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CREATION OF THE ENERGY APPROACH FOR ESTIMATING AUTOMOBILE DYNAMICS AND FUEL EFFICIENCY

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Розроблено енергетичний підхід до оцінки динамічності і економічності автомобілів, що дозволяє визначити взаємозв'язок між витратами енергії і кінетичної енергією автомобіля. Визначено коефіцієнти зазначеного взаємозв'язку для основних і додаткових (непродуктивних) витрат енергії. Досліджено вибір і обґрунтування показників енергетичної оцінки динамічності й економічності автомобіля шляхом оцінки витрат енергії двигуна на його рух. Отримано рівняння, що визначає залежність додаткових втрат енергії руху від пружних і динамічних параметрів автомобіля та його моторно-трансмісійної установки. Визначено взаємозв'язки між енергетичними показниками динамічності й економічності автомобілів

Ключові слова: оцінка динамічності, енергетична економічність, додаткові втрати енергії, нерівномірність крутного моменту

Разработан энергетический подход к оценке динамичности и экономичности автомобилей, позволяющий определить взаимосвязь между затратами энергии и кинетической энергией автомобиля. Определены коэффициенты указанной взаимосвязи для основных и дополнительных (непроизводительных) затрат энергии. Исследован выбор и обоснование показателей энергетической оценки динамичности и экономичности автомобиля путем оценки затрат энергии двигателя на его движение. Получено уравнение, определяющее зависимость дополнительных потерь энергии движения от упругих и динамических параметров автомобиля и его моторно-трансмиссионной установки. Определены взаимосвязи между энергетическими показателями динамичности и экономичности автомобилей

Ключевые слова: оценка динамичности, энергетическая экономичность, дополнительные потери энергии, неравномерность крутящего момента

1. Introduction

The emergence of motor vehicles that employ the new power units, alternative to those already known, necessitated replacement of the notion of (operational property), "fuel efficiency" with the concept of "energy efficiency". The latter includes not only the consumption of thermal energy from liquid and gaseous fuels, but also other types of energy (electrical and mechanical).

The magnitude of maximum kinetic energy of translational motion characterizes energy level of the vehicle. The maximum kinetic energy is determined at full weight on a horizontal straight-line hard-surface road.

The use of the concept and indicators of car fuel efficiency does not allow comparing fuel efficiency of cars with an internal combustion engine (ICE) with that of electric vehicles. At the same values of forces of the motion external resistance, cars with electric drive of the driving wheels spend a less magnitude of engine energy than motor vehicles with ICE. This is predetermined by the non-uniformity of the ICE torque.

Assessment of the additional losses of engine energy that occur during motion is an important step in order to provide motor cars with high dynamics and fuel efficiency.

2. Literature review and problem statement

Requirements for the energy efficiency of motor vehicles are constantly increasing in the world [1], especially in the countries with a high level of development of the automotive industry and road transport [2]. Paper [3] gives a review of the practice in the United States in the field of standardization of indicators for fuel efficiency of motor vehicles.

In most countries, the main indicator of fuel efficiency is fuel consumption Q_s, measured in liters per 100 kilometers of the distance covered. To assess the effectiveness (fuel efficiency) of transportation work, specific indicator Q_{tr} is applied. This indicator is the ratio of the actual fuel consumption to the transportation work performed. In addition to the specified indicators, hourly Q_t and specific g_e fuel consumption are employed in order to estimate fuel efficiency.

There are also the following characteristics and fuel economy indicators for a motor vehicle's fuel efficiency:

– control fuel consumption;
– fuel consumption in a main driving cycle on the road;
– fuel consumption in city driving cycle on the road;
– fuel characteristic of steady motion;
– fuel-speed characteristic on the highway-hilly road.

