Methodology for calculating the energy consumption of freight wagons during transportation by trains for private enterprises

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Abstract. Fuel-energy consumption is one of the key factors in choosing the optimal type of locomotives for train operations. The quantity of fuel and energy used for train transportation is significantly influenced by the parameters of wagons and the transported goods. This article recommends an algorithm and an instrumental method in the form of software complexes for calculating the amount of fuel and energy resources used by locomotives of a private transportation company for train transportation under existing conditions, taking into account the planned cargo volume. Based on this, technical and technological solutions have been developed for selecting the planned and rational type of locomotives, considering the parameters of the wagon and the transported goods, the distance of transportation and the characteristics of the railway.

1 Instruction

Currently, private transportation companies from foreign countries are organizing transportation on the main railway line. The Joint Stock Company “O’zbekiston temir yo’llari” is conducting work to substantiate technical and technological solutions for the procurement of locomotives to be used for train hauling by private transportation companies. The primary criterion for selecting the optimal type of locomotive units, intended for operation, is fuel and energy consumption. This, in turn, underscores the necessity of calculating the fuel and energy consumption of private locomotives for train traction, based on the volume of cargo intended for transportation.

2 Literature review

The latest edition of the “Rules for calculating traction during train movement” was developed in 2016 in railway transport. These rules define the procedure for calculating the quantity of fuel and energy used for train traction on main railway lines [1]. However, these rules determine the calculation of fuel-energy quantity for train traction based on the train's

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mass as initial information, rather than considering the cargo volume. Therefore, there are ongoing scientific research efforts aimed at regulating and reducing fuel-energy consumption for train traction, considering various influencing factors [2-24, etc.]. In particular, A.V. Klimovich’s monograph [18] examines the physical foundations of the process of energy resource consumption during train movement and proposes an objective function. It is concluded that minimizing this function allows for managing the train in a way that ensures the minimum energy expenditure for movement along a given section. Organizational and technical measures aimed at reducing energy consumption during train movement have also been considered in locomotive management, locomotive construction, and transportation organizations.

Scientists A.N. Komarov and Yu.P. Boronenko believe that one way to improve the energy efficiency of railway transport is to reduce the fuel and energy consumption of trains by improving the rolling stock designed for transportation. They compared the resistance to motion of a freight wagon on two innovative types of freight trucks and a truck of traditional design, including an analysis of energy losses in various components of the truck. Based on the calculation results, graphs of relative resistance to motion were constructed for a curved track with radii of 650 m and 350 m, as well as for a straight track. Based on the obtained results, it was determined that the investigated innovative design trucks allow for a reduction in the resistance to motion of the wagon on straight sections of track and curves with small and medium radii across the entire range of operating speeds [19].

In his doctoral dissertation [20], Esaulov V.A. investigated the effectiveness of combining container trains in organizing traffic on the Far Eastern Railway. The utilization of this technique over a two-month period in 2022 involved 235 graphical “lines” in four railway depots, 487 locomotive crew shifts, and a labor payment fund of 4.04 million rubles for the locomotive crews. Additionally, it resulted in an energy savings of 1500.1 thousand kWh. These measures also allowed for an increase in the average weight of trains by 15.2 tons and a locomotive productivity improvement of 5.5 thousand ton-kilometers per day. Furthermore, an indicator of economic efficiency was proposed for evaluating the implementation of the traffic schedule through dispatching regulatory measures. The proposals developed within the scope of this research led to an increase in the reliability of delivery times. In 2020, the delivery reliability improved by 5.1 percent compared to the level in 2019.

The study [21] identifies the key directions for the development of railway transport, which are considered the highest priorities in Russia at the present time. It showcases strategically important transportation corridors that traverse the railway network and presents theoretical investigations into the traction capabilities within the framework of prospective electric traction, resulting in significant increases in train weight standards. Graphical representations depict the variation in traction force and power of mainline freight and passenger electric locomotives as a function of train speeds along the track shoulders on different sections of the route. The main parameters of the new series of traction electric rolling stock are presented. The methodology for determining the energy performance indicators of mainline freight electric locomotives, taking into account the influencing coefficient on the specific energy consumption used for train traction, based on the locomotive mass and content, is described. It is determined that the annual electricity consumption of the railway enterprise accounts for approximately 1.2% of the total electricity consumption in the country.

