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D. Kozachenko[1],
orcid.org/0000-0003-2611-1350,
Z. Tursymbekova[*2],
orcid.org/0000-0001-6483-5451,
E. Manafov[3],
orcid.org/0000-0001-5697-577X,
T. Bolvanovska[1],
orcid.org/0000-0001-6462-8524,
V. Rudyi[1],
orcid.org/0009-0001-0155-2670

1 – Ukrainian State University of Science and Technologies, Dnipro, Ukraine
2 – International University of Transportation and Humanities, Almaty, Republic of Kazakhstan
3 – National Aviation Academy, Azerbaijan, Baku, Republic of Azerbaijan
* Corresponding author e-mail: zakiratursymbekova22@gmail.com

ANALYTICAL METHOD FOR SHUNTING MOVEMENTS TIME STANDARDIZATION IN STATION THROATS

Purpose. Development and substantiation of a simplified analytical method for determining the duration of shunting movements, based on the use of averaged design parameters of station throats and characteristics of shunting consists.

Methodology. The study employs the methods of railway operation theory, kinematic modelling, integral calculus, mathematical statistics, and simulation modelling.

Findings. The research presented in the paper is aimed at confirming the hypothesis that the average time norm for shunting movements in a station throat is close in value to the time norm for movement over an average distance. Validation of the proposed method by comparing its established norms with the results of simulation modelling showed that the relative calculation error does not exceed 5 %. This confirms the scientific validity of the hypothesis and the suitability of the developed approach for practical use in railway operations.

Originality. The study improves the method for standardising time consumption for shunting movements in station throats. As a result of the research, it is proven that the time norms for shunting movements established based on average distances and the average number of wagons in a shunting consist do not differ significantly from the average time norms for these operations. Unlike existing statistical methods, the proposed method allows for determining norms based on simpler analytical models and is built on a common methodological basis with the norms for wagon transfer.

Practical value. The proposed method allows for a detailed consideration of the local operational features of individual stations and industrial sidings. The method can be used in the design of railway stations and the development of their technological processes. Furthermore, the results presented serve as a basis for research into improving standardisation methods for comprehensive shunting operations.

Keywords: *railways, railway stations, shunting operations, station throats, time standards*

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Introduction. A prerequisite for ensuring the cost-effectiveness and safety of railway transport operations is the prior development of advanced technological processes for the operation of stations and industrial sidings. An important element in fulfilling this requirement is the standardisation of time consumption for shunting operations. The costs of shunting operations account for approximately one-tenth of the total costs of freight transport on public railways. Furthermore, a significant volume of shunting work is concentrated at industrial enterprises, particularly in the metallurgical industry, the mining sector, and at seaports.

Recently, the operating conditions for rail transport have undergone significant changes. In particular, the increase in the proportion of privately owned rolling stock has necessitated additional sorting of wagons according to their ownership, whilst the progressive wear and tear of the freight wagon fleet requires them to be sorted according to their technical condition. In a market economy, changes in the operational profile of enterprises are a fairly common occurrence; therefore, the rail transport system supporting their activities must rapidly adapt its operational procedures to the requirements of core production. Taking these factors into account, improving methods for standardising the time required for shunting operations is a pressing issue for mainline and industrial rail transport.

Literature review. The problem of standardising the duration of shunting operations arose in the late 19^{th} century due to the need to evaluate design solutions. Initially, standardisation applied to simple shunting operations, during which the number of wagons in the trains and the distance they travelled remained constant. Historically, the first specialised scientific studies in the field of standardising the duration of shunting operations were linked to the statistical analysis of the results of timekeeping observations. In 1901, engineer Alexander Frolov [1] obtained a linear dependence of the duration of the rearrangement of groups of wagons from one track to another on the number of wagons in the train

$$t_{sm} = a + bm_t, \quad (1)$$

where a, b are model coefficients, min and min/wagon; m_t is the number of wagons in the shunting consist.

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Unlike simple shunting movements, when performing comprehensive shunting operations, the distance travelled, the number of wagons in the shunting consist, or both of these values change. Comprehensive shunting operations include, in particular, sorting, assembly and completion of train formation. Their execution involves the movement of groups of wagons between parallel tracks via a station or yard throat and a draw-out track. Since, at the technology development stage, the location of wagons on the tracks and their destination are unknown [2], the time required to perform such operations is a random variable. As a rule, the mathematical expectation of these values is used as a standard. Analytical, statistical, and simulation methods are used to evaluate time standards.

A historical analysis of the development of analytical models is presented in [3]. The scientific foundations of these methods were laid in the 1930s. In accordance with this approach, a comprehensive shunting operation is decomposed into simple operations of the same type. Based on this analysis, the number of such operations and the average length of the trains involved in the shunting work are determined. Using formula (1), the average duration of individual elements is determined and, ultimately, the total time required to perform a comprehensive shunting operation. In the 1950s, this approach formed the basis for the development of guidance documents on the standardisation of shunting operations. These documents, following a series of reprints, remain in force in the railway sector to this day. A critical shortcoming of the described approach is that, when determining time standards for comprehensive shunting operations, model coefficients (1) averaged across the entire network are used. Consequently, the resulting standards do not account for the local operational characteristics of individual stations and industrial sidings, therefore, they require refinement.

