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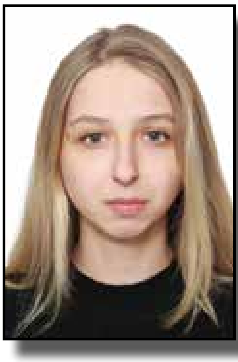
The Influence of Train Composition on the Nature of the Impact of Factors Affecting Energy Consumption



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ABSTRACT

Currently, the development of technical standards and functional operating standards of specific fuel and power consumption for railway traction on the railways of the Russian Federation and the CIS countries is carried out using methods developed back in the 60s of 20th century. The use of modern methods of data mining in calculating standards involves a preliminary study and selection of factors that have a significant impact on the amount of fuel and energy resource consumption.

The study is aimed at identifying differences in the nature of the impact of locomotive's operation indicators, such as sectional and technical speed, train weight, axle load, on the amount of specific energy consumption for railway traction for various types of railway cargo rolling stock. Particular attention in the article is paid to determining the nature of the influence of factors on the specific energy consumption of container trains.

The work uses the Student's t-test statistical data processing method used to determine the homogeneity of the studied samples, and the Pearson correlation analysis method for determining the coefficients of correlation between the specific energy consumption for railway traction and the factors that presumably affect the value of this consumption. The multiple linear regression method is used to build regression models describing the dependence of the specific energy consumption for train traction on the influencing factors under consideration.

The article contains the results of checking the homogeneity of the studied samples of specific energy consumption in the form of Student's t-test values, scatter diagrams of the specific energy consumption depending on the value of the influencing factors, a description of the values of the calculated correlation coefficients for each studied group of cargo trains. The study also focuses on possible reasons entailing difference in the nature and degree of influence of factors for different types of cargo rolling stock.

The study argues for the need to develop a methodology for standard setting regarding consumption of fuel and energy resources for train traction, which allows considering the influence of train composition using modern data analysis methods.

Keywords: railway transport, energy consumption analysis, energy consumption standardisation, train composition, correlation analysis, container trains.

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The original text of the article in Russian is published in the first part of the issue.
Текст статьи на русском языке публикуется в первой части данного выпуска.

BACKGROUND

Currently, the process of analysis, planning and standardisation of fuel and energy resources (FER) for train traction on the railways of the Russian Federation and the CIS countries is governed by various regulatory documents in the field of planning, standardisation, analysis and forecasting of fuel and energy resource consumption for train traction[1].

The planned volume of FER consumption for train traction is determined at an enterprise within the framework of allocated funding limits and considering the planned volume of transportation operations. Then, the corresponding volumes are calculated at various levels of the organisational structure of the rail industry. The specific consumption of fuel and energy resource is used as the main indicator of the energy intensity of the transportation process per ride and is considered as the ratio of the volume of energy consumption to the volume of operations expressed in the corresponding units.

To motivate the departments involved to respect the planned volumes of FER consumption, standards and rates for the specific consumption of fuel and energy resource for train traction are established: by type of resource (electric power, diesel fuel, gas, fuel oil, coal); by the level of standard and rate setting (technical standards, operational standards for locomotive crews, group standards for structural divisions and higher corporate entities); by type of traction; by type of traffic and operations performed; by work areas and by standardisation periods.

The most important vector for the analysis of the energy efficiency of the transportation process is establishment of technical and functional (for each operation) standards for locomotive crew rides. Technical standards for specific FER consumption are developed based on traffic mode maps depending on the series of rolling stock for each section, depending on the track profile with gradation by train weight, as well as axle load or train composition. The basic data for determining technical standards are cumulated through trial rides of traction and energy mobile inspection laboratories, data on energy-optimal modes of train driving (using automated systems for constructing energy-optimal train schedules), as well as traction calculations performed both manually and using modern software. Functional (for each operation) standards for specific FER consumption are being developed to consider running conditions that differ from the average statistical ones provided for in the technical standard. Functional standards consider energy consumption for individual technological operations, such as idle time of rolling stock in working condition, catching up on the delay of passenger and cargo trains to get into the schedule, warming up cars of multiple unit rolling stock at layover points, respecting speed limit warnings, stopping to respect prohibiting signals, unscheduled stops, testing the train brakes en route after a long stop not provided for by the train schedule, etc.

