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Improvement evaluation methodology of vehicle load and energy efficiency

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Annotation. Problem. *There was a need to expand the well-known concept of vehicle operational properties - fuel efficiency arose in connection with the advent of new alternative power plants (electric motors, flywheel engines, hybrid power plants, etc.), which requires the inclusion of not only the thermal energy of the fuel, but also other types of energy (electrical and mechanical). In the paper the research of choice and justification of the vehicle energy efficiency indicators by assessing the energy costs of the engine for its movement was made. The analysis of the relationship between energy characteristics of dynamics and vehicle efficiency was made.* ***Goal.*** *The aim of the study is to analyze methods for assessing the vehicle energy efficiency. To achieve this goal, it is necessary to determine indicators that will allow a comparative analysis of energy efficiency indicators of various vehicles.* ***Methodology.*** *The approaches taken in the work to solve this goal are based on substantiating the indicators of the energy efficiency of the car by assessing the energy consumption of the engine for its movement.* ***Results.*** *In our opinion, in projecting and evaluating the dynamic properties of vehicles, it is rational to use the energy indicators of the vehicle, for which it is necessary to develop appropriate assessment criteria. Analysis of the results of indicators calculation and, in table 1, has shown that the indicator in comparison with has less dispersion.* ***Originality.*** *The obtained results of the influence of the parameters of vehicles on the level of their energy load shows that the indicator has less dispersion than. In addition, the value does not correlate with the year of manufacture of the vehicle, which allows the use of this indicator at the design stage of vehicles. It is only necessary to set the rational normative value of this indicator.* ***Practical value.*** *The results obtained can be recommended to specialists for use in the design, production, certification and operation of automotive vehicles, vehicle energy efficiency, combined power plant.*

Key words: *dynamic properties, aerodynamic resistance, engine power density, vehicle energy efficiency, car design, fuel efficiency.*

Introduction

The efficiency of any vehicle with an internal combustion engine is determined primarily by its traction and speed properties and fuel economy associated with the consumption of petroleum fuels. Fuel consumption is directly related to the level of perfection and technical condition of the car and its components. Energy costs for the movement of the car consist of the costs caused by overcoming of road and aerodynamic resistances.

The emergence of new alternative power plants (electric motors, hydrogen internal combustion engines, hybrid power plants, etc.), energy sources (batteries, flywheels) has necessitated a revision of the criteria characterizing the energy efficiency of the car.

The dynamic properties of vehicle are determined by engine power and its costs to overcome external and internal resistances. According to the US Environmental Protection Agency [1] only about 12 % – 30 % of the energy from the fuel you put in a conventional vehicle is used to move it down the road, depending on the drive cycle. The rest of the energy is lost to engine and driveline inefficiencies or used to power accessories. Therefore, the potential to improve fuel efficiency with advanced technologies is enormous.

Analysis of publications

The approximate distribution of fuel combustion energy in gasoline engine of a passenger car operating in an urban environment is as follows:

– fuel combustion energy – 100 %;

– energy loss in engine – 68 % - 72 %;

– losses from electrical units (heated seats and steering wheel, lights, etc.) – up to 2 %;

– energy consumption for driving auxiliary mechanisms – up to 6 %;

– energy consumption of vehicle driving wheels (to provide movement) – 12.6 % (aerodynamic drag – 2.6 %; rolling resistance of the wheels – 4.2 %; vehicle acceleration – 5.8 %).

The authors of [2, 3] showed that the most important factor that determines the energy load and energy efficiency of vehicles is the aerodynamic drag. Therefore, the paper proposes to refine the calculation of aerodynamic drag parameters, which allowed to clarify the relationship between the realized effective engine power and the maximum kinetic energy of steady translational motion of the car, it was also found that with increasing car speed engine power and kinetic energy of the car monotonically decreases in the range of real speeds.

