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ANALYSIS AND IMPROVEMENT OF THE METHODOLOGY FOR TRACTIVE CALCULATIONS OF OPEN-PIT RAIL TRANSPORT

Purpose. Based on the existing Norms of Technological Design for Mining Enterprises with Open-Pit Mining of Mineral Deposits, an improved methodology is proposed for efficient traction calculations of industrial open-pit railway transport using MS Excel; this opens up opportunities for further research, design, and analysis of industrial open-pit railway transport movement.

Research methods. Thanks to the inclusion in Appendix B to the Norms of Technological Design for Mining Enterprises with Open-Pit Mining of Mineral Deposits, the reader can find a methodology for conducting traction calculations for industrial open-pit railway transport. In this article, the authors focused on the methodology, providing detailed explanations and conducting a thorough analysis of its key aspects. The inclusion of this material opens up new opportunities for understanding and improving traction calculation processes in the field of industrial open-pit railway transport, as well as laying the groundwork for further research and development in this area.

Scientific novelty. For the first time, a deep analysis of the traction calculation algorithm for industrial open-pit railway transport, described in the methodology of the current Norms of Technological Design for Mining Enterprises with Open-Pit Mining of Mineral Deposits, has been conducted. After careful analysis, flaws and inaccuracies in the mentioned methodolo-

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gy were identified. It was determined that the calculation example provided in the methodology of the current Norms of Technological Design was executed incorrectly. In light of this, recommendations, adjustments, and corrections have been provided in this study to improve the traction calculation algorithm for industrial open-pit railway transport.

Practical implementation. The methodology discussed in the article can be utilized as a powerful tool in the process of designing and conducting research for performing efficient traction calculations in the field of industrial open-pit railway transport using the MS Excel spreadsheet software. This provides a practical and effective approach to achieving accurate and reliable results in carrying out the specified tasks.

Results. Following the analysis, a detailed explanation of the traction calculation algorithm was provided, errors were identified and corrected, and adjustments were made to the methodology for conducting efficient traction calculations for industrial open-pit railway transport using the MS Excel spreadsheet software.

Keywords: methodology, traction calculations, industrial open-pit railway transport, MS Excel.

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Problem and its connection to scientific and practical tasks. In the present day, an integrated approach is used in the Krivoy Rog iron ore basin for transporting ore, which includes a combination of road-rail and conveyor transport. This article pays special attention to the examination of the current use of railway transport in conditions that have arisen as a result of the long-term evolutionary development of mining operations in quarries and dumps. The key aspects of traction calculations for industrial open-pit railway transport are identified and analyzed.

The problem arising in the context of using railway transport in the mining sector lies in the need to optimize traction calculations and develop effective approaches to the planning and operation of transportation infrastructure.

The practical significance of this problem lies in improving the efficiency of transportation processes and reducing the costs associated with their implementation, which can lead to increased productivity and competitiveness of mining enterprises. The analysis and improvement of traction calculation methodology are key elements in optimizing the operation of industrial open-pit railway transport.

Research and Publication Analysis. The main reference point for conducting efficiency calculations of railway transport is the Norms of Technological Design for Mining Enterprises with Open-Pit Mining of Mineral Deposits [1]. This key document sets standards and methodologies for calculations necessary in the mining transport sector. It serves as a foundational guide that defines requirements and norms in the field of technological design, taking into account the specifics of open-pit mining of mineral deposits. These norms provide an important basis for determining optimal parameters and approaches in the planning and operation of railway transport in the mining sector.

It is important to note that 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 currently unavailable. According to these norms, the mentioned website hosts ready-made Microsoft® Office Excel tables with embedded formulas for solving various tasks related to traction calculations and other technological performance calculations for railway transport. Simultaneously, the specified norms [1, pages 204-220] contain a detailed description of the structure of these Microsoft® Office Excel electronic tables.

It should be mentioned that traction calculations for industrial open-pit railway transport have been addressed previously [2-11], but the most detailed methodology for traction calculations of industrial open-pit railway transport is provided in Appendix B of the Norms of Technological Design for Mining Enterprises with Open-Pit Mining of Mineral Deposits [1, pages 204-220].

The article makes a significant contribution to the development of the contemporary understanding of this issue by addressing certain aspects and proposing new approaches.

Problem Statement. Based on the existing Norms of Technological Design for Mining Enterprises with Open-Pit Mining of Mineral Deposits [1], the authors of the article propose an improved methodology for efficient traction calculations of industrial open-pit railway transport using MS Excel. This opens up opportunities for further research, design, and analysis of industrial open-pit railway transport movement.