Due to the significant complexity of performing rides with involvement of a traction and energy mobile inspection laboratory and the use of software packages for performing traction calculations, in practice, train driving instructors responsible for heat engineering widely use the statistical method for determining technical rates for specific FER consumption. In this case, from the general set of journeys of locomotives of each series of traction rolling stock, and for corresponding type of traffic, with trains of the corresponding weight (or with the corresponding load on the car axle) on a specific section, those rides are selected that, in the opinion of the train driving instructor, are exemplary and performed under average statistical conditions. The average value of the specific fuel and energy consumption for the specified samples, considering the factors for seasonality, weather conditions, the use of optimal train control methods (determined based on the expert assessment method), is considered the specific rate, which can be adjusted in case of deviation from the considered conditions of performing trips. Thus, the value of the calculated specific energy consumption rate for train traction contains a significant share of subjectivity, and the selected rides may not fully consider the potential of energy-efficient train operation methods and may contain errors inherent in previous rate setting. Besides, when upgrading the system for analysing and

[1] See, for example: STP BC 17.217–2012 Calculation of diesel fuel consumption rates for train traction for locomotive units of the Belarusian Railway. Minsk, Ministry of Transport and Communications of the Republic of Belarus, 2012, 23 p; Regulation on the planning and standardisation of fuel and energy resource consumption for train traction at JSC Russian Railways. Approved by the order of JSC Russian Railways dated May 17, 2019, No. 962/r.

standardising energy consumption for train traction, it is necessary to consider the capabilities of modern computing tools, as well as data mining methods.

The *objective* of the work was to study differences in the nature of the influence of factors on the value of specific electric power consumption for the types of cargo trains most widely used on the railways of Russia and the CIS countries.

MATERIALS AND METHODS

Many foreign [1–8] and domestic studies [9–15] are devoted to identifying and studying the factors influencing the energy consumption of a train.

Traditionally, the analysis focuses on the impact on the value of specific electric energy consumption w_{spec} (SEC) of the following features of locomotive operation: sectional speed V_{sec}, technical speed V_{tech}, mass of the train m_t, axle load q. To determine the nature of the impact of the listed factors on the value of SEC, an analysis is provided of data on more than 9000 trips of electric trains made by locomotive crews of one of the operational locomotive depots of the West Siberian Railway for the period from October 2022 to April 2023. The main source of information on the values of influencing factors is the data of the centralised train driver's route processing system (CDRPS). The Microsoft Excel spreadsheet processor and the Visual Basic for Applications programming language allows calculating the values of series of factors, information about which is contained in the reporting forms in an implicit form (SEC, train mass, axle load).

The study of the nature of the influence of factors is conducted for 5 groups of trains: the totality of all types of cargo trains (group 1), through trains (group 2), through trains weighing more than 5500 tons (group 3) and less than 5500 tons (group 4) and container trains (group 5). This partition is explained by a few distinctive features in organisation of the transportation process for the rolling stock representing each group. For example, through trains weighing more than 5500 tons are often trains with bulk liquid cargo, trains with a high rate of utilisation of wagon load capacity. In turn, container trains have following distinctive features: low axle load of the wagon, relatively small mass of trains, the use of a special type of rolling stock, flatcars, for transportation of containers. Through trains weighing less than 5500 tons are allocated to a separate group due to the presence of similar features with container trains: low mass and axle load. The data set representing group 1 is the general sample in this study. The sample of the second group contains data on the journeys of all through trains, excluding data on the trips of container trains.

To check the presence of a dependence of the nature of the impact of factors on the type of rolling stock, we study the homogeneity of samples as for SEC of groups 2 and 5 and groups 4 and 5 of trains using the Student *t*-test method [16]. The use of the traditional method of statistical analysis is acceptable, since the samples are independent of each other, and the number of observations in the samples is large [17].

