UDC 622.2 https://doi.org/10.33271/crpnmu/76.091

© A. Romanenko[1], O. Romanenko[2]
[1] Technical University "Metinvest Polytechnic" LLC, Zaporizhzhia, Ukraine
[2] Academy of Mining Sciences of Ukraine, Kryvyi Rih, Ukraine

ANALYSIS AND IMPROVEMENT OF THE METHODOLOGY FOR SOLVING THE BRAKING TASK OF OPEN-PIT RAIL TRANSPORT

© А.О. Романенко[1], О.В. Романенко[2]
[1] Технічний університет ТОВ "Метінвест Політехніка", Запоріжжя, Україна
[2] Академія гірничих наук України, Кривий Ріг, Україна

АНАЛІЗ ТА УДОСКОНАЛЕННЯ МЕТОДИКИ РІШЕННЯ ГАЛЬМІВНОЇ ЗАДАЧІ КАР'ЄРНОГО ЗАЛІЗНИЧНОГО ТРАНСПОРТУ

Purpose. Based on the existing Norms of technological design for mining enterprises with open-pit mining of mineral deposits, provide an enhanced methodology for the effective solution of braking task in industrial open-pit rail transport using the MS Excel spreadsheet; opening prospects for further study, design, and analysis of research on the movement of industrial open-pit rail transport.

The methods. The methodology for solving braking task in industrial open-pit rail transport is presented in Appendix B of the Norms of technological design for mining enterprises with open-pit mining of mineral deposits. The authors of this article provided a detailed explanation and thorough analysis of this methodology.

Findings. As a result of the performed analysis, errors have been corrected, and an improved methodology for effective solution of the braking problem in industrial quarry railway transport has been proposed using the MS Excel spreadsheet software. Specifically, it is suggested to consider $K_{тип.к}$ (coefficient characterizing the track type; if it is a fixed track, then $K_{тип.к}$ = 1, if it is movable, then $K_{тип.к}$ = 1.3). Additionally, automation of the search for the value of V_n (initial braking speed, km/h) for the vertical profile $i_{г,i}$ (slope at the i-th integration step where braking occurs, ‰) is proposed with the given value of the braking distance $L_{гальм}$.

The originality. For the first time, a detailed analysis of the braking calculation algorithm for railway transport, as outlined in the methodology of the current Norms of technological design for mining enterprises with open-pit mining of mineral deposits, has been conducted. Recommendations, adjustments, and corrections are provided to enhance the braking calculation algorithm for railway transport. For the first time, with corrections to the deficiencies and errors of the methodology, an improved Methodology for Solving the Braking Task of Open-Pit Rail Transport using the MS Excel spreadsheet has been proposed. It takes into account the type of track and includes automated search for the initial braking speed.

Practical implementation. The methodology presented in the article can be applied as a tool in the design and execution of research for the effective solution of braking task in industrial open-pit rail transport using the MS Excel spreadsheet.

Keywords: *braking task solution, industrial open-pit rail transport, MS Excel.*

Introduction. Currently, in the careers of the Kryvyi Rih iron ore basin, a combination of automotive-rail and conveyor transport is used for transporting ore. This article examines the use of rail transport in modern conditions, which have evolved during the long-term development of mining operations in quarries and dumps.

The main guiding document for calculating indicators of rail transport is the Norms of technological design for mining enterprises with open-pit mining of mineral deposits [1].

It should be noted that currently the website ***http://www.kipdiit.dp.ua***, referenced in the Norms of technological design for mining enterprises with open-pit mining of mineral deposits [1], is unavailable. According to these norms, ready-made Microsoft® Office Excel tables with formulas for solving braking and other tasks for calculating technological indicators of rail transport are supposed to be available on this website. At the same time, these norms [1, p. 198–203] provide a detailed description of the construction of such Microsoft® Office Excel spreadsheets.

Main part. It should be noted that solutions to the braking problem of industrial quarry railway transport have been considered previously [2–8], but the most detailed methodology for solving the braking problem of industrial quarry railway transport is provided in Appendix B of the Norms of technological design for mining enterprises with open-pit mining of mineral deposits [1, pp. 178–203]. Let's analyze this proposed methodology.

For the calculation, we will consider the same initial data as in [1, p. 198–200].

The need to note is that the methodology provided in [1, p. 178–203] does not include the calculation in MS Excel of solving the braking problem with different types of tracks (constant and movable). In other words, it is possible to perform the calculation only when the entire track is constant or when the entire track is movable. This is a drawback of the methodology.

For solving the braking problem using MS Excel, [1] provides an example based on the proposed methodology B. In the example, ЕЛ 10 traction units with cast-iron brake shoes and 7-m dumpcars 2ВС-105 - variant 1 with composite brake shoes are used for transporting ore by rail transport without the use of magnetic rail brakes.

The solution to the braking problem using MS Excel in the methodology [1, p. 178–203] is proposed to be carried out according to an algorithm. Detailed explanation of this algorithm is absent in [1] and is provided in this article.

Firstly, it should be noted that the algorithm involves solving the braking problem by calculating the train's movement indicators through step-by-step integration. Each ***i***-th integration step represents a time interval, for example (recommended), 1 second. The indicators for each ***i***-th step are calculated in MS Excel in rows. The indicators of the zeroth step are located in the 6th row of the MS Excel table; the indicators of the first step are located in the 7th row of the MS Excel table; the indicators of the second step are located in the 8th row of the MS Excel table, and so on. That is, the ***i***-th step is located in the MS Excel table in the row with the number (***i+7***), where the value of i is not less than zero.

It should also be noted that all formulas of the 7th row are then copied to the lower rows in the usual way (for example, using the Ctrl+C and Ctrl+V commands). It should be ensured that the number of steps (rows filled with formulas, starting from the 7th row) is sufficient to solve the braking problem – to calculate the time when the train reaches zero speed.