In order to achieve energy savings and enhance the efficiency of high-speed railway operations, a qualitative and quantitative analysis of factors influencing the traction power consumption of trains was conducted in this study. Initially, the influential factors were identified and categorized into three groups. Subsequently, based on data obtained from combined train servicing and operations, a quantitative analysis was conducted using a self-organizing data collection method to analyze factors affecting the traction power
consumption of high-speed trains. The intelligent data analysis and empirical results were compared for validation, demonstrating that self-organizing intelligent analysis for train energy consumption analysis is feasible, efficient, and superior to empirical analysis. As its parameters are dynamic, the results of self-organizing intelligent data analysis can be easily and accurately compared with the results of independent analysis [22].

The study [23] addresses the relevant issue of improving the traction energy efficiency of rolling stock in the railway industry through the implementation of energy and resource-saving technologies. It is determined that the cost of acquiring fuel and energy resources in JSC “Russian Railways” accounts for approximately 14% of the transportation cost. This is based on the fact that the primary expenditure of fuel and energy resources is attributed to the traction effort of trains, thus energy conservation should be implemented in this area.

In the scientific work of Aliyanov [24], an indicator was proposed for the comparative assessment of the energy efficiency of different types of electric locomotives. This indicator is based on the ratio of specific energy consumption at a given speed to the magnitude of that speed. According to this indicator, for a train mass of 1500 tons and a gradient of 6‰, the specific energy consumption per unit of constant speed of the four-axle electric locomotive KZ4A is 2.5 times lower than that of the eight-axle electric locomotive VL80S, which is a 33-position locomotive.

As evident from the above, in the existing scientific works, experienced researchers have obtained certain scientific results. However, the method of calculating the fuel and energy consumption of locomotives for train traction based on specified load parameters, especially the type and size of the cargo intended for transportation by private enterprises, has not been thoroughly investigated.

3 Literature review development of a methodology for calculating fuel and energy consumption of private locomotives that operate trains, taking into account wagon parameters and load characteristics

In general, it is considered that the amount of fuel-energy used for any transportation primarily depends on the cargo size and transport distance. Such a general estimation would be insufficient for freight transportation on mainline railways by private locomotives. Therefore, when calculating the fuel-energy consumption of private locomotives for train traction, all parameters are divided into two categories: constant and variable. In this case, the constant parameters are described as follows: \( L_t \) - transport distance, km; \( i \) - leading slope, ‰; \( R_r \) - minimum radius of the railway track curvature, m; \( m_{\text{max}} \) - maximum number of wagons in a freight train, limited by the useful length of the receiving and departure tracks and approved by the Chairman of JSC “Uzbekistan Temir Yullari”, wagons; \( N_{\text{passenger}} \) - number of passenger trains, \( N_{\text{freight}} \) - number of freight trains, \( \text{composition} \); \( e_{10^3} \) - price of one kilogram of fuel, \( \text{sum} \); \( e_{1 \text{kVh}} \) - price of one kilowatt-hour of electricity, \( \text{sum} \).

The variable parameters are influenced by the following factors: \( F \) - locomotive tractive force, kN; \( P \) - locomotive weight, t; \( L_l \) - locomotive length, m; \( V \) - section speed, km/h; \( \Delta \) - ratio of freight train average speed to passenger train average speed; \( P_{\text{year}} \) - annual freight volume handled, t; \( q_l \) - tare weight of the wagon, t; \( q_k \) - load capacity of the wagon, t; \( \beta_{\text{sch}} \) - section speed coefficient; \( \alpha_{\text{p}} \) - train motion package coefficient; \( K_0 \) - year-round regularity coefficient of train schedules; \( \gamma_n \) - year-round regularity coefficient of freight schedules.

The daily freight volume is determined based on the train movement graph, and it is identified by \( P_{\text{year}} \) [25].

\[
P_{\text{sut}} = \frac{1000 \cdot P_{\text{yil}} \gamma_n}{365}, \ t
\]
Depending on the type of cargo, the wagon type intended for its transportation is selected, and the daily wagon requirement \( n_{su} \) is determined by dividing \( P_{su} \) by \( q_k \). For “light” types of cargo, its net weight \( q_{n} \) is determined by the coefficient of wagon payload utilization as specified \[25\]. As a result, \( n_{su} \) is determined by dividing \( P_{su} \) by \( q_{n} \) for “light” loads. Thus, based on \[26-27\], the total wagon mass \( (q_{br}) \) and average axle mass \( (q_{o'q}) \) can be determined, as well as the average specific rolling resistance of wagon movement \( \overline{\omega_a'} \).