An analysis of modern requirements to energy efficiency of motor vehicles is given in papers [3–5]. Fulfilling the indicated requirements is possible when reducing the unproductive energy engine consumption during motion of a vehicle [6, 7]. According to data released by the US Environmental Protection Agency [8], energy consumption due to losses in the drivetrain is 5, 6 % of the energy of fuel combustion. A resource for bringing down these losses can be a reduction in the non-uniformity of the ICE torque. Torque fluctuations of ICE cause oscillations in the angular velocity of transmission shafts and linear speed of the vehicle, resulting in additional losses of engine energy [9]. However, the impact of uneven torque of the engine on the additional losses of energy was not investigated in articles [1–8].

Application of combined electromechanical drives for the driving wheels of a motor car makes it possible to reduce additional losses of energy [10, 11]. To reduce additional energy losses in the drivetrain of a vehicle caused by the ICE torque fluctuations, papers [12–14] proposed a mechanical continuously variable transformer (mechanical "rectifier").

Authors of the specified articles [11–14], however, did not separate energy losses in the transmission into possible components, which makes it impossible to identify ways to reduce them.

Papers [15, 16] examined energy efficiency of hybrid cars and electric vehicles. Significant energy losses cause the need to regenerate it [17] and predetermine employing intelligent automobile systems [18]. Authors of [15–18] did not consider energy losses caused by fluctuations in the unsprung masses, by a change in the car chassis geometry and by wheel imbalance. These questions were not considered in articles [19–21] either.

3. The aim and objectives of the study

The aim of present study is to improve indicators of dynamics and fuel efficiency of motor vehicles by reducing the unproductive consumption of energy.

To achieve the set aim, the following tasks are to be solved:

– to determine indicators for energy assessment of dynamics and fuel efficiency of motor vehicles;
– to estimate additional (unproductive) energy losses and to determine their interrelation with the decline in the indicators of dynamic properties of cars.

4. Determining the indicators of energy dynamics and motor car fuel efficiency and their interrelation

4. 1. Assessment of the indicators of energy dynamics and car fuel efficiency

The car dynamics [22] refers to their capability of achieving high motion speed under the influence of traction (motive) forces applied to them. In order to estimate dynamic properties of motor cars, paper [19] proposed an indicator – the coefficient of dynamics, determined from expression

$$K_{dyn} = \frac{P_k}{\sum P_c}, \tag{1}$$

where P_k is the traction force on the driving wheels of the car (total); $\sum P_c$ is the total resistance force to the motion of the car.

The total resistance force to the motion of a car is typically understood as a sum of the forces of road and aerodynamic resistances

$$\sum P_c = m_a \cdot g \cdot \psi + \frac{C_x}{2} \cdot \rho_{air} \cdot F \cdot V_a^2, \tag{2}$$

$$\psi = f \pm i, \tag{3}$$

where m_a is the mass of the vehicle; g is the free fall acceleration; g=9.81 m/s^2; ψ is the total road resistance coefficient; C_x is the frontal aerodynamic drag coefficient of the vehicle; ρ_{air} is the air density; F is the car frontal cross-sectional area (midsection); V_a is the linear vehicle speed; f is the coefficient of wheel rolling resistance of the vehicle; i is the longitudinal slope of the road.

After substitution expression (2) in relation (1) and following the transform, we shall obtain:

$$K_{dyn} = \frac{P_k}{m_a \cdot \left(g \cdot \psi + \frac{C_x}{2 \cdot m_a} \cdot \rho_{air} \cdot F \cdot V_a^2 \right)} = \frac{\left(\dot{V}_a\right)_0}{g \cdot \psi + \frac{C_x}{2 \cdot m_a} \cdot \rho_{air} \cdot F \cdot V_a^2}, \tag{4}$$

where $\left(\dot{V}_a\right)_0$ is the linear acceleration of the car that occurs at zero value of the motion resistance forces $\left(\sum P_c = 0\right)$.

The less the total motion resistance force $\sum P_c$ and the larger P_k, the higher K_{dyn}, which means better car dynamics and a faster period of its acceleration to the required or maximal motion speed.