The work by Lashenyh, et al. [4] is devoted to the issue of improving analytical methods for determining the duration of shunting movements. In this work, an improved method for determining time standards for shunting operations has been developed based on the factorial experiment planning method. Unlike (1), the resulting expression takes into account the distance and speed of shunting movements. The approach proposed in [4] is compact and does not require the use of the coefficient tables from model (1). A drawback of this approach is that smooth polynomials do not account for changes in the mode of movement as the distance travelled increases. It should be noted that the use of the regression coefficient as the main criterion of adequacy in [4] is debatable, since it reflects only the mathematical strength of the relationship within a specific sample, but does not guarantee the physical validity of the model.

Historically, the first models used to standardise the duration of shunting operations were statistical models based on timekeeping data [1, 3]. The problem with this approach is that observational data cannot be used to standardise the time required for shunting operations for various reasons. The main reasons are, firstly, that the actual time spent on shunting operations includes downtime caused by route incompatibility with other trains and shunting movements; and secondly, that shunting operations are often optimised according to criteria other than minimum time expenditure [5]. Targeted experiments to standardise the duration of shunting operations require significant expenditure of time and resources. It should be noted that, to this day, timekeeping observations are still being carried out. In particular, this method was used in the works by Kałuża [6], Yu & Tao [7], Chuijiang [8], and Bakyt, et al. [9]. However, the purpose of the presented statistical observations is either the validation of models or the search for reserves for improving the operating technology of stations. Recent research in the field of transport technology demonstrates the effectiveness of combining analytical and probabilistic models to assess the operational performance of rolling stock. In particular, the work by Monastyrskyi, et al. [10] uses Markov processes to justify an approach to assessing the productivity of quarry transport, taking into account operational conditions and route parameters.

The most accurate method for determining the duration of shunting movements is traction calculations based on the numerical solution of the differential equation of motion. This approach was used in the works by Kuznetsov, et al. [11] when selecting the type of shunting locomotive, as well as by Kostenko, et al. [12] and Deveci [13] to assess the traction characteristics of shunting locomotives, and by Novytskyi, et al. [14] to solve braking problems. Despite the high accuracy of the modelling, the complexity of the mathematical apparatus and the need for detailed input data limit its widespread application for standardising the duration of shunting operations.

Modern methods for standardising the duration of shunting movements are based on kinematic models, which represent a simplified solution to the equations of motion for cases where rolling stock moves in AB and ACB modes [3]. It is precisely this approach that has been chosen as the primary one in this study.

The problem of standardising the duration of comprehensive manoeuvring operations lies in the variability of time expenditure depending on the chosen sequence of actions during their implementation. Selecting the optimal sequence for carrying out such operations constitutes an optimisation problem that requires consideration of the dynamic changes in the parameters of the shunting consists and the location of wagons on the tracks. To select the order of shunting operations with specific trains, various methods of operations research are used: Particle Swarm Optimisation Algorithm [15], Algorithm for finding the shortest paths on a graph [16], Simulated Annealing Algorithm [17], Integer Linear Programming [18], and heuristic methods [19, 20]. Such algorithms make it possible to determine the optimal order for performing shunting operations with a specific train in operational conditions and serve as the basis for developing software for information and control systems for smart stations [21, 22]. In addition, the use of optimisation methods of operations research together with methods of simulation modelling and mathematical statistics allows the development of statistical models that describe real processes with high accuracy, in particular for assessing the processing capacity of sorting devices [23, 24], the throughput of station throats [25] and the assessment of railway stations in general [26]. Despite the high potential of modern simulation

and optimisation methods, their practical application is limited by significant computational complexity and the need to adapt models to the technologies and topology of the track development of each station. In this study, the simulation modelling method is used to validate analytical models.

The historical analysis of the development of railway operations theory shows that, traditionally, classical analytical methods for finding extrema, based on the calculation of derivatives, are used when standardising the duration of comprehensive shunting operations. When using such methods, smooth functions are required to determine the duration of elementary operations, which do not correspond to real shunting processes. Simplifications made when formalising such functions are a source of error when standardising the duration of shunting operations. Therefore, the accuracy of analytical models used to standardise the duration of elementary shunting operations requires quantitative evaluation.

Purpose. The review of the literature shows that there is a methodological gap in the theory of railway operation regarding the consideration of the discrete nature of shunting processes and the combinatorial complexity involved in their standardisation. In this regard, the study aims to develop and justify a simplified analytical method for determining the duration of shunting movements, based on the use of average design parameters of station throats and the characteristics of shunting consists.

In this article, the term 'shunting movement' refers to the basic operation of moving a locomotive, with or without wagons, over a specified distance without changing direction.

