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Development of a methodology for determining an energy efficient technology for the freight transportation on a single-track railway line

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Abstract. In the context of the search for strategies for the development of railway infrastructure, it is important to theoretically substantiate the choice of constructive and organizational measures that will allow the development of promising passenger and freight traffic. This study proposes an approach to determining the rational parameters of energy efficient technology for the transportation of freights on the site in the context of the implementation of one of the reconstruction measures - modern dispatch centralization of train traffic control. The main aim of research is to develop a methodology for determining an energy efficient technology for transporting freights on a single-track railway line. It is proposed to use analytical methods for calculating the average speed of trains with a combination of micromodeling of traction characteristics of freight trains of different mass. Theoretical calculations of the change in the section speed were carried out when the dispatch centralization was introduced, taking into account the choice of various options for the mass of freight trains. The calculations performed for a single-track line and the dependences of the cost change per one shipped carriage and the section speed on the train mass were obtained, which made it possible to determine the optimal parameters of the energy-efficient technology for the transportation of freights by the line. The proposed method for determining the energy efficient technology for the transportation of freights can be used in the technical and economic calculations of projects for the implementation of various systems of train dispatch control on single-track railway lines.

1. Introduction

In the context of the search for strategies for the development of railway infrastructure, it is important to theoretically substantiate the choice of constructive and organizational measures that will allow the development of promising passenger and freight traffic [1]. One of the elements of the railway infrastructure that often become limiting in the network and need to improve the organization of transportation or technical equipment is single-track lines. To increase the competitiveness of rail transportation, limit impact, reduce costs, it is important to determine the feasibility of implementing the proposed measures, taking into account the efficient use of energy, resources – energy efficiency [2, 3, 4, 5]. Considering that in the field of train operation there is a significant potential for reducing energy consumption without any significant capital costs, this study proposes to consider in detail the approach to determining the rational parameters of energy efficient technology for transporting



freights on the site in the context of the introduction of modern dispatch centralization of train traffic control.

2. Literature review and problem statement

Taking into account the necessity to search for measures to improve the competitiveness of rail transport in the context of the importance of reducing costs and reducing environmental impact, the number of studies devoted to improving energy conservation and energy efficiency in the railway industry is greater [6, 7]. There are quite a lot of studies aimed at finding energy efficient technologies for the transportation of freights by optimizing train operation strategies [8, 9, 10]. This is driven by the high potential for reducing energy costs through improved driving and driven by the significant rate of cost reduction in road transport, which is one of the main competitors for the railway.

It is reviewed that the calculation of energy efficient train speed profiles is usually called the train trajectory optimization problem. According to [11], determining an energy efficient train path can lead to potential energy savings in the range of 5-20%. In the work [12] it is proposed to optimize the costs of train movement by minimizing its thrust energy based on solving a nonlinear optimization problem by methods of evolutionary search – Genetic Simulated Annealing, Firefly, and Big Bang-Big Crunch algorithms. Within the framework of the problem statement, speed limits, profile, norms of travel time and train weight were taken into account, and punctuality as a penalty factor. Research [13] in determining energy efficient trajectories of train movement focused on taking into account the effect of forecast changes in wind speed and direction, which is available before departure, on train movement. In [15], optimization modeling is applied to solve the issues of aerodynamics and energy efficiency of railway intermodal trains. The authors note that the potential to reduce fuel consumption per intermodal train is 15,000,000 gallons per year, with a corresponding savings of 28 million USD. This confirms the importance of introducing energy efficient technologies for the freights transportation.

However, the focus on improving driving by better adapting to track profile does not allow for the interdependence of train traffic in the flow, and therefore has limited potential for cost savings. Much higher energy costs arise from improperly planned stops of freight trains in lines under overtaking or crossing operations on single-track lines. Under such conditions, studies are aimed at finding balanced train schedules, reducing the number of stops and delays, and making it possible to determine energy efficient train trajectories, taking into account the traffic plan on the railway line, or the network polygon, are promising and relevant. It should be noted that the most difficult task is to build a train schedule for a single track line [14]. In [16], an optimization model is proposed, taking into account a possible speed limit to find the optimal speed for each train on a single-track railway line. An interesting study is [17], which notes the importance of the influence of train length on energy efficiency. It is proposed to expand the mathematical model of scheduling, which takes into account train length, energy efficiency and minimizes not only delays, but also energy consumption.