The car's kinetic energy grows during acceleration. The higher the car's speed, the higher its dynamics. That is why the level of kinetic energy, at full mass m_{full} and maximal vehicle speed $V_{\max}$, is an indicator of the energy dynamics. Thus, the energy indicator of a car dynamics is the level of its kinetic energy, that is,

$$E_{di} = \left(W_{kin}\right)_{\max} = \frac{m_{full} \cdot V_{\max}^2}{2}. \quad (5)$$

Paper [20] proposed the following indicators of energy efficiency of the vehicle:

– in the reserve of energy source ΔW_u while the car travels a measured road section S_m;

– distance S, traveled by car, when spending the measured amount of source ΔW_{um}.

Accordingly, we shall obtain expressions:

$$\Delta W_u = \frac{S_m}{\eta_e \cdot \eta_{tr}} \cdot \left(m_a \cdot g \cdot \psi + \frac{C_x}{2} \cdot \rho_{air} \cdot F \cdot V_a^2 \right); \quad (6)$$

$$S = \Delta W_{um} \cdot \frac{\eta_e \cdot \eta_{tr}}{m_a \cdot g \cdot \psi + \frac{C_x}{2} \cdot \rho_{air} \cdot F \cdot V_a^2}, \quad (7)$$

where η_{tr} is the effective efficiency of engine and the car's transmission efficiency.

Fig. 1, 2 show dependence charts $\frac{\Delta W_u}{S_m}(V_a)$ and $\frac{S}{\Delta W_{um}}(V_a)$ for a conditional passenger car at different m_a and ψ.

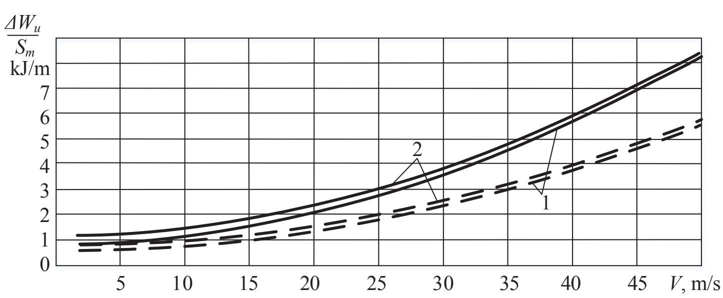

Fig. 1. Dependence of energy change ratio to the length of the measured section on the established car motion speed: 1 — at car weight $m_a = m_{eq}$=1,400 kg; 2 — at $m_a = m_{full}$=1,890 kg: ——— — gasoline engine; — — — diesel engine

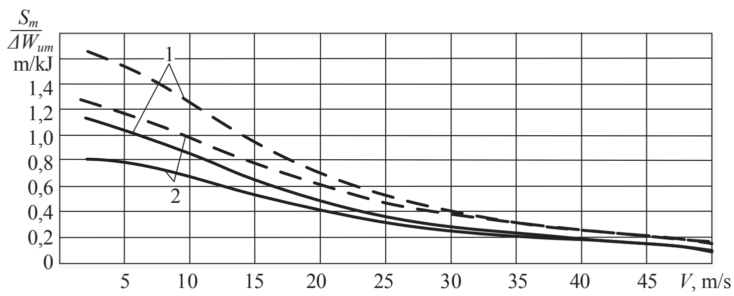

Fig. 2. Dependence of ratio of the length of the measured section to a change in energy on the established car motion speed: 1 — at car weight $m_a = m_{eq}$=1,400 kg; 2 — at $m_a = m_{full}$=1,890 kg: ——— — gasoline engine; — — — diesel engine

It should be noted that authors of article [20] did not quite correctly denote the indicators ΔW_u and S as criteria. Criteria are the normalized (in line with a certain standard or TS) values for these indicators. Expressions (6) and (7) may rightly apply to a technical condition of vehicles. In order to assess technical level of vehicles, it is more appropriate to investigate performance efficiency of the car.