To achieve this objective, it is necessary to confirm the hypothesis that the average time standard for shunting movement in a station throat is close to the time standard for shunting movement over an average distance, so that when

$$\overline{l}_{sm} = \frac{\sum_{i=1}^{p} l_{sm,i}}{p};$$

$$\overline{m}_{t} = \frac{\sum_{i=1}^{p} m_{t,i}}{p};$$

$$\overline{t}_{sm} = \frac{\sum_{i=1}^{p} t_{sm,i}\left(l_{sm,i}, m_{t,i}\right)}{p}. \quad (2)$$

It holds that

$$\overline{t}_{sm} \approx t_{sm}\left(\overline{l}_{sm}, \overline{m}_{t}\right), \quad (3)$$

where $l_{sm,i}$ is the distance of the i^{th} shunting movement, m; $m_{t,i}$ is the number of wagons in the i^{th} shunting consist, wagons; p is the number of shunting movements.

Confirmation of this assumption will allow the use of design parameters of the station throat and the average number of wagons in shunting consists, rather than random values for movement distances and their consist size, when standardising time consumption. This can significantly simplify the task of establishing time standards for comprehensive shunting operations involving the movement of wagons between tracks.

Methodology. Based on the nature of speed changes during shunting movements, four main elements of motion are distinguished: acceleration (A), braking (B), constant-speed motion (C) and motion by inertia (I). The combination of these elements allows for the execution of various types of movements, differing in the time and energy required to perform them.

The highest speed of movement is achieved with a combination of elements of the 'acceleration–braking' (AB) type. In this case, the shunting unit accelerates to the maximum possible speed such that, with intensive braking, it is capable of stopping at the end point of the specified route. This mode achieves the highest average speed and, consequently, the shortest duration of the shunting movement. The AB mode is usually used for short-distance movements, as the shunting unit cannot accelerate to the maximum permissible speed in this mode.

Given that the speed during shunting is limited by operational requirements, the combination of elements 'acceleration – constant speed – braking' (ACB) is also used when establishing time standards for shunting movements.

The time standard for AB-type shunting movements is determined by the expression [3]

$$t_{sm,i}^{AB}\left(l_{sm,i}, m_{t,i}\right) = \frac{\sqrt{20 l_{sm,i}\left(\alpha_{AB} + \beta_{AB} m_{t,i}\right)}}{100}, \quad (4)$$

where α_{AB} is a shunting parameter, taking into account the time required to change the locomotive's speed by 1 km/h during acceleration and braking, α_{AB} = 2.44 s/km/h; β_{AB} is a shunting parameter accounting for the additional time required to change the speed of each wagon in the shunting consist by 1 km/h during acceleration and braking, β_{AB} = 0.1 s/km/h per wagon.

The standard time for ACB-type shunting movements is determined by the formula

$$t_{sm,i}^{ACB}\left(l_{sm,i}, m_{t,i}\right) = \frac{\left(\alpha_{AB} + \beta_{AB} m_{t,i}\right) v_{\max}}{120} + \frac{0.06 l_{sm,i}}{v_{\max}}, \quad (5)$$

where $v_{\max}$ is the maximum permissible speed, km/h.

To determine the type of shunting movement, the maximum distance that the shunting consist can cover in AB mode is calculated using the formula [3]

$$l_{AB,i} = \frac{\left(\alpha_{AB} + \beta_{AB} m_{t,i}\right) v_{\max}^2}{7.2}.$$

If the movement distance $l_{sm,i}$ is less than the maximum possible distance for AB mode $l_{AB,i}$, then the duration of the shunting movement is determined for AB mode using formula (4); otherwise, the duration of the shunting movement is determined for ACB mode using formula (5).

Let us consider the case of an ACB-type shunting movement. According to expression (5), the time required to perform the i^{th} movement $(i = \overline{1..p})$ can be expressed as a function of the number of wagons in the consist and the shunting distance

$$t_{sm}^{ACB}\left(l_{sm,i}, m_{t,i}\right) = \frac{\alpha_{AB} v_{\max}}{120} + \frac{\beta_{AB} v_{\max}}{120} m_{t,i} + \frac{0.06}{v_{\max}} l_{sm,i} = A + B m_{t,i} + C l_{sm,i},$$

where *A, B, C* are constant coefficients

$$A=\frac{\alpha_{AB}v_{\max}}{120};\quad B=\frac{\beta_{AB}v_{\max}}{120};\quad C=\frac{0.06}{v_{\max}}.$$

Given that the functional dependence $t_{sm}^{ACB}\left(l_{sm,i},m_{t,i}\right)$ is linear, then according to Jensen's inequality [27] for ACB-type manoeuvres, the following equality holds

$$t_{sm}^{ACB}\left(\overline{l}_{sm},\overline{m}_{t}\right)=\overline{t}_{sm}^{ACB}. \quad (6)$$

Consider relation (4), which determines the standard time for AB-type shunting movements depending on the length of the shunting route $l_{sm,i}$ and the number of wagons $m_{t,i}$. If the number of wagons $m_{t,i}$ is fixed, then the standard time (4) can be expressed as

$$t_{sm}^{AB}\left(l_{sm,i},m_{t,i}\right)=D\sqrt{l_{sm,i}}, \quad (7)$$

where *D* is a constant coefficient

$$D=\frac{\sqrt{20\left(\alpha_{AB}+\beta_{AB}m_{t,i}\right)}}{100}.$$

Since the second derivative of function (7) is always negative for l_{sm}, $I > 0$, this function is concave with respect to the distance $l_{sm,i}$.