Initially, the corresponding cells are filled with the respective input data. In row 2 of the MS Excel table, data provided by the [1, p. 178–203] methodology are entered, as shown in Table 1.

In this and the following tables, we provide detailed explanations of the algorithm, which are missing in [1, p. 178–203].

Table 1

Input data (values) to be entered in the 2nd row of the MS Excel table as specified in the methodology [1, p. 178–203]

№	Indicator Name	Value	Cell for Filling
1	$\boldsymbol{i_г}$ - slope of the track at all $\boldsymbol{i}$-th integration steps where braking occurs, ‰	-40	*A2*
2	$\boldsymbol{V_н}$ - initial braking speed, km/h	26,8	*B2*
			C2
3	$\boldsymbol{a_{лок}}$ - 1st empirical coefficient for determining $\boldsymbol{k_{t.лок}}$ - coefficient of filling the brake cylinders depending on ($\boldsymbol{t_г}$) time elapsed since the start of braking. For locomotive ЕЛ 10 with cast-iron brake shoes. [1, p. 190, table B.11, formula B.16]	0,0000107	*D2*
4	$\boldsymbol{b_{лок}}$ - second empirical coefficient …	-0,0017300	*E2*
5	$\boldsymbol{c_{лок}}$ - third empirical coefficient …	0,0760000	*F2*
6	$\boldsymbol{a_{ваг}}$ – 1st empirical coefficient for determining $\boldsymbol{k_{t.ваг}}$ - coefficient of filling the brake cylinders depending on ($\boldsymbol{t_г}$) time elapsed since the start of braking. For cars (dumpcars) 2ВС105 with composite brake shoes. [1, p. 190, table B.11, formula B.16]	0,0000237	*G2*
7	$\boldsymbol{b_{ваг}}$ - second empirical coefficient …	-0,002530	*H2*
8	$\boldsymbol{c_{ваг}}$ - third empirical coefficient …	0,0880	*I2*
9	$\boldsymbol{F_{s.лок.к}}$ - sum (force) of the locomotive brake shoe pressures (from [1, p. 186, table B.6] at a pressure of 390 kPa 38400 kg · 3 units = 115200 kg), kgf	115 200	*J2*
10	$\boldsymbol{P}$ - weight of the locomotive [1, p. 194, table B.16] For ЕЛ 10, t	360	*K2*

Continuation of Table 1

№	Indicator Name	Value	Cell for Filling
11	$a_{1,л,i}$ - 1st empirical coefficient for determining $\varphi_{л,i}$ - calculated coefficient of wheel-rail coupling of the locomotive wheels at the end of the ***i***-th integration step. For locomotive ЕЛ 10 with standard cast-iron brake shoes. [1, p. 185, table B.4, formula B.14]	0,78	*L2*
12	$a_{2,л,i}$ - 2nd empirical coefficient …	0,016	*M2*
13	$a_{3,л,i}$ - 3rd empirical coefficient …	100,0	*N2*
14	$a_{4,л,i}$ - 4th empirical coefficient …	0,080	*O2*
15	$a_{5,л,i}$ - 5th empirical coefficient …	100,0	*P2*
16	$a_{6,л,i}$ - 6th empirical coefficient …	0,00	*Q2*
17	$a_{7,л,i}$ - 7th empirical coefficient …	100,0	*R2*
18	$a_{8,л,i}$ - 8th empirical coefficient …	3,180	*S2*
19	$a_{9,л,i}$ - 9th empirical coefficient …	100,0	*T2*
20	$N_{г.к.лок}$ - number of locomotive brake shoes (from [1, page.186, table B.6] - 38400/2400 · 3 units, i.e., $N_{віс.лок} \cdot N_{о.лок}$ - see additional input data)	48	*U2*

For convenience, in row 2 of the MS Excel table, data not provided by methodology [1, p. 178–203] (Table 2) is suggested to be entered. For clarity, the text "Additional input data not provided by methodology [1, стор. 178–203]:" is entered into cell W2.

The additional input data (not provided by methodology [1, p. 178–203]) entered into the MS Excel table is recommended to be used for automatic lookup of corresponding input data in reference tables using the VLOOKUP function and the HLOOKUP function.

In row 1 of the MS Excel table, the corresponding names of the indicators (for clarity) entered in row 2 (i.e., those corresponding names listed in Tables 2 and 3) are entered. Additionally, for clarity, more detailed information can be included in the notes.

In row 4 of the MS Excel table, data provided by methodology [1, p. 178–203], as listed in Table 3, is entered. In row 3 of the MS Excel table, the respective names of indicators (not provided by the methodology [1, p. 178–203]) are entered for clarity, which are input in row 4 (i.e., those corresponding names as listed in Table 3). Additionally, for clarity, more detailed information can be included in the notes.

Table 2

Input data (values) to be entered in the 2nd row of the MS Excel table, not provided by methodology [1, p. 178–203]

