Regulation of liquefied petroleum gas consumption for a passenger car in the mountain conditions of the Republic of Tajikistan

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Abstract. In the article the main results of research work to determine the consumption rates of liquefied petroleum gas (LPG) for a car brand KIA Optima are presented. The research was accomplished for high-mountain conditions of operating in the Republic of Tajikistan (RT). The basic factors, influencing fuel and economic indicators of the car in mountain conditions of operation, are considered, and the main analytical dependences, received on the basis of the developed mathematical models, are presented. The practical realization of the developed mathematical models allows for individual rationing of fuel consumption, taking into account the parameters of the mountain road and, accordingly, the assessment of the road complexity.

On the basis of the experimental data obtained, graphical dependences of fuel consumption in mountain conditions of vehicle movement are constructed and presented.

1. Introduction
The effective using of automobile transport (AT) in the mountain conditions of the RT (93 % of area is occupied by mountains) is an important task, because mountain roads are characterized by a large number of ascents, descents and sharp turns, which significantly increases the fuel consumption [4–6, 8]. In such operating conditions, it is required to conduct theoretical and experimental research, allowing realizing the effective control of the gas flow rate regulation during vehicles operation [3, 8].

2. Main part
The practical realization of tasks related to the regulation of fuel consumption of vehicles, running on LPG in the mountain conditions, provides for the construction of mathematical models and their realization, enabling the determination of fuel economy of bottled gas driven automobiles by the values of factors, describing the routes. The basis for the construction of mathematical models is theoretical and experimental research of fuel consumption estimates, depending on the complexity of the route in the movement of vehicles, reflected in the works [1–4].

In expression (1) the transformed extended formula of the estimation of route movement complexity with set of the factors, reflecting parameters of mountain conditions of vehicles operation, is presented:
\[
Y_{Ai} = \frac{L_H \cdot H_i \cdot K_i \cdot X_{RH} \cdot X_{II}}{V^2 \cdot X_t \cdot X_T \cdot X_P} ,
\]

where: \(L_H\) – the lower tolerance limit of the normalized sections lengths, accepted in the calculation as a reference point, providing sufficient accuracy and sensitivity of measurements of all researched values, km (accepted for a given probability of 0.8-0.9 [5]; \(H\) – average height of the section on the route, km; \(K\) – steepness of ascent or descent of the section on the route, \(\alpha\); \(X_{RH}\) – relative humidity of the ambient air, (RH) %; \(X_{II}\) – frequency of turns, (\(\Pi\)) ea.; \(V\) – average speed of the vehicle, km/h; \(X_t\) – average movement time of the vehicle, sec., min., hour; \(X_T\) – ambient air temperature, (T) ºC; \(X_P\) – ambient air atmospheric pressure, \(P\); \(Z_{RH}, Z_{II}, Z_t, Z_T, Z_P\) – takes 0 if the relevant factor is not taken into account in the complexity formula, and 1 if the factor in question is taken into account.

Given that in the expression (1), the parameters under consideration have different dimensions of the value of the route complexity index, it should be subject to regulation through the standard deviation, i.e.:

\[
\sigma(Y_A) = \sqrt{\frac{\sum_{i=1}^{n}(Y_{Ai} - \bar{Y})^2}{n-1}} .
\]

In the final form, the normalized value of the route difficulty can be written as:

\[
Y_{Bi} = \frac{L_H \cdot H_i \cdot K_i \cdot X_{RH} \cdot X_{II}}{V^2 \cdot X_t \cdot X_T \cdot X_P} \cdot \sigma(Y_A) .
\]

Given the fact that in the expression (3) there is a factor of the slope angle of the road \((K_i)\), taking depending on the ascent or descent positive or negative value respectively, the expression (3) of the complexity assessment is converted in order to shift the result to the region of positive values, i.e.:

\[
Y_{Ci} = Y_{Bi} - Y_{Bmin} ,
\]

where \(Y_{Bmin}\) – minimum values \(Y_{Bi}\).

As a target function of fuel efficiency indicators \((Q_{LPG})\) in l/100km of the vehicle in mountain conditions operation on the route, the model of the form is accepted:

\[
Q_{LPG} = f(Y_{Ci}) .
\]

In the process of constructing models of fuel consumption of the vehicle, the analysis of experimental data obtained by the values of the factors under consideration was made. The analysis included checking for the presence of the interconnection factor with the resulting sign.

