COST ESTIMATE FOR FILLING WITH DIFFERENT MOTOR FUELS IN FREIGHTING BY LIGHT-DUTY VEHICLES

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The use of natural gas as a motor fuel in road transport can significantly reduce fuel costs and the adverse environmental impact of motor vehicles. However, an insufficiently developed infrastructure for compressed natural gas (CNG) constrains the growth in the number of natural gas-powered road transport enterprises. The limited number of automobile gas-filling compressor stations (AGFCS) increases the mileage of motor vehicles, which reduces the efficiency of natural gas use in road transport. This study aims to assess the costs of filling with different types of motor fuel regarding the overall costs of road freight. The scientific novelty of the work lies in establishing the dependence of costs for filling with motor fuel on the operational performance of vehicles and the development of fueling infrastructure of specific motor fuel types. For the first time, the authors evaluated the share of fueling costs for light-duty vehicles (LDVs) for different hydrocarbon fuels regarding the costs associated with the transportation process. It was found that the share of fueling costs varies depending on the type of hydrocarbon fuel used and can range from 1.5 to 15%, depending on the fueling infrastructure development. The results obtained can be used in decision-making on choosing the fuel type in the transportation process by LDVs to minimize overall costs.

Key words: motor fuel, filling station, fueling costs, light-duty vehicles

INTRODUCTION

When transporting goods and passengers, carriers try to reduce the cost of these services as much as possible. The study [1] presents the analysis of uncertainty in road transportation, affecting the overall costs of the enterprise and the region under conditions of economic instability [2]. An assessment of the efficiency of trucks in urban transportation is presented in (Putra et al., 2020). However, these costs considered by road transport enterprises in the Russian Federation do not take into account the costs associated with fueling. Currently, the most common are five types of fuel, which cost ranges from 20 rubles per m³ of CNG to 53 rubles per liter of diesel fuel [3]; the cost to charge an electric car is 10 rubles per kilowatt-h [4]. A detailed literary analysis of using different types of alternative fuels for road transport is presented in [5, 6]. The work [7] presents the review on performances of motor fuel production, which, certainly, is the aspect of strategic planning of infrastructure development of one or another alternative type of motor fuel. Although the replacement of fossil fuel vehicles with lighter electric vehicles has the greatest potential to reduce CO2 emissions [8], the widespread use of electric power on freight and passenger transport (excluding trolleybuses and streetcars) in the Russian Federation is currently impossible due to the lack of infrastructure for charging [9], maintenance and repair of such vehicles. In Europe [6, 10-12], North America [13], China [14-16], India [17, 18], and other countries, the use of electric transport is a priority for the transport industry. The use of CNG, as the cheapest [19] and economical by more than 15% [20] among hydrocarbon motor fuels, does not always provide the maximum economic effect of the transportation process [19, 20] that caused by the insufficiently developed AGFCS infrastructure [19, 21-23]. In [15], an evolutionary analysis of the impact of a three-dimensional model of technology, market, and policy on the development of the automobile industry on new energy sources in China is conducted. The comparison study [24] substantiates that the emission reduction of hydrocarbon fuel products is most effectively achieved with a reasonable investment in road transport and transport infrastructure. Based on the game model, it was shown that a certain state policy, for example, in taxi services, determines a winning strategy for motor vehicles based on CNG [23]. Five aspects of strategic management of road infrastructure are described in [25], but they are general and do not make it possible to specifically assess the effectiveness of using a particular type of fuel in the transportation process. An overview of studies conducted on the environmentally friendly vehicle routing problem and its classification, given all types and variants of environmentally friendly vehicle problems, is presented [26]. Keeping the number of gas-filling stations and gas-fueled vehicles in line is necessary. For example, there are two AGFCS in Omsk with 186 registered vehicles using CNG as fuel (Form 1 – Traffic Safety). At the same time, in existing international practice, it is considered optimal to have 1 AGFCS per 1,000 gas-powered vehicles to balance the infrastructure economic efficiency and its capacity. Simultaneously, [27] proposes a methodology for ensuring high accuracy in forecasting...
