THEORETICAL RESEARCH OF THE EXTERNAL TEMPERATURE INFLUENCE ON THE TRACTION AND SPEED PROPERTIES AND THE FUEL ECONOMY OF CARGO-CARRYING VEHICLES

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**THEORETICAL RESEARCH OF THE EXTERNAL TEMPERATURE INFLUENCE ON THE TRACTION AND SPEED PROPERTIES AND THE FUEL ECONOMY OF CARGO-CARRYING VEHICLES**

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The aim is to develop a methodology for determining analytically the fuel consumption in a hot climate and substantiate reliability, as well as the possibility of its application by comparison with test results. The article proposes analytical methods for calculating fuel economy and traction-speed properties when modeling the movement of cargo-carrying vehicles on real routes, based on theoretical and experimental studies in a hot and dry climate, which allows for determining the efficiency of cargo-carrying vehicles objectively in terms of traction and speed, fuel and economic indicators. Using the statistical processing of experimental, theoretical research data, the authors calculate the coefficient X2, which allows for evaluating the adequacy of the mathematical model and experimental data. The paper provides for an assessment of fuel economy and traction and speed properties. The authors presented the results in graphs for the ease of evaluating the effect of external temperature on fuel consumption and the average speed of a road train. The authors’ methodology allows for determining the efficiency of cargo-carrying vehicles in a hot and dry climate.

Key words: fuel consumption, driving mode, cargo-carrying vehicle, external temperature

**INTRODUCTION**

The most important problems of our time are the development of ways of rational use of energy resources and their economy. Issues of fuel economy are of extremely high importance. Cargo-carrying vehicles and road trains are parts of the main consumers of liquid fuel and, therefore, increasing the fuel economy of this type of transport is a significant reserve of its economy [1, 2].

When developing measures to increase the constructive efficiency of cargo-carrying vehicles that contribute to improving fuel economy, it is necessary to have data on the value of each of the components of resistance to vehicle movement and on the influence of structural and operational factors on them in hot climates [3-5].

Using theoretical and experimental data banks on the operational properties of cargo-carrying vehicles, especially the interaction of wheels with the road, tire design, internal aerodynamic drag, etc., significantly complicates their use due to the complexity of the application of measurement methods, as well as processing of results. In addition, the absence of reliable analytical dependencies between the components of resistance to movement and fuel consumption influence the results; it is difficult to determine by calculation the effectiveness of the introduced structural changes, and the choice of optimal solutions in conditions of elevated external temperatures. In connection with the above, the development of rational methods for assessing fuel economy is relevant [3].

The development of analytical methods for calculating fuel economy in modeling the movement of cargo-carrying vehicles in hot climates is a relevant task. The solution to this task can significantly reduce the cost of material and financial resources at the design and rationing stage in operating conditions [6].

**MATERIALS AND METHODS**

Gusakov et al. [7] discuss a method for improving the fuel economy of a power plant of a motor vehicle with an electromechanical transmission. Calculation studies of the energy balance of the power plant of the car during its movement under the new European Driving Cycle (NEDC). Driving cycles, used for evaluation of the integral exhaust gas toxicity indicators of motor vehicle engines, helped in simulating the actual operating modes of a motor vehicle engine. Gusakov et al. [7] consider the main factors affecting fuel economy indicators. The authors developed a model and conducted virtual tests using the GT-SUITE software package.

According to Zezyulin et al. [4, 5] the analysis of the results demonstrated the possibility of using the calculation and experimental methodology for estimating the fuel consumption of a motor vehicle when driving along a given route at the design and development stage. This analysis can serve as the basis for developing an improved...
stimated at the acceleration in ith gear; 
\[ r_w \] is the wheel effective radius; 
\[ r_p \] is the rolling radius; 
\[ J_f \] is the flywheel’s mass moment of inertia; 
\[ \sum J_{aw} \] is the total inertia moment of the wheel; 
\[ U_n \] is the total gear reduction; 
\[ \eta_g \] is the gear’s coefficient of efficiency.