Construction of models, describing the researching phenomena, is carried out with the mathematical apparatus of correlation and regression analysis using. Mathematical models of the form can be used as target functionals, linking fuel consumption with the complexity indicator of the route of the vehicle, running on LPG:

\[
Q_{LPG} = a + a \cdot Y_{Ci} ,
\]

\[
Q_{LPG} = a + a \cdot \ln Y_{Ci} ,
\]
\[ Q_{LPG} = a \cdot e^{Y_{CI}}, \]  
\[ Q_{LPG} = a \cdot Y_{CI}^6, \]  
\[ Q_{LPG} = a + b \cdot Y_{CI} + c \cdot Y_{CI}^2. \]

For understanding the nature of the individual factors link, characterizing the driving conditions impact on fuel consumption, a differentiated assessment of the degree of their impact on fuel efficiency was carried out, i.e.:

\[ Q_{LPG} = f(X), \quad X = \{V\}, \{t\}, \{K\}, \{H\}, \{L\}. \]  

Detection of the dependence of gas fuel consumption on operating conditions was revealed in the process of experimental researches on a mountain highway with a maximal elevation difference on the Dushanbe-Shahristan-Dushanbe route in the RT [3–5]. As the object of research a passenger car of KIA Optima brand was chosen in which gas equipment of the (HBO) 4th generation was installed. The modern ultrasonic fuel level sensor (UFLS) Sigma (hereinafter – the sensor) is used as measuring equipment to determine the gas flow rate on the vehicle. The sensor is connected to the satellite monitoring system of transport for storage and processing of data about the amount of fuel in the gas cylinder [4, 5].

Within the framework of the experimental research, in order to determine the dependence of LPG consumption on traffic conditions, the factors and their influence on the target function of the route complexity [2] were identified, and then their influence on the fuel consumption of the vehicle \( Q_{LPG} \).

As such factors (in the summer test conditions) have been chosen: \( V_i \) – the average vehicle speed on the section, km/h; \( H \) – the average height of land on the route of the vehicle, km; \( K \) – the steepness of ascent of the sections on the route of the vehicle, \( \alpha \);

On the basis of primary data the analytical dependence of complexity of movement of the motor vehicle on each \( i \)-m site of a route, depending on set of above noted factors, taking into account normalization on a standard deviation, was revealed \( \sigma(Y) \) [4].

Dependences of fuel consumption on the route complexity has regular character – as the complexity of the route increases, fuel consumption increases. The function graph of fuel consumption dependence on the route complexity is close to the quadratic dependence.

Processing of the collected information allowed to obtain mathematical models of fuel consumption \( Q_{LPG} \) as a function of the route complexity \( Y \) in the forward (12) and in the reverse direction (13) on the Dushanbe – Shahristan highway. Graphical dependences of fuel consumption on the complexity of the route are shown in figure 1:

\[ Q_{LPG} = 1.4019 \cdot Y^2 - 0.0698 \cdot Y + 3.0287, \]  
\[ Q_{LPG} = 1.6722 \cdot Y^2 - 2.8195 \cdot Y + 5.2367, \]

where \( Y \) – takes the form:

\[ Y_i = Y_{i \text{ min}} - Y_{i \text{ min}}, \]  

\( Y_i \) is defined from the expression:

\[ Y_i = \frac{L \cdot H \cdot K}{V_i^2 \cdot \sigma(Y^*)}, \]  

where \( \sigma(Y^*) \) – mean square deviation of the parameter \( Y_i^* \) [4]:
This is $Y_i^*$ reflected in the form of the equation (16):

$$Y_i^* = \frac{L_i \cdot H_i \cdot K_i}{V_i^2}.$$  

Figure 1. Dependences of LPG consumption on the complexity of the route on the Dushanbe-Shahristan highway

Large values of fuel consumption in the forward direction "Dushanbe-Shahristan" in comparison with the reverse direction of movement on the route "Shahristan-Dushanbe" are associated with different heights of the 1st and 2nd parts of the route. When moving in the forward direction, ascents prevail, and when moving in the opposite direction – descents, which causes a stronger dependence of the consumption on the complexity in the forward direction than in the reverse.