One of the measures to increase the capacity of a single-track railway line is the introduction of more modern train control systems [18]. The construction of an energy efficient technology for the transportation of freights on a railway line when introducing a new dispatching system requires a combination of the above approaches. It is important to determine the optimal train trajectories, taking into account their interdependence in the train schedule. In the work [19], relying on the simulation of train movements using the "OpenTrack" software, scenarios of the equipment of the railway line with ETCS Level 2 and ETCS Level 3 (L3) are investigated. The OpenTrack software application is developed by the Swiss Federal Institute of Technology's Institute for Transportation Planning and Systems (ETH IVT) [4]. This is a train movement model, refers to a micro-level simulation, designed for traction calculations, train scheduling and simulation based on train databases, infrastructure and timetables defined by the user.

However, these methods and software products can't be used for the 1520 mm railway track of the post-Soviet railway space, in particular, the Ukrainian railway and the like. Due to the various technical characteristics of the infrastructure and the peculiarities of the organization of transportation.

The Ukrainian railway system belongs to the railways of mixed movement of passenger and freight trains on the same infrastructure with partial observance of the freight train timetable. This makes it difficult to determine the average speed of train movement due to the lack of a timetable for the movement of freight trains on the site after the implementation of the proposed centralization dispatch system. Under such conditions, approaches with a combination of micro- and macromodeling of train traffic are more acceptable to determine an energy-efficient technology for transporting freights. One of the software applications that allows for traction calculations is the “Traction calculations” module of the “Railway” grapho-analytical system GAS [20, 21].

To solve the problem in this work, it is proposed to use analytical methods for calculating the average speed of trains with a combination of micromodeling of traction characteristics of freight trains of different weights. The work carried out realistic calculations for a single-track line and obtained the dependences of the cost change per one shipped car and the section speed on the train mass, which made it possible to determine the optimal parameters of the energy-efficient technology for the transportation of freights by the line. The rest of the articles are structured as follows. Line 4 presents the results. After that, a conclusion is made and instructions for further research are given.

3. Materials and methods

Considering that one of the least costly measures to increase the throughput and carrying capacity of a single-track line is the introduction of dispatch centralization, it is proposed to study in more detail the possibility of searching for rational parameters of energy-efficient technology for transporting freights on a single-track line. Using the example of the Poltava - Kremenchuk - Burty line of the regional branch “Southern Railway” of Ukrzaliznytsia JSC, it is proposed to theoretically substantiate the introduction of dispatch centralization with the search for an energy efficient technology for transporting freights on the line. The Poltava - Kremenchuk - Burty line is a double-track line with a limiting element, the Kremenchuk - Kriukov-on-Dnipro stretch, which is single-track. It is for this stretch that experimental calculations have been proposed. Line Kremenchuk - Burty electrified with alternating current. The line Kremenchuk - Kriukov-on-Dnipro is equipped with automatic blocking, and all stations are equipped with electrical interlocking.

To search for an energy efficient technology for the transportation of freights with the introduction of dispatch centralization, the study proposed to find a balance between the energy costs arising when a line of freight trains of different mass and length moves along and their effect on the section speed, which characterizes the quality of the organization of the transportation process on the line. In this study, the section speed is understood as the average speed of trains on the line, taking into account the time spent on acceleration, deceleration and parking at separate points.

Taking into account the limited initial data for technical and economic calculations with sufficient accuracy for practical purposes, the site speed (V_s) can be found using the speed coefficient (β_x) by the formula

$$V_s = \beta_x \cdot V_m, \quad (1)$$

where β_x – speed coefficient; V_m – train movement by the line, excluding stops at intermediate stations and time for acceleration and deceleration, km/h.