№	Indicator Name	Value	Cell for Filling
	Additional input data:		*W2*
1a	$\boldsymbol{K_{тип.к}}$ - coefficient characterizing the type of track (if it's a fixed track, then $\boldsymbol{K_{тип.к} = 1}$, if it's movable, then $\boldsymbol{K_{тип.к} = 1.3}$)	1	*X2*
2a	$\boldsymbol{T_{л}}$ - locomotive type [1, p.198, table B.19]	ЕЛ 10	*Y2*
3a	$\boldsymbol{T_{ж.л}}$ - locomotive power supply type with electric current [1, p.194, table B.16 and p.217, table B.27]	alternating	*Z2*
4a	$\boldsymbol{N_{о.лок}}$ - number of units (sections) composing the locomotive (traction unit and two motorized dumpcars) [1, p.217, table B.27], units	3	*AA2*
5a	$\boldsymbol{N_{віс.лок}}$ - number of axles in one section of the locomotive (3 sections) (from [1, p. 186, table B.6] - 38400:2400 = 16 ; 16 : 4 = 4), units	4	*AB2*
6a	$\boldsymbol{T_{г.л}}$ - type of locomotive brake pads	cast iron	*AC2*
7a	$\boldsymbol{M_{з.в}}$ - indicator of wagon load. If the wagons are empty then $\boldsymbol{M_{з.в} = 1}$ If the wagons are loaded $\boldsymbol{M_{з.в} = 2}$	2	*AD2*
8a	$\boldsymbol{T_{ваг}}$ - type of wagons (dumpcars) [1, p. 186, table B.6]	2ВС105 -1st option (к)	*AE2*
9a	$\boldsymbol{T_{г.в}}$ - type of wagon (dumpcar) brake pads	composite	AF2
10a	$\boldsymbol{N_{ваг}}$ - number of wagons (dumpcars), units	7	AG2
11a	$\boldsymbol{N_{віс.ваг}}$ - number of axles in one wagon (dumpcar) (from [1, p. 186, table B.6] 21600:(2200+500)·2 = 16)	16	AH2

Table 3

Input data (values) to be entered in the 4th row of the MS Excel table, as stipulated by the methodology [1, p. 178–203]

№	Indicator Name	Value	Cell for Filling
1	a'_x - 1st empirical coefficient for determining w'_0 - the main specific resistance of locomotives depending on speed for **idle** mode. For locomotive ЕЛ 10 [1, p.181-182, table B.2, formula B.2]. *Attention, in [1, p. 199, table B.20] incorrect data were mistakenly entered, which are provided here; according to table B.2 [1, p. 182], the corresponding coefficients should be as follows:* a'_x*=2,8;* b'_x*=0,023;* c'_x*=0,00075 !!!*	2,9	A4
2	b'_x - 2nd empirical coefficient ...	0,080	B4
3	c'_x - 3rd empirical coefficient ...	0,0	C4
4	a''_0 - 1st empirical coefficient for determining w''_0 - the main specific resistance of wagons (dumpcars) depending on speed ***V*** for **loaded** wagons. For wagons (dumpcars) 2ВС105. [1, p.183, table B.3, formula B.5] *Attention, in table B.3 [1, p. 183], there is a typographical error:* ***ВС105*** *is indicated, but it should be* ***2ВС105****.*	3,6	D4
5	b''_0 - 2nd empirical coefficient ...	0,04	E4
6	c''_0 - 3rd empirical coefficient ...	0,0	F4
7	$M_{м.р.г}$ - indication of considering magneto-rail brakes. Specify "1" for their consideration; otherwise, enter "0".	0	G4
8	$t_{г1.л}$ - time to reach full brake pad pressure for the locomotive [1, p. 190, table B.11], sec	30,4	H4
9	$t_{г1.в}$ - time to reach full brake pad pressure for wagons [1, p. 190, table B.11], sec	30,0	I4
10	$F_{s.ваг.к}$ - sum of brake pad pressures for wagons [1, p.186, table B.6], multiplied by the number of wagons 21600·7=151200), kgf	151 200	J4
11	$M_{с.п}$ - train composition weight (excluding locomotive), [1, p. 222, fig. Г.1], t	**1 095**	K4

Continuation of Table 3

№	Indicator Name	Value	Cell for Filling
11	*Attention!!! In the provided example [1, p. 199, table B.20), $M_{с.п}$ = 1095 tons. 1095 tons : 7 units = 156 tons per wagon. From [1 , p. 222, fig. Г.1]: tare weight = 47 tons; 156 tons - 47 tons = 109 tons. Thus, the wagons are overloaded. Each wagon is not 105 tons but 109 tons.*		
12	$\boldsymbol{a_{1,в}}$ - 1st empirical coefficient for determining $\boldsymbol{\varphi_{в,i}}$ (the actual coefficient of friction of the brake pad against the wheel at the beginning of the ***i***-th integration step). For wagons (dumpcars) 2BC105 with composite brake pads. [1, p.185, table B.4, formula B.14]	0,603	L4
13	$\boldsymbol{a_{2,в}}$ - 2nd empirical coefficient …	0,005	M4
14	$\boldsymbol{a_{3,в}}$ - 3rd empirical coefficient …	100	N4
15	$\boldsymbol{a_{4,в}}$ - 4th empirical coefficient …	0,02	O4
16	$\boldsymbol{a_{5,в}}$ - 5th empirical coefficient …	100	P4
17	$\boldsymbol{a_{6,в}}$ - 6th empirical coefficient …	0	Q4
18	$\boldsymbol{a_{7,в}}$ - 7th empirical coefficient …	100	R4
19	$\boldsymbol{a_{8,в}}$ - 8th empirical coefficient …	1,406	S4
20	$\boldsymbol{a_{9,в}}$ - 9th empirical coefficient …	100	T4
21	$\boldsymbol{N_{г.к.лок}}$ - number of brake pads for wagons (dumpcars) from [1, p.186, table B.6]. **2BC105 1 variant (k)** with a pressure of 390 kPa in the brake cylinder. (Number of axles $\boldsymbol{N_{віс}}$=16 - see Additional input data) (7 dumpcars · 16 axles = 112)	112	U4
22	$\boldsymbol{M_{ваг.сум}}$ - weight of all loaded dumpcars 2BC105, with each dumpcar fully loaded at 105 tons (7 units - total number of dumpcars) [1, p. 222, fig. Г.1], t	1064	X4

In row 6 of the MS Excel table, the corresponding names of indicators from Table 4 are entered, and in row 7, the respective data is entered.

