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SAVING ENERGY RESOURCES DURING OPERATION OF ROLLING STOCK OF UNDERGROUND ELECTRIFIED TRANSPORT

Purpose. To analyze the energy saving reserves under the conditions of implementation and integration of the system in order to find rational driving modes in the general system of managing underground electrified transport.

Methodology. The work presents the method for processing data arrays obtained experimentally with the help of a measuring system and theoretically with the use of the "Rational Trajectory" software.

Findings. Experimental studies were carried out using a testing system created on the basis of a refurbished train with energy recovery system. Theoretical studies were carried out using the "Rational Trajectory" software, which is based on the principle of solving a multi-criteria problem by the method of the main criterion. The minimum amount of electricity consumption from the overhead contact line was chosen as the main criterion. The software was developed in the LabVIEW graphical programming environment in order to determine the rational modes of driving rolling stock and energy indicators in a given area of its operation. The amount of electricity consumed for traction and the amount of electricity generated by the train during regenerative braking were determined based on the results of experimental and theoretical studies, respectively, under typical and rational modes of driving the train for given identical operating conditions.

Originality. Further research on the analysis of energy saving reserves on the rolling stock of underground electrified transport was achieved due to the introduction of a system for finding a rational driving mode.

Practical value. It has been established that the implementation and incorporation of the "Rational Trajectory" software into the train control system will save up to 14.7 % of the amount of electricity consumed for traction, compared to typical modes operation on a given track section.

Keywords: *energy saving, energy resources, underground electrified transport, rolling stock, control system*

Introduction. The formation of the "intellectual" component in transport is recognized as relevant for the development of railway transportation both in Ukraine and in the European Union, which is confirmed by the relevant regulatory documents [1]. In particular, the National Transport Strategy of Ukraine for the period until 2030 defines the task of stimulating the introduction of innovative technologies and intelligent transport systems [2]. Research by scientists of UkrINTEI [3] of the dynamics of scientific publications and their citations, as well as the dynamics of patenting in the relevant directions in transport prove that the most promising technologies in the world in the field of railway transport are: artificial intelligence, big data, 5G – technologies, memory on a neural network. Moreover, according to the authors of the work [3] in the direction of artificial intelligence and neural networks, one of the promising directions of technology development is the control system of railway vehicles.

Formulation of the problem. As an experimental rolling stock, a modernized train was adopted, which is a five-car formation with an asynchronous traction drive and energy recovery systems, in which the main cars are non-motorized, and the intermediate ones are motorized. The train consists of wagons models 81-7080, 81-7081, 81-7081-01 (Fig. 1).

The main technical characteristics of the train and traction transmission parameters are as follows:

- mass of the train (m, t): under empty load – 155.3; under nominal/maximum load – 246.9/262;
- design speed (V_k, km/h) – 90;
- maximum operational speed (V, km/h) – 80;
- efficiency ratio of the reducer (η_{rd}, %) and inverter (η_{inv}, %) – 98 and 96.

The parameters of the asynchronous traction motors (ATM) installed on the modernized train are as follows: P_n = = 150 (kW); U_n = 610 (V); I_n = 185 (A); n_n = 1,900 (rpm); f_n = = 65 (Hz); M_n = 2.21 (kN · m).

Graphs of the dependence of traction and braking force on the speed of this train are shown in Fig. 2. The main resistance to the movement of the train is shown in Fig. 3.

Literature review. Recently, scientists in their research have paid enough attention to the issue of development and implementation of control systems on railway and city electric vehicles. Thus, the article [4] is devoted to the formalization of the train traction control problem based on the apparatus of neuromathematics. Research studies [5, 6] proposed a methodology for determining energy-saving movement trajectories of locomotives with electric transmission, taking into account mathematical methods of uniform search and parametric op-