The speed factor makes it possible to obtain the most qualitative characteristic of the impact of measures for the implementation of dispatch centralization on the section speed. The speed factor reflects the effect on the section speed of both the total duration of train stops at intermediate stations and the time spent on stops to complete crossings and overtakes.

To determine the estimated sectional speed V_s , it is proposed to use the analytical dependence of the speed coefficient proposed by Professor B. Maksimovich [22]

$$\beta_x = \frac{V_s}{V_t} = \frac{T'_{tt} + T''_{tt}}{T'_{tt} + T''_{tt} + T_{st}} = 1 - \frac{T_{st}}{T'_{tt} + T''_{tt} + T_{st}}, \quad (2)$$

where $T'_{tt} + T''_{tt}$ is the travel time of a pair of trains on the line without stopping at intermediate stations ("clean" travel time); T_{st} is the total stopping time of a pair of trains at intermediate stations, including the time for acceleration and deceleration; V_t is technical speed, km/h.

From formula (2) it can be seen that in order to establish the dependence of the local speed on the factors determining it, it is necessary to find the dependence of the value on the same factors. This time for freight trains for single-track lines can be expressed as the sum of the parking time at crossing and under overtaking

$$T_{st} = t_{cr}K_{cr} + t_{ov}K_{ov}, \quad (3)$$

where K_{cr} is the total number of train crossings on a pair of freight trains; K_{ov} is the number of overtaking freight trains by passenger per pair of freight trains; t_{cr} , t_{ov} is average duration of the train stop, respectively, for crossing and overtaking, min.

The approximate number of crossings on the line of freight trains with freight trains can be determined (Fig. 1) by the formula

$$k_{cr}^{fr} = \frac{T'_{tt} + T''_{tt} + T_{st}}{I_{gr}} - \delta k = \frac{(T'_{tt} + T''_{tt} + T_{st})N_{fr}}{1440} - \delta k, \quad (4)$$

where I_{gr} is estimated graphical interval for the possible departure of freight trains in this direction, min, $I_{gr} = \frac{1440}{N_{fr}}$; δk is correction due to non-multiples time $T'_{tt} + T''_{tt} + T_{st}$ of the interval I_{gr} and varies widely $0 \div 1$.

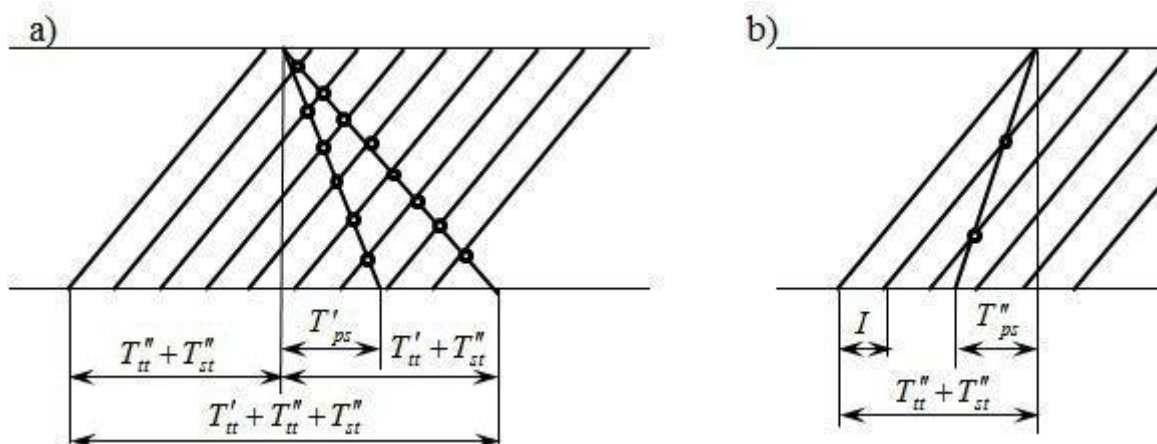


Figure 1. Scheme of the number of crossing and overtaking of trains on the line: a – scheme of the number of crossings; b – scheme of the number of overtaking

When freight trains cross each other, one of them, as a rule, is passed through a separate point continuously, so the number of crossings (4) will also determine the number of stops per pair of freight trains.

