*, WNT, Warszawa 1993.

[8] Romaniszyn, K., *Alternatywne zasilanie samochodów benzyną oraz gazami LPG I CNG*, pp. 178, WNT Warszawa 2007.

[9] Kropiwnicki, J., *The aplication of spline funktion for approximation of engine charakterystics.* Archiwum Motoryzacji, No 4, pp.235-242, 2004.

[10] Ubysz, A., *Sprawność efektywna silnika ZI samochodu osobowego w dynamicznych warunkach pracy*, Diagnostyka No 1 (45), pp. 69-73, 2008.

[11] Ubysz, A., *Optymalizacja zużycia paliwa w samochodzie osobowym w ruchu na obszarze zabudowanym*, Diagnostyka No 1 (45), pp. 65-72, 2008.

[12] Mamala, J., Jantos, J., *Bezwładność mechaniczna układu napędowego w procesie przyspieszania*, PAN Oddział w Krakowie, Teka Komisji Naukowo-Problemowej Motoryzacji, z. 6-M/2008, pp. 167-178, Kraków 2008.

[13] Ubysz, A., *Studium przebiegowego zużycia paliwa w samochodzie w warunkach rzeczywistych*, Manuskrypt wydawniczy rozprawy habilitacyjnej, Katowice 2007.

[14] Ubysz, A., *New insights into energy-saving aspectof car engine performance on the basis of S.F.C. map*. Kongres PTNSS–2009–SC–180, Combustion Engines 2009-SC1, pp. 408-415, Opole 2009.

[15] Kneba, Z., Makowski, S., *Zasilanie i sterowanie silników,* WKŁ, seria: Pojazdy Samochodowe, WKŁ, Warszawa 2004.

[16] Wendeker, M., *Sterowanie wtryskiem benzyny w silniku samochodowym.* Lubelskie towarzystwo Naukowe, Politechnika Lubelska, Lublin 1999.