In article [21], it is proposed to use, as an indicator of energy efficiency, the magnitude that is reverse to the vehicle's efficiency, that is,

$$H_a = \frac{1}{\eta_a} = \frac{W_{pow}}{A_u} \geq 1, \quad (8)$$

where η_a is the vehicle's efficiency; W_{pow} is the energy, supplied from the source to the vehicle; A_u is the useful work done by a car.

It should be noted that the definition of the supplied energy W_{pow} meets no objections as it is the absolute notion that characterizes consumed electricity or energy of the fuel consumed. The problems in determining the performance efficiency are related to the lack of consensus about what constitutes useful work of the car. Performance efficiency must be determined through the loss factor, which takes into account both losses that cannot be avoided and the losses that can be reduced or brought down to zero. In this case, an increase in the efficiency of a car by reducing the non-productive losses will improve its energy performance.

4. 2. Assessment of additional (unproductive) energy losses and their interrelation with the decline in dynamic properties of cars

When determining the required capacity of the engine and performing theoretical analysis of the car dynamics, one takes into account only energy losses in the transmission, as well as engine energy consumption to overcome resistance to the vehicle motion. During uniform motion of the car

$$\Delta W_u = \frac{\Sigma P_c}{\eta_{tr}} \cdot S. \quad (9)$$

After substituting expression (2) in (9) and following the transforms

$$\Delta W_u = \frac{S}{\eta_{tr}} \cdot \left(m_a \cdot g \cdot \psi + \frac{C_x}{2} \cdot \rho_{air} \cdot F \cdot V_a^2 \right) = \frac{m_a \cdot V_a^2}{2} \cdot \frac{\frac{2 \cdot g \cdot \psi}{V_a^2} + C_x \cdot \rho_{air} \cdot F}{\eta_{tr}} = W_{kin} \cdot S \cdot \frac{\frac{2 \cdot g \cdot \psi}{V_a^2} + C_x \cdot \rho_{air} \cdot F}{\eta_{tr}}. \quad (10)$$

The largest engine energy consumption occurs at full weight m_{full} of the car and maximal speed of its motion $V_a = V_{\max}$. In this case,

$$W_{kin} = \left(W_{kin}\right)_{\max} = E_{di} = \frac{m_{full} \cdot V_{\max}^2}{2}. \quad (11)$$

Thus,

$$\left(W_u\right)_{\max} = E_{di} \cdot S \cdot \frac{\frac{2 \cdot g \cdot \psi}{V_{\max}^2} + C_x \cdot \rho_{air} \cdot F}{\eta_{tr}}. \quad (12)$$

The largest engine energy consumption is convenient to reduce to the unit of the travelled distance. In this case, equation (12) takes the form

$$\frac{(W_u)_{\max}}{S}=E_{di}\cdot\frac{\frac{2\cdot g\cdot\psi}{V_{\max}^2}+C_x\cdot\rho_{air}\cdot F}{\eta_{tr}}. \tag{13}$$

If one adopts E_{di} as the measurement unit of energy consumption per one meter of the distance traveled by car during uniform motion, then the number of units of energy consumption will be equal to

$$K_{ws}=\frac{\frac{2\cdot g\cdot\psi}{V_{\max}^2}+C_x\cdot\rho_{air}\cdot F}{\eta_{tr}}. \tag{14}$$

With a decrease in $K_{ws,}$ energy efficiency of the car increases. The magnitude K_{ws} decreases with an increase in the maximal speed $V_{\max}$ of car motion. With a decrease in the coefficient of frontal aerodynamic resistance the magnitude K_{ws} also decreases.

With a decrease in the efficiency of transmission η_{tr}, the magnitude K_{ws} grows. The existing techniques for determining performance efficiency of the transmission consider only dissipative (caused by dry and viscous friction) losses of energy. The estimated transmission efficiency values are within η_{tr}=0.75–0.9. Results of the experimental study, however, show in some cases very low values of transmission efficiency. This is due to the fact that additional losses emerge in transmissions resulting from uneven rotation of inertial links and oscillatory nature of turning the elastic links. The fluctuations in kinetic and potential energy of transmission links, caused by these processes lead to a reduction in the performance efficiency of transmission.

