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Assessment of increased energy efficiency of vehicles with a rational reduction of engine capacity

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Annotation. Problem. *The tendency to reduce Engine displacement, which has emerged in recent years in the global automotive industry, is due to the need to improve the environmental situation and energy efficiency of vehicles.* ***Goal.*** *The aim of the study is to increase the energy efficiency of vehicles by rationally reducing the maximum effective engine capacity.* ***Methodology.*** *In the paper authors used the method of partial accelerations implemented in a mobile registration and measurement complex, which allowed authors to obtain an improved formula for calculating aerodynamic drug. Experimental studies of car aerodynamics were also conducted.* ***Results.*** *In the study presents the results of the authors' research, which made it possible to prove the possibility of reducing the e internal combustion engine capacity while maintaining the specified maximum speed and the specified level of indicators of the car dynamic properties.* ***Originality.*** *The relationship between the use of maximum engine capacity and the relative change in the effective specific fuel consumption of a carburetor gasoline engine, with direct injection of gasoline and diesel were determined.* ***Practical value.*** *Calculations performed on the example of the ZAZ-1103 "Slavuta" car showed that a rational reduction in effective engine capacity allows to reduce fuel consumption by 9.5% for carburetor gasoline engine, and for an engine with direct injection of gasoline by 6.7 % and for diesel engines, by 20.3%.*

Key words: *energy efficiency, vehicle, internal combustion engine, aerodynamic drag, fuel consumption*

Introduction

The tendency to reduce the capacity of internal combustion engines, which has been observed in recent years in the global automobile industry, is due to the need to improve the environmental conditions and energy efficiency of vehicles. In the paper authors presents the results of the research, which allowed them to prove the possibility of reducing the capacity of the internal combustion engine while maintaining the specified maximum speed and the specified level of indicators of the vehicles dynamic properties. The relationship between the increase in the degree of use of the nominal internal combustion engine capacity and the change in the effective specific fuel consumption for a carburetor gasoline engine, an engine with direct gasoline injection, and a diesel engine is determined.

Analysis of publications

Energy efficiency is an operational property that characterizes the rational use of engine energy (or another source of mechanical energy) in the process of vehicle operation. The energy consumption of limited and high cross-country vehicles during operation, on paved roads and off-road, was determined in [1]. In the paper [2] it is shown that the energy efficiency of a car is largely determined by the degree of its aerodynamics, which has become an attribute of almost all recognized design solutions. From this, we can come to the disappointing conclusion that aerodynamic drag indicators are decisive in evaluating the energy efficiency of vehicles. The work [3] presents scientific and technical developments dedicated to improving the energy efficiency of vehicles.

In the paper [4] research is devoted to the development of new indicators and criteria of energy efficiency of vehicles. The need for a new approach to energy efficiency assessment is due to the appearance of vehicles with alternative energy sources. In the paper [4], it is proposed to consider not fuel consumption, but energy consumption as indicators of the economy of vehicles.

In the paper [5-7] studies are devoted to the energy efficiency of vehicles using the indicators and criteria proposed in [4], in which vehicles with a mechanical drive, as well as hybrid vehicles and electric vehicles are considered.

At the beginning of the creation of automobile theory [8] by experts in the field of aviation, a calculation formula for aerodynamic drag was proposed

$$P_W = \frac{C_x}{2} \rho F V_a^2 , \qquad (1)$$

where C_x is the coefficient of frontal aerodynamic resistance; ρ is air density; F is the midel (frontal area) of the vehicle; V_a is vehicle speed.

Since that time, when calculating the aerodynamic drag, engineers, taking the value of the index degree at V_a equals 2, believed that the value of C_x should be chosen in the calculations depending on the speed of the vehicle. But then, everyone forgot about this and began to accept C_x at some constant value of speed, spreading the use of the specified value of C_x throughout the entire speed range of the vehicle.

The well-known German scientist Alfred Jante [9], who studied vehicles in detail in the wind tunnel, recommended determining the C_x coefficient at an air blowing speed equal to 10 m/s.