Teaching Material and Results. We will conduct a detailed analysis, correction, and improvement of the methodology for traction calculations of industrial open-pit railway transport provided in Appendix B of the Norms of Technological Design for Mining Enterprises with Open-Pit Mining of Mineral Deposits [1, pages 204-220].

For calculations, we will adopt the same input data as in [1, pages 206-209].

The methodology outlined in [1, pages 204-220] does not include traction calculations in MS Excel for different types of tracks (fixed and movable), meaning that calculations are only possible when the entire track is either fixed or movable. This is a drawback of the methodology.

To conduct traction calculations using MS Excel, [1] provides an example calculation based on the proposed Methodology B. In the example, traction units ОПЭ2 with cast iron brake blocks and 12 dumpcars 2BC-105 - variant 3 with composite brake blocks are used for transporting mined mass (loaded wagons) by railway transport on a fixed track without the use of magnetic rail brakes [1; page 206, table 24; page 213].

Traction calculations using MS Excel in the methodology [1, pages 204-220] are proposed to be performed according to the algorithm. A detailed explanation of this algorithm is absent in the methodology and is provided in this article. It should also be noted that this article addresses only the data that require commentary and the data regarding which errors and inaccuracies have been made.

The algorithm involves conducting traction calculations by determining the train motion parameters through stepwise integration. Each ***i***-th integration step represents an interval of track of a specified length dS_i. In the example, the first and second steps are 5 meters, the third step is 10 meters, and the fourth and fifth steps are 15 meters, with subsequent steps having an interval of 50 meters. (In section B.10.10 of the methodology [1, page 206], it is indicated that the integration interval dS_i should not be less than 50 meters. The authors of this article consider this statement to be incorrect; on the contrary, the integration interval dS_i should be no more than 50 meters.) The parameters for each i -th integration step are calculated in MS Excel rows. The parameters for the zeroth step are located in the 16th row of the MS Excel table; the parameters for the first step are in the 17th row, for the second step in the 18th row, and so on. Thus, the i-th step is located in the MS Excel table in the row with the number ($i+16$), where the value of i is not less than zero. In our opinion, considering the modern capabilities of computers and to increase the accuracy of calculations, it is advisable to set the track length dS_i equal to 1 meter for each ***i***-th integration step.

It should also be noted that all formulas from the 17th row are then copied to the lower rows using the usual method (for example, by using the Ctrl+C and Ctrl+V commands). The number of integration steps is determined by the total length of the track section for which the train motion traction calculation is performed.

Initially, the corresponding input data is entered into the respective cells. In row 2 of the MS Excel table, the data specified by the methodology [1, pages 206-207], as presented in Table 1, is entered.

Table 1

Input data (values) entered into the 2nd row of the MS Excel table, as specified by the methodology [1, pages 206-207]

Indicator Name	Value	Cell for entry
P - locomotive (ОПЭ2) mass, t [1, page 194, table B.16] *Attention, in [1, page 206, table B.24] mistakenly refers to table B.12, not B.16 !*	368	B2
Q - mass of wagons, t [1; page 213; page 194, table B.16] *Attention !!! In the given example,* *$M_{c.n}$ = 2470t. 2470t:12 units = 205.83t/wagon* *From [1, page 222, figure Г.1]: wagon tare weight = 47t.;* *205.83t - 47t = 158.83t.* *Thus, the wagons are overloaded. Each wagon carries not 105t, but 158.83t.* To avoid such situations, the authors of this article propose entering the value of the maximum permissible weight of wagons Q_{max} into cell AN2. (See table 2)	2470	C2
V_n - initial velocity on the section, km/h	0	D2
a'_0 - the 1st empirical coefficient of approximation to determine w'0 - the basic specific resistance of locomotives depending on the speed for the traction mode. For the ОПЭ2 locomotive (Industrial electric locomotive and traction unit with alternating current) [1, p. 181-182, table B.2, formula B.1] *Attention !!! In [1, p. 206, table B.24], reference is made incorrectly to table B.20 instead of table B.2.*	2,6	E2
b'_0 - the 2nd empirical coefficient ...	0,07	F2
c'_0 - the 3rd empirical coefficient ...	0,0025	G2
a''_0 - the 1st empirical coefficient of approximation to determine w''_0 - the main specific resistance to motion of loaded cars (dumpcars) depending on the speed V. For cars (dumpcars) 2BC105. [1, p. 183, table B.3, formula B.5]. *Attention, there is a typographical error in table B.3 [1, p. 183]: it indicates BC105 instead of 2BC105.*	3,6	H2