The analysis of the dependence of fuel consumption on the complexity of the route reveals the influence of the average vehicle speed and, accordingly, build the dependence of fuel consumption on the average speed in the considered sections (fig. 2), as well as to obtain a mathematical model of fuel consumption at the average speed of the vehicle in the forward (18) and in the reverse direction (19) on the Dushanbe – Shahristan highway:

$$Q_{LPG} = 113.37 \cdot V^{-0.596},$$

$$Q_{LPG} = 25.115 \cdot V^{-0.306}.$$

Figure 2 illustrates a regular decrease in fuel consumption with an increase in the average speed of movement on the site, which is associated with a decrease in the complexity of the movement.

At the same time, on the basis of information about the initial and final heights of the route sections obtained with the help of the satellite transport monitoring system [4, 5], the average height of the Dushanbe – Shahristan highway sections above sea level was determined. Equations were identified and graphical dependences of their influence on the vehicle fuel consumption were constructed (fig. 3). The equations of fuel consumption, depending on the average height of the section on the straight line (20) and in the opposite direction (21), are described by logarithmic dependences and have the form:

$$Q_{LPG} = 5.7462 \cdot \ln(H) + 9.6406,$$

$$Q_{LPG} = 6.4057 \cdot \ln(H) + 4.5158.$$
Graphical dependencies (fig. 3) show that with the growth of the average height of the section on the route there is an increase in fuel consumption and vice versa.

At the same time, taking into account such factors as the average vehicle speed and the average section height on the Dushanbe-Shahristan highway, it is possible to identify their combined effect on fuel consumption (fig. 4) and obtain the corresponding analytical dependencies (22)–(23):

\[
Q_{LPG} = -227578 + 0.266 \cdot \bar{H} + 324185 \cdot V + 0.001 \cdot \bar{H}^2 - 0.2776 \cdot \bar{H} \cdot V - 3.8156 \cdot V^2; \quad (22)
\]

\[
Q_{LPG} = -116702 + 0.5731 \cdot \bar{H} + 3503 \cdot V - 0.0025 \cdot \bar{H}^2 - 0.2292 \cdot \bar{H} \cdot V + 3.5304 \cdot V^2. \quad (23)
\]

From the presented three-dimensional graphs (fig. 4) it follows that fuel consumption depends not only on the speed of the vehicle, but also on the altitude above sea level (a.s.l.). When driving in the city of Dushanbe (0.8–1.0 km a.s.l.) fuel consumption from the speed of the vehicle is in proportion. When driving in the mountains at the level of road tunnels "Istiqlol" and "Shahristan" (2.2–2.8 km
a.s.l.) [4, 5] the factors of traffic complexity change the dependence of fuel consumption on speed to the reverse: than less the speed, the more consumption.

Figure 4. Dependences of fuel consumption on the average height of the section and speed of the vehicle on the Dushanbe – Shahristan (a) and Shahristan – Dushanbe (b) highway

On the basis of primary experimental data, such as the initial and final height of the section, as well as its length, the steepness of ascent of the sections on the route of the vehicle was determined.

The equations of fuel consumption, depending on the steepness of ascent in the forward (24) and in the reverse direction (25), have the form:

\[ Q_{LPG} = 9,2355 \cdot e^{8,5761 \cdot K}, \quad (24) \]

\[ Q_{LPG} = 7,8271 \cdot e^{7,1728 \cdot K}. \quad (25) \]

A graphical representation of the dependence of fuel consumption on the steepness of the route sections is shown in fig. 5.

Figure 5. Dependence of fuel consumption on the steepness of ascent on the Dushanbe – Shahristan highway
It can be seen from the graph (fig. 5) that with an increase in the steepness of ascent, fuel consumption increases. For fig. 6 the estimation of fuel efficiency of Kia Optima car on Dushanbe-Shahristan-Dushanbe sections is graphically reflected, depending on the steepness of ascent and average speed of movement both in forward (26) and reverse (27) directions:

$$Q_{LPG} = 10,0679 + 0,0169 \cdot K + 199,7453 \cdot V - 0,0008 \cdot K^2 - 1,3463 \cdot K \cdot V + 613,256 \cdot V^2;$$  \hspace{1cm} (26)

$$Q_{LPG} = 1,4294 + 0,306 \cdot K + 123131 \cdot V - 0,0034 \cdot K^2 - 0,8887 \cdot K \cdot V + 432,0705 \cdot V^2;$$  \hspace{1cm} (27)

**Figure 6.** Dependences of fuel consumption on the steepness of the ascent and the average speed of the vehicle

At almost all speeds, there is a characteristic increase in fuel consumption with an increase in the steepness of the ascent, which is a natural result.