The number of crossings of freight trains with one passenger train will be

$$k'_{cr} = \frac{T'_{tt} + T''_{st} + T_{ps}}{1440} - \delta k, \quad (5)$$

where T_{ps} is travel time on a line of a passenger train of one direction, min; T''_{st} is stopping time for freight trains, per train, min.

Number of crossings of freight trains with a pair of passenger trains

$$k^{PS}_{cr} = k'_{cr} + k''_{cr} = \frac{(T'_{tt} + T''_{tt} + T_{st} + T'_{ps} + T''_{ps})N_{fr}}{1440} - 2\delta k. \quad (6)$$

Let us denote the ratio of the travel time of a pair of passenger and freight trains $\frac{T'_{ps} + T''_{ps}}{T'_{tt} + T''_{tt}}$ by Δ .

Then formula (6) can be represented as:

$$k^{PS}_{cr} = \frac{[(T'_{tt} + T''_{tt}) + \Delta + T_{st}]N_{fr}}{1440} - 2\delta k. \quad (7)$$

Since freight trains pass them when crossing with passenger trains, formula (7) also expresses the number of stops of freight trains on a couple of passenger trains, that is $k^{PS}_{cr} = k^{PS}_{ov}$.

Substituting dependence (4, 7) into formula (2), we obtain a detailed expression for determining the speed coefficient β_x

$$\beta_x = 1 - \frac{N_{fr}t_{cr} + N_{PS}[(1 + \Delta)t_{cr} + (1 - \Delta)t_{ov}]}{1440 - N_{PS}(t_{ov} - t_{cr})}. \quad (8)$$

Formula (7) only very roughly reflects the dependence of the speed coefficient on the main factors that determine the conditions for the passage of trains on the line: the size of the movement of freight and passenger trains and the duration of train stops during crossing and overtaking. To obtain a calculation formula from it, it is necessary to take into account: the coincidence of crossings with overtaking, the time intervals between trains at the extreme race, lines, the ratio of the duration of parking under overtaking and when crossing, and some other conditions and provisions. The influence of all factors on the speed factor can be taken into account by the appropriate type of graph.

To clarify the calculations, taking into account the type of schedule, the section speed coefficient on a single-track line with a normal (non-batch) traffic schedule can be obtained on the basis of formula (8), taking into account the fact that more accurately the number of train stops for crossing will be determined from the expression:

$$k_{cr} = k^{fr}_{cr} + k^{PS}_{cr} - k_C, \quad (9)$$

where k_C – the number of crossings that are combined with overtaking.

As the analysis of train schedules shows, about 90% of overtaking is combined with crossed trains. Hence:

$$k_C = 0,9k_{ov} = \frac{0,9(1 - \Delta)(T'_{fr} + T''_{fr})N_{PS}}{1440} - \delta k \cdot 1,8 \frac{N_{PS}}{N_{fr}}, \quad (10)$$

When this correction is included in formula (8) and after transformations, let's obtain the formula:

$$\beta_X = 1 - \frac{(0,75 + 0,3\gamma_f^{GR})[(N_{fr} + 1,2\Delta N_{PS})t_{cr} + (1 - 0,7\Delta)N_{PS}t_{ov}]}{1440}, \quad (11)$$

where γ_f^{GR} - the fill factor of the graph.