It should be noted that the data provided in item 1 and item 4 of Table 4 are not covered by the methodology for solving the braking problem of industrial open-pit railway transport, as outlined in Appendix B of the Norms for Technological Design of Mining Enterprises with an Open Development Method of Mineral Deposits [1, p. 178–203].

Table 4

Input data for the 6th and 7th rows of the MS Excel table

№	Indicator Name	Value	Column
1	$T_{S,0}$ - time from the beginning of braking at the start of the ***zero*** integration step (this is input data), (specified at intervals of 1 sec, starting from 1 sec), sec	**0,0**	*S*
2	S_0 - final traveled distance (i.e., the distance traveled from the beginning of the first integration step to the current ***0***th (initial) integration step) (Always equal to zero), m	**0,0**	*T*
3	V_0 - velocity at the end (i.e., at the end of the ***0***th (initial) integration step), (This is the train speed at the start of braking), km/h	=$B$2	*U*
4	***i*** - integration step	**0**	*X*

According to Table 5, in row 8 of the MS Excel table, values or formulas specified in curly brackets, as provided in [1] methodology, are entered. In row 6, for clarity, the names of the indicators, also listed in Table 5, are proposed to be included. It should be noted that the formula given in item 0 and item 1 of Table 5 is not covered by the methodology for solving the braking problem of industrial open-pit mining railway transport, which is presented in Appendix B of the Norms of Technological Design of Mining Enterprises with Open Development of Mineral Deposits [1, p. 178–203].

Table 5

Input data and formulas entered in row 8 of the MS Excel table, as provided by the methodology for solving the braking problem of industrial open-pit mining railway transport [1, p. 178–203]

№	Indicator Name, Calculation Formula, or Value (entered in the 6th row) (In this column, at the end of each position, the calculation formula for filling the corresponding cell of the 8th row is indicated in curly brackets)	Column
1	**2**	**3**
0	***i*** - integration step **{ =1+X7 }**	X
1	$T_{S,i}$ - time from the beginning of braking at the beginning of the ***i***-th integration step (these are input data), (specified at 1-second intervals, starting from the first second), sec. Enter the value 1 in row 8, 2 in row 9, and so on. **{ =1+A7 }**	A
2	$V_{n,i}$ - speed at the beginning of the ***i***-th integration step, km/h. If $V_{K,(i-1)} > 0$, then $V_{n,i} = V_{K,(i-1)}$. Otherwise, $V_{n,i} = 0$.	B

Continuation of Table 5

1	2	3
2	$V_{к,(i-1)}$ - speed at the end of the previous (***i-1***)-th integration step (column U), km/h. **{ =IF(U7>0,U7;0) }**	
3	$k_{t.лок,i}$ - filling coefficient of the brake cylinders for the locomotive at the end of the ***i***-th integration step [1, p.190, table B.11, formula B.16]. If $T_{S,i} < t_{г1.л}$, then $k_{t.лок,i} = a_{лок} \cdot T_{S,i} + b_{лок} \cdot T_{S,i}^2 + c_{лок} \cdot T_{S,i}^3$ Otherwise, $k_{t.лок,i} = 1$ $t_{г1.л}$ - time to reach full brake pad pressure for the locomotive [1, p.190, table B.11] (input data (constant) in cell H4), sec $a_{лок}$, $b_{лок}$, $c_{лок}$ - empirically determined coefficients (input data (constants) in cells F2, E2, D2). $T_{S,i}$ - time from the beginning of braking at the beginning of the ***i***-th integration step (these are input data), (specified at 1-second intervals, starting from 1 second), (column A), sec. **{ =IF(A8<$H$4,D2A8^3+E2A8^2+$F$2*A8,1) }**	C
4	$K_{S.лок,i}$ - actual (considering the filling coefficient of the brake cylinders $k_{t.лок,i}$) total force ($\sum K$) of the locomotive brake pad pressure at the end of the ***i***-th integration step, kgf $K_{S.лок,i} = k_{t.лок,i} \cdot F_{s.лок.к}$ $k_{t.лок,i}$ - filling coefficient of the brake cylinders for the locomotive at the end of the ***i***-th integration step [1, p. 190, table B.11, formula B.16], (column C) $F_{s.лок.к}$ - sum (force) of the locomotive brake pad pressures, kgf (from [1, p. 186, table B.6] for ВЛ 10 at a pressure of 390 kPa - 38,400 kgf · 3 units = 115,200 kgf) (Input data, cell J2) **{= C8*$J$2}**	D
5	$\varphi_{л,i}$ - actual friction coefficient of the locomotive brake pad on the wheel at the beginning of the ***i***-th integration step. (For locomotive ЕЛ 10 with standard cast iron brake pads.) [1, p. 185, table B.4, formula B.14] $\varphi_{л,i} = a_{1,л} \cdot ((a_{2,л} \cdot K_{S.лок,i} : N_{г.к.лок} + a_{3,л}) : (a_{4,д} \cdot K_{S.лок,i} : N_{г.к.лок} + a_{5,л})) \cdot$ $\cdot ((a_{6,л} \cdot V_{n,i} + a_{7,л}) : (a_{8,л} \cdot V_{n,i} + a_{9,л}))$ $K_{S.лок,i}$ - actual (considering the filling coefficient of the brake cylinders $k_{t.лок,i}$) total force ($\sum K$) of the locomotive brake pad pressure at the beginning of the ***i***-th integration step (column D), kgf $N_{г.к.лок}$ - number of locomotive brake shoes (from [1, page.186, table B.6] 38400/2400 · 3 units, i.e., $N_{віс.лок} \cdot N_{о.лок}$; see additional input data); (cell U2). $V_{n,i}$ - speed at the beginning of the ***i***-th integration step (column B), km/h $a_{1,л}$ ... $a_{9,л}$ - empirical coefficients [1, p. 185, table B.4], (Input data, cells L2 ... T2). **{=$L$2*(($M$2*D8/$U$2+$N$2)/($O$2*D8/$U$2+$P$2))*($Q$2*B8+ $R$2)/($S$2*B8+$T$2)}**	E