If the distance $l_{sm,i}$ is fixed in expression (4), then the time standard for shunting can be expressed as

$$t_{sm}^{AB}\left(l_{sm,i},m_{t,i}\right)=E\sqrt{\alpha_{AB}+\beta_{AB}m_{t,i}}, \quad (8)$$

where *E* is a constant coefficient

$$E=\frac{\sqrt{20l_{AB,i}}}{100}.$$

Since the second derivative of the function (8) is always negative for $m_{t,i} > 0$, this function is concave with respect to the number of wagons $m_{t,i}$.

Thus, function (3) is concave with respect to both its variables. Therefore, based on Jensen's inequality [27], it can be stated that for AB-type shunting movements

$$t_{sm}^{AB}\left(\overline{l}_{sm},\overline{m}_{t}\right)>\overline{t}_{sm}^{AB}. \quad (9)$$

To estimate the magnitude of the error in calculating the average time standard for shunting movement based on the values of the average consist size and the average length of the route, it is assumed that the values l_{sm} and m_t are uniformly distributed in the intervals $[l_{\min}, l_{\max}]$ and $[m_{\min}, m_{\max}]$, respectively. Under this assumption, the average time standard can be determined by the expression

$$\overline{t}_{sm}^{AB}=\frac{1}{\Delta l_{sm}\cdot\Delta m_{t}}\int_{m_{\min}}^{m_{\max}}\int_{l_{\min}}^{l_{\max}}t_{sm}^{AB}\left(l_{sm},m_{t}\right)dl_{sm}dm_{t}, \quad (10)$$

where $\Delta l_{sm}=l_{\max}-l_{\min}$, and $\Delta m_{t}=m_{\max}-m_{\min}$.

Since function (10) is separable and can be factored into terms depending only on l_{sm} and only on m_t, then

$$\overline{t}_{sm}^{AB}=\frac{\sqrt{20}}{100\Delta l_{sm}\cdot\Delta m_{t}}\left(\int_{l_{\min}}^{l_{\max}}\sqrt{l_{sm}}dl_{sm}\right)\times\left(\int_{m_{\min}}^{m_{\max}}\sqrt{\alpha_{AB}+\beta_{AB}m_{t}}dm_{t}\right). \quad (11)$$

In this expression

$$\int_{l_{\min}}^{l_{\max}}\sqrt{l_{sm}}dl_{sm}=\frac{2}{3}\left(l_{\max}^{1.5}-l_{\min}^{1.5}\right);$$

$$\int_{m_{\min}}^{m_{\max}}\sqrt{\alpha_{AB}+\beta_{AB}m_{t}}dm_{t}=$$

$$=\frac{2}{3\beta_{AB}}\left(\left(\alpha_{AB}+\beta_{AB}m_{\max}\right)^{1.5}-\left(\alpha_{AB}+\beta_{AB}m_{\min}\right)^{1.5}\right).$$

The final average time norm required for movements with wagons can be determined using the formula

$$\overline{t}_{sm(w)}^{AB}=$$

$$=\frac{(l_{\max}^{1.5}-l_{\min}^{1.5})((2.44+0.1m_{\max})^{1.5}-(2.44+0.1m_{\min})^{1.5})}{5.03\Delta l_{sm}\cdot\Delta m_{t}}. \quad (12)$$

Based on similar considerations, for the movement of locomotives without wagons, the average time standard can be determined using the formula

$$\overline{t}_{sm(l)}^{AB}=\frac{l_{\max}^{1.5}-l_{\min}^{1.5}}{21.4724\Delta l_{sm}}. \quad (13)$$

To assess the accuracy of the simplified method for determining the average time standard, the relative error is used, the value of which is calculated using the formula

$$\delta=\frac{t_{sm}\left(\overline{l}_{sm},\overline{m}_{t}\right)-\overline{t}_{sm}}{\overline{t}_{sm}}100\ \%. \quad (14)$$

To estimate the magnitude of the error, calculations were performed for $l_{\min}=100$ m and $l_{\max}=\overline{200–1{,}000}$ m. In doing so, movements without wagons were considered, for which $m_{\min}=m_{\max}=0$, and movements with wagons for which $m_{\min}=1$ and $m_{\max}=\overline{5–30}$. The results of the calculations are given in Table 1.