Usually, the average value of the graph filling can be accepted $\gamma_f^{GR} = 0,5$. Substituting these values in (11), let's obtain:

$$\beta_X = 1 - \frac{(0,75 + 0,3 \cdot 0,5)[(N_{fr} + 1,2\Delta N_{PS})t_{cr} + (1 - 0,7\Delta)N_{PS}t_{ov}]}{1440}, \quad (12)$$

⇓

$$\beta_X = 1 - \frac{0,9 \cdot [(N_{fr} + 1,2\Delta N_{PS})t_{cr} + (1 - 0,7\Delta)N_{PS}t_{ov}]}{1440}, \quad (13)$$

⇓

$$\beta_X = 1 - \frac{0,9/0,9 \cdot [(N_{fr} + 1,2\Delta N_{PS})t_{cr} + (1 - 0,7\Delta)N_{PS}t_{ov}]}{1440/0,9}, \quad (14)$$

⇓

$$\beta_X = 1 - \frac{1 \cdot [(N_{fr} + 1,2\Delta N_{PS})t_{cr} + (1 - 0,7\Delta)N_{PS}t_{ov}]}{1600}. \quad (15)$$

where N_{fr} - the number of pairs of freight trains; N_{PS} - the number of pairs of passenger trains; t_{cr} , t_{ov} - respectively, the average stops of freight trains under crossing and overtaking, min.

Taking into account that, within the framework of the problem statement, it is necessary to calculate the section speed depending on the mass of the freight train, which determines the time of its movement T'_u or T''_u , in expression (15), by the variables, the duration of the crossing operation t_{cr} and the overtaking operation t_{ov} , and the size of freight trains N_{fr} on the line.

The most probable value of the average duration of train stops under the crossing can be taken equal to

$$t_{cr} = \frac{t_{cr}^{\min} + t_{cr}^{\max}}{2} = \frac{k_{cr}^{fr} t_{cr}^{fr} + k_{cr}^{PS} t_{cr}^{PS}}{k_{ex}^{sam} + k_{ex}^{nac}}. \quad (16)$$

Under such conditions, after the calculations of the search for the weighted average time of the duration of the crossing operation between trains of different categories for different variants of the mass and length of freight trains, it is possible to calculate the section speed according to expression (1).

4. Results

To determine the travel time and power consumption of a freight train on the line, depending on its weight, traction calculations were carried out for the Kremenchuk - Burty line with the maximum stretch Kriukov-on-Dnipro - Burty, the steering grade of calves $i_{st} = 8,3$ ‰. The calculations were carried out using the GAS "Railway" software package [20, 23, 24]. The calculations were carried out

for freight locomotives – VL80T throughout the entire line. The results of the performed thrust calculations are shown in table 1.

Based on the results of traction calculations and the found running speeds of freight trains of different weights in the study with the above proposed approach (see line 3), the precinct speed calculations are carried out. The dependences of the costs of train traction and section speed on the mass of a freight train on the line are shown in Figure 2.

Table 1. Results of the performed traction calculations for the maximum distance Kremenchuk-Burty

Parameters	Train mass, t						
	4600 t m=57 c.w.	5000 t m=57 c.w.	6000 t m=65c.w.	6100 t m=67c.w.	6200 t m=69c.w.	6300 t m=71c.w.	7000 t m=77c.w.
Distance, km	19,374						
steering grade	ict = 8,3 ‰						
multiplicity of thrust	Kriukov-on-Dnipro station – Burty station push locomotive						
Total electricity consumption, kWh	1865,33	1940,23	2568,15	2602,5	2635,45	2663,39	2913,23
Electricity consumption for additional traction, kW*h	-	-	967,91	983,15	999,19	1010,9	1121,66
Electricity cost for train traction, UAH	1427,17	1510,379	2795,668	2851,895	2902,72	2950,737	3340,875
Travel time, min	25,79	26,24	26,65	26,81	26,92	27,07	27,91
Technical speed V_{tech} , km/h	43,1	43,1	43,1	43,1	43,1	43,1	41,5