Coefficients \( a_i \), \( b_i \), \( c_i \) are determined by the Equation:
\[
\begin{align*}
    a_i &= \frac{a_i}{m_w \cdot \eta_{el} \cdot K_p} - \frac{K_n \cdot F}{r_d \cdot r_k} \cdot \left( 1 - \frac{\beta_a}{\beta_0} + \frac{1}{K_n \cdot \beta} \sum_{i=1}^{m} (-1)^{i+1} \cdot \frac{\sigma^i \cdot r_{i+1} + r_i}{2 T_i} \right) \\
    b_i &= \frac{b_i}{m_w \cdot \eta_{el} \cdot K_p} \cdot \frac{r_d \cdot r_k}{T_{f}} \\
    c_i &= \frac{c_i}{m_w \cdot \eta_{el} \cdot K_p} \cdot \left( 1 - \frac{\beta_a}{\beta_0} \right) \cdot \left( 1 - \frac{1}{K_n \cdot \beta} \sum_{i=1}^{m} (-1)^{i+1} \cdot \frac{\sigma^i \cdot r_{i+1} + r_i}{2 T_i} \right) - f \cdot G_a \cdot \cos \alpha \pm \sin \alpha
\end{align*}
\]
where \( a_m, b_m, c_m \) are the coefficients of the Equation
\[
M_e^P = a_m^P \cdot \omega_e^2 + b_m \cdot \omega_e + c_m^P
\]
of the dependence of torque on the angular velocity of the motor shaft. The coefficients are determined by the value of the external temperature and the rack travel position;
\( K_{cwh} \) is the correction factor of engine power;
\( K_{oac} \) is the air drag coefficient;
\( F \) is the frontage area of the motor vehicle;
\( \beta_\mu \) and \( \beta_a \) are the coefficients of the relative clear area of the input and output sections;
\( \rho \) is the atmospheric density;
\( T_r \) is the external temperature.
\( f \) is the coefficient of rolling resistance;
\( G_a \) is the weight of the vehicle.

The \( f \) coefficient is determined by the Equation:
\[
f = f_0 + K_f \cdot \delta f^2
\]
where \( f_0 \) is the coefficient of rolling resistance at low speed;
\( K_f \) is the speed factor.

It follows that when simulating the movement of a road train on a PC, it is necessary to know the angular velocity of the engine crankshaft and the rack travel position to determine motion indicators. The angular velocity is calculated based on the speed of the train using the well-known Equation:
\[
\omega_e = \frac{\theta_a T_{vi}}{r_k}
\]
(3)

External and partial engine characteristics are used to determine the rack travel position. First, the power to overcome the total resistance forces is calculated:
\[
N_\Sigma = N_{ja} + N_{\psi f} + N_b + N_\tau
\]
(4)
where
\( N_{ja} \) is the power spent to overcome acceleration resistance;
\( N_{\psi f} \) is the power spent to overcome the resistance of the road;
\( N_b \) is the power spent to overcome air resistance;
\( N_\tau \) is the power spent on overcoming transmission resistance.

Using the Equation \( N_\Sigma = N_{ja} + N_{\psi f} + N_b + N_\tau \), it is possible to find the required engine power. By comparing Ne with engine power values for different hp for a given value of \( \omega_e \) and \( T_{ext} \) it is possible to find the power values of the closest Ne and the corresponding rack travel position. It should be noted that the given \( \omega_e \) corresponds to the initial moment of the calculation step, and the obtained value of hp is used for the next calculation step.

Since partial speed characteristics are available only at values of \( h_\tau \) multiple of 10, the values of the power \( N_e \) are not always equal to \( N_{ja}, N_{\psi f}, N_b, N_\tau \), and this causes a certain error. Despite this, the proposed method has advantages over others, according to which engine power is found from the given values of the position of the fuel supply body and the angular velocity of the engine crankshaft. In this case, it is impossible to consider all the concomitant factors affecting the operating mode and fuel consumption of the engine. According to the authors’ methodology \( Q_v, \omega_e, h_\tau \) are more real, since they are determined taking into account the influence of both design factors and the total resistance to movement on them, which allows for considering the change in engine power, efficiency transmission, coefficient of rolling resistance, drag coefficient, as well as external temperature.

The solution of the differential Equation 1 allows for determining the nature of the change in the movement of the road train on each section of the route. In this case, the initial speed on the road section and the segment length are taken as initial data.

In the model of a cargo-carrying vehicle’s movement, the studied route is introduced as a set of segments of a certain length, each of which has constant profile parameters.

A road profile in the form of a sequence of linear sections of the corresponding length with a constant slope can be obtained either by processing the design documentation of the road, or experimentally using a special set of equipment.