Thus, when performing shunting in ACB mode, the following exact equality holds

$$\overline{t}_{sm}^{ACB}=t_{sm}\left(\overline{l}_{sm},\overline{m}_{t}\right), \quad (15)$$

and when performing shunting in AB mode

$$\overline{t}_{sm}^{AB}t_{sm}\left(\overline{l}_{sm},\overline{m}_{t}\right). \quad (16)$$

Table 1

Relative error in calculating the duration of shunting movements using the simplified method, %

$l_{\max}$, m	Movements without wagons	$m_{\max}$ for movements with wagons, wagons					
		5	10	15	20	25	30
200	0.48	0.47	0.55	0.65	0.77	0.89	1.02
300	1.11	1.11	1.18	1.28	1.40	1.53	1.66
400	1.64	1.64	1.72	1.82	1.94	2.07	2.20
500	2.08	2.08	2.16	2.26	2.38	2.51	2.64
600	2.44	2.44	2.51	2.62	2.74	2.87	3.00
700	2.74	2.74	2.81	2.92	3.04	3.17	3.30
800	2.99	2.99	3.06	3.17	3.29	3.42	3.55
900	3.20	3.20	3.28	3.38	3.50	3.63	3.77
1,000	3.39	3.39	3.46	3.57	3.69	3.82	3.95

In this case, the relative error in the calculation of time standards for AB-type shunting movements under normal railway station operating conditions does not exceed 5 %. Therefore, it can be stated that with sufficient accuracy for engineering calculations, when standardising the time consumption for comprehensive shunting, the average time expenditure for shunting movements can be determined as the time required for the movement of a shunting consist of average consist size along the average length of the route.

Results. When performing an analytical assessment of the error magnitude, an assumption was made regarding the uniform distribution of the random variables l_{sm} and m_t within the intervals $[l_{\min}, l_{\max}]$ and $[m_{\min}, m_{\max}]$, respectively. However, such assumptions do not fully correspond to the actual operating conditions of railway stations and industrial sidings, due to several objective factors, namely:

- the discreteness of the value l_{sm}, since the actual length of the routes is determined by the track layout plan of the station throat and can take on a limited number of values;

- the discreteness and non-uniformity of the value m_t, since the number of wagons can only take integer values, and one of the factors influencing standardisation is often the total number of wagons in the consist

$$M_t = \sum_{i=1}^{p} m_{t,i};$$

- the interdependence of the parameters l_{sm} and m_t during the standardisation of individual shunting operations.

On the other hand, according to analytical findings, a significant relative error is characteristic only of shunting operations over long distances using the AB mode. At the same time, under real operating conditions, long-distance movements rarely occur during shunting within station throats. Furthermore, as the length of shunting movements increases, so does the likelihood of using the ACB mode, for which the accuracy of the simplified calculation has been analytically proven (15).

Given the discrepancies between the simplified analytical model and actual operating conditions, and to empirically validate the theoretical conclusion regarding the feasibility of estimating the average time required for shunting movements based on the time taken by a shunting consist of average consist size to travel an average route length, comparative calculations were carried out for a typical station throat with a draw-out track, the layout of which is shown in Fig. 1.

Depending on the method of point control, the boundary of shunting movements (the point where the direction of travel changes) within the station throat is defined as follows:

- a shunting signal on the draw-out track – in the case of route-based control of points and signals (hereinafter referred to as 'route control');

- the point toe, which divides the routes into the required sorting tracks – in the case of individual point control from the station duty officer's console, a local control panel, or manual operation (hereinafter referred to as 'individual control').

The distances from the track edge to the point where the direction of travel changes to another track are given in Table 2.

To verify the limitations of this approach, a quantitative assessment of the error in the traditional method was carried out. The number of sorting tracks and the maximum permissible speed were taken as the key factors determining operating conditions.

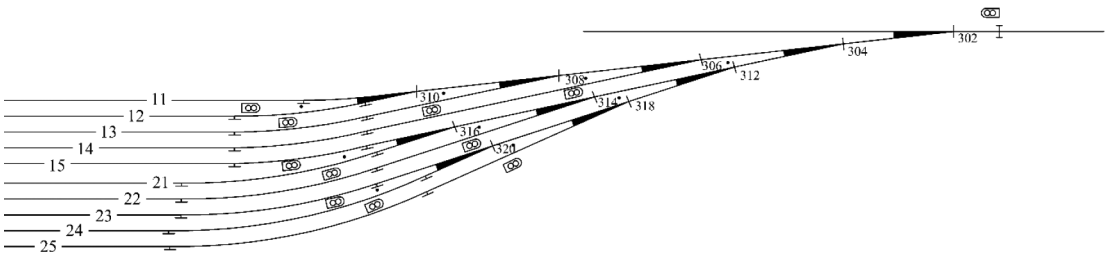

Fig. 1. Diagram of the track layout of the station throat with a draw-out track

Table 2

Distances from the track edge to the point where the direction of travel changes to another track