Article [21] derived the equation that determines dependence of additional losses of motion energy on the elastic and dynamic parameters of the car and its engine-transmission unit. The expression takes the following form

$$\Delta W_e^{sp}=\frac{m_a\bar{V}_a^2}{2}S\frac{\left(\frac{m_a g\psi}{\bar{V}_a}+\frac{C_x}{2}\rho_{air}F\bar{V}_a\right)(0{,}08_c+14{,}44)U_{tr}}{4\pi\eta_{tr}^{dis}\cdot\eta_e^m\left(1+\frac{\frac{m_a r_d^2}{U_{tr}^2}}{J_{pow}^e+J_{pow}^{tr}}\right)\left(\frac{4k^2}{\bar{\omega}_e^2 i_c^2}-1\right)}\times$$
$$\times\left[\frac{\bar{V}_{ac}}{r_d^2k^2}\left(\frac{U_{tr}}{m_a}+\frac{r_d^2}{J_{pow}^e+J_{pow}^{tr}}\right)+\right.$$
$$\left.+\frac{2r_d^3\left(g\psi+\frac{C_x}{2m_a}\rho_{air}F\bar{V}_a^4\right)}{\bar{V}_a^4\cdot i_c^2}\cdot\frac{0{,}49-\frac{1{,}81}{i_c}}{J_{pow}^e+J_{pow}^{tr}}\right], \tag{15}$$

where U_{tr} is the transmission ratio of the car; i_c is the number of cylinders of an internal combustion engine; r_∂ is the dynamic radius of the wheel; $\bar{V}_a$ is the average speed of the established car motion; J_{pow}^e, J_{pow}^{tr} are the moments of inertia of the engine and transmission, reduced to the input shaft; $\bar{\omega}_e$ is the average angular velocity of the engine crankshaft rotation; k is the circular frequency of free fluctuations of the transmission input shaft; η_{tr}^{dis} is the dissipative efficiency of transmission; η_e^m is the mechanical efficiency of an engine; $\bar{V}_a$ is the average value of vehicle linear speed per one cycle of speed change during steady motion.

At $\bar{V}_a=\bar{V}_{\max}$, expression (15) takes the form

$$\Delta W_e^{sp}=E_{di}\times$$
$$\times S\frac{\left(\frac{m_a\cdot g\cdot\psi}{\bar{V}_{\max}}+\frac{C_x}{2}\cdot\rho_{air}\cdot F\cdot\bar{V}_{\max}\right)\cdot(0{,}08\cdot i_c+14{,}44)\cdot U_{tr}}{4\cdot\pi\cdot\eta_{tr}^{dis}\cdot\eta_e^m\left(1+\frac{\frac{m_a\cdot r_d^2}{U_{tr}^2}}{J_{pow}^e+J_{pow}^{tr}}\right)\left(\frac{4k^2}{\bar{\omega}_e^2\cdot i_c^2}-1\right)}\times$$
$$\times\left[\frac{\bar{V}_{\max}\cdot i_c}{r_d^2\cdot k^2}\left(\frac{U_{tr}}{m_a}+\frac{r_d^2}{J_{pow}^e+J_{pow}^{tr}}\right)+\right.$$
$$\left.+\frac{2r_d^3\left(g\psi+\frac{C_x}{2m_a}\rho_{air}F\bar{V}_{\max}^4\right)}{\bar{V}_{\max}^4\cdot i_c^2}\cdot\frac{0{,}49-\frac{1{,}81}{i_c}}{J_{pow}^e+J_{pow}^{tr}}\right], \tag{16}$$

or

$$\Delta W_e^{sp}=E_{di}\cdot S\cdot K_{ws}. \tag{17}$$

The number of units of energy losses caused by elastic and dynamic losses of the car and transmission (per one traveled meter)

