May, 28-29, 2019, Ternopil, Ukraine

ICCPT 2019: Current Problems of Transport: Proceedings of the 1st International Scientific Conference, May 28-29, 2019, Ternopil, Ukraine

Improvement of the method for assessing the energy load of vehicle

Mikhail Podrigalo, Yurii Tarasov, Dmitry Abramov, Mykhailo Kholodov

Kharkov National Automobile and Highway University, st. Yaroslav the Wise 25 Kharkov, Ukraine
yuriy.ledd@gmail.com

Abstract: The aim of the research is to improve the indicators assessment accuracy of the vehicle energy load by improving the method of experimentally - theoretical determination of the aerodynamic drag parameters of vehicle in motion. To achieve this goal, it is necessary to solve the problem of determining the dependence of the energy load level on vehicle speed with varying frontal aerodynamic drag coefficient. Studies we carried out to clarify the calculation of the parameters of vehicle aerodynamic drag in motion made it possible to clarify the correlation between the actual effective engine capacity and the maximum kinetic energy of vehicle at translational motion. When determining the vehicle aerodynamic drag, the constant coefficient of aerodynamic drag is used depending on the speed in all range of vehicle speeds. This leads to significant mistakes in determining the necessary engine capacity expendable to overcome the aerodynamic drag, and vehicle fuel consumption. Analytical expressions, allowing to take into account additional energy losses and correlation between the kinetic energy of the vehicle steady motion and the effective engine capacity are obtained. The correlation coefficient between the kinetic energy of vehicle in motion and the effective engine capacity – K_w have been proposed. Studies have shown that if speed of vehicle increases the indicator K_w will monotonously decrease in the range of actual speeds.

Keywords: aerodynamic drag, energy load, vehicle, accuracy of estimation, energy losses, effectiveness of the car

1. Introduction

Energy load characterizes both dynamic and economic properties of vehicle. The most important factor determining the energy load and energy efficiency of vehicles is aerodynamic drag to vehicle movement.

One of the most important areas is the vehicle aerodynamic design, based on the system optimization of its aerodynamic properties, which allows significantly increase fuel efficiency, dynamic properties, vehicle productivity, reduce pollution and noise. At the same time, achieving the minimum value of the aerodynamic drag coefficient is not the only objective of the vehicle aerodynamic design. In this case a number of important tasks are solving, affecting the technical, economic, consumer and environmental qualities of vehicle. New methods are developing for determining and refining the aerodynamic characteristics of vehicles on the road, when complete geometric and kinematic aerodynamic similarity is ensured [1-3].

In the study, using the refined method of calculating the parameters of aerodynamic drag, the calculation of indicators of energy load and energy efficiency of vehicle was improved. An improved

Peer-review under responsibility of the Scientific Committee of the 1st International Scientific Conference ICCPT 2019: Current Problems of Transport

method for estimating energy load is based on the results of experimental studies of vehicle aerodynamics.

2. Methodology

Energy load characterizes the necessary consumption of engine capacity for the translational motion of vehicle with a given level of kinetic energy [4-7]. In case for vehicle with laden mass moving at maximum speed, in paper [4], there was proposed an indicator called the energy load level.

$$Y_W = \frac{2N_{e_{max}}}{m_{полн} V_{max}^2}, \tag{1}$$

where $N_{e_{max}}$ is the maximum effective engine capacity; $m_{полн}$ Is laden mass of vehicle; V_{max} is vehicle maximum speed.

The smaller the value of Y_W, the lower the energy load of vehicle [1]. The inverse of value Y_W is an indicator of energy efficiency

$$Э_W = \frac{1}{Y_W} = \frac{m_{полн} V_{max}^2}{2N_{e_{max}}}, \tag{2}$$

because it characterizes the amount of kinetic energy of vehicle per unit of maximum effective engine capacity.

From the point of view of the physical meaning, the value $Э_W$ (has the dimension of time) it is a vehicle acceleration time, if $N_e = N_{e_{max}} = const$ it provides that all the productive and non-productive expenditures of capacity (energy) are zero.

The calculations given in [4] showed that for a number of passenger car models produced from 1959 to 2004, the value Y_W of the indicator Y_W varies in the range of [0.037; 0.055], which is significantly below the limits [27.63; 115.37] of the power density $N_{уд}$ for the same cars [4]. It is because of the known power density indicator

$$N_{уд} = \frac{N_{e_{max}}}{m_{полн}}. \tag{3}$$

does not take into account the vehicle's maximum design speed V_{max}

The authors [8, 9] convincingly showed that aerodynamic drag plays a major role in consumption of engine capacity, especially at high speeds (the total road resistance on paved roads is relatively small). Therefore, a correct calculation of the aerodynamic drag forces increases the accuracy of estimating the energy load of vehicle.