However, the generally accepted methods of assessing the energy efficiency and load of the car do not allow to compare the energy efficiency of vehicles whose engines run on different fuels that differ in calorific value. The emergence of electric cars, hybrid cars and cars with inertial energy batteries [4] requires the replacement of the assessment of energy efficiency of the car to more general criteria - energy efficiency, which takes into account energy costs per unit distance traveled by the car.

To evaluate energy efficiency, a number of authors [4] proposed the use of vehicle efficiency. However, there was a problem. If there was no doubt about the value of engine energy consumption, then the value of useful work caused certain difficulties.

Some authors [5] suggested accepting the work spend on moving cargo from point A to point B like useful work. Moreover, air resistance P_w was considered as non-production resistance force, which can be reduced by a rational choice of the vehicle aerodynamic parameters. Since a decrease in non-productive energy costs contributes to an increase of capacity that can be used for vehicle acceleration (improving acceleration dynamics), a number of authors [6] suggested taking the power spent to accelerate the car as useful work.

Nowadays, the rational use of engine capacity is possible while minimizing non-productive losses in the engine and transmission [7]. This approach provides high vehicle energy efficiency [8].

According to J. Matskerl [7] for energy consumption economy, first of all, it is necessary to find out the minimum amount of required to overcome movement resistance, and compare it with the actual energy consumptions. We are talking about wheels rolling resistance, aerodynamic drag, uphill movement resistance and vehicle acceleration consumptions [7].

Purpose and Tasks

The aim of the study is to analyze methods for assessing the vehicle energy efficiency.

To achieve this goal, it is necessary to determine indicators that will allow a comparative analysis of energy efficiency indicators of various vehicles.

The advent of hybrid electric vehicles, and vehicles with inertial energy batteries requires replacement of the indicator fuel economy with more general indicators of energy efficiency.

From the point of view of ensuring the sequence of solving scientific problems related to fuel and energy efficiency, it is necessary to start the study with an assessment of the engine energy consumption for vehicle movement. At the same time, a number of sources of additional engine energy losses during vehicle movement are still unexplored.

Determination of vehicles energy efficiency indicators

Vehicle energy efficiency is largely determined by the degree of its aerodynamics, which has become an attribute of almost all recognized design solutions [8]. It should be noticed that the formula (1) proposed by Chudakov E.A., [9] for calculating the aerodynamic drag force P_w is approximate:

$$P_w = \frac{C_x}{2}\rho F V_a^2 . \tag{1}$$

Studies carried out in [10, 11] using the method of partial accelerations [10] made it possible to propose a more accurate equation:

$$P_w = \frac{C_{xo}}{2}\rho F V_a^{2-n} = \frac{C_{xo}}{2}\rho F V_a^{k}, \qquad (2)$$

where C_{xo} – the value of aerodynamic drag coefficient at $V_a = 1$ m/s; n – the coefficient obtained experimentally; k – the exponent at the base V_a (V_a measured in m/s):

$$k = 2 - n. \qquad (3)$$

For an automobile class B, k = 0.885 and C_{xo} =3.252 (m/s)^n were determined in [10, 11]. Power spent to overcome aerodynamic drag:

$$N_w = P_w V_a = \frac{C_{xo}}{2}\rho F V_a^{3-n} = \frac{C_{xo}}{2}\rho F V_a^{k} + 1. \qquad (4)$$

In the Fig. 1 and 2 shows the dependency graphs $P_w(V_a)$ and $N_w(V_a)$ for automobile ZAZ using equations (1) and (2) [10]