The papers [10-15] are devoted to the method of experimental investigation of vehicles aerodynamics. A huge amount of material was accumulated to determine the constant value of C_x for various vehicles.

The use of the method of partial accelerations, implemented in a mobile registration and measurement complex, allowed the authors of [16] to obtain an improved equation to calculate the force of aerodynamic drag, which has the form

$$P_W = \frac{A_w}{2} \rho F V_a^{2-n} , \qquad (2)$$

where A_w is the coefficient of regression corresponding to the value of the coefficient of frontal aerodynamic drag at V_a=1 m/s.

The equation (2) under consideration corresponds to the law of change of the coefficient of frontal aerodynamic drag, which has form

$$\hat{C}_x = \frac{A_w}{V_a^n} , \qquad (3)$$

where n is the index of degree (regression coefficient).

In the paper [18], using the method of partial accelerations and a mobile registration and measurement complex, conducted experimental studies of 9 models of passenger cars. As a result, the coefficients A_w and n were determined (Tabl. 1).

Table 1. Results of determining A_w and n [18]

Car brand	A_w	The index of degree n
VAZ-2170 «Priora»	3.60484	0.977252
VAZ-2110	2.697116	0.877632
VAZ -2111	11.41	1.298592
VAZ -2115	8.000009	1.124172
VAZ -2121	5.401333	0.947272
ZAZ-1103 «Slavuta»	3.837434	1.151153
Toyota Corolla E110	2.385834	0.903548
Daewoo Lanos	1.822555	0.808
VAZ-2107	1.897	0.866

Graphs of dependence (3) for 9 passenger car models studied in [17] are presented in Fig. 1

By the co-authors of the article Podrigalo M.A. and Tkachenko A.S. were previously obtained equations to determin the maximum power of the engine with the traditional calculation of the force of aerodynamic drag according to equation (1) and with the refined calculation according to equation (2). The ratio between the calculated maximum effective power of the engine, calculated according to the traditional method using equation (1) and the refined one proposed by the authors, has the form

$$N''_{e\max} = N'_{e\max} - \frac{C_x \rho F}{8} V_{a\ \max}^3 \times \\ \times \frac{1 - \dfrac{A_w}{C_x(1-0.25n)} V_{a\ \max}^n}{\eta_{tr}^{mgn} \times \eta_k^{mgn} \times \lambda N} , \qquad (4)$$

where $N'_{e\max}$ is the maximum effective engine capacity, which is determined by the traditional calculation of the force of aerodynamic drag according to equation (1); $N''_{e\max}$ the maximum effective engine capacity, which is determined by the refined calculation of the force of aerodynamic drag according to equation (2); $\eta_{tr}^{mgn}, \eta_k^{mgn}$ are instantaneous efficiency of the transmission and wheels of the vehicle; λN is the ratio of the effective power of the engine n_e developed at a given speed V_a to $N_{e\max}$.

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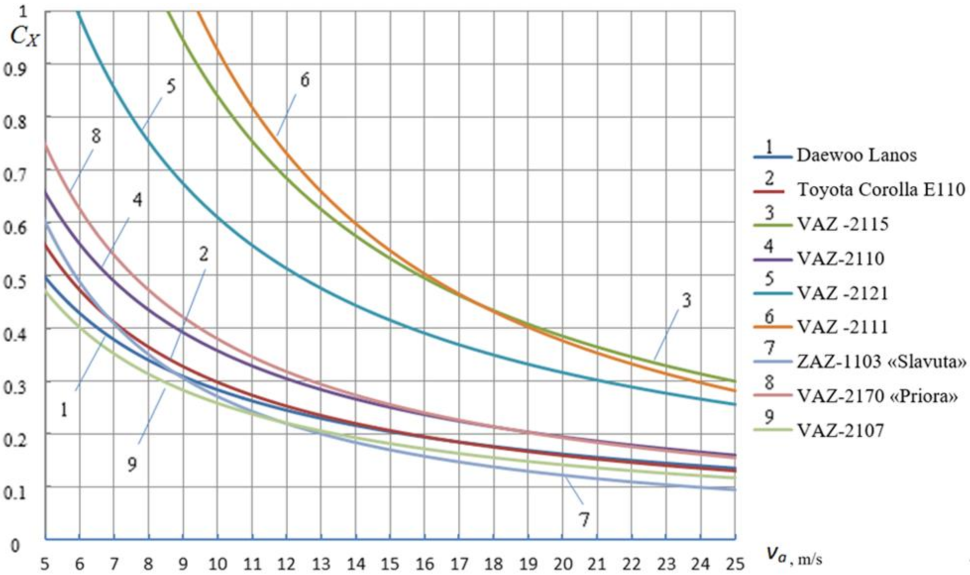