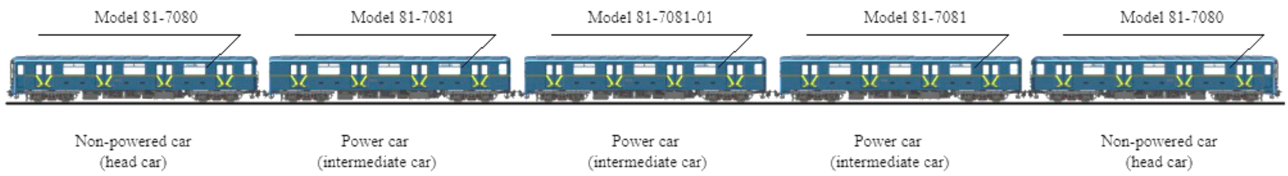

Fig. 1. Schematic diagram of the experimental train

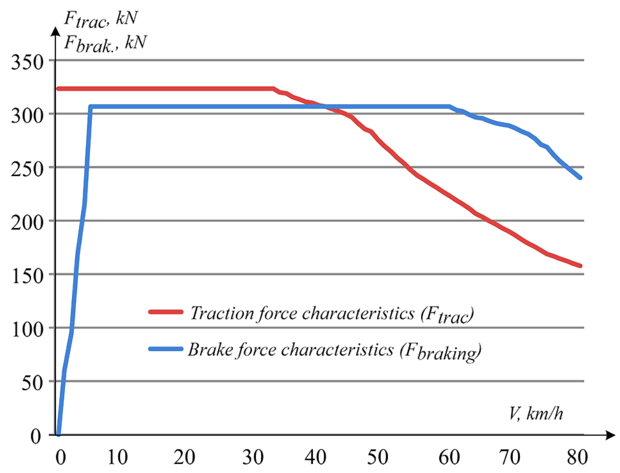

Fig. 2. Graphs of dependences of force and braking on speed of movement

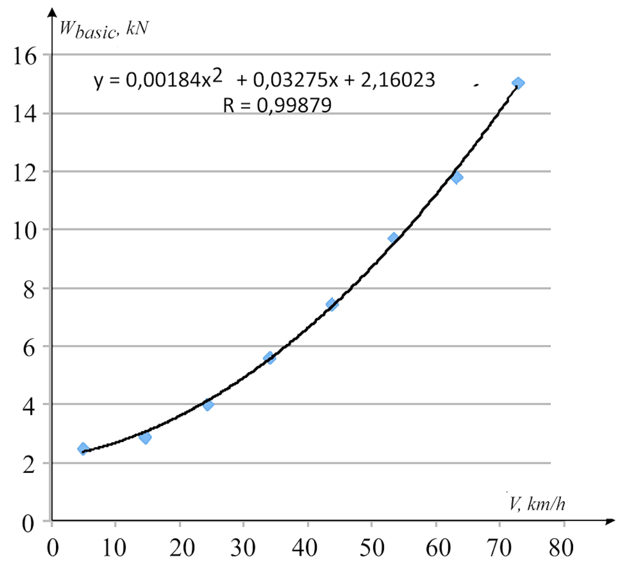

Fig. 3. The main resistance to the movement of a train

timization. Papers [7, 8] are aimed at determining the rational modes of movement of a suburban electric train with asynchronous traction motors using the developed models. Research [9, 10] is aimed at improving the methodology of traction calculations and driving modes of traction rolling stock through the use of optimization models and the law of conservation of mechanical energy. In the works [11, 12], the formulation and solution of the optimization problem of the selection of electric transport control modes during given speed limits according to the criterion of minimum energy consumption is presented. The article [13] provides an overview of promising systems for driving trains, which will allow optimizing their movement during races. Studies [14, 15] developed the theory of reducing energy consumption by electric rolling stock and proposed a simulation model of a subway car with an on-board capacitive storage and a control system in the Matlab Simulink environment. In works [16, 17] it is proposed to minimize the consumption of electricity from the catenary network due to the optimization of train driving modes and the use of capacitive energy storage devices.

Unsolved aspects of the problem. From the analysis of the considered works, it is noticeable that the vast majority of them are aimed at creating control systems that will allow determining energy-saving modes of driving the rolling stock of underground electrified transport. At the same time, insufficient attention has been paid to the practical application of these systems, their integration into the general train control system, and the analysis of energy saving reserves under the conditions of their use.