CNG demand. Choosing the fuel type and the corresponding vehicle has been studied quite extensively. There are also many publications devoted to the impact on urban planning, forming supply routes [28], distribution networking [14], and design changes in the vehicles themselves [19]. A methodology for multi-criteria choice of vehicles depending on the available infrastructure of the transport network is presented in [29]. In [30], using China as an example, the issue of choosing the vehicle type in terms of reducing CO2 emissions based on the Theory of Planned Behavior is studied, offering some reasonable suggestions for the government and corporate service providers of electric vehicles toward increasing the distribution only of electric vehicles. The study [31] considers the relationship between symbolic meanings and the choice of electric vehicles in China, which can be an effective expression of consumer identity. An algorithm for selecting a rolling stock for freight transportation based on the specific conditions of a motor transport enterprise was developed and proposed in [32]. The research [5] presents the design requirements for the rolling stock to effectively manage road transportation, considering the assessment of the vehicle dimensions. The impact of technological innovations on emissions in transport is considered by the case of China [33]. Scientific research [34] considered the issue of improving the efficiency of road freight transport in cities through the development of a two-factor analysis of vehicles, but without considering the choice of rolling stock. Improving the transport system efficiency is described by [16]. However, this work does not consider the influence of fuel. The work [35] presents a new way to collect data on freight traffic to ensure efficient urban planning, but it does not consider fueling infrastructure. The authors of [14] proposed optimizing distribution routes in terms of time and costs, but this study does not consider fueling costs. The work [28] studies the logistics of freight and passenger transportation in the existing layout of the city. Based on a microscopic model, [36] assesses the environmental impact of transport, including gas fuel, given the configuration of the road network, characteristics, and modes of its operation, but also without considering fueling infrastructure. The role of fueling infrastructure in road transport efficiency regarding electric transport is shown by [37], establishing that the following postulate is crucial for optimization — large fleet size and high charging infrastructure capacity can reduce the minimum required battery capacity. A universal model based on which the driver can choose a filling station should consider the fueling network development, road conditions, and exactly the required amount of fuel in intercity and international transportation. According to [38-40], each truck can have different average daily mileage, depending on the assigned city districts. A detailed simulation of the transportation process was built to determine the impact of the transported cargo weight and transportation conditions, but only relating to electric transport with the efficiency criterion of the battery discharge [41]. In the case of motor fuel, the range depends on a certain consumption of motor fuel and the volume of motor fuel in the fuel tank (cylinder). Determining the consumption of the certain fuel type per 100 km is presented in the methodology [42], and assessing the costs of fueling the rolling stock is described in [43], but there is no comparative assessment of costs depending on fuel and its share in the total costs of the transportation process. Of some interest are studies [44], which compare the energy efficiency of road freight transport by the example of timber transportation, based on which the payload for the maximum environmental effect is ensured. These studies consider the characteristics of the transported cargo in detail, but the impact of the fueling number is not considered. However, almost all publications study the problem of choosing the type of fuel and the factors influencing this choice concerning passenger transport and determining the waiting time at the filling station. As for freight and passenger transportation, they focus on assessing the efficiency of the process: optimization of traffic routes and rolling stock selection but do not consider the costs of travel to the filling station and the cost of time for fueling. Thus, on the one hand, the strategic solution for increasing the economic efficiency of alternative fuels is described; on the other hand, the recommendations for increasing the economic efficiency of the transportation process, considering fueling and fuel type at the level of a particular driver are substantiated in detail. However, the tactical task of increasing the efficiency of intracity transportation by choosing alternative fuel types for companies and owners of the transportation fleet has not been fully solved. The study hypothesis is that the lack of cost accounting for fueling with motor fuel makes it impossible to assess the total cost objectively. The study aims to assess the share of costs for fueling with different types of motor fuel relative to the total cost of freighting by road transport.