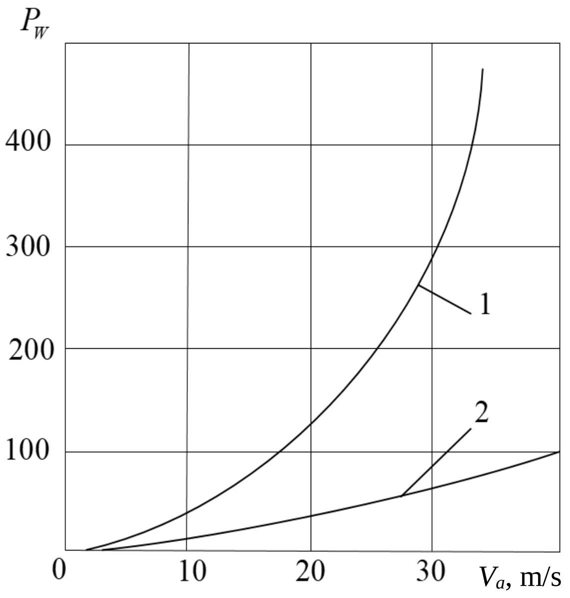

Fig. 1. Dependence graphs aerodynamic drag P_w at vehicle speed V_a: 1 – calculation by equation (1); 2– calculation by equation (2) [10]

Evaluating according to equation (1), the factory data for an automobile class B were used C_x =0.375; F=1.753 m^2 and ρ =0.8 kg/m^3 [24].

In the work [10], after analyzing the graphs presented in Fig. 1 and Fig. 2, it was concluded that for an automobile class B at a speed V_a = 35 m/s (126 km/h), calculation according to equation (2) gives information about a decrease of P_w from 492 N to 81 N in comparison with the results of calculation according to equation (1). The corresponding calculated values of power consumptions N_w are reduced from 17.245 kW to 2.841 kW, i.e. 6 times.

However, evaluation of aerodynamic drag is still making by equation (1), and it does not give an objective assessment of vehicle energy efficiency.

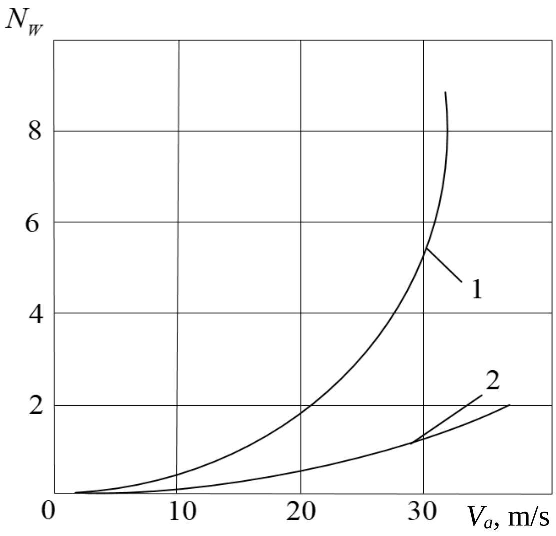

Fig. 2. Dependence graphs of the power consumptions for overcoming aerodynamic drag N_w depending on vehicle's speed V_a: 1 – calculation made by equation (1); 2 – calculation made by equation (2) [10]

In the work [12] Tokarev A.A/ proposed to name the ratio of the capacity consumption spent on vehicle's acceleration to the engine capacity consumptions as intake capacity.

The engine power spent on vehicle's acceleration can be determined by equation [13]:

$$P_{acc} = \frac{m_a V_a \dot{V}_a}{\eta_{fr}}. \qquad (5)$$

For over a century, the history of vehicle existence, it is remained inalienable to use an internal combustion engine as its power plant, despite the relatively low efficiency of using the potential energy potential of oil fuel in it [13]. In addition, ICE generates an uneven torque, it leads to additional energy consumption.

The advent of vehicles with combined power plants (hybrid cars) can reduce additional energy losses caused by uneven torque due to a decrease in the amplitude of oscillation A_p of the traction force.

The choice of engine capacity at the design stage determines the energy efficiency of the vehicle. The paper [16] is devoted to the issues of standardizing indicators of vehicles energy efficiency. In this work, a method for a comprehensive assessment of the impact on the vehicle energy efficiency, improving the design of power plants and the use of alternative fuels taking into account the full life cycle of vehicle was proposed. The work of M.V. Nagaytsev [16] is devoted to the problem of ensuring modern requirements for the energy efficiency of motor vehicles. The work of A.A. Blagonravov and A.V. Yurkevich [17] is devoted to improving the vehicles energy efficiency through the use of continuously variable mechanical gears with adjustable power functions., it was proposed mechanisms to smooth out vibrations in the transmission. At the same time, the transmission efficiency was increased. However, in this works [14–17] the influence of engine power was not considered and recommendations for its choice at the design stage of the vehicle were not given.