Continuation of Table 1

b''_0 - the 2nd empirical coefficient... *Attention, in [1, p. 206, table B.24] this row is missing (omitted)!!!*	0,04	I2
c''_0 - the 3rd empirical coefficient ...	0,0	J2
a_ψ - the 1st empirical coefficient for determining $\Psi_{л,i}$ (the calculated coefficient of wheel-rail adhesion at the beginning of the i-th integration step). (For the locomotive ОПЭ2 - industrial electric locomotives with alternating current on permanent tracks) [1, p. 191-192, table B.13, formula B.18]	0,21	K2
b_ψ - the 2nd empirical coefficient ...	7	L2
c_ψ - the 3rd empirical coefficient ...	53	M2
d_ψ - the 4th empirical coefficient …	3	N2
e_ψ - the 5th empirical coefficient ...	0	O2
h_ψ - the 1st empirical coefficient for determining $\Psi_{R,i}$ - the calculated coefficient of wheel-rail adhesion on curved track sections with a radius R_i < 500 m, at the beginning of the i-th integration step. (For the locomotive ОПЭ2 - industrial electric locomotives with alternating current on fixed tracks) [1, p. 192, table B.14, formula B.19]	250	P2
m_ψ - the 2nd empirical coefficient ...	1,55	Q2
n_ψ - the 3rd empirical coefficient ...	500	R2
z_ψ - the 4th empirical coefficient …	1,1	S2
$R_г$ - the limiting value of the radius R, beyond which the reduction of the coefficient of adhesion is no longer considered, m [1; p. 192, table B.14; p. 207, table B.24]	500	T2

In this and subsequent tables, we provide detailed explanations of the algorithm, which is missing in [1, pp. 204-220].

Furthermore, for convenience, in row 2 of the MS Excel table, data not provided by the methodology [1, pp. 204-220] are suggested to be entered (Table 2). For clarity, in cell W1, the text "Additional input data not provided by the methodology [1, pp. 204-220]:" is entered.

Table 2

Input data (values) to be entered in the 2nd row of the MS Excel table, which are not specified in the methodology [1, pp. 178-203]

Indicator Name	Value	Cell for entry
Additional input data:		*W2*
$Т_л$ - locomotive type [1; p. 206, table B.24; p. 213]	ОПЭ2	*X2*
$Т_{ж.л}$ - locomotive power supply type [1, p. 194, table B.16 and p. 217, table B.27]	AC (Alternating Cur-rent)	*Y2*
$N_{о.лок}$ - number of units (sections) composing the locomotive (traction unit and two motorized dumpcars) [1; p. 213; p. 217, table B.27], units	3	*Z2*
$N_{віс.лок}$ - number of axles in one section (3 sections) of the ОПЭ2 locomotive (from [1, p. 186, table B.6]; 68800:4300:4 = 4), units	4	*AA2*
$N_{лок.к.заг}$ - total number of brake pads in one section of the locomotive (ОПЭ2) [1, p. 186, table B.6]	16	*AB2*
$\boldsymbol{T}_{г.л}$ - type of locomotive brake pads	Cast iron	*AC2*
$M_{з.в}$ - wagon loading indicator. If the wagons are empty then $M_{з.в}$ = 1. If the wagons are loaded $M_{з.в}$ = 2.	2	*AD2*
$T_{ваг}$ - type of wagons (dumpcars). [1, p. 186, table B.6]	2ВС105 3rd variant (к)	*AE2*
$T_{г.в}$ - type of wagon (dumpcar) brake pads.	Composite	AF2
$N_{ваг}$ - number of wagons (dumpcars), units [1; p. 213]	12	AG2
$N_{віс.ваг}$ - total number of axles in one wagon (dumpcar) [1, p. 186, table B.6], [9]	6	AH2
$N_{віс.ваг.кр}$ - number of axles on the end of one wagon (dumpcar) [1, p. 186, table B.6], [9]	4	AI2
$N_{віс.ваг.с}$ - number of axles in the middle of one wagon (dumpcar) [1, p. 186, table B.6], [9]	6	AJ2
$N_{в.к.заг}$ - total number of brake pads in one wagon (dumpcar) [1, p. 186, table B.6], [9]	16	AK2
$N_{в.к.кр}$ - number of brake pads for the end axles of one wagon (dumpcar) [1, p. 186, table B.6], [9]	8	AL2
$N_{в.к.с}$ - number of brake pads for the middle axles of one wagon (dumpcar) [1, p. 186, table B.6], [9]	8	AM2
Q_{max} - maximum weight of wagons, t [1; p. 213; p. 194, table B.16] Dumpcars 2ВС105 - variant (k) (47 t + 105 t) · 12 wagons = 1824 t	1824	*AN2*