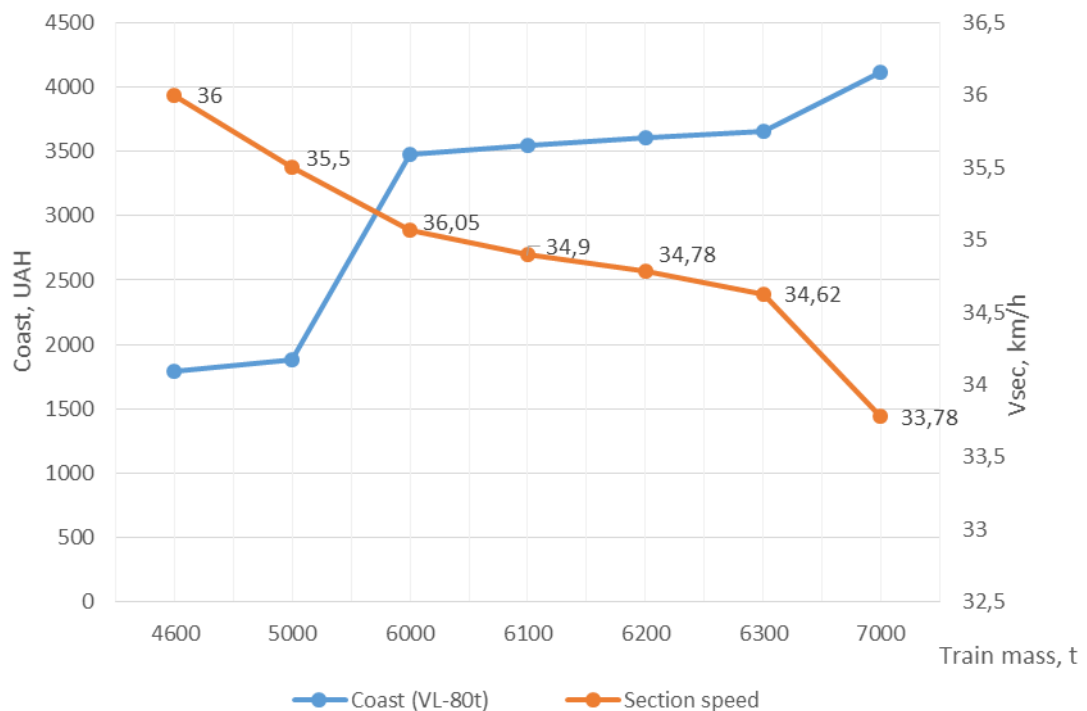


Figure 2. Dependence of electricity costs for train traction and section speed on train

weight

The dependence is shown in Figure 2 assesses the technology of freights transportation on the site under the conditions of the current dispatch control system for train traffic. However, in order to assess measures to increase the throughput and carrying capacity of a railway line, it is important to assess the change in the operating parameters of the line in the context of the introduction of dispatch centralization (DC). After the implementation of the DC, it is planned to improve the technical and technological capabilities of train dispatching due to the possibility of implementing zero-point crosses. This is possible in the conditions of automatic control of train movement on the line and improvement of the quality of planning of train traffic, including by eliminating negotiations between the train dispatcher and the station attendants. The main condition for ensuring a zero-point crossing of trains is the presence of two tracks on the Kriukov-on-Dnipro - Burty line. An analysis of the conditions for the implementation of a zero-point crossing of trains in accordance with the Instructions for Determining Station and Interval Intervals [25] confirms the possibility of performing this operation on the boundary element of the line. The specified conditions correspond to the track and technical support for the implementation of DCs on the tracks and separate points of the Kremenchug-Burty line. Based on the Instruction (SD 0034) and data on the permissible speeds and distances of the track development of the race and the receiving-departure tracks on the line, the calculation of station intervals and section speed after the DC implementation was carried out.

According to the calculations, the dependence of the cost per wagon dispatched and the section speed on the train weight on the single-track line Kremenchuh-Burty is found after the introduction of dispatch centralization, which is shown in Figure 3.