**Figure 7.** Dependences of fuel consumption on the average height of the section and the steepness of ascent of the vehicle on the Dushanbe – Shahristan (a) and Shahristan – Dushanbe (b)

The combined effect of the steepness of the ascent and the average height of the site above sea level on fuel consumption is shown in fig. 7. The equations describing the respective interconnections of the Dushanbe – Shahristan (28) and Shahristan – Dushanbe (29) highway have the form:
\[ Q_{\text{LPG}} = 7.7082 + 69.2213 \cdot K + 1.2756 \cdot V - 658.7635 \cdot K^2 + 27.1641 \cdot K \cdot V + 0.7993 \cdot V^2; \] 
\[ Q_{\text{LPG}} = 8.1683 - 31.6496 \cdot K - 3.7472 \cdot V + 557.1181 \cdot K^2 + 49.4571 \cdot K \cdot V + 1.5821 \cdot V^2. \]

As follows from the graphical dependencies fig. 7, the highest fuel consumption is observed at maximal ascent at maximal altitude. The minimal fuel consumption is almost independent of the average height and is observed on a moderate (not maximal) descent. At the maximal descent, there is a slight increase in the allowance, which is associated with transient modes of operation of the ICE in such modes.

Using of models (5)–(10) creates conditions for reliable formation of allowances to route norms for extreme mountain conditions of the Republic of Tajikistan. At the same time, the developed model of gas fuel consumption allows adapting the original formula of NIIAT, for passenger vehicles to the level of individual route norms (refer expression 30):

\[ Q_{br} = 0.01 \cdot Q_H \cdot L_y \cdot (1 + 0.01 \cdot D), \] 

where \( Q_{br} \) – fuel consumption of the vehicle corresponding to the base rate (corresponds to the minimal height above sea level);

\( Q_H \) – standard fuel consumption per vehicle mileage;

\( L_y \) – the length of the plot having a minimal height above sea level, km;

\( D \) – allowance correction factor corresponding to the base rate of consumption (minimal height of the route section above sea level) in percentage.

By converting the original expression (30), it is possible to determine the fuel allowance:

\[ D = \left[ \frac{Q_E}{0.01 \cdot Q_{br} \cdot L_y} - 1 \right] \cdot 100\%, \] 

where \( Q_E \) – the fuel consumption of the vehicle corresponding to experimental data.

Expression (31) allows to determine the value of the allowance on any considered part of the route. This coefficient of allowance, determined on the basis of approximation of experimental data, corresponds to the operating conditions of vehicles in the Republic of Tajikistan.

If it is necessary to estimate the allowance for fuel consumption for high-altitude operating conditions relative to the standard fuel consumption of a car \( Q_T \), use an expression of the form:

\[ D_T = \left[ \frac{Q_P^T}{0.01 \cdot Q_H \cdot L_y} - 1 \right] \cdot 100\%, \] 

where \( Q_P^T \) – fuel consumption, corresponding to the accepted models (see expressions (5-3), was calculated through the complexity of traffic conditions:

\[ Q_P^T = f \left( Y_{Ci} \right). \]

The individual route norm is determined by the calculation of the correction factor for the allowance \( D_T \), is consistent with expression (32) for the selected sections of the route and the subsequent summation to assess the allowance for the entire route as a whole.

An example of dependency allowances \( D_T \) for specific sections of the route are shown in Figures 8-9 of which shows a high degree of convergence on \( D_T \) and \( Q_T \).
Figure 8. Dependence of the theoretical allowance $D_T$ on the route section and fuel consumption in the corresponding section $Q_T$ Dushanbe – Shahristan

Figure 9. Dependence of the theoretical allowance $D_T$ on the route section and fuel consumption in the corresponding section $Q_T$ Shahristan – Dushanbe

3. Conclusion

Based on the obtained research results, it follows that the proposed mathematical models make it possible to objectively describe the functional dependence of the LPG flow rate and surcharges on it from the generalizing parameter of the route complexity in the mountain conditions of the Republic of Tajikistan. On the basis of the offered models it is possible to receive individual norms of the consumption of gas fuel for any sites and their quantity of the considered road profile. The graphic dependences, constructed on the basis of experimental data, allow to judge about functional dependence of fuel consumption on the generalizing parameter of complexity of a route in concrete conditions. The research results, proposed approaches, principles and models create the conditions for the formation of a regulatory basis by its development and the equation consumption of LPG cars in the mountain conditions of the Republic of Tajikistan.
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