Additional input data (Table 2), not covered by the methodology [1, pages 204-220], is recommended to be entered into the MS Excel spreadsheet for both calculations and for monitoring and automatic retrieval of corresponding input data from reference tables, using the VLOOKUP function and the HLOOKUP function.

The authors of this article propose the following: Following the path taken, in column AN, starting from cell AN17, enter the value of $K_{тип.к}$ - the coefficient characterizing the type of track (if it is a fixed track, then $K_{тип.к} = 1$, if it is a movable track, then $K_{тип.к} = 1.3$).

In row 5 of the MS Excel table, data specified in the methodology [1, pages 207-208].

In row 4 of the MS Excel table, the corresponding indicator names are entered (not provided in [1, pp. 204-220]) for clarity, which are listed in row 5. Additionally, for clarity, more detailed explanations can be included in the notes.

In row 8 of the MS Excel table, the data provided by the methodology [1, p. 208].

In row 7 of the MS Excel table, the corresponding names of indicators (for clarity) are entered, which are entered in row 8. Additionally, for clarity, more detailed information can be provided in the notes.

The following values of speeds $V_{т.д,j}$, are entered into cells C10 … Q10, taken from [1, pp. 217-220, Table B.27]: 0; 5; 10; 15; 20; 25; 30; 35; 40; 45; 50; 60; 70; 80; 90.

The corresponding values of traction force $F_{т.д,j}$ (kgf) from the locomotive's traction characteristics are entered into cells C11 … Q11: 126600; 126600; 126600; 126600; 126600; 99000; 63000; 40500; 27900; 20400; 15900; 10500; 7800; 0; 0.

Values within the range of traction force limitation can be set equal to $F_{зр}$ (total traction force of the locomotive during starting from rest, kgf [1, pp. 180-181, Table B.1; pp. 196, Table B.17]), as they will be calculated during the calculation process.

It should be noted that in the example provided in [1, p. 209, Table B.24], $F_{зр}$ is given as 126600 kgf, but $F_{зр}$ (total traction force of the locomotive during starting from rest, kgf [1, p. 196, Table B.17]) is stated as $F_{зр} = 120000$ kgf. The authors consider the correct value to be given in [1, p. 209, Table B.24], and there is a typographical error in [1, p. 209, Table B.24], and the correct value should be indicated as 120000, not 126600. However, to ensure that the calculation results correspond to those presented in the table shown in [1, p. 215, Fig. B.1], incorrect data should be entered into cells C11 … Q11, namely: 126600; 126600; 126600; 126600; 126600; 99000; 63000; 40500; 27900; 20400; 15900; 10500; 7800; 0; 0.

Additionally, it should be noted that the traction force of the locomotive on sections limited by coupling $F_{д.зч}$ is determined based on the formulas [1, p. 192, Formulas B.20 and B.21]:

for straight track sections

$$F_{д.зч,i} = 1000 \cdot P \cdot \Psi_{л,i}$$

where P - locomotive mass (OE2), t; [1, p. 194, Table B.16], (input data, cell B2); $\Psi_{л,i}$ - calculated coefficient of wheel-rail adhesion at the beginning of the ***i***-th integration step. (For locomotive OE2 – industrial AC electric locomotives on standard gauge tracks) [1, pp. 191-192, Table B.13, Formula B.18]

$$\Psi_{л,i} = a_\psi + (b_\psi : (c_\psi + d_\psi \cdot V_i) - e_\psi \cdot V_i)),$$

where a_ψ , b_ψ , c_ψ , d_ψ , e_ψ - empirical approximation coefficients (for locomotive OE2 – industrial AC electric locomotives on standard gauge tracks) [1, pp. 191-192, Table B.13, Formula B.18] (Table 1, cells K2 … O2); V_i - train speed at the beginning of the ***i***-th integration step, km/h;