The current method of calculating the force of aerodynamic drag was proposed at the beginning of the last century in the well-known work [10]. According to [10], the force of aerodynamic drag can be defined as

$$P_W = \frac{C_x}{2} \rho F V_a^2. \tag{4}$$

where C_x is the coefficient of aerodynamic drag; ρ is air density; F is midsection of vehicle (the largest cross-sectional area of the body, perpendicular to the direction of movement) or any other measurement of the area characterizing the size of the body; V_a is vehicle speed, m/s.

The coefficient C_x depends on the shape of the body [10]. If we consider it independent of speed, then, as shown the results of theoretical and experimental studies, expression (4) is not valid for the entire range of speeds [10]. At low speeds (up to 1 m/s), the law of the first speed degree is justified; at high speeds, close to the speed of sound, the law of cubes seems to take place; at speeds above the speed of sound, the law of squares is observed [10]. In this work [10] it is noted that taking the square law everywhere, one should set the coefficient C_x depending on speed V_a [10]. Fig. 1 shows dependence graph of the coefficient C_x on the ratio of the body velocity to the speed of sound

However, in the range of speeds when it is necessary to use aeroplane details (from 20 to 80 m/s), the square law of speeds is quite well justified [11].

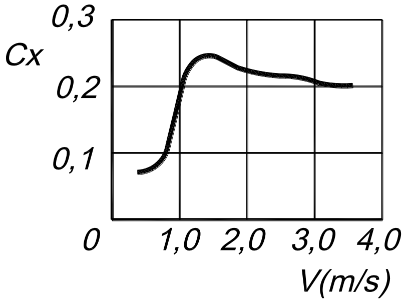


Figure 1. The dependence of the aerodynamic drag coefficient $C_x\left(V_a\right)$ on the vehicle speed [10]

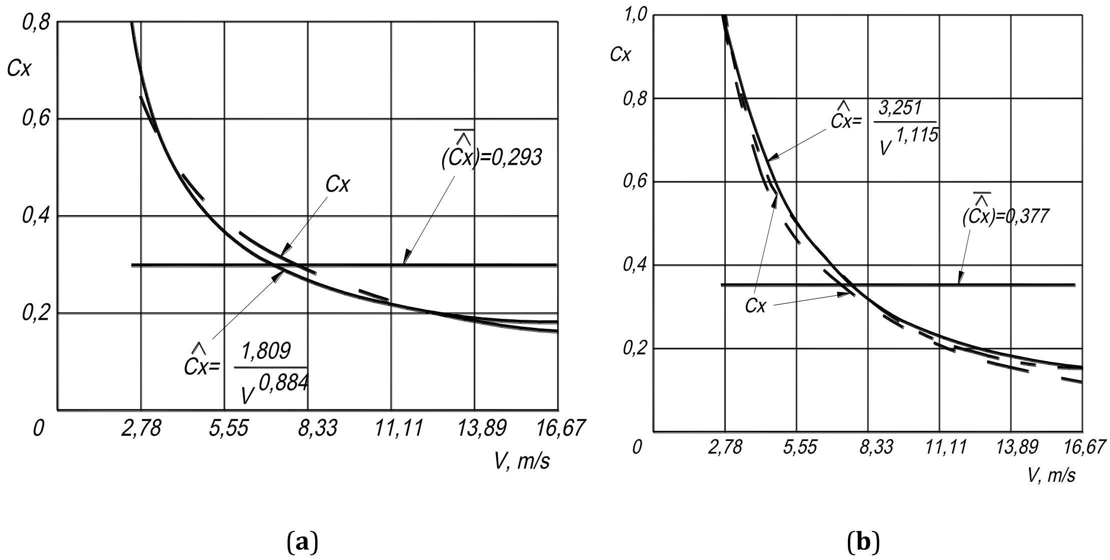


Figure 2. Dependence of the vehicle aerodynamic drag coefficient C_x on speed: C_x - approximating dependencies, (a) – passenger car VAZ-2107, (b) - passenger car ZAZ-1103 «Slavuta».

In work [11], using the method of partial accelerations, the dependencies of the coefficient C_x on speed are experimentally determined for passenger cars ZAZ-1102 "Slavuta" and VAZ-2107 (Fig.2). For approximation of experimental curves $C_x(V_a)$, an approximating hyperbolic dependence [11] is proposed like

$$\widehat{C}_x = \frac{C_x}{V_a^n} \quad , \tag{5}$$

where C_{xo} is the coefficient of aerodynamic drag at V_a = 1 m/s; *n* is exponent at V_a.