Traditionally, at the design stage of vehicle [9], the maximum engine power is selected according to the specified values of the maximum speed $v_{a_{\max}}$ and gross weight m_t:

$$P_{e_{\max}} = V_{a_{\max}} \frac{\left(m_t g \psi_V + \frac{C_x}{2} \rho F V_{a_{\max}}^2 \right)}{\eta_{fr}}, \quad (6)$$

where ψ_V – the coefficient of the total road resistance at $V_a = V_{a_{\max}}$.

It is obvious, that high values of maximum engine power $P_{e_{\max}}$ for new vehicles make it possible to reach high acceleration values during starting from standstill, accelerating and performing various maneuvers. Studies of vehicles actual speeds and accelerations in urban and suburban driving modes made it possible to authors of the work [18] to propose a method for choosing the maximum engine power:

$$P^*_{e_{\max}} = P_{e_1} + P_{e_2}, \quad (7)$$

where P_{e_1} – the engine power realized in the steady-state motion in the urban cycle:

$$P_{e_1} = \frac{\bar{V}_{a_{st}} \left(m_t g \psi + \frac{C_x}{2} g F \bar{V}_{a_{st}}^2 \right)}{\eta_{fr}}, \quad (8)$$

where $\bar{V}_{a_{st}}$ – the mathematical expectation of the average steady-state speed in urban conditions; P_{e_2} – engine power required to realize the maximum linear accelerations of the V_{amax} in urban conditions; using equation (5):

$$P_{e_2} = \frac{m_t \bar{V}_{a_{st}} \dot{V}_{a_{\max}}}{\eta_{fr}}. \quad (9)$$

With the approach proposed in [19], the maximum vehicle speed should be chosen by condition:

$$P_{e_{\max}} = P^*_{e_{\max}}, \quad (10)$$

and, if it is necessary, the maximum engine power can be adjusted in the direction of increasing.

To estimate engine power at the design stage, an indicator – the specific power of vehicle is used [19]. Authors interpret this indicator differently. For example, in the work [20] according to the specific power of vehicle, the ratio of unladed mass to the effective engine capacity. The less the ratio of mass to capacity, the more acceleration value, acceleration intense and ability to overcome uphill moving.

In the work [21], the specific vehicle power is determined by the ratio of the maximum effective engine power $P_{e_{\max}}$ to the vehicle total mass m_t:

$$P_{sp} = \frac{P_{e_{\max}}}{m_t}. \quad (11)$$

Usually passenger cars have a specific power in the range P_{sp} = 15–50 kW/t [21].

The specific power of top-class automobiles manufactured in the USA and racing cars reaches P_{sp} = 150–700 kW/t [21]. In Fig. 3 are shown dependency graphs specific power of trucks and road trains with diesel engines to speed [21].

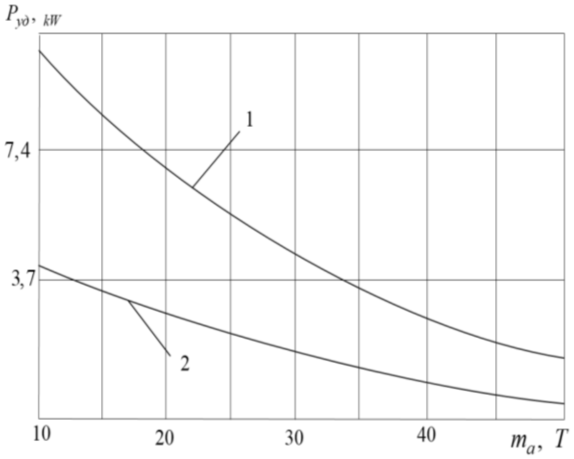

Fig. 3. Dependence graphs of Change in the specific power P_{sp} of trucks and road trains with diesel engines to the mass of the vehicle: 1 – hilly terrain; 2 – plain area [21]