Starting track	Destination track for individual point control										Route control
	11	12	13	14	15	21	22	23	24	25	
11		54	102	150	198	198	198	198	198	198	273
12	54		102	150	198	198	198	198	198	198	261
13	54	54		102	150	150	150	150	150	150	213
14	54	54	54		102	102	102	102	102	102	165
15	54	54	54	54		54	102	150	150	150	262
21	187	187	187	187	54		102	150	150	150	250
22	140	140	140	140	55	55		103	103	103	202
23	179	179	179	179	142	142	142		57	105	250
24	179	179	179	179	142	142	142	57		105	238
25	131	131	131	131	94	94	94	57	57		189

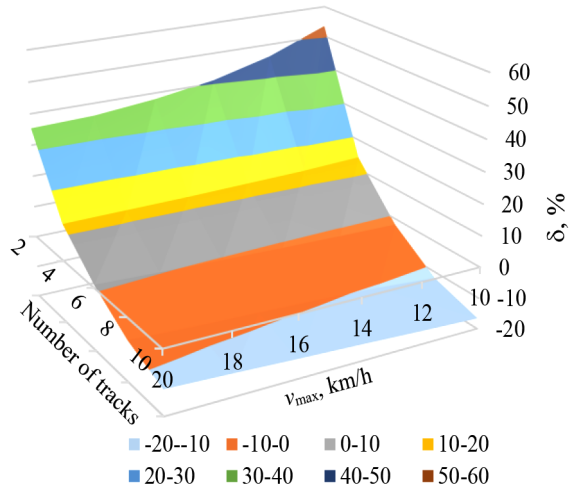

Fig. 2. Dependence of the relative error of the simplified method for determining the travel time standard for a single locomotive on the maximum permissible speed and the number of sorting tracks

The current time standards for shunting operations are based on average performance indicators for the station throat, which do not fully account for the specific characteristics of individual sites. Based on a series of computational experiments, a functional relationship between the relative error and these parameters was established. This relationship is illustrated in Fig. 2.

The results of the calculations show that the error range is between –16.6 and +53.4 % for v_{max} = 10 km/h and between –11.9 and +35.4 % for $v_{max} \geq 20$ km/h. These results indicate a significant error in the current time standards and confirm the need to transition to individual calculations using the proposed methodology.

This paper establishes the error values for different methods of point control.

The dependencies of the error (14) of the simplified method for determining the average travel time for elementary shunting operations on the maximum permissible speed under individual point control are shown in Fig. 3. This figure presents the error values for the following elementary shunting operations:

- light locomotive movement between sorting tracks (curve 1);

- movement of a locomotive with wagons from the point of change of direction to the boundary of the sorting track, or vice versa (curve 2);

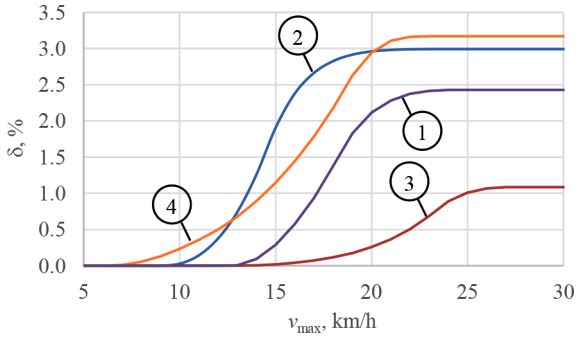

Fig. 3. Dependencies of the error of the simplified method for determining the average time standard for shunting operations on the maximum permissible speed under individual point control

- propelling a consist onto a sorting track from the point of change of direction, or pulling a consist from the sorting track beyond the point of change of direction (curve 3).

Furthermore, Fig. 3 shows the relationship between the error and the maximum permissible speed for the elementary operation of propelling or pulling a group of wagons over its own length (curve 4), the form of which does not depend on the method of point control. Analysis of Fig. 3 shows that these dependencies have a sigmoid shape. The first plateau of this sigmoid (d = 0) arises because, at low values of v_{max}, all movements occur in ACB mode. The second plateau arises because, at high values of v_{max}, all shunting movements occur in AB mode and the value of v_{max} does not affect the time standard (4).

The dependencies of the error (14) of the simplified method for determining the average time standard for elementary shunting operations on the maximum permissible speed under route control are shown in Fig. 4.

The analysis of Fig. 4 shows that, under route control, these relationships take the same form as under individual control; however, their magnitude is smaller, as the proportion of movements in ACB mode increases with the lengthening of shunting distances.

Validation of the theoretical conclusion regarding the validity of expression (3) was carried out based on a series of simulation experiments on train sorting using the Monte Carlo method. It was assumed that the trains consist of 25 wagons, which are assigned to 10 sorting tracks shown in Fig. 1. In this case, individual point control is used. The average distance of movements in the specified station throat is defined as the average length of routes according to Table 2 and amounts to 128.39 m. The maximum permissible speed is set at 25 km/h. In the initial state, all sorting tracks are clear; the train is on one of the sorting tracks, the number of which does not correspond to the destination of the first unit. A separate stage of train sorting, involving the movement of a cut to the sorting track, comprises three types of shunting movements:

- hauling the train in the direction of the draw-out track beyond the reversal point (type 1);

- propelling the train from the draw-out track to the edge of the sorting track for the shunter to dismount (type 2);

- propelling the train and wagons on the track by the length of the cut (type 3).