Continuation of Table 5

1	2	3
6	$k_{t.ваг,i}$ - filling coefficient of the brake cylinders for the wagons at the beginning of the ***i***-th integration step [1, p. 190, table B.11, formula B.16] If $T_{S,i} < t_{г1.в}$ then $k_{t.ваг,i} = a_{ваг} \cdot T_{S,i} + b_{ваг} \cdot T_{S,i}^2 + c_{ваг} \cdot T_{S,i}^3$ Otherwise, $k_{t.ваг,i} = 1$ $t_{г1.в}$ - time to reach full brake pad pressure for the wagons [1, p. 190, table B.11] (input data (constant) in cell I4), sec $a_{ваг}$, $b_{ваг}$, $c_{ваг}$ - coefficients determined empirically (input data (constants) in cells G2, H2, I2). $T_{S,i}$ - time from the beginning of braking at the beginning of the ***i***-th integration step (these are input data), (specified at 1-second intervals, starting from 1 second), (column A), sec **{=IF(A8<$I$4;$G$2*A8*A8*A8+$H$2*A8*A8+$I$2*A8;1)}**	F
7	$K_{S.ваг,i}$ - actual (considering the filling coefficient of the brake cylinders $k_{t.ваг,I}$) total force (∑ ***K***) of the wagon brake pad pressure at the beginning of the ***i***-th integration step, kgf $K_{S.ваг,i} = k_{t.ваг,i} \cdot F_{s.ваг.к}$ $k_{t.ваг,i}$ - filling coefficient of the brake cylinders for the wagons at the beginning of the i-th integration step [1, p. 190, table B.11, formula B.16], (column F) $F_{s.ваг.к}$ - sum (force) of the wagon brake pad pressures, kgf [1, p. 186, table B.6] with multiplication by the number of wagons 21600·7=151200 kgf) (Input data, cell J4), kgf **{=F8*$J$4}**	G
8	$\varphi_{в,i}$ - actual friction coefficient of the wagons (dumpcars) brake pad on the wheel at the beginning of the ***i***-th integration step. For wagons (dumpcars) 2ВС105 with composite brake pads. [1, p. 185, table B.4, formula B.14] $\varphi_{в,i} = a_{1,в} \cdot ((a_{2,в} \cdot K_{S.ваг,i} : N_{г.к.в} + a_{3,в}) : (a_{4,в} \cdot K_{S.ваг,i} : N_{г.к.в} + a_{5,в})) \cdot$ $\cdot ((a_{6,в} \cdot V_{n,i} + a_{7,в}) : (a_{8,в} \cdot V_{n,i} + a_{9,в}))$ $K_{S.лок,i}$ - actual (considering the filling coefficient of the brake cylinders $k_{t.лок,I}$) total force (∑ ***K***) of the locomotive brake pad pressure at the beginning of the ***i***-th integration step (column G), kgf $N_{г.к.лок}$ - number of brake pads for wagons (dumpcars) from [1, p.186, table B.6]. **2ВС105 1 variant (k)** with a pressure of 390 kPa in the brake cylinder. (Number of axles $N_{віс}$=16 - see Addit. input data) (7 dumpcars · 16 axles = 112) $V_{n,i}$ - speed at the beginning of the ***i***-th integration step (column B), km/h $a_{1,в}$ ... $a_{9,в}$ - empirical coefficients [1, p. 185, table B.4], (cells L4 ... T4). *Warning !!! There was an erroneous formula here [1 p. 200]: =$L$4*(($M$4*G8/$U$4+$N$4)/($O$4*G8/<u>**$U$2**</u>+$P$4))*($Q$4* B8+ $R$4)/($S$4*B8+$T$4) but correctly it should be like this:* **{=$L$4*(($M$4*G8/$U$4+$N$4)/($O$4*G8/<u>$U$4</u>+$P$4))*($Q$4* B8+ $R$4)/($S$4*B8+$T$4)}**	H

Continuation of Table 5

1	2	3
9	$F_{S.пнг,i}$ - total braking force from the pneumatic brake at the beginning of the ***i***-th integration step, kgf $F_{S.пнг,i} = K_{S.лок,i} \cdot \varphi_{л,i} + K_{S.ваг,i} \cdot \varphi_{в,i}$ $K_{S.лок,i}$ - actual (considering the filling coefficient of the brake cylinders $k_{t.лок,i}$) total force (∑ ***K***) of the locomotive brake pad pressure at the beginning of the ***i***-th integration step (column D), kgf $\varphi_{л,i}$ - calculated coefficient of wheel adhesion of the locomotive to the rails at the beginning of the ***i***-th integration step. (For the ЕЛ 10 locomotive with standard cast iron brake pads.) [1, p. 185, tab. B.4, formula B.14], (column E) $K_{S.ваг,i}$ - actual (considering the filling coefficient of the brake cylinders $k_{t.ваг,i}$) total force (∑ ***K***) of the wagon brake pad pressure at the beginning of the ***i***-th integration step (column G), kgf $\varphi_{в,i}$ - calculated coefficient of wheel adhesion of the wagons (dumpcars) to the rails at the beginning of the ***i***-th integration step. For wagons (dumpcars) 2ВС105 with composite brake pads. [1, p. 185, table B.4, formula B.14] (column H). **{=D8*E8+G8*H8}**	I
10	$B_{м,i}$ - braking force from the electromagnetic rail brakes at the beginning of the ***i***-th integration step (this braking force reaches its full value 4.6 seconds after the start of braking, so in the time range $T_{S,i}$ from 0 sec to 5 sec, the value of $B_м$ needs to be multiplied by the coefficient $0{,}2 \cdot T_{S,I}$) [1, p. 191, formula B.17], kgf If $T_{S,i} < 5$ then $B_{м,i} = 0{,}2 \cdot T_{S,i} \cdot M_{м.р.г} \cdot 21940 - e^{-0{,}0184 \cdot Vn,i}$ Otherwise, $B_{м,i} = M_{м.р.г} \cdot 21940 \cdot e^{-0{,}0184 \cdot Vn,i}$ $V_{n,i}$ - speed at the beginning of the ***i***-th integration step, km/h $T_{S,i}$ - time from the start of braking at the beginning of the ***i***-th integration step (these are input data), (specified at intervals of 1 sec, starting from 1 sec), ((column A), sec. *Warning !!! There was an erroneous formula here [1 p. 200]:* *= IF(**A29**<5;0,2* **A29***$G$4*21940*EXP(-0,0184***B29**); $G$4*21940*EXP(-0,0184***B29**))* *but correctly it should be like this:* **{=IF(A8<5;0,2*A8*$G$4*21940*EXP(-0,0184*B8);** **$G$4*21940*EXP(-0,0184*B8))}**	J
11	$F_{S,i}$ - total braking force (due to the application of brakes) at the beginning of the ***i***-th integration step, kgf $F_{S,i} = F_{S.пнг,i} + B_{м,i}$ $F_{S.пнг,i}$ - total braking force from the pneumatic brake at the beginning of the ***i***-th integration step (column I), kgf.	K