The correlation analysis was preceded by building scatter diagrams w_{spec} depending on the magnitude of the influencing factors under study.

The degree of influence and the nature of the impact of factors are determined using the Pearson correlation analysis method, including the calculation of the coefficients of correlation r and construction of correlation matrices.

The calculation of the coefficient of correlation is carried out according to the expression:

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{S_x \cdot S_y (n-1)}, \qquad (1)$$

where x_i, y_i are i^{th} values of random variables;

$\bar{x}$, $\bar{y}$ are average values of random variables;

n is sample size;

S_x, S_y are standard (average square) deviations of random variables.

The strength of the correlation is assessed in accordance with the Chaddock scale.

The construction of regression models for SEC relative to four factors under study is carried out using the multiple linear regression method. In this paper, two regression models are constructed. The first model is implemented based on the data of the general population, the second – on the data on the trips of container trains only. The samples are divided into two parts: data on 80 % of the trips are used directly in construction of the model, the remaining 20 % (test sample) – in assessing the accuracy of the model. The general form of the resulting regression equations is described by the expression:

$$w_{spec} = \Delta_0 + \Delta_1 V_{sec} + \Delta_2 V_{max} + \Delta_3 m_t + \Delta_4 q, \qquad (2)$$

where Δ_j are j^{th} coefficients of regression equation.

Table 1

Empirical values of the *t*-criterion for the studied samples [obtained by the authors]

Period	Studied samples			
	Groups 2 and 5		Groups 4 and 5	
	odd direction	even direction	odd direction	even direction
January	-7,89	-8,69	1,12	-3,89
February	-5,13	-3,06	1,23	0,08
March	-5,92	-2,6	-0,73	0,13
April	-5,76	-3,54	-0,09	-0,55
October	-4,1	-7,76	3,01	-3,46
November	-3,76	-4,28	4,88	-1,05
December	-4,83	-5,46	4,15	-1,07
7 months	-13,78	-13,08	5,25	-3,65

The accuracy of the models is tested using the SEC values of container trains from the test sample.

RESULTS

Based on the results of Student's statistical analysis, Table 1 was compiled, which reflects the empirical t_{emp} *t*-criterion values for the studied samples. The critical value of the criterion t_{crit} at a significance level of 0,05, determined according to the statistical table [18], is 1,96 for all studied samples, since the number of degrees of freedom in them exceeds 120.

According to the data in Table 1, all the studied samples of SEC of groups 2 and 5 turned out to be heterogeneous. When compared with the samples of SEC of groups 4 and 5, the samples are homogeneous in 9 out of 16 cases. The presence of heterogeneity in the compared samples allows us to conclude that there are differences in the nature of the impact of influencing factors (train weight, axle load, train speed, etc.) on the SEC value for the studied types of cargo trains. Moreover, heterogeneity with the samples of trains of group 4 may mean that the reason for differences in the nature of the impact of influencing factors on container trains compared to others is not associated only with their relatively small weight.

Before conducting the correlation analysis, the scatter diagrams of SEC value depending on the magnitude of the influencing factors were examined. As an example, Pic. 1 shows scatter diagrams for trips made in April 2023 for group 1 under study. The diagrams have a similar appearance for all studied train groups.