However, a methodological mistake was made in work [11], because the value C_{xo} in equation (5), in contrast to the dimensionless value, C_x should have the dimension (m/s)^n. Therefore, the equation (5) must be represented in the form:

$$\widehat{C}_x = \frac{A_W}{V_a^n} \, , \tag{6}$$

where A_W is the coefficient numerically equal C_x at = 1 m/s.

Therefore, it is necessary to clarify the indicator of the vehicle energy load level by more correctly determining the forces of aerodynamic drag.

3. Research results

Equation of the capacity balance at translational motion of vehicle

$$N_e \eta_{mp} = V_a (P_\psi + P_w) , \quad (7)$$

where P_φ is the strength of the total road resistance;

$$P_\varphi = m_a g \psi , \quad (8)$$

N_e is current value of the effective engine capacity; g is acceleration of gravity, g = 9.81 m/s²; ψ is the coefficient of total road resistance;

$$\psi = f \pm i , \quad (9)$$

f is rolling resistance coefficient; i is the longitudinal slope of the road; η_{mp} is transmission efficiency.

Equation (4) with the expression (6) takes the form:

$$P_w = \frac{A_w}{V_a^n} \cdot \frac{\rho F}{2} V_a^2 = \frac{A_w}{2} \rho F V_a^{2-n} \quad . \quad (10)$$

After substituting expressions (8) and (10) into the power balance equation (7) we get:

$$N_e \eta_{mp} = V_a (m_a \ g \psi \frac{A_w}{2} \rho F V_a^{2-n}) \quad . \quad (11)$$

By analogy with the work [4], we take out the value from the brackets $\frac{m_a V_a}{2}$. As a result, we get

$$N_e \eta_{mp} = \frac{m_a V_a^2}{2} \left(\frac{2 g \psi}{V_a} + \frac{A_W}{m_a} \rho F V_a^{1-n} \right), \quad (12)$$

Dividing the left and right parts η_{mp} we get:

$$N_e = \frac{m_a V_a^2}{2 \eta_{mp}} \left(\frac{2 g \psi}{V_a} + \frac{A_w \rho F}{m_a} V_a^{1-n} \right) = \frac{m_a V_a^2}{2} K_w = W_{кин} K_w \quad , \quad (13)$$

where K_w is the coefficient of the correlation between the kinetic energy of the vehicle translational motion and effective actual engine capacity [4]

$$K_w = \frac{1}{\eta_{mp}} \left(\frac{2 g \psi}{V_a} + \frac{A_w \rho F}{m_a} V_a^{1-n} \right) \quad . \quad (14)$$

With $m_a = m_{полн}$; $V_a = V_{max}$ the value K_w = Y_W (see the equation (1)).

To ensure high energy efficiency (low energy load) it is necessary to strive to obtain the lowest values K_w. The dependency graph $K_w(V_a)$ has the form shown in fig. 3

speed: 1 - $\frac{A_W \rho F}{\eta_{mp} m_a} V_a^{1-n}$, 2 - $\frac{2 g \psi}{\eta_{mp} V_a^2}$

The condition for finding the point of minimum $V_a = V_{opt}$ and minimum of functions $(K_w)(V_{opt})$

$$\begin{cases} \partial K_W / \partial V_a = 0 \\ \partial^2 K_W / \partial V_a^2 \Big|_{npu V_a = V_{opt}} > 0 \end{cases} . \quad (15)$$

In this way

$$\frac{\partial K_W}{\partial V_a} = - \frac{2 g \psi}{\eta_{mp} V_a^2} + (1 - n) \frac{A_W \rho F}{\eta_{mp} m_a} V_a^{-n} = 0 , \quad (16)$$

Then we find

$$V_a = V_{opt} = \sqrt[2-n]{\frac{2m_a g\psi}{(1-n)A_W \rho F}}. \qquad (17)$$

Solving logarithm equation (16) with following potentiation, we can obtain an invariant formula of expression (17), which allows to simplify arithmetic calculations

$$V_a = V_{opt} = exp\left[\frac{ln\left|\frac{2m_a g\psi}{(1-n)A_W \rho F}\right|}{2-n}\right]. \qquad (18)$$

Equation (14) if $V_a = V_{opt}$ will take the form

$$K_w = (K_W)_{min} = \frac{2g\psi}{\eta_{mp}}\frac{2-n}{1-n}\sqrt[2-n]{(1-n)\frac{A_w \rho F}{2m_a g\psi}} = \frac{2g\psi}{\eta_{mp}}\frac{2-n}{1-n}exp\left[-\frac{ln\left|\frac{2m_a g\psi}{(1-n)A_w \rho F}\right|}{2-n}\right]. \qquad (19)$$