for curved track sections

$$F_{д.зч/i} = 1000 \cdot P \cdot \Psi_{R,i}$$

$\Psi_{R,i}$ - during locomotive movement on the calculated and steepest grades under electric traction on curved track sections with a radius less than 500 m, and under diesel traction - less than 800 m, the adhesion coefficient Ψ_i is reduced to the value $\Psi_{R,i}$, which is determined by the formula

$$\Psi_{R,i} = \Psi_i \cdot (h_\psi + m_\psi \cdot R_i) : (n_\psi + z_\psi \cdot R_i)$$

where h_ψ , m_ψ , n_ψ , z_ψ - empirical approximation coefficients (for locomotive ОПЭ2 – industrial AC electric locomotives on standard gauge tracks) [1, pp. 191-192, Table B.13, Formula B.18] (see Table 1, cells P2 … S2); R_i – radius of curvature at the beginning of the i-th integration step, m.

Data provided in Table 7 as specified in [1, p. 209] are entered into cells S10 … X10 of the MS Excel table.

The direct traction calculation starts from the 17th row. In the 16th row, initial values of "0" are set for cells C16, T16, U16, AG16, AJ16. The formula "=D2" is entered into cell Q16, and the initial design mark in meters is entered into cell AN16. The integration step is set in column B, starting from cell B17 and onwards. Since the speed changes rapidly during the train's acceleration, according to the methodology [1, p. 209], it is recommended to set the integration step at the beginning to 5, 5, 10, 15, 15 (in meters), and then - 50 m. In the authors' opinion, it is recommended to set the integration step for the first 100 m to 1 m, and then to 2 m, which improves the calculation quality. The formula "=C16+B17" is entered into cell C17 to calculate the traveled distance and then copied down the column C, starting from row 18.

If the length of any profile element is not a multiple of 50 m, then the integration step is recorded in the corresponding cell to be less than 50 m. In columns B and C, the number of rows to be filled is determined by the length of the section. At the end of the section, the integration step value should be "0". In column A, starting from cell A17, the values of the radius "1000" are recorded, which does not reduce the traction. Then, the values of curve radii in meters are recorded in the respective cells of the column according to the section plan. Starting from the 17th row, the straightened longitudinal profile gradients in thousandths are recorded in column D. Negative values are specified for descents. In the 17th row, formulas for calculating auxiliary coefficients (conditional constants) are entered in column E and onwards according to Table [1; pp. 209-212, table B.25].

Conclusions and Future Research Directions. A detailed analysis of the implementation algorithm of traction calculations for industrial quarry railway transport, as outlined in [1, pages 204-220], has been provided for the first time. The analysis revealed deficiencies and errors inherent in the methodology. It has been demonstrated that the sample calculations presented in [1, pages 206-216] were performed incorrectly. Recommendations, corrections, and improvements have been suggested to enhance the algorithm for executing traction calculations for railway transport.

Currently, the website http://www.kipdiit.dp.ua, referenced in the Standards for Technological Design of Mining Enterprises with Open Pit Mining of Mineral Deposits [1], is unavailable. According to these standards, this website hosted ready-made Microsoft® Office Excel tables with formulas for performing traction calculations for railway transport.

The algorithm for calculating specific resistance to train movement has been enhanced to enable traction calculations that account for the type of track (fixed, movable) on track sections.

For convenience, data not provided in the methodology of traction calculations [1, pages 204-220] have been proposed to be included in Table MS Excel (Table 2). Explanations not covered in the methodology [1] have also been suggested for clarity.

Incorrectness of the initial data regarding excessive loading of wagons in cell C2 of the MS Excel table [1, page 206] has been identified.

Data on Q_{max}, regarding the maximum weight of all loaded wagons (dumpcars), have been entered into cell AI2 of the MS Excel table for comparison with Q, the weight of the train composition (excluding the locomotive), thus preventing excessive loading of wagons (dumpcars).

The absence of a row in [1, page 206, Table V.24] for entering data into cell I2 has been noted.

An error in the initial data has been detected. In [1, page 208, Table B.24], incorrect data were mistakenly entered ($a_{8,в}$ = 3.18), whereas according to [1, page 185, Table B.4], $\boldsymbol{a}_{8,в}$ = 1.406.

To automate the search and entry of corresponding initial data into cells of the MS Excel table, sourced from reference tables provided in the methodology [1, pages 204-220], the use of the VLOOKUP (Vertical Lookup) and HLOOKUP (Horizontal Lookup) functions has been proposed.

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