Fig. 1. Dependence of the coefficient C_x on speed [18]

The ratio between the calculated maximum effective power of the engine, calculated according to the traditional method using equation (1) and the refined one proposed by the authors, has the form

$$N''_{e\max} = N'_{e\max} - \frac{C_x \rho F}{8} V^3_{a\max} \times \frac{1 - \dfrac{A_w}{C_x(1-0.25n)} V^n_{a\max}}{\eta_{tr}^{mgn} \cdot \eta_k^{mgn} \cdot \lambda N}, \quad (4)$$

where $N'_{e\max}$ is the maximum effective engine capacity, which is determined by the traditional calculation of the force of aerodynamic drag according to equation (1); $N''_{e\max}$ the maximum effective engine capacity, which is determined by the refined calculation of the force of aerodynamic drag according to equation (2); $\eta_{tr}^{mgn}, \eta_k^{mgn}$ are instantaneous efficiency of the transmission and wheels of the vehicle; λN is the ratio of the effective power of the engine n_e developed at a given speed V_a to $N_{e\max}$.

Regardless of whether the calculation of the necessary maximum engine capacity was carried out using the traditional or refined method of determining the force of aerodynamic drag, the actual consumption of engine capacity when the vehicle is moving at maximum speed will be the same. Only the degree of utilization of the maximum effective capacity of the engine will differ. Suppose that in the case of a refined calculation of the maximum effective power of the engine, an increase in the degree of its use at the maximum speed of the vehicle, a decrease in fuel consumption will occur.

Purpose and Tasks

The aim of the study is to increase the energy efficiency of vehicles by rationally reducing the maximum effective capacity of the engine.

To achieve the goal, the following tasks must be solved:

– to determine the relationship between the degree of use of the maximum effective engine capacity and the effective specific fuel consumption;

- to evaluate the reduction of fuel consumption of the vehicle with a rational reduction of the maximum effective engine capacity.

Determination of the relationship between the degree of use of engine capacity and effective partial fuel consumption

To solve the problem, let us use the load characteristics of carburetor gasoline and diesel engines given in [18]. In Table 2 shows the main indicators of a carburetor engine at throttling [18].

Analysis of the data in Table 2 [18] shows that throttling of a carburetor gasoline engine (CGE) leads to a decrease in the indicator and effective capacity. At the same time, the capacity of mechanical losses remains unchanged, and the specific fuel consumption increases.

Let us enter the notation:

$$\delta N_e = \frac{N_e}{N_{e\max}} - \quad (5)$$

the degree of use maximum effective engine capacity;

$$\delta g_e = \frac{g_e}{g_{eN}} \text{ – relative change in the effective specific engine fuel consumption} \tag{6}$$

where $N_{e,} g_e$ are the current values of effective capacity and specific fuel consumption; g_{eN} the effective specific fuel consumption when realizing the maximum effective capacity of the engine.

In Table 3 shows the calculation of parameters δN_e and δg_e for the CGE presented in the Table 2

In Figure 2 shows the graph of the dependence of the relative change in the effective specific fuel consumption on the degree of utilization of the maximum effective capacity of the CGE.

Table 2. The main indicators of the carburetor engine during throttling [18].