Let us check the equation to obtain a minimum (equation (15))

$$\frac{\partial^2 K_w}{\partial V_a^2} = +\frac{4g\psi}{\eta_{mp}V_a^3} - n(1-n)\frac{A_W \rho F}{\eta_{mp}m_a}V_a^{-(n+1)}. \qquad (20)$$

From the equation (16) we get

$$(1-n)C_x \rho F V_2^{2-n} = 2gm_a\psi. \qquad (21)$$

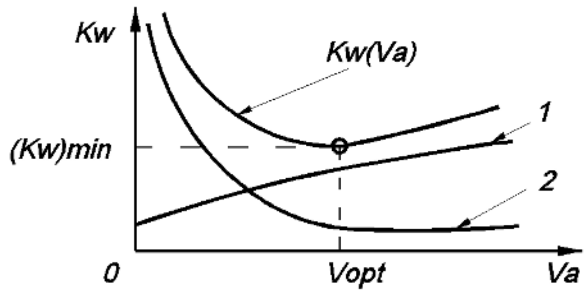


Figure 3. Dependency of the correlation coefficient between the kinetic energy of the vehicle steady motion and the effective engine capacity power $K_w(V_a)$ from the optimal

Substituting the equation (21) into the equation (20), we get if $V_a = V_{opt}$

$$\frac{\partial^2 K_w}{\partial V_a^2} = \frac{A_W \rho F}{\eta_{mp}m_a}V_{opt}^{2-n}\left[2(1-n) - n(1-n)\right] = \frac{A_W \rho F}{\eta_{mp}m_a}V_{opt}^{2-n}(2-3n+n^2). \qquad (22)$$

The value $\frac{\partial^2 K_w}{\partial V_a^2} > 0$ if the condition

$$n^2 - 3n + 2 > 0. \qquad (23)$$

We solve the quadratic inequality in the form

$$n_1 < 1; \qquad (24)$$

$$n_2 > 2 \qquad (25)$$

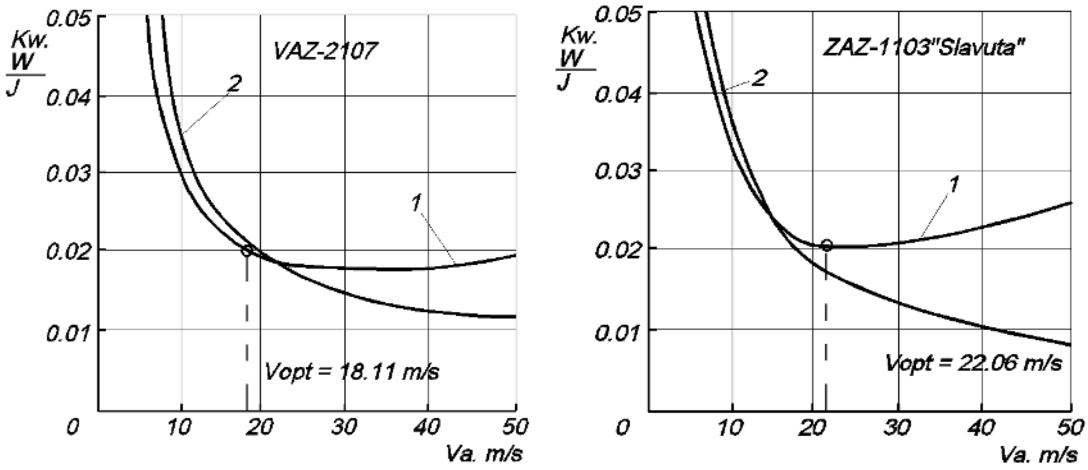
Thus, for n_1 <1 and n_2> 2, we have $K_w = (K_W)_{min}$ for $V_a = V_{opt}$. For values of n falling in the interval [1, 2], $K_w = (K_W)_{max}$ ($V_a = V_{opt}$). It means that the curve $K_w(V_a)$ in this case has a bulge in the opposite direction.

Figure 4 shows dependency graphs $K_w(V_a)$ for VAZ-2107 and ZAZ-1103 «Slavuta» cars if $C_x = const$ and $\widehat{C}_x$ changing according to the law (5). Analysis of these graphs shows that if $C_x = const$ the curves $K_w(V_a)$ have a minimum. The minimum point is equal V_{opt} = 18.11 m/s (65.2 km/h) for the passenger car VAZ-2107 and V_{opt} = 22.06 m/s (79.4 k /h) for the passenger car ZAZ-1103 «Slavuta».