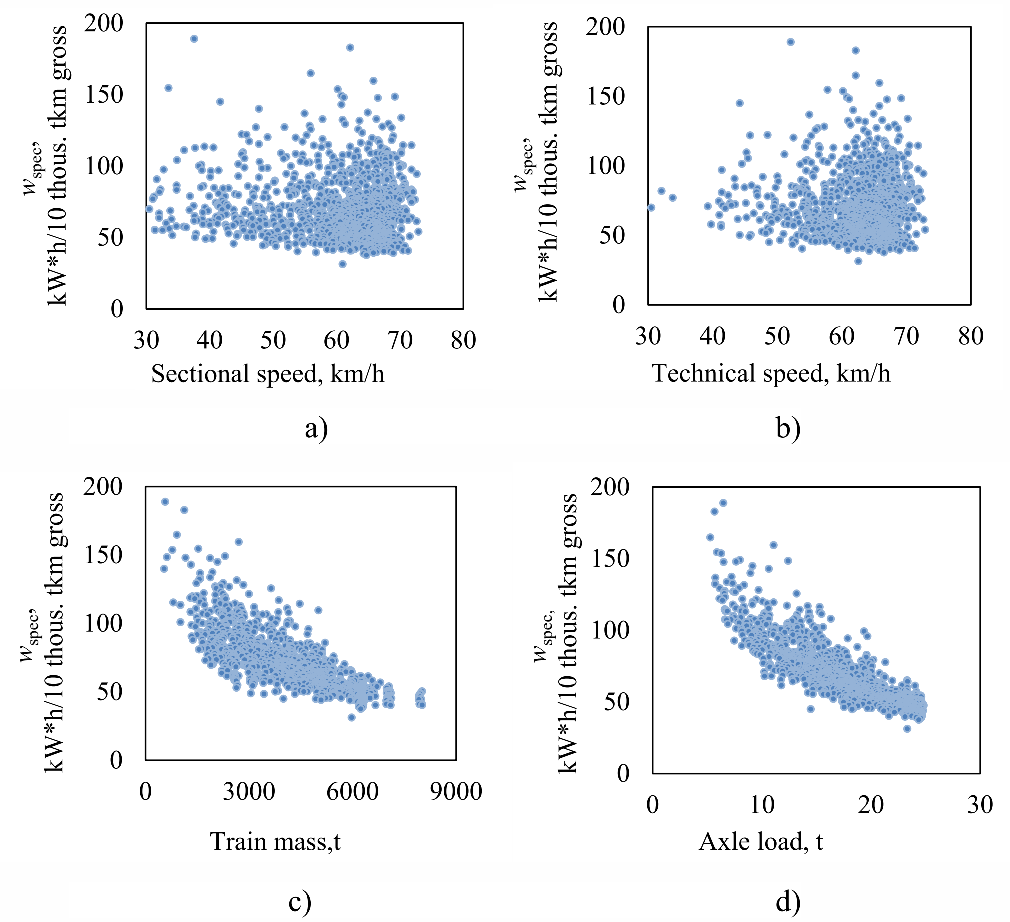
Visual analysis of scatter diagrams allows us to assume a weak and very weak correlation between w_{spec} and V_{sec} (Pic. 1a), between w_{spec} and V_{tech} (Pic. 1b), medium and strong correlation between w_{spec} and m_t (Pic. 1c) and between w_{spec} and q (Pic. 1d).

Let us consider the results of the study of correlations between w_{spec} and sectional (V_{sec}) and technical (V_{tech}) speeds, train mass m_t and axle load q.

Sectional speed V_{sec} is the average value of the train speed considering the time of stops, time for deceleration and acceleration. Technical speed V_{tech}, unlike sectional speed, does not consider the time of stops. Depending on the selected train operation mode, an increase in the average speed can lead to both an increase and a decrease in SEC [19]. The analysis has shown that the correlation between SEC and sectional speed V_{sec} and technical speed V_{tech} is characterised as weak. The coefficient of correlation with the sectional speed $r_{V\text{sec}}$ varies in the range from –0,17 to 0,09, the coefficient of correlation with the technical speed $r_{V\text{tech}}$ – in the range from –0,12 to 0,11. The largest negative coefficients of correlation by absolute value are characteristic of trains of group 3, and the largest positive ones are characteristic of trains of groups 4 and 5.

A negative effect of the sectional and technical speed on SEC is noted for trains of group 3, which may be associated with significant energy consumption for accelerating trains weighing more than 5500 tons after a stop. The existence of statistically significant positive coefficients of correlation with the speeds of container trains and trains weighing less than 5500 tons is due to the fact that the trains of the smallest mass in these groups, which, as a rule, have a higher specific consumption, also have the highest speed.