When determining the duration of train sorting, only the time required for shunting operations was taken into account. The duration of the initial and final operations was not considered.

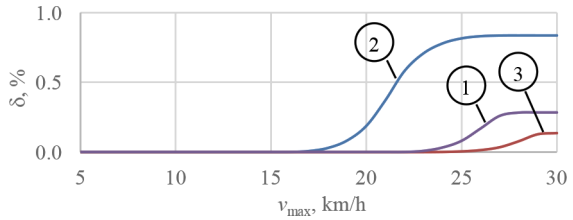

Fig. 4. Dependencies of the error of the simplified method for determining the average time standard for shunting operations on the maximum permissible speed under route control

During the computational experiments, the distribution of wagons across 300 trains was modelled. The exact time standard for train sorting was established based on modelling the sorting duration of each train for individual movements, depending on the actual number of wagons in the trains and the distance of the movements. It amounts to 30.85 min/train.

The average number of cuts in the simulated trains was 12.417 cuts/train. The average cut consists of 1.9665 wagons and has an average length of 27.531 m. The average number of wagons in a train moving during type 1 and 2 shunting operations is determined as the average of the number of wagons in the original train and in a single cut

$$\bar{m}_{\bar{n}} = \frac{25+1.9665}{2} = 13.4833.$$

The average time taken to complete a single type 1 or type 2 shunting movement is 0.9863 min.

The average number of wagons that are on the sorting track before the next cut is placed on it $\bar{m}_{ct}$ is determined from the condition that, before the sorting of the train, all tracks are clear $\bar{m}_{cts} = 0,$ and before shunting the last cut, the average number of wagons on the sorting tracks is

$$\bar{m}_{ctf} = \frac{25-1.9665}{10} = 2.30335.$$

Therefore

$$\bar{m}_{ct} = \frac{0+2.30335}{2} = 1.1517.$$

Thus, a shunting movement of type 3 involves the repositioning of a train consisting of an average of 14.6350 wagons over an average distance of 27.531 m. The average time required for the movement of type 3 is 0.4636 min.

Consequently, the average time standard for shunting operations per cut is 2.4362 min, and for the train as a whole, 30.97 min.

For individual trains, due to the specific distribution of wagons across cuts and the destinations of these cuts, the deviation of the time required for sorting from the average value can be significant. The histogram and probability density function of the random variable representing the error in determining the time standard for sorting trains are shown in Fig. 5.

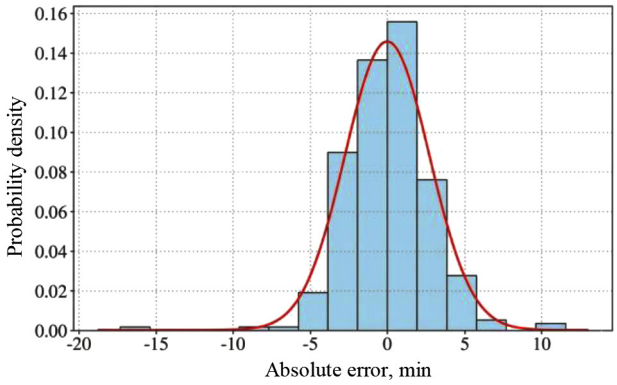

Fig. 5. Histogram and probability density function of the random variable representing the error in determining the time standard for sorting trains

Statistical analysis of the results of the computational experiments shows that there are no grounds for rejecting the hypothesis of a normal distribution of the error value, since, according to the observed data, the Pearson goodness-of-fit criterion is $\chi^2_{obs} = 1.633,$ and its critical value is 3.841. Overall, the relative error in the time standard for train sorting when using the simplified method was 0.4 %, indicating the method's acceptability for engineering calculations.

Time standards were also established using a similar methodology for route-based point control. As a result, the exact time standard for train sorting is 38.53 min, whilst the time standard established using the simplified method differs from this by 2.4 % and amounts to 39.48 min. This result confirms the applicability of the methodology for engineering calculations. At the same time, the results also highlight the need to take into account local station operating conditions. In particular, it was found that changing the method of point control, whilst keeping the train parameters and station throat geometry constant, led to a 28 % increase in the time required for shunting movements.

Under real operating conditions, the distribution of the number of wagons in the trains is often characterized by a concentration of values around the mean. To assess the sensitivity of the proposed method to the type of probability distribution, a series of computational experiments was carried out assuming a binomial distribution of the number of wagons, whilst maintaining the basic mathematical expectation. The resulting average time required for train sorting was 30.65 min. The slight deviation from the results obtained under a uniform distribution confirms the analytical model's robustness to changes in the probabilistic characteristics of the train structure.