**METHODS**

The current filling network infrastructure is not evenly developed. The fuel filling stations for petrol and diesel fuel are quite well developed. The network of automobile gas filling stations (AGFS) in most regions of Russia is almost as developed as the network of fuel stations [45]. Fig. 1 shows the percentage ratio of the number of filling/charging stations located in Russia [46, 47] and the average relative cost of 1 fuel liter (kW) relative to the most expensive fuel in rubles [3, 4]. Development trends of filling/charging stations for different fuel types for the last two years are shown in Fig. 2 [48]. The figure shows that AGFCSSs have a significant potential for their development which, against the background of economic costs of fuel purchase, looks quite promising for all vehicle owners. Thus, the key consumers of CNG are currently large enterprises. At the same time, 62% of all LDVs in the Russian Federation are mainly GAZ Gazelle of different modifications [49]. LDVs in intracity transportation are used for various goods and passengers.
As the average daily mileage increases, the fueling number increases proportionally. However, depending on the type of fuel used, the enterprise location, and the vehicle's route, the mileage to the fueling place will vary because the infrastructure of filling stations is not evenly developed.

Costs were determined based on the following assumptions:

- The driver's tariff rate is constant and does not depend on the fuel type;
- Only intracity transportation is considered.

Let us determine the number of days, $D$, prior to full fueling:

$$ D = \frac{l}{l_{ad}} $$

where $l_{ad}$ – average daily mileage (excluding the mileage for fueling), km; $l$ – range, km. Range $l$, for GAZ Gazelle depending on the hydrocarbon fuel type is presented in Table 1. Let us assume a linear law of the fueling duration at the filling station and its independence from the fuel type, and then the time of fuel filling into the vehicle's tank will be as follows:

$$ t_f = \frac{W}{Q} \tag{2} $$

where $W$ – free volume in the tank (amount of consumed motor fuel), l; $Q$ – performance of the dispenser according to the data in Table 1 [50]. The amount of fuel consumed over the average daily mileage $l_{ad}$ is determined by the formula:

$$ W = l_{ad} \cdot H_m \tag{3} $$

where $H_m$ – motor fuel consumption, l/km. Then the fueling time for one work shift after substituting (3) in (2) will be:

$$ t_f = \frac{l_{ad} \cdot I}{Q} \tag{4} $$

The fueling time of a full tank for several working days without fuel top-up will look like (1):

$$ t_f = \frac{D \cdot l_{ad} \cdot I}{Q} \cdot \frac{l_{r}}{V_{tech}} \tag{5} $$

where $l_{r}$ – distance from the truck parking to the filling station and from the filling station to the first discharge point, km; $V_{tech}$ – average technical speed, km/h. Then the fueling cost $C_f$ will be:

$$ C_f = C_{rh} \left( \frac{D \cdot l_{ad} \cdot H_m}{Q} + \frac{l_{p}}{V_{tech}} \right) + l_{r} \cdot H_m C_{mf} \tag{4} \)$$

where $C_{rh}$ – driver’s tariff rate per hour, rub./h. Expression (4) does not explicitly account for the costs of filling with a particular fuel. The cost of a particular fuel will be accounted for by determining the operating costs directly related to the transportation process as another summand in equation (4) and replacing the average daily mileage with the product of the average technical speed by the work shift duration:

$$ C_f = C_{rh} \left( \frac{T \cdot D \cdot V_{tech} \cdot H_m}{Q} + \frac{l_{p}}{V_{tech}} \right) + l_{r} \cdot H_m C_{mf} \tag{5} \)$$

where $H_m$ – motor fuel consumption, l(m$^3$)/km; $C_{mf}$ – the cost of motor fuel, rubles. Presenting the average daily mileage as the product of the average technical speed by the work shift duration, we finally get the total costs,
excluding the costs associated with fueling (5):

\[ C = T \cdot C_{rh} + T \cdot D \cdot V_{tech} \cdot H_m \cdot C_{mf} \]  \hspace{1cm} (6)

where \( T \) – duration of the driver’s work shift, \( T = 8 \) hours. Thus, given the accepted assumptions, the obtained expression is a function of the two varying parameters of the average technical speed \( V_{tech} \) and the distance to the filling station, \( l_{rp} \). In order to obtain a solution by equation (6), it is necessary to determine the possible number of shifts of the vehicle operation without fuel top-up by formula (1). The calculation results by formula (1) for values of average technical speed \( V_{tech} \), which varied from 20 km/h to 55 km/h in increments of 5 km/h, are presented in Fig. 3.