$$K_{ws}=\frac{\left(\frac{m_a\cdot g\cdot\psi}{\bar{V}_{\max}}+\frac{C_x}{2}\cdot\rho_{air}\cdot F\cdot\bar{V}_{\max}\right)\cdot(0{,}08\cdot i_c+14{,}44)\cdot U_{tr}}{4\cdot\pi\cdot\eta_{tr}^{dis}\cdot\eta_e^m\left(1+\frac{\frac{m_a\cdot r_d^2}{U_{tr}^2}}{J_{pow}^e+J_{pow}^{tr}}\right)\left(\frac{4k^2}{\bar{\omega}_e^2\cdot i_c^2}-1\right)}\times$$
$$\times\left[\frac{\bar{V}_{\max}\cdot i_c}{r_d^2\cdot k^2}\left(\frac{U_{tr}}{m_a}+\frac{r_d^2}{J_{pow}^e+J_{pow}^{tr}}\right)+\right.$$
$$\left.+\frac{2r_d^3\left(g\psi+\frac{C_x}{2m_a}\rho_{air}F\bar{V}_{\max}^4\right)}{\bar{V}_{\max}^4\cdot i_c^2}\cdot\frac{0{,}49-\frac{1{,}81}{i_c}}{J_{pow}^e+J_{pow}^{tr}}\right]. \tag{18}$$

For the case of cornering, we shall determine energy consumption of the engine

$$W_e=\frac{m_a\cdot V_a^2}{2\cdot\eta_{tr}}\cdot S_R\cdot\left[2\cdot f\cdot\left(\frac{g}{V_a^2}+\frac{h-r_d}{R^2}\right)+\frac{C_x\cdot\rho_{air}\cdot F}{m_a}\right], \tag{19}$$

where S_R is the distance that a car travels when turning; R is the turning radius of the vehicle; h is the height of the car mass center.

At V_a=$V_{\max}$, expression (19) will be transformed to the form

$$W_e=E_{di}\cdot K_{wsr}. \tag{20}$$

where K_{WSR} is the number of units of energy losses of the car when turning,

$$K_{wsr}=\frac{1}{\eta_{tr}}\cdot\left[\frac{2\cdot g\cdot f}{V_{\max}^{2}}+\frac{C_x\cdot\rho_{\text{air}}\cdot F}{m_a}+2\cdot\frac{f\cdot(h-r_d)}{R^2}\right]. \quad (21)$$

At fluctuations of the guide wheels of the car in the horizontal plane, we shall determine additional consumption of the engine energy

$$\Delta W_s=\frac{m_a\cdot V_a^2}{2}\cdot S\times$$
$$\times\frac{\frac{A_\alpha^2}{L^2}\left[f(h-r_d)+2\Omega\cdot\frac{b^2+i_z^2+f\cdot b\cdot(h-r_d)}{\pi\cdot V_a}\right]-\frac{8\Omega}{\pi\cdot V_a}\ln\left|\cos A_\alpha\right|}{\eta_{tr}}, \quad (22)$$

where A_α is the amplitude of fluctuations of the guide wheels in the horizontal plane; L is the longitudinal wheel base of the car; Ω is the circular frequency of the car's guide wheels in the horizontal plane; i_z is the radius of car inertia relative to the vertical axis; b is the distance from the rear axle to the projection of mass center onto the horizontal plane.