When modeling the acceleration mode, the following Equations were used:

a) To determine the change in speed on the path segment equal to \( \Delta S \):
\[
\Delta \theta_a = \left( (a_1 \cdot \delta a^2 + b_1 \cdot \theta a + c_1) / (m_a \cdot 9.8 \cdot \delta b^2) \right) \cdot \Delta S
\]
(5)
b) To determine the speed at the end of the segment:
\[
\theta a_2 = \theta a + \Delta \theta a
\]
(6)
c) To determine the time of movement on the segment:
\[
T_a = \frac{\Delta \theta a}{\omega_e}
\]
(7)

The following equations were used to determine the change in speed in deceleration mode:

a) During engine braking:
\[
a_i = K_b \cdot P + K_f
\]
\[
b_i = \frac{b_z \cdot U_{T1}^2}{(r_k \cdot \eta_r)}
\]
\[
c_i = a_z \cdot U_{T1}^2 / (r_k \cdot \eta_r) + (f_0 + i) \cdot m_a \cdot 9.8
\]
(9)

where \( a_z \) and \( b_z \) are the coefficients depending on the type and design features of the engine.

b) When braking by the engine and brake mechanisms:
\[
a_i = K_b \cdot P + K_f
\]
\[
b_i = \frac{b_z \cdot U_{T1}^2}{(r_k \cdot \eta_r \cdot m_a \cdot 9.8)}
\]
\[
c_i = a_z \cdot U_{T1}^2 / (r_k \cdot \eta_r) + (f_0 + i) \cdot 9.8 + m_a \cdot 9.8 \cdot \varphi
\]
(10)
where $\varphi$ is the adhesion coefficient.

Traveling fuel consumption at each section and along the entire route as a whole is calculated based on the speed obtained at the previous stage. When the engine power is fully turned on in a section $S_i$, long and when the speed changes from $v_n$ to $v_k$, the fuel consumption is determined by the following equation:

$$Q_i = a_{\varphi} m \cdot \delta \cdot \frac{\ln\left(\frac{a_i v_n^2 + b_i v_n + c_i}{a_i v_k^2 + b_i v_k + c_i}\right)}{2 a_i} + \tau \left(c_{\varphi} + \frac{b_{\varphi} - 2 a_{\varphi} c_{\varphi}}{2 a_{\varphi}} + b_{\varphi} S_i\right)$$

where $\tau_i$ is the time required for passing the $i$th section $S_i$, long;

$$a_{\varphi}, b_{\varphi}, c_{\varphi}$$

is the fuel-flow rate equation coefficient

$$a_{\varphi} = \frac{a_{\varphi} U_{n}}{3600 r_k}; \quad b_{\varphi} = \frac{b_{\varphi} U_{n}}{3600 r_k}; \quad c_{\varphi} = \frac{c_{\varphi}}{3600}$$

(12)

Coefficients $a_{\varphi}, b_{\varphi}, c_{\varphi}$ are calculated depending on the hourly fuel consumption approximated by a polynomial of the second degree:

$$Q_n = a_{\varphi} v_n^2 + b_{\varphi} v_n + c_{\varphi}$$

(13)

Modeling of the motion process is done according to a rather complex algorithm. The simulation program consists of a main program and four subprograms, which are provided by Kulmukhamedov [3].

RESULTS AND DISCUSSION

The results of computational studies on the influence of external temperature on the generalized TSP and FE indicators are illustrated by the example of the KamAZ-54112+OdAZ-9385 road train and are presented in Figure 1. The graph is built for three values of the coefficient of utilization of carrying capacity ($\gamma = 0$; $\gamma = 0.5$; $\gamma = 1$).

Figure 1 indicates that with increasing external temperature, fuel consumption increases, and the average speed decreases. The modes of movement of the road train are analyzed to identify the causes of this influence.

The analysis of the driving modes (Figures 2, 3) showed that when the external temperature rises from $+25^\circ C$ to $+43^\circ C$, the distance traveled at the highest gear is reduced. The reason for using lower gears is a change in engine operating conditions and, consequently, a further increase in fuel consumption.

Figure 2: A histogram of the distribution of the KamAZ-54112-OdAZ-9385 road train in the modes: $A$ - acceleration; $SSS$ - steady-state speed; $S$ - slowdown

Figure 3: The histogram of the distribution of the path of the KamAZ-54112-OdAZ-9385 road train at the III (1), IV (2), and V (3) gears
The analysis of the engine operating modes in Figures 4-6 allows for stating that in three weight states (γ = 0; γ = 0.5; γ = 1), an increase in the external temperature significantly reduces the engine torque.