Continuation of Table 5

1	2	3
11	$B_{м,i}$ - braking force from the electromagnetic rail brakes at the beginning of the ***i***-th integration step, (this braking force reaches its full value 4.6 sec after the start of braking, therefore, in the time range $T_{S,i}$ from 0 sec to 5 sec, the value of $B_м$ must be multiplied by the factor $0.2\cdot T_{S,i}$) [1, p. 191, formula B.17], (column J), kgs **{=I8+J8}**	
12	$w'_{x,i}$ - primary specific resistance of locomotives for idle mode at the begin-ning of the ***i***-th integration step [1, p. 181-182, table B.2, formula B.2], kgf/t $w'_{x,i} = a'_x + b'_x \cdot V_{n,i} + c'_x \cdot V_{n,i}^2$ a'_x, b'_x, c'_x - empirical coefficients [1, p. 182, table B.2], (Input data, cells A4, B4, C4). $V_{n,i}$ - speed at the beginning of the ***i***-th integration step (column B), km/h *Note: Primary specific resistances of movement for industrial locomotives, electric locomotives, and AC traction units on mobile tracks, calculated using formulas B.1 and B.2 [1, p. 181], are assumed to be 30% higher than on fixed tracks. Add and consider* $К_{тип.к}$ *- a coefficient characterizing the track type (if it's a fixed track,* $К_{тип.к} = 1$*; if it's mobile, then* $К_{тип.к} = 1.3$*).* **{=$A$4+$B$4*B8+$C$4*B8*B8}**	L
13	$w''_{o,i}$ - primary specific resistance of wagons for industrial loaded wagons (if the wagons are empty, use $a''_{ox}, b''_{ox}, c''_{ox}$ instead of a''_o, b''_o, c''_o) at the beginning of the ***i***-th integration step [1, p. 183, table B.3, formula B.5], kgf/t $w''_{o,i} = a''_o + b''_o \cdot V_{n,i} + c''_o \cdot V_{n,i}^2$ a''_o, b''_o, c''_o - empirical coefficients [1, p. 183, table B.3], (Input data, cells D4, E4, F4). $V_{n,i}$ - speed at the beginning of the ***i***-th integration step (Column B), km/h. *Note: Primary specific resistances of movement for all types of wagons on mobile tracks, calculated using formulas B.5 and B.6 [1, p.183], are assumed to be 30% higher than on fixed tracks. It is necessary to add and take into account* $К_{тип.к}$ *- coefficient characterizing the type of track (if it's a fixed track,* $К_{тип.к} = 1$*; if it's mobile, then* $К_{тип.к} = 1.3$*).* **{=$D$4+$E$4*B8+$F$4*B8*B8}**	M
14	$w''_{ox,i}$ - primary specific resistance of the train (due to friction between surfaces) determined as the average for the locomotive and wagons at the beginning of the i-th integration step [1, p. 183, formula B.7], kgf/t $w''_{ox,i} = (w'_{x,i} \cdot P + w''_{o,i} \cdot Q) : (P + Q)$ P - mass of the locomotive [1, p. 194, table B.16] For ЕЛ 10. (Input data, cell K2), t	N