Parameters	Throttle position					
	Open on 100%	Gradual reduction of opening				Idling
Intake pressure, kg/cm^2	0.88	0.8	0.7	0.6	0.5	0.4
Fuel consumption, kg/h	5.0	4.4	3.7	3.0	2.2	1.5
Capacity, hp:						
Indicator	23.0	19.7	15.3	10.9	6.5	2.2
Effective	20.8	17.5	13.1	8.7	4.3	0
Mechanical losses	2.2	2.2	2.2	2.2	2.2	2.2
Specific fuel consumption, g/(kWh)						
Indicated	217	223	241	275	338	680
Effective	240	252	282	345	512	∞
Mechanical efficiency	0.9	0.89	0.86	0.8	0.66	0

Table 3. Calculation of parameters δN_e and δg_e for CGE.

Parameters	Throttle position					
	Open on 100%	Gradual reduction of opening				Idling
Effective capacity N_e, kW	15.29	12.87	9.63	6.40	3.16	0
Efficient fuel consumption g_e,	0.091	0.095	0.107	0.130	0.193	∞
δN_e	1.000	0.842	0.630	0.419	0.207	0
δg_e	1.000	1.043	1.176	1.429	2.121	∞

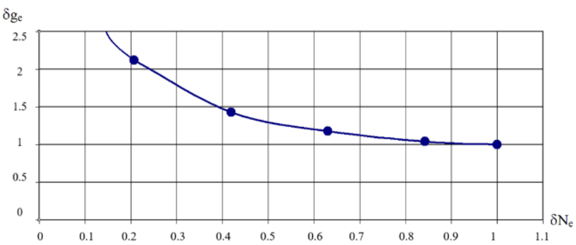

Fig. 2. Dependence of g_e (δN_e) for CBD

To approximate the obtained dependence, it is advisable to use a response function of the form

$$\delta \hat{g}_e = (\delta N_e)^{-n_1}. \tag{7}$$

Using the method of least squares, the optimal regression coefficient n_1=0.453 was determined.

In Table 4 shows the results of the estimation approximation error.

In Figure 3 shows diesel engine load characteristics at the angular speed of the crankshaft ω_e = 136 s^{-1} [18].

In Table 5 shows the main parameters of the tractor diesel under different cyclic fuel supplies.

Table 4. Estimation of the approximation error of the dependence δg_e (δN_e) for CGE.

δN_e	1	1.043	1.176	1.429	2.121
δg_e	1	0.872	0.630	0.419	0.207
$\delta \hat{g}_e$	1	1.081	1.233	1.482	2.041
Relative error of approximation, %	0	3.6	4.8	3.7	-3.8

Table 5. The main parameters of a tractor diesel according to different cycle fuel supplies[18].

Mode	Cyclic fuel consumption G_{mcycle}, mg/(cycle l)	Mean effective pressure p_e		Specific effective fuel consumption g_e	
		kg/sm^2	%	g/(kWh)	%
Economical (points 2 and 2')	35	5	75	205	127
Powerful (points 4 and 4')	60	6.7	100	260	100
Effective (points 3 and 3')	50	6.4	96	220	107