Figure 4: Distribution curves of engine operating modes during the movement of a road train on the Tashkent-Jizzakh route (torque): a) γ = 1; b) γ = 0.5; c) γ = 0. Respectively, 1 - 25°C; 2 - 28°C; 3 - 31°C; 4 - 34°C; 5 - 37°C; 6 - 40°C; 7 - 43°C
Figure 5: Distribution curves of engine operating modes during the movement of a road train on the Tashkent-Jizzakh route (crankshaft rotational speed):
(a) γ = 1; (b) γ = 0.5; (c) γ = 0. Text = 25°C...43°C

Figure 6: Distribution curves of engine operating modes during the movement of a road train on the Tashkent-Jizzakh route (rack travel position): (a) γ = 1; (b) γ = 0.5; (c) γ = 0. Text = 25°C...43°C

The distribution curves of the torque show that an increase in the external temperature leads to a change like this distribution, and for different weight conditions, the road train has the same character. As the external temperature rises, the distribution values shift toward lower torque values.

Within the range of changes in the external temperature $T_{ext}$, the torque values were in the range from 593.4 to 607.4 Nm, and at $T_{ext} = +35°C\ldots+40°C$ - in the range from 580.4 to 597.4 Nm, and at $T_{ext} = +40°C\ldots+43°C$ - in the range from 577.4 to 587.4 Nm.

Reducing engine torque results in the fact that overcoming the resistance to movement at the same gear stage at various external temperatures becomes impossible, and the lower gears are switched on, and the position of the fuel supply control changes towards the maximum values. Thus, the change in fuel consumption with increasing external temperature is a consequence of the complex interaction of the engine and the transmission of the road train.

An analysis of Figure 1 shows that the effect of $T_{ext}$ on $Q_s$, $v_{stav}$ grows with an increase in the total mass of the road train. At the rated carrying capacity ($γ = 1$) of the road train, increasing $T_{ext}$ from +25°C to +43°C leads to an increase in fuel consumption by 9%. For road trains with $γ = 0.5$ and $γ = 0$, these data are 7 and 3%, respectively.

As can be seen from Figure 1, the values of velocity at $γ = 0.5$ and $γ = 0$ are significantly higher than at $γ = 1$. This is because the speed of the road train in the first two cases is limited by road signs and permissible speed values, and for a road train with a full load, the speed is limited by its traction-speed properties and road conditions. At the same time, the road train does not always reach the speed permitted by the traffic rules.

Simulation of the movement modes of the road train and determining the fuel consumption on a real route requires checking the adequacy of the calculation methods. In this case, such a check can be carried out by comparing the calculated data with the test results to establish the modes of motion and fuel consumption of the road train [3].

The results of the calculation and experiment to determine the movement mode and fuel consumption of the road train on the Tashkent-Jizzakh route with a length of 100 km are shown in Figures 7 and 8.

As can be seen from Figures 7 and 8, the assessment of the adequacy of the model by the average fuel consumption and the average value of speed is wrongful, because, with equal average performance, the actual situation of the process may differ. The study and analysis of methods comparing experimental and calculated data showed that the most acceptable is the use of the agreement criterion $x_u$ - square. In this case, the probability density of the calculated and experimental data is compared with a certain hypothetical density.

The general methodology for applying the criterion is as follows: the authors take a sample of N observations...
of a random variable X with density P(X). The authors group of N observations at i intervals, and the authors call grouping intervals, which together form a histogram of frequencies. The number of observations falling into the ith interval is called the observed frequency of the ith interval; denote this frequency $f_i$. The number of observations that could fall in the ith interval if the true density of X was $P(X)$ is called the expected frequency of the ith interval; the authors denote it by $F_i$. The discrepancy between the observed and expected frequencies in each interval is $f_i - F_i$. To measure the total discrepancy over all intervals, the squares of the discrepancy are normalized with the corresponding expected frequencies, the sum of which gives the sample statistics.

$$X^2 = \sum_{i=1}^{k} \left( \frac{f_i - F_i}{F_i} \right)$$  \hspace{1cm} (14)

When assessing the adequacy of the model for fuel consumption, a set of fuel consumption values is used as a sample of a random variable. The authors give an example of checking the adequacy of the model for fuel consumption values obtained by calculation and experimentally at a temperature of +300°C on the Tashkent-Jizzakh route assuming that these values are distributed according to the normal law.