The correlation between SEC and the mass of the train, according to the scatter diagram in Pic. 1c, should be characterised as strong or very strong. The conducted correlation analysis yielded the following results:



Pic. 1. Scatter diagrams of w_{spec} values depending on the value of: a) – sectional speed V_{sec}, b) – technical speed V_{tech}, c) – train mass m_t, d) – axle load q [obtained by the authors].

– the coefficient of correlation of SEC with the mass of the train r_m has negative values for all the studied train groups during each time period;

– the modulus of the correlation coefficient r_m has the highest values for groups 1 and 4 and varies in the range from 0,91 to 0,67 with a predominance of a strong correlation;

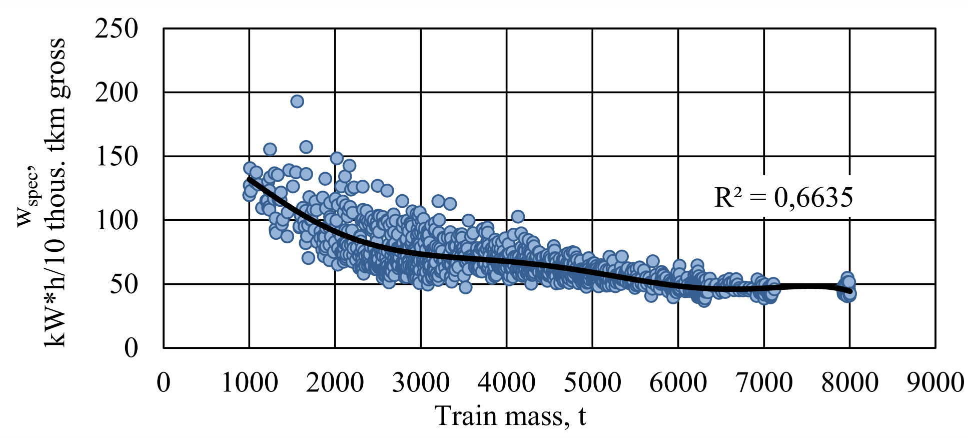
– the smallest values of the modulus of the correlation coefficient, in the range from 0,60 to 0,21 with a predominance of an average correlation, are characteristic of trains of groups 3 and 5, even though the average masses of these groups differ by more than two times.

Pic. 2 shows a graph of the dependence of SEC on m_t for trips in October. The lower values of r_m for trains of group 3 may be due to the fact that for an electric locomotive with large masses of a train, operating conditions are created in a mode close to the nominal one, where the current loads have optimal values. A further increase in the mass of the train will lead to an increase in SEC [20].

The range of values of the masses meeting optimal values of SEC corresponds to the horizontal section of the approximating curve. The curve, having passed the minimum point, will begin to raise. However, this is not reflected in Pic. 2, since there are no data on operation of trains weighing more than 9000 tons on the section under study.

To clarify the reason for the weaker nature of the influence of the change in m_t on SEC for container trains, scatter diagrams of the masses of trains were constructed depending on the number of axles for container trains (Pic.3a) and for the set of other groups of cargo trains (Pic.3b).

Based on the range of mass changes for each number of axles in Pic.3a, the increase in the mass of container trains is mainly due to the increase in the number of axles. The change in

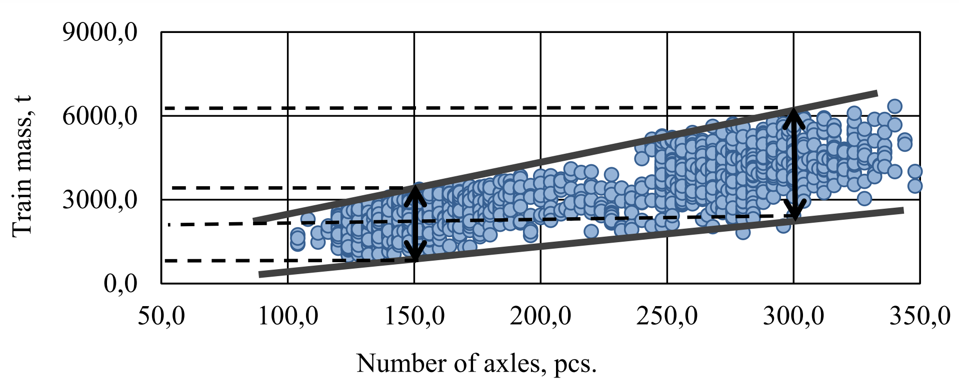


Pic. 2. Dependence of specific energy consumption on the train mass [obtained by the authors].