The purpose. In this article, it is proposed to perform an assessment of reserves of energy savings, subject to the implementation and integration of one of these systems on the rolling stock of underground electrified transport.

The purpose of the work is to analyze the energy saving reserves under the conditions of implementation and integration of the system in order to find rational driving modes in the general system of managing underground electrified transport.

To achieve the goal, the following tasks have been formulated:

- to conduct a theoretical and experimental study for given operating conditions;
- to perform calculations according to the method of the main criterion;
- to estimate reserves of saving energy resources in the rolling stock of underground electrified transport.

Description of the research methodology. It is proposed to evaluate reserves of saving energy resources on the train due to the introduction of on-board systems to find rational modes of its operation by conducting experimental and theoretical studies.

Experimental and theoretical studies were carried out under regular, identical conditions of train operation.

The following identical operating conditions were adopted for the experimental rolling stock of the underground electrified transport during experimental and theoretical studies: the train moves on the section between the final stations of the Sviatoshynsko-Brovarska line of KP “Kyiv metro” in compliance with “peak” and “off-peak” traffic schedules; maximum loading of the train.

Main material and research results. Experimental studies were carried out using a test complex created on the basis of a modernized train. This complex includes a train and a measuring system installed on board (Fig. 4) [17].

On the flow chart (Fig. 4), the following designations of the power part of the train are conventional: 3M+2T equipment, automatic switch (QF), current collector (SP), unit of own needs (BVP), asynchronous traction motor (ATM), static traction converter (STP), block of resistors (BR), main switch (GV), quick-coding switch (SHV).

The developed measuring system allows analyzing the energy processes between the train and the catenary network in real operating conditions. It provides acquisition, display and storage of controlled parameters from sensors of current (SC), voltage (SV) and angular velocity (SS) using matching blocks (BM), switching (BS) and analog-to-digital conversion (ADC).

For standard typical operating conditions on a given section of the track, a study of energy processes was carried out using a test complex. The driving mode is considered to be

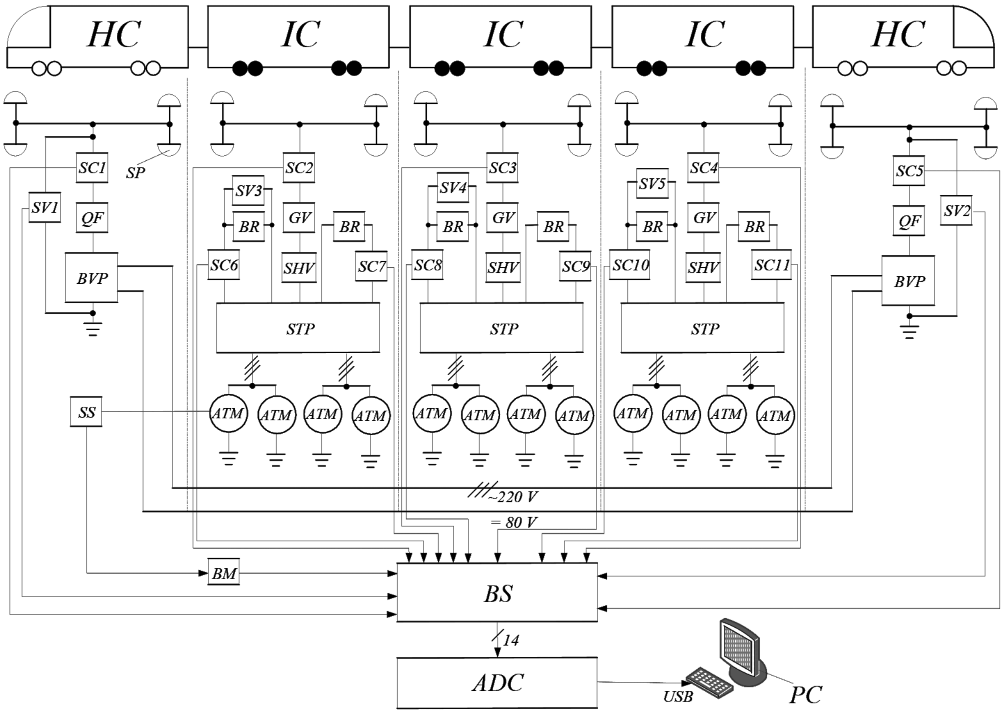

Fig. 4. Flow chart of the experimental testing system

typical, in which the execution of the graphic movement is ensured. At the same time, the number of passes for each running line was at least 3 times.