Continuation of Table 5

1	2	3
14	***Q*** – mass of the wagons (from table B.16) (Mass of the train (excluding the locomotive), [1, p. 194, table B.16; p. 222, fig. Г.1] (Input data, cell K4), t $w'_{x,i}$ - primary specific resistance of locomotives for idle mode at the beginning of the ***i***-th integration step [1, p. 181-182, table B.2, formula B.2], (column L), kgf/t $w''_{o,i}$ - primary specific resistance of wagons for industrial loaded wagons (if the wagons are empty, use a''_{ox}, b''_{ox}, c''_{ox} instead of a''_{o}, b''_{o}, c''_{o}) at the beginning of the ***i***-th integration step [1, p. 183, table B.3, formula B.5], (column M), kgf/t **{=(L8* $K$2+M8* $K$4)/($K$2+$K$4)}**	
15	r_i – total specific (braking) force acting on the train at the beginning of the ***i***-th integration step, kgf/t $r_i = i_г + w''_{ox,i} + F_{S,i} : (P + M_{c.n})$ *Warning ! This formula is not in [1] the methodology, it is only in table B.21 [1, p. 201], and in table B1 [1, p. 180] it is indicated what the sign **r** means, that is, how **r** is calculated in [1] is not indicated.* $i_г$ - track slope on all ***i***-th integration steps where braking occurs (input data, cell A2), ‰ $w''_{ox,i}$ - primary specific resistance of the train (due to friction between surfaces) determined as the average for the locomotive and wagons at the beginning of the ***i***-th integration step [1, p. 183, formula B.7], (column N), kgf/t $F_{S,i}$ - total braking force (due to the application of brakes) at the beginning of the ***i***-th integration step (column K), kgf ***P*** - mass of the locomotive [1, p. 194, table B.16], (input data, cell K2). For ЕЛ 10, t $M_{c.n}$ - mass of the train (excluding the mass of the locomotive), [1, p. 222, figure Г.1], (input data, cell K4) **{=$A$2+N8+K8/($K$2+$K$4)}**	O
16	ΔV_i - speed reduction during braking at the beginning of the ***i***-th integration step [1, p. 197, formula B. 33], km/h $\Delta V_i = r_i : 30$ r_i - total specific (braking) force acting on the train at the beginning of the ***i***-th integration step (column O), kgf/t **{=O8/30}**	P
17	$V_{c,i}$ - average speed at the ***i***-th integration step, km/h $V_{c,i} = V_{n,i} - \Delta V_i : 2$ $V_{n,i}$ - speed at the beginning of the ***i***-th integration step (column B), km/h	Q

Continuation of Table 5

1	2	3
17	ΔV_i - speed reduction during braking at the beginning of the ***i***-th integration step [1, p. 197, formula B.33] (column P), km/h **{=B8-P8/2}**	
18	$S_{n,i}$ - initial traveled distance at the beginning of the ***i***-th integration step (i.e., the entire distance traveled from the beginning of the first integration step to the beginning of the current ***i***-th integration step), m $S_{n,i} = S_{к,(i-1)}$ $S_{к,(i-1)}$ - final traveled distance on the previous (***i-1***)th step of integration (i.e., the distance traveled from the beginning of the first integration step to the beginning of the previous (***i-1***)th integration step) (column T), m **{=T7}**	R
19	ΔS_i – distance (interval) traveled on the ***i***-th integration step (during the ***i***-th integration step) [1, p. 197, formula B.34], m $\Delta S = V_{c,i} : 3,6$ $V_{c,i}$ - average speed at the ***i***-th integration step (column Q), km/h **{=Q8/3,6}**	S
20	$S_{к,i}$ – final traveled distance at the ***i***-th integration step (i.e., the distance traveled from the beginning of the first integration step to the current ***i***-th integration step), m $S_{к,i} = S_{n,i} + \Delta S_i$ $S_{n,i}$ - initial traveled distance at the beginning of the ***i***-th integration step (i.e., the entire distance traveled from the beginning of the first integration step to the beginning of the current i-th integration step) (column R), m ΔS_i - distance (interval) traveled on the ***i***-th integration step (during the ***i***-th integration step) ([1], p. 197, formula B.34) (column S), m **{=R8+S8}**	T
21	$V_{к,i}$ – speed at the end of the ***i***-th integration step, km/h $V_{к,i} = V_{n,i} - \Delta V_i$ $V_{n,i}$ - speed at the beginning of the ***i***-th integration step (column B), km/h ΔV_i - speed reduction during braking at the beginning of the ***i***-th integration step [1, p. 197, formula B.33] (column P), km/h **{=B8-P8}**	U

For convenience and to maintain the created structure of the MS Excel table, the formula for determining the braking distance ($L_{гальм}$) is proposed to be entered into cell C2, which is located next to cell B2 containing the initial speed value (V_n). Also, it is appropriate to enter the name of the indicator in cell C1, which is located in cell C1. Thus, in cell C1, the text "Result. $L_{гальм}$ - braking distance, m" is entered.

To obtain the value of the braking distance ($L_{гальм}$) in cell C2, initially in MS Excel format, the corresponding formulas are entered into cells Y8, Z8, AA8: "=IF(T8>0,3,-3)", "=IF(Y9<0,IF(Y8>0,11,-5),-5)", "=IF(Z8>0,T8,0)".

Then, copying is performed (for example, using Ctrl+C Ctrl+V) to other integration rows. Afterward, the formula "=SUM(AA8:AA211)" is entered into cell C2. If the last integration step is not 211, then in this formula, instead of 211, the row number in which the last integration step is located is specified (see the "X" column).

Next, use the MS Excel "Goal Seek" function, located in the "Data" tab under the "What-If Analysis" menu. Then, in the "Goal Seek" window, enter the following data: Set cell C2; Value 300; By changing cell B2. After that, click the "Ok" button. As a result, cell B2 will contain the value of V_n (initial braking speed, km/h) for the vertical profile $i_г$ (track gradient on all i-th integration steps where braking occurs, ‰).

In this case, $i_г$ = constant. However, if necessary, it is possible to organize a separate column and, for each integration step, specify the required gradient value for each i-th integration step.

Conclusions.

1. For the first time, a detailed analysis of the braking calculation algorithm for railway transport, presented in the methodology [1, p. 178–203], is provided. The analysis reveals deficiencies and errors in the methodology. It is demonstrated that the example calculations [1, p. 198–203] are incorrect. Recommendations, corrections, and improvements are provided to enhance the braking calculation algorithm for railway transport.

2. Currently, the website ***http://www.kipdiit.dp.ua***, referenced in the Norms of Technological Design for Mining Enterprises with Open Pit Mining [1], is not available. According to these norms, this website contained ready-to-use Microsoft® Office Excel tables with formulas for solving braking and other tasks related to calculating technological indicators for railway transport.

3. For convenience, additional data not covered by the methodology [1, p. 178–203] is suggested to be entered into the MS Excel table. Explanations, also not covered by the methodology [1], are proposed for clarity.