![Graph showing the maximum number of days D without fuel top-up depending on vehicle average technical speed Vtech](image)

**Figure 3: Maximum number of days D without fuel top-up depending on vehicle average technical speed \( V_{tech} \)**

<table>
<thead>
<tr>
<th>Petrol</th>
<th>Diesel fuel</th>
<th>LPG</th>
<th>CNG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range ( l_{r} ), km</td>
<td>365</td>
<td>360</td>
<td>447</td>
</tr>
<tr>
<td>Motor fuel consumption ( H_m ), l/km</td>
<td>0.14</td>
<td>0.112</td>
<td>0.161</td>
</tr>
<tr>
<td>Motor fuel cost ( C_{mf} ), rubles</td>
<td>4541</td>
<td>5629</td>
<td>2867</td>
</tr>
<tr>
<td>Performance of the dispenser, l (m³)/h</td>
<td>3000</td>
<td>3000</td>
<td>2700</td>
</tr>
</tbody>
</table>

**Table 1: Initial data for different hydrocarbon fuels**

The dependences of fueling costs \( C_f \) for daily fueling and fueling every other day when the filling station is 2 and 10 km away from the route are shown in Fig. 4 and 5. Fig. 6 shows, as an example, a general view of fueling costs in fueling with CNG motor fuel every other day, depending on the average technical speed \( V_{tech} \) and the distance of the filling station from the route. The total cost of fueling associated with the average technical speed \( V_{tech} \) and the distance of the filling station from the route is well approximated by a polynomial function of the form of standard functions in MATLAB environment, and the regression analysis gave \( R^2 = 0.9999 \). The polynomial function has the form:

![Graph showing fueling costs Cf for daily fueling and fueling every other day](image)

**Figure 4: Dependences of fueling costs \( C_f \) for daily fueling and fueling every other day when the filling station is 2 (a) and 10 km (b) away from the route**

![Graph showing the share of the difference in fueling costs Cf](image)

**Figure 5: Share of the difference in fueling costs \( C_f \) for daily fueling and fueling every other day when the filling station is 2 (a) and 10 km (b) away from the route**
Figure 6: General view of the dependence of fueling costs \( C_f \) in the case of fueling with CNG motor fuel every other day, on the average technical speed and the distance of the filling station from the route

\[
C_f = P_{00} + P_{10} \cdot l_{tp} + P_{01} \cdot V_{tech} + P_{11} \cdot l_{tp} \cdot V_{tech} + P_{02} \cdot V_{tech}^2 + P_{12} \cdot l_{tp} \cdot V_{tech}^2 + P_{03} \cdot V_{tech}^3
\]  

(7)

where \( P_i \) are polynomial coefficients for different types of hydrocarbon fuels whose numerical values are presented in Table 2. Let us compare the total costs, including fueling, and the costs incurred directly for fueling. For comparison, let us use the ratio of costs related to fueling to the cargo delivery costs expressed as a percentage:

\[
P_f = \frac{C_{rh}(T \cdot D \cdot V_{tech} \cdot H_m + l_{tp} \cdot H_m C_{nf})}{T \cdot C_{rh} + T \cdot D \cdot V_{tech} \cdot H_m C_{nf}} \times 100\%
\]  

(8)

The lower this value, the more correct the choice of fuel is. Fig. 7 shows dependencies of the ratio of costs connected with fueling to the cargo delivery costs at daily fueling and every other day on the average technical speed \( V_{tech} \) for various hydrocarbon fuels at a distance of 2 and 10 km to the filling station from the route.