According to the results of the research, with the measuring system, the voltage on the current receiver $u(t)$, the current of the train in the modes of traction and regenerative braking $i(t)$ were recorded with a sampling frequency of 2.5 kHz; the voltage on the braking resistors $u_R(t)$, the current on the braking resistors $i_R(t)$, the speed of the train $v(t)$.

Based on the results of experimentally obtained data processing on a given site, the following indicators were determined: average operating speed on the run (V_{sereks}); braking start speed (V_{br}); driving time in traction and regenerative braking modes (t_{tyagy}, t_{rek}); average values of contact network voltage in traction/regenerative braking modes ($U_{sertyagy}/U_{serrek}$); average current values in traction/regenerative braking modes ($I_{sertyagy}/I_{serrek}$); the average value of the voltage and current on the braking resistors (U_{serR}, I_{serR}).

In general, the amount of electricity consumed or generated by a train is determined by the formula [18, 19]

$$A = \frac{\int_0^t U_{ser} \cdot I_{ser} dt}{3{,}600 \cdot 1{,}000}, \tag{1}$$

where U_{ser} is the average voltage on the current collector; I_{ser} is the average current of the train.

Since the voltage fluctuations are insignificant compared to the current, during data processing it is assumed that the average voltage values are constant. Taking into account the adopted simplification, formula (1) can be presented in the form

$$A = \frac{U_{ser} \cdot \sum_{i=1}^{n} I_{ser} \cdot \Delta t}{3{,}600 \cdot 1{,}000}. \tag{2}$$

where Δt is time; n is the number of integration steps.

Taking into account (2), the amount of electricity consumed in traction mode is calculated according to the formula [18]

$$A_{tyagy} = \frac{U_{sertyagy} \cdot \sum_{i=1}^{n} I_{sertyagy} \cdot t_{tyagy}}{3{,}600 \cdot 1{,}000}. \tag{3}$$

The amount of electricity generated by the train during regenerative braking is calculated according to the formula [18]

$$A_{rek} = \frac{U_{serrek} \cdot \sum_{i=1}^{n} I_{serrek} \cdot t_{rek}}{3{,}600 \cdot 1{,}000} + \frac{U_{serR} \cdot \sum_{i=1}^{n} I_{serR} \cdot t_{rek}}{3{,}600 \cdot 1{,}000}. \tag{4}$$

Theoretical studies were carried out using the “Rational Trajectory” software. It was developed in the LabVIEW graphical programming environment in order to determine the rational modes of driving the rolling stock under the given conditions of its operation. At the same time, the developed certified software “Rational Trajectory” allows you to automate the calculations of the dynamic qualities of the movement and energy indicators of the composition during its rational driving mode.

The basis of the creation of the “Rational Trajectory” software is the principle of solving a multi-criteria problem by the method of the main criterion. At the same time, the main criterion is the minimum amount of electricity consumption from the contact network. Other criteria (running time, distance traveled, and speed at the end of the last step of the variation) are subject to certain specified restrictions [20].

The algorithmic support of the “Rational Trajectory” program for determining the rational mode of driving the rolling stock of underground electrified transport includes the following stages:

- specification of technical characteristics of the train;
- setting the track profile and speed limits on the section (race);
- setting control influences and variation steps;
- track profile straightening routine;
- construction of high-speed grids;
- subroutine for calculating the variation step;
- determination of driving modes that ensure the given distance covered and the time of movement in the race, and the speed at the end of the last step of the variation is zero, taking into account the given deviations and limitations;
- determination of the rational mode of driving a subway train according to the main criterion.