If $\widehat{C}_x$ changing according to the law (5), the extremum points (curves 2 in Fig. 4) are absent in the interval of actual vehicle speeds V_a.

Table 1 shows the results of assessments of the energy load level Y_W and energy efficiency indicator $Э_W$ for the considered models of passenger cars.

Analysis of the results of the calculations given in the table shows that the energy load of the VAZ-2107 is higher than the ZAZ-1103, and the energy efficiency indicator, on the contrary, is lower.



(a) (b)

Figure 4. Dependencies of the correlation coefficient between the kinetic energy of the vehicle steady motion and the effective engine capacity power $K_w(V_a)$ from speed: 1– at $C_x = const$,

2– at $C_x = A_w V_a^{-n}$

Table 1. Calculation of indicators Y_W and $Э_W$

Automobile model	$N_{e_{max}}$, **kW**	$m_{полн}$, **kg**	V_{max}, **m/s**	$\frac{m_{полн} V^2_{max}}{2}$, **J**	Y_W, **Vt/J**	$Э_W$, **J/Vt**
VAZ -2107	56,6	1430	42	1261	0,0566	17,67
ZAZ -1103 «Slavuta»	48,53	1190	41	1000	0,0485	20,61

4. Conclusions

Resulting analytic expressions can serve as a basis for evaluating the energy efficiency of cars during steady. Refinement of the aerodynamic drag calculation parameters to motion made it possible to clarify the correlation between the actual effective engine capacity and the maximum kinetic energy of the steady translational motion of the vehicle. With an increase of vehicle speed, the indicator K_W

characterizing the link between the actual effective engine capacity and the kinetic energy of vehicle monotonously decreases in the range of actual speeds. Refinement of the calculation of the aerodynamic drag to the movement of the vehicle using the equation (10) made it possible to determine that at high speeds the value of the indicator K_w significantly lower than with the traditional method of calculation (equation (4)). This reduction is up to 33% (at speed $V_a = 40$ m/s) for the VAZ-2107 and at the same speed - 46%.

References

1. Bayraktar, I., Landman, D., Baysal, O. Experimental and Computational Investigation of Ahmed Body for Ground Vehicle Aerodynamics. *SAE Technical Paper* 2001-01-2742, 2001, https://doi.org/10.4271/2001-01-2742.
2. Desai Manan, Channiwala S.A., Nagarsheth H.J. Experimental and Computational Aerodynamic Investigation of a Car, *Wseas Transactions on Fluid Mechanics*, October 2008; 3, 359-368.
3. Upendra S. Rohatgi. Methods of Reducing Vehicle Aerodynamic Drag. Presented at the ASME 2012 Summer Heat Transfer Conference Puerto Rico, USA July 8-12, 2012.
4. Mazin A.S.; Kaidalov R.O.; Podrigalo M.A. Assessment of the energy load of vehicles. *Zbirnik naukovih prats National Academy of the National Guard of Ukraine* 2017, 28-36.
5. Podrigalo, M.; Klets D., Podrigalo, N.; Abramov, D.; Tarasov, Y.; Kaidalov, R.; Gat'ko V., Mazin A., Litvinov A., Barun M. Creation of the energy approach for estimating automobile dynamics and fuel efficiency. *Eastern-European Journal of Enterprise Technologies* 2017; 5(7) (89), 58-64.
6. Fangjie Yu, Zhao Liu. Direct Energy Rebound Effect of Family Cars: An Analysis Based on a Survey in Chang-Zhu-Tan City Group, *Energy Procedia* 2016; 104, 197-202.
7. Evgrafov, N.A. *Aerodynamics car*. Moscow: MGIU 2010; 356 p. ISBN: 978-5-2760-1707-5.
8. Matzkerle Y. *Modern efficiency vehicle*. Translation from Czech. Mechanical Engineering: Moscow, 1987; 320 p.
9. Gashchuk P.N. *Car energy efficiency*. Svit: Lviv, 1992; 208 p.
10. Bak A.N., Weiss A.L. *Technical Encyclopedia*. Mospoligraph: Moscow, 1927; 1, 858 p.
11. Artyomov, NP, Lebedev, A.T., Podrigalo, M.A, Polyansky, AS, Klets, D.M., Korobko, AI, Zadorozhnyaya, V.V. *The method of partial accelerations and its applications in the dynamics of mobile machines*. Miskdruk: Kharkiv, 2012; p.220.