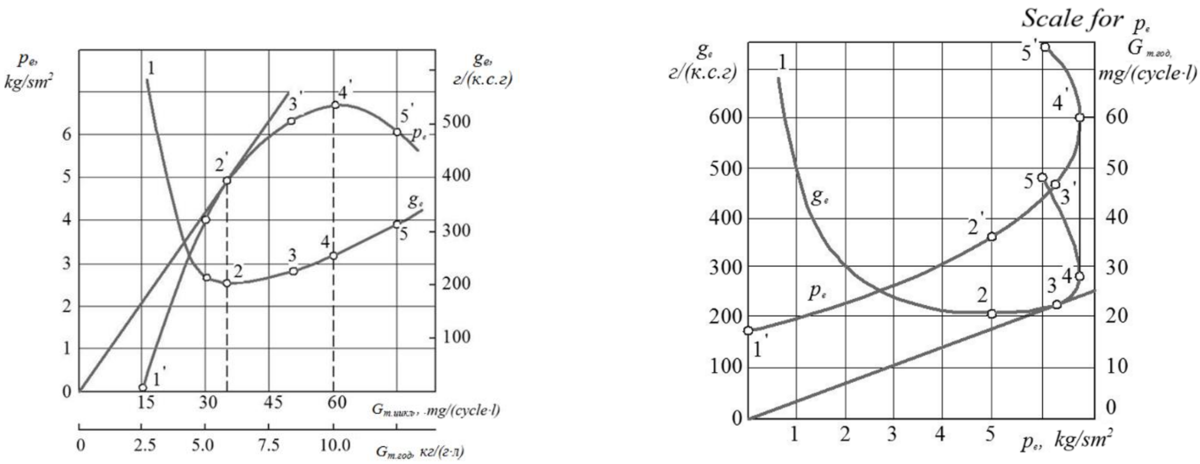

Fig. 3. Diesel engine load characteristics (ω_e =136 s^{-1}) [19]

The results of the processing load characteristics for diesel engine, taken from the work [18], made it possible to obtain the dependence δg_e (δN_e) (Table 6, Figure 4).

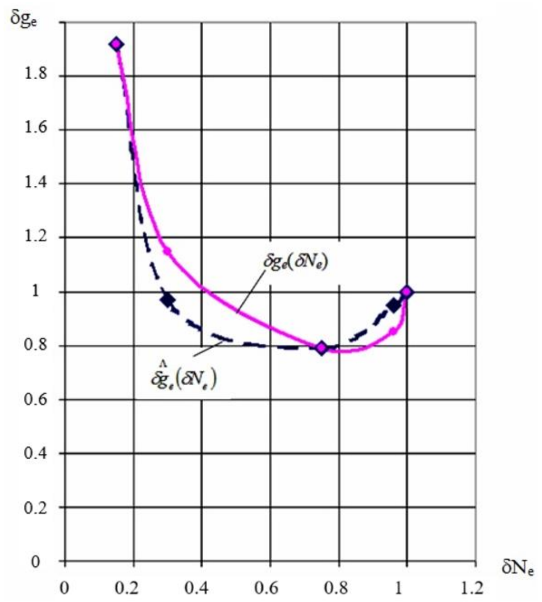

Fig. 4. Dependencies of δg_e (δN_e) and $\hat{\delta g}_e(\delta N_e)$ for diesel engine [19]

Table 6 shows the results of estimation of the approximation error. The average error of approximation for 5 points is 5.47%, which is acceptable. Figure 4 shows the dependences of δg_e (δN_e) and for diesel engine presented in [18].

Table 6. Determination of the dependence of δg_e (δN_e) for diesel engine.

δN_e	0.15	0.30	0.75	0.96	1.0
δg_e	1.92	1.15	0.79	0.85	1.0
$\hat{\delta g}_e$	1.92	0.97	0.79	0.95	1.0
Relative error of approximation, %	0	-15.65	0	11.7	0

As a result of approximation by three points (δN_e=1.0; δN_e=0.75; δN_e=0.15) a response function was obtained, which has the form

$$\hat{\delta g}_e = 0.063^{1-\delta N_e}\cdot\left(\delta N_e\right)^{-1.58} \quad (8)$$

For engine with direct gasoline injection, we use the load characteristic obtained by professor A.A. Prokhorenko and associate professor O.P. Kuzmenko.

In Table 7 shows the results of the calculation of the parameter δg_e at the angular crankshaft velocity ω_e =419 s^{-1}

Table 7. Calculation of the parameter δg_e depending on δN_e for an engine with direct gasoline injection at ω_e =419 s^{-1}.

δN_e	0.185	0.298	0.400	0.519	0.653	0.795	0.891	0.982	1
δg_e	1.557	1.227	1.107	1.009	0.960	0.916	0.906	0.888	1
$\hat{\delta g}_e$	1.463	1.268	1.161	1.074	1.002	0.945	0.913	0.887	1
Relative error of approximation, %	-6.0	3.3	4.9	6.44	4.4	-3.16	0.77	-0.11	0

In Figure 5 shows the dependence graph of δg_e (δN_e), made according to the calculation results given in Table 7.