The stages of algorithmic and mathematical support, the list of input and output parameters of the “Rational Trajectory” program, as well as the instructions for working with the software are described in more detail in [16].

It should be noted that the result is the determination of such energy indicators as the amount of electricity consumed for traction (A_{tyagy}) and the amount of electricity generated by the train during regenerative braking (A_{rek}). The calculation of the specified indicators is carried out according to formulas (3) and (4).

The appearance of the graphical user interface of the “Rational Trajectory” software is shown in Fig. 5. The program interface is conditionally divided into several blocks according to their functional purpose.

The graphical user interface has three tabs: input parameters, intermediate data and result. After starting the “Rational Trajectory” software tool, the “Input parameters” tab always opens, where the operator can enter all the data necessary for the calculation and use the “Straightening” subroutine (stages 1–4). The functional purpose of the other two tabs is to display intermediate ones (stages 5–7) and final calculation results (stage 8).

With the use of the “Rational Trajectory” software, the rational modes of driving a train on a given section, as well as the resulting energy parameters, such as the amount of traction and recuperation electricity, are determined.

Discussion of experimental results. The results of experimental and theoretical studies of indicators of the amount of electricity under the same specified conditions of operation of rolling stock of underground electrified transport are given in Table 1.

With the use of the data in Table 1, the reserves of saving energy resources are determined under the condition of integrating the system for finding rational modes of driving the train according to the formulas

$$\alpha = 100 - \left(\frac{\sum_{j=1}^{k} A^{RT}_{tyagy}}{\sum_{j=1}^{k} A^{VK}_{tyagy}} \cdot 100 \right); \quad (5)$$

$$\beta = 100 - \left(\frac{\sum_{j=1}^{k} A^{RT}_{rek}}{\sum_{j=1}^{k} A^{VK}_{rek}} \cdot 100 \right), \quad (6)$$

where α is the amount of electricity saved due to the rationalization of movement in traction mode, %; β is the amount of increase or decrease in regenerative braking electricity due to rationalization of movement in the braking mode, %; A^{RT}_{tyagy} is the amount of electricity consumed by the train obtained using the software “Rational Trajectory”, kWh; A^{VK}_{tyagy} is the amount of electricity consumed by the train, obtained experimentally using the test complex, kWh; A^{RT}_{rek} is the amount of electricity generated by the train, obtained using the software “Rational Trajectory”, kWh; A^{VK}_{rek} is the amount of electricity generated by the train, obtained experimentally using the test complex, kWh.

The results of calculations performed according to formulas (5, 6) are given in Table 2.

According to the results of the analysis of energy saving research for the specified operating conditions (Table 2) it is established that the integration of the “Rational Trajectory” software into the train control system will allow:

- saving 11.5 % of the amount of electricity consumed by the train for traction in the “off-peak” schedule;
- saving 14.7 % of the amount of electricity consumed by the train for traction in the mode of movement during the “peak” schedule;
- in the mode of movement during the “off-peak” schedule, increasing the amount of electricity generated by the train to the contact network by 3.3 % during regenerative braking;
- in the traffic mode during the “peak” schedule, reducing the amount of electricity generated by the train to the contact network by 5.2 % during regenerative braking.

Conclusions and direction of further research.

1. The research on the analysis of energy saving reserves on the rolling stock of underground electrified transport was further developed due to the introduction of a system for determining the rational driving mode.

2. It was established that for the specified operating conditions, the integration of the “Rational Trajectory” software into the on-board train control system will save up to 14.7 % of the amount of electricity consumed by the subway train for traction, due to the rationalization of its driving modes.

At the same time, there is also a possibility of increasing the volume of generated electricity to the catenary network by 3.3 % during the operation of the train according to the “off-peak” traffic schedule.