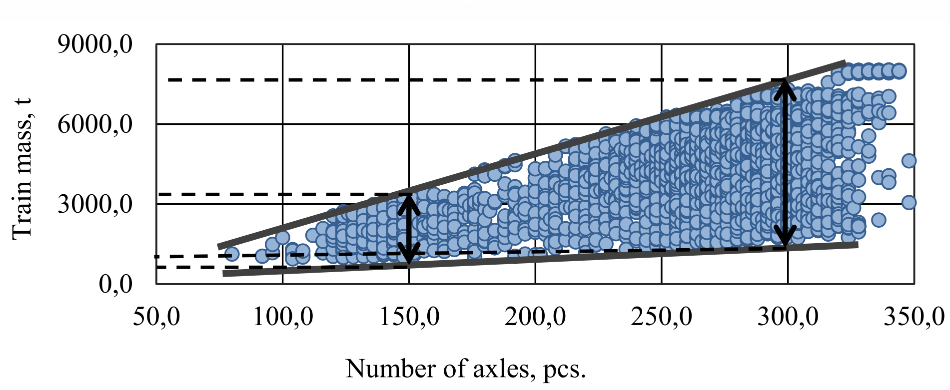
mass for other cargo trains is due to the increase in axle load to a greater extent than for container trains. This may explain the weaker effect of increasing m_t on reducing SEC for container trains.

Increasing m_t by adding axles leads to a greater increase in the resistance to train movement than by increasing q, since some components of the main resistance to train movement do not depend on q, for example, air resistance.

The analysis of correlation of the relationship between the value of SEC and the car axle load q has the following results:



a



b

Pic. 3. Range of masses per number of axles for: a – container trains, b – cargo trains [obtained by the authors]

Table 2

Results of construction and testing of regression models [obtained by the authors]

	Δ_j-coefficient	p-value	R^2	δ, %
Model 1(based on data on all trips)				
Δ_0	133,223		0,81	10,77
V_{sec}	-0,102	0,018		
V_{tech}	0,179	0,001		
m_t	-0,003	0		
Q	-3,192	0		
Model 2 (based on data on container trains)				
Δ_0	146,793		0,65	9,92
V_{sec}	-0,097	0,251		
V_{ech}	0,165	0,108		
m_t	-0,006	0		
q	-3,579	0		

– coefficient of correlation of SEC with the axle load r_q, like r_m, has negative values for all the studied samples;

– modulus of the coefficient of correlation r_q has the highest values for the same groups of trains as the modulus r_m and varies in the range from 0,83 to 0,91;

– the lowest values of the modulus of the coefficient of correlation, in the range from 0,44 to 0,78 with a predominance of the average correlation relationship, are characteristic of trains of groups 4 and 5;

– r_q modules for container trains have values on average 1,4 times greater than r_m modules, for other groups of trains – on average 1,2 times greater.

The results of constructing regression models are shown in Table 2, which summarises the values of Δ regression coefficients, R^2 determination coefficients, p-values, and δ average values of relative errors of models.

The use of model 1 for calculating w_{spec} of container trains yielded an average relative error of 10,77 %, given that in the general population, container train traffic makes up 25,9 %.

Based on R^2 value obtained for model 2, only 65 % of the w_{spec} variance can be explained by the factors under consideration. Excluding the variables V_{sec} and V_{tech} does not increase R^2 value, but the standard regression error decreases from 3,41 to 1,29. To improve the accuracy of the second model, it is necessary to consider other influencing factors, such as weather conditions.