The values of \( F \), \( P \) and \( L_t \) can be automatically determined depending on the type of locomotives planned to haul the trains. As a result, the primary specific resistance to train locomotion is calculated as follows \[1\]:

\[
\overline{\omega_a'} = 1.9 + 0.01 \cdot V + 0.0003 \cdot V^2, \text{ N/kN}
\]  

(2)

The weight of the train on the planned railway section is determined as follows \[1, 13-14\]:

\[
Q = \frac{F \cdot (\omega_a' + i_r) \cdot P}{\omega_a'' + i_r}, \text{ t}
\]

(3)

By dividing \( Q \) by \( q_{br} \), the calculated number of wagons in the freight train \( (m_h) \) is determined. The accepted number of wagons in the freight train \( (m_q) \) is limited by the useful length of the receiving and departure tracks. If \( m_h > m_{max} \), then \( m_q = m_{max} \); otherwise, \( m_q = m_h \). As a result, the calculated daily number of freight trains \( (N_{su(h)}) \) is determined by dividing \( n_{su} \) by \( m_q \). Depending on \( (N_{su(h)}) \), the daily accepted number of freight trains \( (N_{su(q)}) \) is determined as specified in \[28\]. The average duration of a freight train run (tour) on the railway section is determined by dividing \( (t_yur) \) \( L_t \) by \( V \).

When calculating the fuel and energy consumption of private locomotives for train traction, their load volume is divided into two types: movement and traction costs \[29\]. In this case, the consumption of electricity used for hauling freight trains is determined as follows:

\[
E_h = E_w \cdot P \cdot \left( \frac{\omega_a' + i_r}{9.8} \right) + Q \cdot \left( \frac{\omega_a'' + \frac{i_r}{9.8}}{9.8} \right) \cdot 10^{-3}, \text{ kWt-hour}
\]

(4)

here, \( E_w \) – the amount of electricity used for mechanical work per ton-km, kWh.

The number of stops \( (K_t) \) on the railway section should be calculated to determine the electricity consumption for the total traction of freight trains. In turn, the value of \( K_t \) mainly depends on the number of passenger trains on the railway section and its equipped control systems, and it is determined as follows \[30\].

- in a one-way semi-automatic block system

\[
K_{lya}^I = \frac{L_t \left[ N_{yuk}K_n + N_{yotl}(1 + 1.33 \cdot A \cdot \beta) \right]}{12 \cdot V \cdot \beta} \cdot \left( 0.5 + \frac{N_{yotl}}{N_{yuk}} \right) + 2;
\]

(5)

- in a one-way semi-automatic block system

\[
K_{lya}^I = \frac{L_t \left[ N_{yuk}(1 - 0.5A) + N_{yotl}(1 + 1.33 \cdot A \cdot \beta) \right]}{12 \cdot V \cdot \beta} \cdot \left( 0.5 + \frac{N_{yotl}}{N_{yuk}} \right) \cdot C + 2;
\]

(6)

- in a two-way semi-automatic block system

\[
K_{lya}^{II} = \frac{L_t \cdot N_{yotl}(1 - 1.09 \cdot A \cdot \beta)}{12 \cdot V} + 2.
\]

(7)

(6) The coefficient reflecting the impact of organizing batch movement of freight trains on the number of stops is determined as follows in the formula:

\[
C = \frac{1 - \alpha_p + 0.5 \cdot \alpha_p^2 + 1.6 \cdot n'}{1 - 0.5 \cdot \alpha_p + 1.6 \cdot n'},
\]

(8)

here, \( n' \) – The ratio of the number of passenger trains to the number of freight trains.

Depending on \( K_t \), the average distance between freight train movements is determined as follows:
\[ l_p = \frac{L_t}{K_t + 1} \text{ km.} \quad (9) \]

Based on the information provided, the consumption of electrical energy used for the movement of freight trains is determined as follows:

\[ E_q = \frac{1.35 \cdot E_w \cdot V^2 (P+Q)}{24 \cdot 10^{-4} \cdot l_p}, \text{ kWt-hour.} \quad (10) \]

Based on formulas (4) and (10), the energy consumption for towing freight trains is determined as follows:

\[ E_{tor} = 1.02 \cdot (E_h + E_q), \text{ kWt-hour.} \quad (11) \]

The energy consumption for traction of all trains is determined as follows:

\[ E_{um} = E_{tor} \cdot N_{sut(q)} \cdot L_t \text{ kWt.} \quad (12) \]

In turn, the cost of electrical energy used for the traction of all trains is determined by multiplying \( E_{um} \) by \( e_{el} \).