The analysis of the course of the curve presented in Figure 5 shows that with δN_e=1 point of the curve falls out and the curve δg_e (δN_e) has a break. And here a partial-linear approximation is proposed, i.e.

$$\delta \hat{g}_e = \begin{cases} 1 - \text{when } \delta N_e = 1; \\ A \cdot (\delta N_e)^{-n_1} - \text{when } \delta N_e < 1. \end{cases} \quad (9)$$

Construction of the response function by selecting one nodal point δN_e =0.982 (see Table 7) and selecting the degree n allowed to obtain A=0.882 and n_1=0.3, i.e.

$$\delta \hat{g}_e = \begin{cases} 1 - \text{when } \delta N_e = 1; \\ 0.882 \cdot (\delta N_e)^{-0,3} - \text{when } \delta N_e < 1. \end{cases} \quad (10)$$

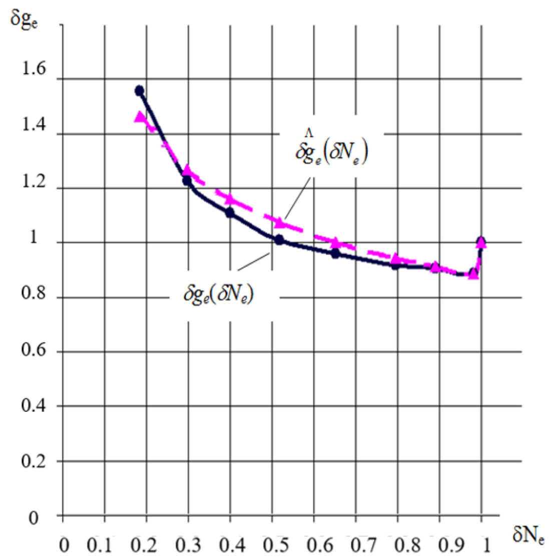

Fig. 5. Graph of dependence δg_e (δN_e) for an engine with direct gasoline injection

Calculations of values $\delta \hat{g}_e$ for different values of δN_e are given in table 7. There is also an estimate of the calculation error based on the approximating dependence. Table 7 shows that the maximum error of calculation exceeds 6.44%.

Figure 5 shows the dependence $\delta \hat{g}_e(\delta N_e)$ graph for an engine with direct gasoline injection.

A comparative analysis of the course of the δg_e (δN_e) curves for different types of internal combustion engines shows (see Tables 3, 6, 7) that for the CGE, a decrease in the degree of utilization of the maximum effective engine capacity δN_e causes an increase in the effective specific fuel consumption δg_e. A different situation with diesel engine and the engine with direct gasoline injection. In a diesel engine at δN_e = 0.3-0.96. Value δN_e<1. In an engine with direct gasoline injection, δN_e<1 at δg_e =0.653-0.982.

Estimation of fuel consumption reduction with a rational reduction of the maximum effective engine capacity

Given that with a rational reduction of engine capacity $N''_{e\max} < N'_{e\max}$, let us determine δN_e from equation (4).

$$\delta N_e = \frac{N''_{e\max}}{N'_{e\max}} = 1 - \frac{C_x \rho F V^3_{a\max}}{8N'_{e\max}} \times \\ \times \frac{1 - \dfrac{A_w V^n_{a\max}}{C_x(1-0.25n)}}{\eta^{mgn}_{tr} \cdot \eta^{mgn}_k \cdot \lambda N}. \quad (11)$$

Let us evaluate the fuel consumption reduction for the car ZAZ-1103 "Slavuta" with a rational reduction of engine capacity. The initial data for the calculation are given in Table 8. When the car ZAZ-1103 "Slavuta" moves, the power consumption both with installed engine with $N'_{e\max} = 45$ kW and the engine with $N''_{e\max}$ is the same and equal $N'_{e\max}$.

But in the second case δN_e=1, and in the first case δN_e<1.

Table 8. Initial data for calculating the reduction of the effective specific fuel consumption of the car ZAZ-1103.

Parameters	$N'_{e\max}$, kW	ρ, g/m^3	F, m^2	$V_{a\max}$, m/s	A_w (m/s)^n	C_x	n	η^{mgn}_{tr}	η^{mgn}_k	N_N
Parameter values	45	1.225	1.753	40.83	3.837	0.375	1.151	0.85	0.9	0.85

The calculation according to equation (11) showed that for the car ZAZ-1103 "Slavuta" with serial engine capacity $N'_{e\max} = 45$ kW, the level of its use is δN_e =0.818.