All calculations necessary for the formation of the criterion are summarized in Table 1. The grouping interval boundaries set by the standard normal distribution are placed in the column under the symbol of $Z_{α}$. The dura-
Table 1: Calculations performed when constructing the fitting criterion

| The number of the interval | $Z_α$ | $x = S\frac{Z_α}{\sqrt{x}}$ | P | F=NP | f | $\frac{(F-f)}{F}$ |
|---------------------------|-------|-----------------------------|---|------|---|----------------|
| 1                         | -2.0  | 9.89                        | 0.0228 | 16.188 | 20 | 3.812 | 0.896 |
| 2                         | -1.6  | 15.93                       | 0.0320 | 27.72 | 21 | 1.72 | 0.076 |
| 3                         | -1.2  | 21.98                       | 0.0603 | 42.813 | 38 | 4.813 | 0.541 |
| 4                         | -0.8  | 28.02                       | 0.0968 | 68.728 | 61 | 7.728 | 0.869 |
| 5                         | -0.4  | 34.05                       | 0.1327 | 94.217 | 92 | 2.217 | 0.052 |
| 6                         | 0     | 40.094                      | 0.1554 | 110.33 | 109 | 1.33 | 0.016 |
| 7                         | 0.4   | 46.13                       | 0.1554 | 110.33 | 108 | 2.33 | 0.049 |
| 8                         | 0.8   | 52.17                       | 0.1327 | 94.217 | 89 | 5.217 | 0.288 |
| 9                         | 1.2   | 58.21                       | 0.0968 | 68.728 | 76 | 7.272 | 0.769 |
| 10                        | 1.6   | 64.25                       | 0.0603 | 42.813 | 49 | 6.187 | 0.145 |
| 11                        | 2.0   | 70.29                       | 0.0320 | 22.72 | 26 | 3.28 | 0.144 |
| 12                        |       | 0.0228                      | 16.188 | 21 | 4.812 | 0.297 |

The calculation of the intervals $\Delta X = 0.4S$. The next column contains the same values in another unit of measurement in l/100 km. Then, using the value of $Z_α$ according to the data of standard tables, the authors determine the probability $P$ of the indicators of sample values in each of the grouping intervals. Multiplying $P$ by sample size $N$ gives the expected frequencies for each interval.

These frequencies are shown in the column marked with $F$. The authors calculate the observed frequencies $(f)$ using the interval boundaries. After that, calculating and summing up the normalized squares of the discrepancies of the expected and observed frequencies, the authors obtain $x^2$.

According to the experimental data obtained when testing the road train on the Tashkent-Jizzakh route ($T_{00}=30^\circ\text{C}$), the calculated value of $x^2$ is 4.144. The amount of degree of freedom equals to $n=K-3=9$.

The distribution of the hypothesis of normality of distribution is found in standard tables, and then the authors obtain $x^2_{9,0.05}=16.92$; i.e., $x^2 < x^2$. Consequently, the hypothesis of normality is accepted with a significance level of $\alpha = 0.05$. In the same way, the value for the calculated data is determined, which is equal to $x^2 = 5.92$.

It follows that the experimental data are distributed according to the normal law, i.e., does not differ from the standard normal distribution with a significance level of $\alpha = 0.05$. This allows for assuming that the model is adequate with the experimental data for the selected significance level.

**CONCLUSIONS**

Based on the graph shown in Figure 1, the authors conclude that the influence of external temperature on fuel consumption and average speed with an increase in the total mass of the cargo-carrying vehicle. At the rated carrying capacity of the road train, an increase in the external temperature from $+25^\circ\text{C}$ to $+43^\circ\text{C}$ leads to an increase in fuel consumption by 9%. For road trains with load factors of 0.5 and 0.7, these data are 7 and 3%, respectively. Thus, with an increase in the external temperature, there is an increase in fuel consumption and a decrease in the speed of movement in all weighted states of motor vehicles.

The manuscript made it clear that as the external temperature rises, there are an increase in fuel consumption and a decrease in the speed of movement in all weighted states of vehicles.

The influence of the external temperature decreases, with a smaller mass of the road train, which indicates the special importance of research to find ways to reduce the resistance to movement of road trains operating in a hot, dry climate.

The mathematical modeling of the process of moving a truck on a real route showed that the modified mathematical model, which considers the effects of elevated external temperatures, allows for determining objectively the degree of efficiency of a cargo-carrying vehicle by traction and speed properties and fuel economy to these conditions, as well as at the design stage.

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