At $V_a=V_{\max}$, equation (22) takes the form:

$$\frac{\Delta W_s}{S}=E_{di}\cdot K_{ws}, \quad (23)$$

where K_{WS} is the number of units of additional energy losses,

$$K_{ws}=$$
$$=\frac{\frac{A_\alpha^2}{L^2}\left[f(h-r_d)+2\Omega\cdot\frac{b^2+i_z^2+f\cdot b\cdot(h-r_d)}{\pi\cdot V_{\max}}\right]-\frac{8\Omega}{\pi\cdot V_{\max}}\ln\left|\cos A_\alpha\right|}{\eta_{tr}}. \quad (24)$$

In the case when fluctuations of the guide wheels in the horizontal are caused by their imbalance, then in the presence of circumferential backlash of these wheels, the additional energy consumption will be equal to

$$\Delta W_S=\frac{m_aV_a^2}{2}\times$$
$$\times S\left\{\frac{S_0^2}{L^2}\frac{a_p^2\cos^2\Delta}{J_{kz}^2\left(\frac{K_1^2r_k^2}{V_a^2}-1\right)^2}\left[f(h-r_\text{d})+\frac{b^2+i_\partial^2+fb(h-r)}{0{,}5\pi\cdot r_k}\right]-\right.$$
$$\left.-\frac{8}{\pi\cdot r_k}\ln\left|\cos\left[S_0\frac{a_\text{p}\cos\Delta}{J_{kz}\left(\frac{K_1^2r_k^2}{V_a^2}-1\right)}\right]\right|\right\}, \quad (25)$$

where S_0 is the total imbalance of the guide wheels of the car; r_k is the radius of a wheel's rolling; a_p is the distance from the vertical axis of wheel's symmetry to the axis of pivot; J_{kz} is the guide wheel's moment of inertia relative to the axis of pivot; K_1 is the circular frequency of free fluctuations of the guide wheel relative to the pivot's axis; Δ is the phase shift angle between fluctuations of the guide wheel and a disturbing moment.

For the case under consideration:

$$K_{ws}=\frac{1}{\eta_{tr}}\cdot\left\{\frac{S_0^2}{L^2}\frac{a_p^2\cos^2\Delta}{J_{kz}^2\left(\frac{K_1^2r_k^2}{V_a^2}-1\right)^2}\left[f(h-r_\text{d})+\frac{b^2+i_\partial^2+fb(h-r)}{0{,}5\pi\cdot r_k}\right]-\right.$$
$$\left.-\frac{8}{\pi\cdot r_k}\ln\left|\cos\left[S_0\frac{a_\text{p}\cos\Delta}{J_{kz}\left(\frac{K_1^2r_k^2}{V_a^2}-1\right)}\right]\right|\right\}, \quad (26)$$

With the vehicle's unsprung mass fluctuations caused by unbalanced wheels, additional engine energy losses can be determined as follows:

$$\Delta W_{HM}=\frac{m_aV_a^2}{2}S\frac{S_0/m_a}{2\pi\cdot r_k^3\sqrt{\left(K_2^2-V_a^2/r_k^2\right)^2+4n^2V_a^2/r_k^2}}. \quad (27)$$

At $V_a=V_{\max}$, the number of units of additional energy losses:

$$K_{WHM}=\frac{2\Delta W_{HM}}{m_aV_a^2S}=$$
$$=\frac{S_0/m_a}{2\pi\cdot r_k^3\sqrt{\left(K_2^2-V_{\max}^2/r_k^2\right)^2+4n^2V_{\max}^2/r_k^2}}, \quad (28)$$

where K_2 is the circular frequency of natural fluctuations of the unsprung weight of the vehicle.

$2n$ is the coefficient ratio (total) of damping in the shock absorbers of suspension.

We shall consider separate factors that influence energy efficiency of the vehicle. The proposed approach could be applied for any examined energy losses of engine during car motion. Maximal total engine energy consumption during car motion can be determined as

$$W_{e\Sigma}=\frac{m_aV_{\max}^2}{2}S\sum_{i=1}^{n_1}K_{W_i}=\text{E}_{\text{di}}\cdot S\sum_{i=1}^{n_1}K_{W_i}, \quad (29)$$

where n_1 is the number of examined factors.