In this case, the increase in effective specific fuel consumption (compared to δN_e =1) is: $\delta \hat{g}_e = 1.095$ – for CGE; $\delta \hat{g}_e = 0.937$ – for direct injection of gasoline; $\delta \hat{g}_e = 0.831$ – for a diesel engine.

The analysis of the calculation results shows that with a carburetor gasoline engine, a rational reduction of the maximum effective capacity allows to reduce the effective specific fuel consumption by 9.5%. This value is proportional to the absolute fuel consumption (if the effective capacity of the engine is equal). It follows that the expected reduction in fuel consumption will also be 9.5%.

When using engines with direct gasoline injection, on the contrary, a decrease in the maximum effective capacity of the engine will lead to an increase in the effective specific fuel consumption. This increase will amount to $\hat{g}_e^{-1} - 1 = 0.937^{-1} - 1 = 0.067$ that is, on 6.7%.

A similar situation occurs to ZAZ-1103 "Slavuta" car with diesel engine. In this case, a decrease in the maximum effective power of the engine will lead to an increase in the effective specific fuel consumption by $\hat{g}_e^{-1} - 1 = 0.831^{-1} - 1 = 0.203$ that is, on 20.3%.

Conclusions

The results of well-known scientific investigations allowed us to draw a conclusion about the possibility of a rational reduction of the maximum effective capacity of the engine while maintaining the specified maximum speed and level of dynamic properties of the vehicle.

Since when installing a serial engine and an engine with a reduced value of effective capacity, the realized power is the same, the degree of realization of the maximum capacity is higher in the latter case. The relationship between the degree of use of the maximum engine capacity and the relative change in the effective specific fuel consumption of a carbureted gasoline engine with direct injection of gasoline and diesel is determined.

Calculations performed on the example of the car ZAZ-1103 "Slavuta" showed that a rational reduction of the effective capacity allows for a 9.5% reduction in fuel consumption for CGE, and for an engine with direct injection of gasoline and diesel, this leads to an increase in fuel consumption by 6.7% and 20.3%, respectively.

Acknowledgement

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Conflict of interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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Оцінка підвищення енергоефективності автомобілів при раціональному зниженні потужності двигунів

Анотація. проблема. *Тенденція до зменшення робочого об'єму двигунів внутрішнього згоряння, що намітилася останніми роками у світовому автомобілебудуванні, обумовлена необхідністю покращення екологічної обстановки та енергоефективності автомобільного транспорту.* ***Мета.*** *Метою дослідження є підвищення енергоефективності автомобілів шляхом раціонального зменшення* *максимальної ефективної потужності двигуна.* ***Методологія.*** *У роботі використано метод парціальних прискорень, реалізованого в мобільному реєстраційно-вимірювальному комплексі, що дозволило авторам отримати удосконалену формулу для розрахунку сили аеродинамічного опору. А також проведені експериментальні дослідження аеродинаміки автомобіля.* ***Результати.*** *У статті наведено результати досліджень авторів, що дозволили довести можливість зменшення потужності ДВЗ при збереженні заданої максимальної швидкості та заданого рівня показників динамічних властивостей автомобілів.* ***Оригінальність.*** *Визначено взаємозв'язок між ступенем використання максимальної потужності двигуна та відносною зміною ефективної питомої витрати палива карбюраторного бензинового двигуна з безпосереднім упорскуванням бензину та дизеля.* ***Практична цінність.*** *Виконані на прикладі автомобіля ЗАЗ-1103 «Славута» розрахунки показали, що раціональне зниження ефективної потужності дозволяє для КБД на 9,5% знизити витрату палива, а для двигуна з безпосереднім упорскуванням бензину та дизелів, це призводить до збільшення витрати палива на 6,7% та 20,3% відповідно.*

Ключові слова: *енергоефективність, автомобіль, двигун внутрішнього згоряння, аеродинамічний опір, витрата палива.*

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