Preliminary regression analysis, considering additional factors, showed that it is possible to reduce δ to 4,87 % for model 2 and to 9,31 % for model 1. The second model has greater potential for increasing accuracy when weather conditions are included in it, which is the subject of further research. To confirm the presence of a relationship between the nature of the influence of factors on the value of specific energy consumption and the composition of trains, similar studies are required for other sections of the rail network.

CONCLUSION

The approaches to the analysis, planning, rate and standard setting of FER currently used on the railways of the Russian Federation and the CIS countries do not allow for the calculation of predicted values of FER consumption for traction, considering the composition of trains.

The article contains the analysis of data on trips made on the territory of the Russian Federation within the boundaries of the West Siberian Railway. Checking the data on specific energy consumption using the Student's t-test for different types of cargo trains showed the heterogeneity of the studied samples. The conducted Pearson correlation analysis allowed us to describe the nature and degree of the impact of influencing factors on the specific energy consumption of the studied types of cargo trains. Significant differences are noted in the influence of the mass of the train and axle load on the specific energy consumption of container trains and trains weighing more than 5500 tons.

Partition of trains according to characteristic features into separate groups allows for an individual selection of influencing factors that have a significant impact on energy consumption. This makes it possible to increase the accuracy of models for predicting the values of specific energy consumption for each type of train.

REFERENCES

1. Ren Junhua, Zhang Qing, Liu Feng. Analysis of factors affecting traction energy consumption of electric multiple unit trains based on data mining. *Journal of Cleaner Production*, 2020, Vol. 262, 121374. DOI: https://doi.org/10.1016/j.jclepro.2020.121374.

2. Fischer, S. Traction energy consumption of electric locomotives and electric multiple units at speed restrictions. *Acta Tech. Jaurinensis*, 2015, Vol. 8, Iss. 3, pp. 240–256. DOI: https:// doi.org/10.14513/actatechjaur.v8.n3.3.

3. Kampczyk, A., Gamon, W., Gawlak, K. Integration of Traction Electricity Consumption Determinants with Route Geometry and Vehicle Characteristics. *Energies*, 2023, Vol. 16, 2689. DOI: https://doi.org/10.3390/en16062689.

4. Pan Deng, Chen Zejun, Mei Meng. Energy efficiency emergence of high-speed train operation and systematic solutions for energy efficiency improvement. *SN Applied Sciences*, 2020, Vol. 2, article number 875. DOI: https://doi.org/10.1007/s42452-020-2692-5.

5. Lukaszewicz, P. Running resistance–results and analysis of full-scale tests with passenger and freight trains in Sweden. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 2007, Vol. 221, Iss. 2, pp. 183–193. DOI: 10.1243/0954409JRRT89.

6. Rozhkov, A., Suyunbaev, Sh., Salfetnikov, V., Balabaev, O., Nartov, M. Determination of Additional Resistance to Train Movement from Profile Elements of Railway Sidings of Industrial Facilities. *Trudy universiteta*, 2022, Iss. 2 (87), pp. 211–216. DOI: 10.52209/1609-1825_2022_2_211.

7. Boschetti, G., Mariscotti, A. The Parameters of Motion Mechanical Equations as a Source of Uncertainty for Traction Systems Simulation. XX IMEKO World Congress, 2012, Busan, South Korea. [Electronic resource]: https://www.researchgate.net/publication/265843501_The_parameters_of_motion_mechanical_equations_as_a_source_of_uncertainty_for_traction_systems_simulation. Last accessed 19.01.2024.

8. Rochard, B., Schmid, F. A review of methods to measure and calculate train resistances. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 2000, Vol. 214, Iss. 4, pp. 185–199. DOI: 10.1243/0954409001531306.

9. Sidorova, N. N. Evaluation of Power Inputs Caused by Unscheduled Stops. *World of Transport and Transportation*, 2013, Vol. 11, Iss. 4 (48), pp. 48–51. EDN: PZREOZ.