4. Incorrectness is identified in the input data regarding wagon overload in cell K4 of the MS Excel table [1, p, 199].

5. Data is entered into cell X4 of the MS Excel table regarding the maximum weight of all loaded wagons (hopper cars) for comparison with $M_{c.n}$ - the mass of the train (excluding the locomotive), preventing the case of wagon (hopper car) overloading.

6. An error is found in the formula for calculating $\varphi_{в,i}$ - the coefficient of wheel adhesion for wagons (hopper cars) with rails at the beginning of the i-th integration step, to be entered into cell H8 of the MS Excel table [1, p. 200].

7. An error is found in the formula for calculating $B_{м,i}$ (braking force from electromagnetic rail brakes at the beginning of the i-th integration step) to be entered into cell J8 of the MS Excel table [1, p. 200].

8. It is suggested to consider $K_{тип.к}$ (coefficient characterizing the type of track; if fixed track, then $K_{тип.к}$ = 1, if movable, then $K_{тип.к}$ = 1.3).

9. Automation is proposed for finding the value of $\boldsymbol{V_n}$ (initial braking speed, km/h) for the vertical profile $\boldsymbol{i_{г,i}}$ (gradient on the ***i***-th integration step where braking occurs, ‰) at the value of the braking path $\boldsymbol{L_{гальм}}$.

10. To automate the search and input of relevant input data into MS Excel cells, taken from reference tables provided in the methodology [1, p. 178-203], it is suggested to use the VLOOKUP function and HLOOKUP function.

References

1. Ministry of Industrial Policy of Ukraine. (2008). *Normy tekhnolohichnoho proektuvannia hirnycho-dobuvnykh pidpryiemstv iz vidkrytym sposobom rozrobky rodovyshch korysnykh kopalin. [Norms of technological design for mining enterprises with open-pit mining of mineral deposits. Part 2. Open pit mining. Volume 1]. SOU-N MPP 73.020-078-2:2008.*
2. Rengevych, A.A. (1976). *Raschet kariernoho elektrovoznoho transporta [Calculation of quarry electric transport].* Dnipropetrovsk: DHI.
3. Akimov, V.I. (1988). *Sbornik zadach po tyahovym raschetam [Collection of problems on traction calculations].* Homel: BelIIZhT.
4. Rengevych, O.O., & Denyshchenko, O.V. (2005). *Ekspuatatsiini rozrakhunky transportnykh kompleksiv krierv [Operational calculations of quarry transport complexes].* Dnipropetrovsk: National Mining University.
5. Frenkel, S. Ya. (2009). *Tekhnika tyahovykh rozrakhunkiv [Technique of traction calculations].* Homel: BelHUT.
6. Daleka, V. Kh., Pushkov, P. M., Andriichenko, V. P., & Mineieva, Yu. V. (2012). *Osnovy elektrychnoi tyahy [Basics of electric traction].* Kharkiv: Kharkiv National Academy of Municipal Economy.
7. Sakharov, P. A., & Frenkel, S. Ya. (2016). *Tyahovi rozrakhunky dlia uchastka zheleznoi dorohy [Traction calculations for railway section].* Homel: BelGUT.
8. Horobchenko, O. M. (2020). *Transportni systemy i tekhnolohii [Transport systems and technologies].* Kyiv: State University of Infrastructure and Technologies.

АНОТАЦІЯ

Мета. На основі діючих Норм технологічного проєктування гірничодобувних підприємств із відкритим способом розробки родовищ корисних копалин, надати удосконалену методику для ефективного рішення гальмівної задачі промислового кар'єрного залізничного транспорту за допомогою табличного процесора MS Excel; що відкриває перспективи для подальшого вивчення, проєктування та аналізу досліджень руху промислового кар'єрного залізничного транспорту.

Методика. Методика рішення гальмівної задачі промислового кар'єрного залізничного транспорту викладена у додатку В Норм технологічного проєктування гірничодобувних підприємств із відкритим способом розробки родовищ корисних копалин. Автори цієї статті виконали детальне пояснення та докладний аналіз цієї методики.

Результати. В результаті виконаного аналізу виправлені помилки та запропонована скорегована удосконалена методика ефективного рішення гальмівної задачі промислового кар'єрного залізничного транспорту за допомогою табличного процесора MS Excel, у тому числі: запропоновано враховувати $K_{тип.к}$ (коефіцієнт, що характеризує тип колії; якщо постійна колія, то $K_{тип.к} = 1$, якщо пересувна, то $K_{тип.к} = 1{,}3$), також запропоновано автоматизувати пошук значення V_n (початкова швидкість гальмування, км/год) для вертикального профілю $i_{г,i}$ (ухил на *i*-му кроці інтегрування, на якому відбувається гальмування, ‰) при значенні гальмівного шляху $L_{гальм}$.

Наукова новизна. Вперше виконано докладний аналіз алгоритму розрахунку гальмівної задачі для залізничного транспорту, що викладено у методиці діючих Норм технологічного проєктування гірничодобувних підприємств із відкритим способом розробки родовищ корисних копалин. Надано рекомендації, корегування та виправлення, щодо поліпшення алгоритму розрахунку гальмівної задачі для залізничного транспорту. Вперше, з виправленням недоліків та помилок методики, запропонована удосконалена Методика рішення гальмівної задачі кар'єрного залізничного транспорту за допомогою табличного процесора MS Excel, що враховує тип колії, автоматизований пошук значення початкової швидкості гальмування.

Практична значимість. Викладену у статті методику можна застосовувати у якості інструмента при проєктуванні та при виконанні досліджень для ефективного рішення гальмівної задачі промислового кар'єрного залізничного транспорту за допомогою табличного процесора MS Excel.

Ключові слова: *рішення гальмівної задачі промислового кар'єрного залізничного транспорту MS Excel.*