Analysis of the graphs shown in Fig. 3 shows that with an increase of vehicle mass, the value of P_{sp} decrease. It is only possible if the same value of P_{sp} for all vehicles has been taken. And, highly likely, in performing the calculations, it was taken into account actual effective capacity needed to overcome a certain road resistance but not the value of $P_{e_{\max}}$. Thus, the indicators of vehicle specific power do not fully characterize the dynamic properties of vehicle, since they do not take into account its speed capabilities.Taken into account this circumstance, authors of the work [21] proposed a new indicator – the level of vehicle energy loading, determined by the following equation:

$$Y_w = \frac{2P_{e_{\max}}}{m_t V^2_{a_{\max}}}. \qquad (12)$$

In the Table 1 statistical analysis of indicators Y_w for vehicles of various years production [22] is shown. For comparison, in the same table the calculation of the indicator P_{sp} for the same vehicles is shown.

Table 1. The influence of vehicle parameters on the level of their energy loading

Car model	Year of issue	Top speed		Maximum power		Gross weight, kg	Maximum kinetic energy, kJ	Y_w W/J	P_{sp}, kW/t	E_W, J/W
		m/s	km/h	h.p.	kW					
ZAZ Class A	1968	33.33	120	43	32	1080	600	0.053	28.63	18.87
AZLK Class B	1964	33.33	120	50	36.75	1330	739	0.050	27.63	20.00
IZH Class B	1967	38.89	140	75	55	1340	1013	0.054	41.04	18.52
VAZ Class B	1970	38.89	140	60	44	1345	1017	0.043	32.71	23.26
VAZ Class B	2004	47.22	170	91	66.7	1500	1672	0.040	44.77	25.00
GAZ Class D	1965	36.11	130	75	55	1875	1224	0.045	29.33	22.22
GAZ Class D	1968	40.28	145	98	72	1825	1480	0.049	39.45	20.41
GAZ Class F	1959	44.44	160	195	143	2625	2592	0.055	54.48	18.18
ZIL Class F	1963	47.22	170	200	147	3130	3489	0.042	46.96	23.81
ZIL Class F	1967	52.77	190	300	220	3610	5026	0.044	60.94	22.73
HONDA Class S	1999	66.67	240	241	177	1535	3411	0.052	115.3	19.23
VOLVO Class D	2004	58.33	210	180	132	2100	3572	0.037	62.86	27.03

An analysis of indicators $У_w$ and P_{sp}, done in the work [22], showed that the indicator $У_w$ in comparison with P_{sp} has less dispersion.

Authors of the work [22] also proposed an indicator of the vehicle energy efficiency, which is a value inverse to the level of energy loading, i.e:

$$E_W = \frac{1}{У_W} = \frac{m_t V_{a_{\max}}^2}{2 P_{e_{\max}}}. \qquad (13)$$

The dimension of the indicator E_W – J/W (kJ/kW).If we move from the derived SI units to the basic ones, then we get the dimension of time (second). Thus, the energy efficiency indicator proposed in the work [22] is the vehicle acceleration time from V_a = 0 to maximum speed $V_{a_{\max}}$, provided that the entire maximum vehicle effective capacity is spent only on its acceleration. In the table 1 also shown the indicator values $Э_W$ for the considered vehicles, however, in the works [20–22] there are no recommendations on the development of regulatory requirements for the vehicle energy efficiency.

It should be noted that in equations (12) and (13), the main vehicle parameters (m_t; $V_{a_{\max}}$ and $P_{e_{\max}}$) in different way affects the values of $У_w$ and E_W. Therefore, in our opinion, it is necessary to develop a comprehensive indicator in which all parameters (m_t; $V_{a_{\max}}$ and $P_{e_{\max}}$) would have the same effect on the final result.