Based on mathematical relations (6 and 9), it can be stated that

$$t_{sm}\left(\bar{l}_{sm}, \bar{m}_t\right) \geq \bar{t}_{sm}.$$

Accordingly, this property enables the use of a simplified method for standardising the duration of shunting movements to preliminarily assess the utilisation level of station throats [25, 26]. It can be argued that if the throughput capacity of station throats is sufficient to perform the specified volume of work under these time standards for shunting operations, then it will also be sufficient when using more precise standardisation methods. If, however, a discrepancy is identified, more detailed calculations must be carried out using simulation modelling methods.

Scientific novelty and practical significance. The scientific novelty of this work lies in the refinement of the method for standardising the duration of shunting movements within station throats. The research has demonstrated that time standards for shunting movements, established on the basis of average distances and the average number of wagons in a shunting consist, do not differ significantly from the average time standards for these operations. Unlike existing statistical methods, the proposed method allows standards to be determined on the basis of simpler analytical models and is built on a common methodological basis with standards for shunting operations.

The practical significance of the research results is that the proposed method enables a detailed consideration of the specific local conditions of individual stations and industrial sidings. The method can be applied both during the design stage and in the development of technological processes for station operations. Furthermore, the findings provide a foundation for further research into improving standardisation methods for comprehensive shunting operations.

Conclusions. The research findings lead to the following conclusions:

1. A methodological gap has been identified in railway operations theory regarding the discrete nature of shunting processes and the combinatorial complexity of their standardisation. It has been established that traditional methods, based on statistical models and the use of averaged network coefficients, do not fully account for local conditions, such as station throat parameters, permissible speeds, and point control methods. This can lead to significant errors that are unacceptable for engineering calculations. This paper proposes an analytical method that allows for the consideration of the discrete nature of shunting movements by applying kinematic equations instead of averaged statistical relationships, while mitigating combinatorial complexity through the use of average parameters for station throats and shunting consists.

2. Utilizing the mathematical apparatus of integral calculus and Jensen's inequality, the validity of employing average design parameters for station throats and shunting consists to determine the duration of shunting movements has been theoretically proven. It has been established that replacing random variables with their mathematical expectation in the proposed kinematic models results in a constant methodological error; however, this error does not significantly affect the final results of the standardisation.

3. Validation of the proposed method through comparison with simulation modelling results demonstrates that the relative error does not exceed 5 %. This confirms the scientific validity of the hypothesis and the suitability of the developed approach for practical application in railway operations. The method allows for a detailed consideration of the local characteristics of individual stations and industrial sidings. It can be applied during the design of railway stations and in the development of technological processes for their operation. Furthermore, the findings provide a foundation for further research into improving standardisation methods for comprehensive shunting operations.

Conflict of interest. *The authors declare that they have no conflict of interest regarding this study, including financial, personal, authorship or any other interests that could influence the study and its results presented in this article.*

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Аналітичний метод нормування тривалості маневрових пересувань у горловинах станцій

Д. Козаченко[1], *З. Турсімбекова* [*2], *Е. Манафов*[3], *Т. Болвановська*[1], *В. Рудий*[1]

1 – Український державний університет науки та технологій, м. Дніпро, Україна
2 – Міжнародний транспортно-гуманітарний університет, м. Алмати, Республіка Казахстан
3 – Національна авіаційна академія, м. Баку, Азербайджанська Республіка
[*] Автор-кореспондент e-mail: zakiratursymbekova22@gmail.com

Мета. Розробка й обґрунтування спрощеного аналітичного методу визначення тривалості маневрових пересувань, що ґрунтується на використанні усереднених конструктивних параметрів стрілочних горловин і характеристик маневрових составів.

Методика. У ході дослідження використані методи теорії експлуатації залізниць, кінематичне моделювання, методи інтегрального числення, математичної статистики й імітаційного моделювання.

Результати. Дослідження, представлені у роботі спрямовані на підтвердження гіпотези про те, що середня норма часу на маневрові напіврейси у стрілочній горловині є близькою за значенням до норми часу на переміщення на середню відстань. Валідація запропонованого методу шляхом порівняння встановлених ним норм із результатами імітаційного моделювання показала, що відносна похибка розрахунку не перевищує 5 %. Це підтверджує наукову достовірність гіпотези та придатність розробленого підходу для практичного використання в експлуатаційній роботі залізниць.

Наукова новизна. У роботі удосконалено метод нормування витрат часу на маневрові пересування у стрілочних горловинах. У результаті дослідження доведено, що норми часу на маневрові пересування, встановлені на основі середніх відстаней і середньої кількості вагонів у составі, несуттєво відрізняються від середніх норм часу на ці операції. На відміну від існуючих статистичних методів, запропонований метод дозволяє визначати норми на основі більш простих аналітичних моделей, що побудовані на спільній методичній базі з нормами на перестановку вагонів.

Практична значимість. Запропонований метод дозволяє детально ураховувати місцеві особливості роботи окремих станцій і під'їзних колій. Метод може використовуватися при проєктуванні залізничних станцій і розробці технологічних процесів їхньої роботи. Також представлені результати є основою для досліджень у галузі удосконалення методів нормування комплексних маневрових операцій.

Ключові слова: *залізниця, залізнична станція, маневрова робота, станційні горловини, норми часу*