### 4 Research results

Within the scope of the study, a program was developed to calculate the fuel and energy consumption of private locomotives for train traction. The algorithm of this program is shown in Figure 1. The results of the calculation of energy consumption for train traction for HXD3 and Uzbekistan are presented in Figures 2 and 3, respectively. As can be seen from Figures 2 and 3, the annual volume amounts to one million. To transport one ton of coal for 500 kilometers, 44 wagons are required per day, with one train being formed per day. To perform these transports, the HXD3 locomotive consumes 10,595 kW of electrical energy per day, which costs 4,767,750 sum per day. Therefore, it is advisable to use the HXD3 locomotive for train traction based on the parameters of the transported goods and wagons, as well as the infrastructure equipment.

The program for the developed Energy Management System (EMS) calculates the fuel and energy consumption of private locomotives for train traction based on the parameters of the transported cargo, wagon type, transport distance, and road characteristics.

Table 1 provides information on the volumes of cargo that the company “Enter Engineering” plans to transport on the sections of the electrified winding railway.

As seen from Table 1, the locomotives considered for acquisition by “Enter Engineering” will be involved in transporting 15,964,000 tons of cargo over a distance of 1,716 kilometers. HXD3 and Uzbekistan are planned to be used. Based on Table 1 and the methodology developed in this article, the energy consumption in traction trains was calculated for HXD3 and Uzbekistan. As a result, it was determined that the difference in energy consumption amounts to 1,968,375.16 kW per year. Currently, the cost of one kilowatt-hour of electricity for industrial enterprises is 450 sum, thus the annual economic efficiency resulting from the use of Uzbekistan is 885,768,822 sum (885 million sum).
Fig. 1. Algorithm of the fuel and energy consumption calculation program for private locomotives in train towing.
Fig. 2. Fragment of the fuel and energy consumption calculation program for HXD3 locomotive in traction trains.

Fig. 3. Fragment of the utilization of the fuel and energy consumption calculation program for locomotives of the Uzbekistan type in train traction.

Table 1. Information regarding the volumes of cargo that “Enter Engineering” plans to transport on the sections of the electrified winding railway

<table>
<thead>
<tr>
<th>O/ n</th>
<th>Route name</th>
<th>Annual volume of cargo, thousand tons</th>
<th>Type of transported cargo</th>
<th>Distance, km</th>
<th>leading slope, ‰</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sariyogoch – Nurbulok</td>
<td>1 280</td>
<td>coal</td>
<td>368</td>
<td>7,7</td>
</tr>
<tr>
<td>2</td>
<td>Sariyogoch – Angren</td>
<td>3 840</td>
<td>coal</td>
<td>149</td>
<td>12</td>
</tr>
<tr>
<td>3</td>
<td>Sariyogoch – Oltiarik</td>
<td>1 280</td>
<td>coal</td>
<td>368</td>
<td>27</td>
</tr>
<tr>
<td>4</td>
<td>Sariyogoch – Jizzakh</td>
<td>6 400</td>
<td>coal</td>
<td>201</td>
<td>7,7</td>
</tr>
<tr>
<td>5</td>
<td>Tinchlik – marokand</td>
<td>1 364</td>
<td>phosphorus concentrate</td>
<td>146</td>
<td>6</td>
</tr>
<tr>
<td>6</td>
<td>Bukhara I – Bekabad</td>
<td>1 800</td>
<td>ore</td>
<td>484</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>15964</td>
<td></td>
<td>1716</td>
<td></td>
</tr>
</tbody>
</table>
5 Conclusion

Although “Rules for Traction Calculations in Train Operations” and existing scientific works have developed a number of methodologies for determining the fuel and energy consumption in train traction on mainline railways, they do not provide specific instructions for accounting for traction parameters, such as transported cargo and wagon type.

Within the scope of the study, an instrumental approach in the form of comprehensive programs and calculation algorithms has been developed to determine the fuel and energy consumption of private locomotives for train traction based on the quantity of cargo planned for transportation.

Technical and technological solutions have been developed for selecting the optimal type of locomotives for train operations, taking into account parameters such as the transported cargo, wagon type, transport distance, and road characteristics. These solutions aim to optimize energy consumption and ensure efficient traction performance.

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