**RESULTS**

The graphs in Fig. 4 show that the cost in the case of fueling every other day is higher than at daily fueling, but Fig. 5 shows that the increase is not proportional, and thus the savings in the case of fueling every other day are between 40% and 50%, and the further away the filling station is, the less pronounced the savings. As distance and the average technical speed \( V_{tech} \) increase, costs monotonically decrease. When using CNG, there is an inverse pattern of change in costs depending on the average technical speed \( V_{tech} \): with its increase at short distances to the filling station, costs for fueling increase monotonically, and at distances over 7 km, there is a minimum of costs depending on the average technical speed \( V_{tech} \) both in the case of daily fueling and every other day. When CNG fueling takes place every other day at short distances to the filling station, savings vary from 14 to 30% and at distances over 7 km – from 30 to 45%. It should also be noted that the growth of fueling costs is non-linear primarily due to the strong impact of the average technical speed \( V_{tech} \). Based on the above, it can be clearly stated that the practice of fueling with petrol and CNG at the end of the shift on the way
to the enterprise and LHG fueling at the start of the shift on the way to the first discharge point used by several enterprises, is irrational in terms of optimizing the fueling costs. The average technical speed Vtech has to be considered for long distances to CNG filling stations. In all cases considered, except CNG fueling, when the average technical speed Vtech is less than 20 km/h, the difference in savings becomes almost invisible, regardless of the fueling strategy chosen. As a result of formula (5) approximation, expressions (7) were obtained, based on which we can directly assess the costs of fueling with hydrocarbon fuel depending on the fuel type, average technical speed Vtech, and the distance to the filling station from the route when fueling every other day. Based on the calculation results by expression (8), it was found that the share of costs for fueling is from 0.25 to 7% of the total costs associated with the transportation process in the range of average technical speeds Vtech under consideration. The lowest values fall on fueling every other day, and with the increase of average technical speeds, the cost ratio monotonically decreases for all types of hydrocarbon fuels under consideration. From the condition of minimizing the ratio of fueling costs to the total costs of driving along the route, the least efficient is, as follows from Fig. 7, CNG motor fuel. In the range of average technical speeds under consideration typical for urbanized areas, the cost ratio falls monotonically with an increase in the average technical speed Vtech when the filling stations are located more than 7 kilometers away. However, it must be remembered that the CNG filling station infrastructure is currently undeveloped, and therefore the cost ratio will be higher than for other fuels due to the long distances to the filling stations and the long fueling time.

**DISCUSSION**

Thus, the practice of daily fuel top-up is inefficient. It should also be noted that the most effective is diesel fuel, which has the lowest consumption and makes it possible to provide fueling once every three days with the existing design of the fuel system. Accordingly, to stimulate the use of CNG, it is necessary to solve the design problem associated with the increase in the vehicle range. CNG seems the least efficient due to the low range and high mileage to the fueling point. The results made it possible to determine the final costs associated with fueling, considering the average daily mileage of LDVs and the available infrastructure of filling stations. Lack of planning these costs will result in financial losses and reduced profits from transportation services. The rationale for choosing the fuel type in the freight transport by road should consider the fueling costs depending on the average daily mileage. It should be noted that the relative costs determined by the formula (6) are the lowest values since the costs associated with a possible queue for fueling and fluctuations in the values of operational indicators of transportation and fueling processes have not been considered, which will require additional research.

Further developing the CNG infrastructure in road transport by increasing the number of AGFCS will lead to a decrease in fueling costs in a hyperbolic law and an increase in the economic efficiency of using this type of motor fuel even with a low value of the average daily mileage. Accordingly, the total costs of the enterprise for the traffic flow will decrease. The evaluation findings of the fueling costs with different motor fuels make it possible to account for all costs arising in the transportation process for any enterprise that uses LDVs, considering the region’s existing infrastructure under consideration.

**CONCLUSION**

For the first time, the average fueling costs and average vehicle movement costs along the route considering the use of different types of motor fuel have been compared. The nature of changes in fueling costs with hydrocarbon fuel depending on the frequency of fueling, the average technical speed of the rolling stock, and the distance to the filling station from the vehicle’s route for different types of hydrocarbon fuel has been established. A criterion for assessing the economic efficiency of vehicle fueling depending on the selected type of hydrocarbon fuel is proposed. Based on the obtained results, specific practical recommendations were formulated related to the frequency of fueling of LDVs with hydrocarbon motor fuel and making a decision on its choice based on the criterion of economic efficiency assessment of vehicle fueling. The proposed approximating equation will make it possible to estimate the fueling costs of LDVs in the practical operation of the rolling stock. Accounting for these costs will minimize the financial losses associated with the transportation process, whose value will significantly increase with the number of LDVs of the transport enterprise. Despite the limitations adopted in this paper (only LDVs and hydrocarbon fuels are considered), the analytical dependencies presented can also be extended to studies related to cost estimation when using other alternative fuels and to vehicles of any carrying capacity. The study results provide a basis for further research related to the impact of infrastructure providing fueling of rolling stock on the economic efficiency of this process: the technical characteristics and distribution density of the filling stations regarding the road network and the direct consumer.

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