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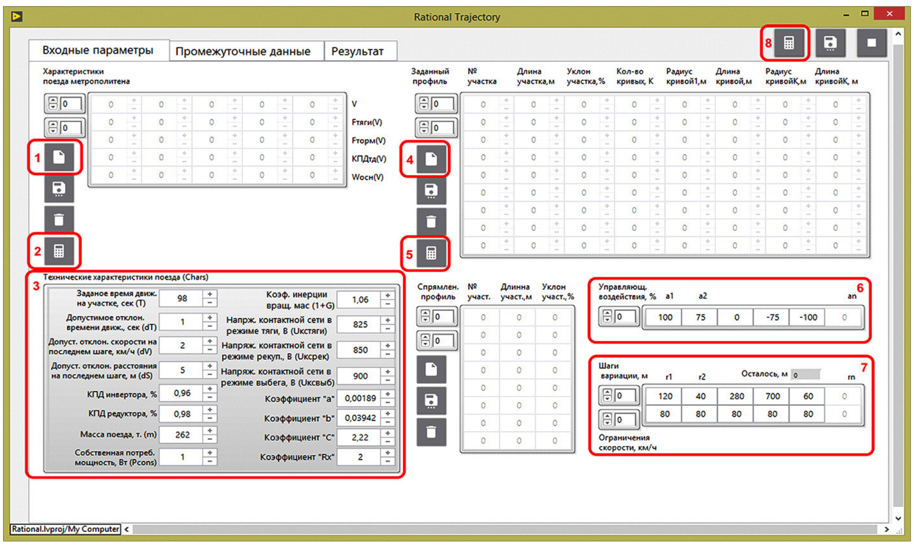

Fig. 5. General view of the Rational Trajectory software interface. “Input parameters” tab

Table 1

Results of experimental and theoretical studies under "off-peak" and "peak" traffic schedules

Researched section	Using the test complex*		Using the software "Rational Trajectory"	
	A^{VK}_{tyagy}, kWh**	A^{VK}_{rek}, kWh**	A^{RT}_{tyagy}, kWh**	A^{RT}_{rek}, kWh**
Lisova-Chernihivska	8.46/14.6	5.33/10.06	6.14/9.74	3.31/6.31
Chernihivska-Darnytsia	11.11/15.92	4.1/7.67	10.61/15.42	3.47/5.78
Darnytsia-Livoberezhna	8.98/13.63	3.49/6.65	8.47/13.03	3.11/3.7
Livoberezhna-Hydropark	9,8/18,68	5.93/10.51	9.76/14.24	5.93/8.75
Hydropark-Dnipro	21.81/23.52	6.75/8.07	21.78/22.65	7.11/8.89
Dnipro-Arsenalna	3.48/2.28	8.97/8.22	2.62/2.62	9.4/9.41
Arsenalna–Khreshchatyk	12.77/13.94	4.89/6.87	10.92/12.95	4.27/4.95
Khreshchatyk–Teatralna	8.25/14.18	4.11/7.69	7.97/11.43	4.00/5.77
Teatralna-University	9.2/13.55	4.14/5.42	8.56/9.64	2.95/3.66
University-Vokzalna	9.85/14.45	3.89/6.54	9.56/12.71	10.79/12.12
Vokzalna -Polytechnic Institute	16.75/20.53	4.74/6.48	13.31/15.45	5.04/5.2
Shuliavska-Polytechnic Institute	13.05/18.37	4.75/7.31	11.42/13.06	3.31/4.37
Shuliavska–Beresteiska	81.31/84.09	4.29/5.52	67.03/67.26	7.12/8.84
Beresteiska–Nyvky	17.68/21.82	9.04/11.64	14.94/18.81	8.47/11.06
Nyvky–Sviatoshyn	12.61/13.69	3.76/3.26	11.77/12.66	2.78/3.23
Sviatoshyn-Zhytomyrska	6.25/11.95	8.69/12.26	5.9/8.68	14.87/15.98
Zhytomyrska-Akademmistechko	2.88/4.15	3.1/3.67	2.82/4.11	3.22/4.17
Akademmistechko-Zhytomyrska	19.03/25.22	3.78/7.35	18.54/23.81	5.72/7.27
Zhytomyrska-Sviatoshyn	24.56/25.92	3.47/4.02	19.01/20.17	3.75/4.35
Sviatoshyn-Nyvky	9.47/12.05	6.46/7.68	9.17/11.88	5.94/7.8
Nyvky–Beresteiska	13.39/17.85	6.35/8.67	12.71/15.42	2.41/4.99
Beresteiska–Shuliavska	5.11/5.72	45.93/45.36	3.21/5.38	44.13/44.25
Shuliavska-Polytechnic Institute	11.78/17.83	6.6/9.86	11.24/13.24	5.73/7.0
Polytechnic Institute-Vokzalna	15.21/16.2	5.0/6.35	13.27/14.52	4.02/5.02
Vokzalna-University	8.15/10.44	2.53/3.89	7.14/10.08	3.65/4.07
University- Teatralna	8.31/10.39	2.7/3.97	7.97/9.81	4.43/5.31
Teatralna–Khreshchatyk	8.14/12.93	2.13/5.49	8.11/11.53	2.19/4.71
Khreshchatyk–Arsenalna	13.83/13.88	5.0/4.83	12.29/12.71	2.87/2.79
Arsenalna-Dnipro	23.13/22.32	4.5/3.78	19.6/19.6	0.42/0.42
Dnipro-Hydropark	12.05/15.91	9.86/13.69	12.03/14.51	10.9/13.02
Hydropark–Livoberezhna	15.07/17.75	4.66/5.64	11.77/14.07	5.0/5.84
Livoberezhna–Darnytsia	10.2/12.83	5.42/7.1	10.08/12.21	11.9/13.02
Darnytsia-Chernihivska	11.52/11.0	6.13/5.19	9.05/9.81	5.72/6.21
Chernihivska-Lisova	11.83/15.4	3.4/6.0	11.73/13.93	3.08/4.19