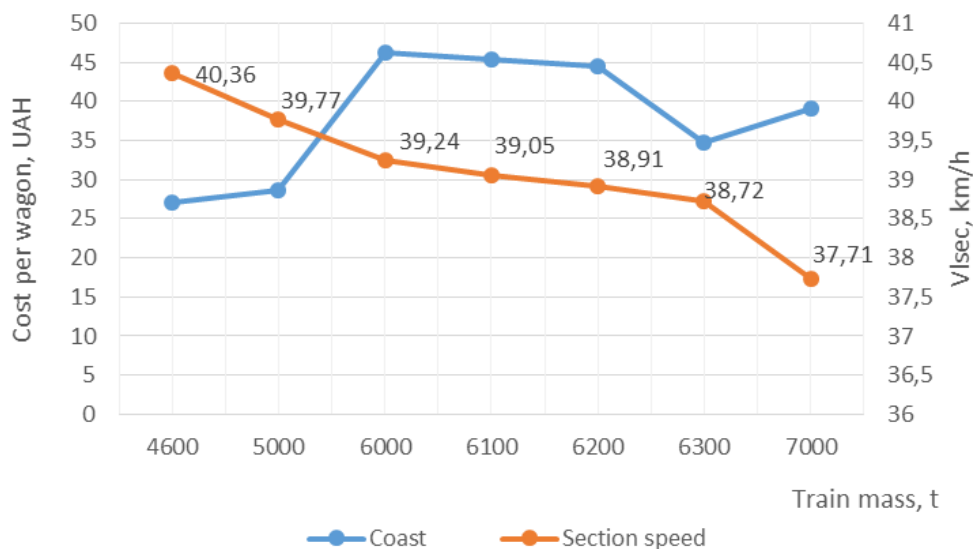


Figure 3. Dependence of the cost per wagon dispatched and the section speed on the train weight on the Kremenchuk-Burty single-track line after the DC implementation.

According to the calculations, the introduction of dispatch centralization and the organization of the passage of trains according to the zero-point crossing scheme will increase the section speed, reduce the time of line movement and reduce the cost of electricity for train traffic.

Figure 3 shows that, as with the DC implementation (Fig. 2), there is a decrease in the section speed with an increase in the train mass, however, the total electricity consumption for traction of trains and the cost per carriage decreases. The most rational mass from the point of view of increasing the energy efficiency of freight traffic on the line, the rational mass of a freight train is 6300 tons and is achieved by using a push locomotive (double traction).

5. Conclusion

Based on the results of this study, a method is proposed for determining an energy efficient technology for transporting freights on a single-track line. Using the example of the Kremenchuk - Burty line of the regional branch "Southern Railway" of JSC "Ukrzaliznytsia", it is proposed to theoretically substantiate the introduction of dispatch centralization with the search for an energy efficient technology for transporting freights on the line. Experimental calculations have shown that the introduction of modern systems of centralized dispatch and dispatch control at the Poltava - Pivdenna - Kremenchuk - Burty lines will reduce the time for making managerial decisions and their implementation, especially in non-standard and emergency situations, which will increase the section speed. The most rational mass of a freight train has been found from the point of view of increasing the energy efficiency of freight traffic on the line after the DC implementation, which is 6300 tons. When operating freight trains weighing 6300 tons, after the implementation of the DC, it will allow reaching a section speed of 38.72 km/h, which is 10.6% more than the section speed under the conditions of the current train traffic dispatch control system. Comparison of the proposed methodology for calculating the section speed based on establishing the running speeds of trains based on traction calculations and determining the weighted average duration of crossing and overtaking operations with the real data of the line operation confirms the adequacy of the calculation results. The discrepancy between the empirical and calculated data of the section speed for the given volumes and characteristics of passenger and freight trains do not exceed an error of 1%. The proposed method for determining the energy efficient technology for the freights transportation can be used in the technical and economic calculations of the proposed projects for the implementation of various train dispatch control systems. In further studies, it is planned to improve this approach based on taking into account the most probable train delays on the line when calculating the section speed.

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