Paper [10] derived a dependence that makes it possible to estimate a reduction of additional costs for the hybrid car motion under established mode with an increase in the share of torque generated by electric motors

$$\Delta W_e=\frac{0{,}08+\frac{14{,}44}{i_c}}{\pi\eta_{tr}}\sum P_c\cdot S\left(1-\frac{M_{em}\cdot n_2}{r_d\sum P_c}\right), \quad (30)$$

where M_{em} is the torque generated at the wheel by electric motor; n_2 is the number of electric motors.

Transform expression (30) with regard to relation (2)

$$\Delta W_e=\frac{m_a\cdot\overline{V_a^2}}{2}\cdot S\cdot\frac{0{,}08+\frac{14{,}44}{i_c}}{\pi\eta_{tr}}(1-K_{em}), \quad (31)$$

where K_{em} is the share of torque generated by electric motors on the driving wheels

$$K_{em}=\frac{M_{em}\cdot n_2}{r_d\sum P_c}. \qquad (32)$$

At $\overline{V_a}=\overline{V_{\max}}$, expression (32) takes the form

$$\Delta W_e=E_{di}\cdot S\cdot K_{WS} \qquad (33)$$

and

$$K_{WS}=\frac{0{,}08+\dfrac{14{,}44}{i_c}}{\pi\eta_{tr}}\left(1-K_{em}\right). \qquad (34)$$

An analysis of expression (34) shows that a growth in K_{em} leads to a decrease in K_{WS}. At K_{em}=1, the magnitude K_{WS}=0.

Dependence (34) allowed us to determine relative energy saving of the internal combustion engine in a hybrid car

$$\delta_W=\left[1-\frac{\eta_{tr}}{\eta_{ed}\cdot\eta_{ch}\cdot\left(1+\dfrac{0{,}04+\dfrac{7{,}22}{i_c}}{\pi}\right)}\right]\cdot\left(\lambda_2\cdot K_{em}+\lambda_3\right), \qquad (35)$$

where η_{ed} is the electric drive efficiency; η_{ch} is the battery charging process efficiency; λ_2, λ_3 are the section of distance traveled by car when using a hybrid and an electric drive of the driving wheels.

5. Discussion of results of the study into determining the indicators of energy dynamics and fuel efficiency of cars and their interrelation

Energy efficiency assessment implies determining summary consumption of engine energy per unit of the distance traveled. This, in contrast to the estimation of fuel efficiency, makes it possible to avoid the influence of fuel quality indicators, which do not always correspond to standard requirements. Existing methods and tools enable to register effective work, performed by the engine, depending on the distance covered, a change in the weight and speed of the car. Separating all types of engine energy costs into basic and additional (unproductive) will make it possible to identify the ways to reduce the latter, which improves energy efficiency of motor cars. Energy efficiency can be an indicator for vehicles that do not utilize liquid, gaseous fuel, making its indicators more objective.

Expression of all engine energy costs (both basic and additional) through the kinetic energy of translational motion of a car, which is carried out in the present work, allows us to obtain interrelation between energy and dynamic indicators of the machine. It will also make it possible in the future to construct a variation series of coefficients of the specified connection, which provides the possibility of making technical decisions when designing and operating motor vehicles.

Energy approach to estimating the dynamics and fuel efficiency of hybrid cars allowed us, by applying equation (35), to determine that at η_{tr}=0.9; η_{ch}=0.9 and η_{ed}=0.9 relative energy saving by the vehicle with a six-cylinder engine is 30 %; with an eight-cylinder engine is 25 %.

6. Conclusions

1. Energy approach to estimating the dynamics and fuel efficiency of cars allowed us to determine interrelation between the consumption of energy and the kinetic energy of a car. We determined coefficients of the indicated interrelation for basic and additional (unproductive) consumption of energy. Based on the obtained coefficients, it is possible to rank energy losses, as well as identify the ways to reduce them.

2. The application of energy approach allowed us, using hybrid cars as an example, to determine energy saving at their steady motion. Such a saving for motor cars with a number of cylinders of 6–8 may reach 25–30 %.

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