* The averaged data of the amount of electricity based on the results of processing the oscillograms of at least three passes of the rolling stock of the underground electrified transport on each of the given races are given.

** The numerator shows the value of the amount of electricity that corresponds to the off-peak schedule of underground electrified transport, the denominator shows the peak

Table 2

Results of energy conservation research

Indicator	Off-peak traffic schedule	Peak traffic schedule
α, %	11.5	–3.3
β, %	14.7	5.2

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Заощадження енергоресурсів під час експлуатації рухомого складу підземного електрифікованого транспорту

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Мета. Аналіз резервів енергозбереження за умови впровадження та інтегрування системи для пошуку раціональних режимів ведення в загальну систему керування рухомим складом підземного електрифікованого транспорту.

Методика. У роботі представлена методика обробки масивів даних, отриманих експериментально за допомогою вимірювальної системи й теоретично з використанням програмного забезпечення «Rational Trajectory».

Результати. Проведені експериментальні дослідження з використанням випробувального дослідного комплексу, створеного на базі модернізованого поїзда з системами рекуперації. Виконані теоретичні дослідження з використанням програмного забезпечення «Rational Trajectory», до основи якого покладено принцип вирішення багатокритеріальної задачі методом головного критерію. Обрано головним критерієм мінімальну кількість споживання електроенергії з контактної мережі. Програмне забезпечення розроблене в середовищі графічного програмування LabVIEW з метою визначення раціональних режимів ведення рухомого складу та енергетичних показників на заданій ділянці його експлуатації. Визначена кількість спожитої електроенергії на тягу й кількість електроенергії, що генерується поїздом під час рекуперативного гальмування, за результатами виконання експериментальних і теоретичних досліджень відповідно до типових і раціональних режимів ведення поїзда для заданих однакових умов експлуатації.

Наукова новизна. Дістали подальшого розвитку дослідження з аналізу резервів енергозбереження на рухомому складі підземного електрифікованого транспорту за рахунок упровадження на ньому системи для пошуку раціонального режиму ведення.

Практична значимість. Встановлено, що впровадження та інтегрування до системи керування поїздом програмного забезпечення «Rational Trajectory» дозволить заощадити до 14,7 % обсягів електроенергії, яка витрачається на тягу, порівняно із типовими режимами його ведення на заданій ділянці колії.

Ключові слова: *енергозбереження, енергоресурси, підземний електрифікований транспорт, рухомий склад, система керування*

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