For a more objective assessment of energy consumptions, we proposed [10] to use the concept of "vehicle energy efficiency" instead of fuel efficiency. The need to expand the well-known concept of operational properties – fuel efficiency has occurred in connection with the advent of new alternative power plants (electric motors, flywheel engines, hybrid power plants, etc.), which requires the inclusion of not only the thermal energy of the fuel, but also other types of energy (electric, mechanical). The proposed indicators [10], on the basis of which it is possible to develop standards (criteria) for the vehicles energy efficiency.

Conclusion

In our opinion, in projecting and evaluating the dynamic properties of vehicles, it is rational to use the energy indicators of the vehicle, for which it is necessary to develop appropriate assessment criteria. Analysis of the results of indicators calculation $У_w$ and P_{sp}, in table 1, has shown that the indicator $У_w$ in comparison with N_{sp} has less dispersion. Expected value (average value estimation) $У_w$=0,047 W/J, and the standard deviation $V'_{yw} = \pm 0{,}006$ W/J, coefficient of variation $У_{yw} = \pm 0{,}128$ [22]. For the same vehicles, the average value of the specific power $\overline{P_{sp}} = 48{,}67$ kW/t, the standard deviation $V'_{yw} = \pm 22{,}95$ kW/t, and the coefficient of variation $У_N = \pm 0{,}471$. The result shows that the indicator $У_w$ has less dispersion than P_{sp}. In addition the value $У_w$ does not correlate with the year of manufacture of the vehicle, which allows the use of this indicator at the design stage of vehicles. It is only necessary to set the rational normative value of this indicator.

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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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Удосконалення методології оцінки навантаження автомобіля та його енергоефективності

Анотація. Проблема. *Виникла необхідність розширити відому концепцію експлуатаційних властивостей автомобіля - економічність палива виникла у зв'язку з появою нових альтернативних електростанцій (електродвигуни, маховики, гібридні електростанції тощо), що вимагає включення не тільки теплову енергію палива, але й інші види енергії (електричну та механічну). У статті проведено дослідження вибору та обґрунтування показників енергоефективності автомобіля шляхом оцінки витрат енергії двигуна на його рух. Було проведено аналіз взаємозв'язку між енергетичними характеристиками динаміки та ефективністю автомобіля.* ***Мета.*** *Метою дослідження є аналіз методів оцінки енергоефективності транспортного засобу. Для досягнення цієї мети необхідно визначити показники, які дозволять проводити порівняльний аналіз показників енергоефективності різних транспортних засобів.* ***Методологія.*** *Підходи, прийняті в роботі для вирішення цієї мети, ґрунтуються на обґрунтуванні показників енергоефективності автомобіля шляхом оцінки споживання енергії двигуном на його рух.* ***Результати.*** *На нашу думку, при проектуванні та оцінці динамічних властивостей транспортних засобів раціонально використовувати енергетичні показники транспортного засобу, для яких необхідно розробити відповідні критерії оцінки. Аналіз результатів розрахунку показників і, у таблиці 1, показав, що показник у порівнянні з має меншу дисперсію.* ***Оригінальність.*** *Отримані* *результати впливу параметрів транспортних засобів на рівень їх енергетичного навантаження показують, що показник має меншу дисперсію, ніж. Крім того, значення не корелює з роком випуску автомобіля, що дозволяє використовувати цей показник на етапі проектування транспортних засобів. Необхідно лише встановити раціональне нормативне значення цього показника.* ***Практичне значення.*** *Отримані результати можна рекомендувати спеціалістам для використання при проектуванні, виробництві, сертифікації та експлуатації автомобільних транспортних засобів, енергоефективності транспортних засобів, комбінованої електростанції.*

Ключові слова: *динамічні властивості, аеродинамічний опір, щільність потужності двигуна, енергоефективність автомобіля, дизайн автомобіля, паливна ефективність*

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