10. Cheremisin, V. T., Nezevak, V. L., Sarkenov, S. S. Influence of traction load on power consumption in the traction power supply system on sections with a mountainous track profile [*Vliyanie tyagovoi nagruzki na elektropotreblenie v sisteme tyagovogo elektrosnabzheniya na uchastkakh s gornym profilem puti*]. *Bulletin of Rostov State Transport University*, 2019, Iss. 1 (73), pp. 112–118. EDN: ZBKLKP.

11. Medlin, R. Ya., Sidorova, E. A. Standardization of energy resource consumption [*Normirovanie raskhoda energoresursov*]. *Elektricheskaya i teplovoznaya tyaga*, 1989, Iss. 2, P. 4.

12. Baklanov, A. A., Domanov, K. I., Esin, N. V. [*et al*]. Classification of factors affecting the power consumption of electric rolling stock. *Innovative transport*, 2020, Iss. 4 (38), pp. 61–66. DOI: 10.20291/2311-164X-2020-4-61-66.

13. Shkurin, K. M. Study of the influence of the mass of cargo trains on their section speed [*Issledovanie vliyaniya massy gruzovykh poezdov na ikh uchastkovuyu skorost*]. *Bulletin of Belarusian State University of Transport: Science and Transport*, 2018, Iss. 1 (36), pp. 70–72. EDN: YWIHYD.

14. Isaev, I. P., Sidorova, N. N., Feoktistov, V. P. Standardization of energy consumption in cargo traffic based on statistical methods [*Normirovanie raskhoda energii v gruzovom dvizhenii na osnove statisticheskikh metodov*]. *Railway transport. Series: Locomotives and locomotive fleet*, 1988, Iss. 5, pp. 1–15.

15. Sidorova, N. N. Analysis of energy intensity of the transportation process in electric traction based on a multifactor model [*Analiz energoemkosti perevozochnogo protsessa v elektricheskoi tyage na osnove mnogofaktornoi modeli*]. *Bulletin of MIIT. Scientific and technical journal*, 2000, Iss. 5, pp. 23–27.

16. Gmurman, V. Probability Theory and Mathematical Statistics [*Teoriya veroyatnostei i matematicheskaya statistika*]. Moscow, Vysshaya shkola publ., 1977, 429 p.

17. Orlov, A. I. Testing the statistical hypothesis of homogeneity of mathematical expectations of two independent samples: the Cramer-Welch criterion instead of the Student's criterion [*Proverka statisticheskoi gipotezy odnorodnosti matematicheskikh ozhidanii dvukh nezavisimykh vyborok: kriteii Kramera-Uelcha vmesto kriteriya Studenta*]. *Polythematic online electronic scientific journal of Kuban State Agrarian University*, 2015, Iss. 110 (06), pp. 197–218. [Electronic resource]: https://orlovs.pp.ru/work/901–1000/954 %20Критерий%20Крамера-Уэлча.pdf. Last accessed 19.01.2024.

18. Bolshev, L. N., Smirnov, N. V. Tables of mathematical statistics [*Tablitsy matematicheskoi statistiki*]. Moscow, Nauka publ., 1965, 464 p.

19. Baklanov, A. A. The influence of travel speed on energy consumption of cargo trains [*Vliyanie skorosti dvizheniya na energozatraty gruzovykh poezdov*]. *Izvestiya Transsiba*, 2018, Iss. 1 (33), pp. 2–12. EDN: XQXUWT.

20. Wilhelm, A. S., Ivanchenko, V. I., Komyakov, A. A., Shtraukhman, A. A. Determining optimal values of operational indicators of electric rolling stock according to the energy efficiency criterion [*Opredelenie optimalnykh znachenii ekspluatatsionnykh pokazatelei elektropodvizhnogo sostava po kriteriyu energoeffektivnosti*]. *Izvestiya Transsiba,* 2021, Iss. 4 (48), pp. 85–96. [Electronic resource]: http://izvestia-transsiba.ru/images/journal_pdf/2021–4(48).pdf [full text of the issue]. Last accessed 19.01.2024. ●

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