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Forecasting the Residual Life of Wheelsets of 81-740/741 «Rusich» Cars of the Metro Electric Trains

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ABSTRACT

A modern approach to determining the useful life of components and parts of rolling stock allows not only to estimate the pre-failure state of an object, but also to predict its useful life.

The objective of the study is to predict the mileage of wheelsets of modern electric trains of the «Rusich» series based on the use of statistical data and assessment of the residual life.

The study used real data recorded during maintenance and repair of electric trains.

The proposed approach allows getting a vivid presentation of the equipment wear rate, since it is based on the use of the measured parameters of the object. The analysis of these values makes it possible to determine the processes occurring in the product. When using large samples, it becomes possible to approximate the obtained numerical values and make a forecast of the technical condition with greater reliability.

The task of predicting the residual life is quite complicated and must be solved separately for each type of equipment. That is why the generally accepted world practices are associated with preventive maintenance and repair system, while modern automated digital systems for technical diagnostics (including on-board and built-in ones) make it possible to partially switch to technical maintenance and repair considering the actual technical condition of the rolling stock.

Keywords: *metro, residual life, metro cars, wheelsets, rolling stock, forecasting, diagnostics, equipment reliability, traffic safety.*

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INTRODUCTION

The duration of useful life of parts is determined at the design stage and indicated in the specifications for the product. For example, for wheelsets of metro electric trains of «Rusich» series, a service life of 31 years is set for their individual elements, subject to respect of the stipulated schedule of technical maintenance and repair (TMR). One of the tasks of technical diagnostic systems is to predict the technical condition of an object, namely, to determine the residual life of the equipment (the remaining time of its run or operation to the limit state)[1]. According to GOST «Reliability in equipment»[2], residual life is the total operating time of the object from the moment of monitoring its technical condition to the moment when it reaches the limit state. The pre-failure state criterion is a sign or a set of signs of the pre-failure state of an object. As a rule, this is falling of one or more parameters outside the tolerance limits. The latter greatly simplifies the solution of the problem of predicting the residual life through approximation of the trend of diagnostic data, which involves selection of a mathematical function for statistical data to calculate the residual life.

The dependence of the change in the parameters of the object being diagnosed on time (mileage) depends on the physical characteristics of the object and can have either linear, or other types of regularities: parabolic, hyperbolic, exponential, and many others [1]. The wear of the wheel flange and tread occurs evenly with a change in mileage, and the values of these parameters will have a linear relationship with a change in mileage. In case of parabolic, hyperbolic, exponential, and other dependences, the solution of the approximation problem is quite difficult. Therefore, in practice, a linear approximation of the function y (in our case, the diameter and thickness of the wheel flange) of the diagnostic argument x ($y = k \bullet x + b$) is usually used, for which, within small observation ranges, the application of least squares method is widespread. This method is based on minimising the sum of squared deviations of the desired function from statistical data [2]. The value of the sought-for function is equal to the sum of the squared deviations of the observed values from the theoretical ones.

To find the function, it is necessary to identify the type of the expected dependence (most often, a linear regression of the form $y = k \bullet x + b$ is used) and solve the system of equations to find the parameters k and b.

While calculating the lifetime of electric train wheelsets, two concepts of useful life can be applied: those based respectively on destruction or on exhaustion of the controlled parameter [3]. In this study, due to the small number of failures of wheelsets associated with destruction of their elements, as well as to determine their useful life, we will use the method of determining the useful life based on the exhaustion of the controlled parameter. Regarding electric trains, the required range for the calculated residual life is based on the soonest coming scheduled TMR, so-called technical maintenance-3, or technical repair-1, executed in metro car depot. With an average daily run of 700 km and a basic overhaul run of 30000 km, this makes 2 months. For such relatively short periods, the least squares method is suitable.

The *objective* of the work is to assess the technical condition of the wheelsets of electric trains of the Moscow Metro based on statistical data. To solve the problem, the least squares method was used followed by further analysis of the results obtained [4, pp. 203–216].

This method makes it possible to obtain the most accurate description of the state of the equipment in the absence of exact values of the parameters of individual parts of the considered assembly [2].

RESULTS

Initial Data

To analyse the process of wheel wear, the values of the diameters and thicknesses of the wheel flange, obtained at fixed operating times, were retrieved from the «Charts of accounting for the condition of wheelsets» for the head cars of model 81–740 and intermediate cars of model 81–741.

We will summarise the numerical values of the diameters of the wheelsets in Table 1, and the thickness of the flange of the wheelsets in Table 2.

Tables 1 and 2 show the numerical values of the wheel flange diameter and thickness of the 81-740/741 cars, which were measured both

[1] GOST [state standard] 20911-89 Technical diagnostics. Terms and definitions. [Electronic resource]: https://docs.cntd.ru/document/1200009481. Last accessed 21.02.2022.

[2] GOST [state standard] 27.002-2015 Reliability in equipment. Terms and definitions. [Electronic resource]: https://docs.cntd.ru/document/1200136419. Last accessed 21.02.2022.

Table 1

The values of diameters of the wheelsets of car No. 0883 of the «Rusich» series [compiled by the authors]

Diameter		Initial mileage	TM-3	TM-3	TM-3	TM-3	TM-4	…	TR-2	TR-2	TM-3	TR-1	TM-3	TR-1
Mileage before next maintenance/repair, km		0	295	3090	22358	28152	11319	…	12333	17799	13630	25251	16051	9930
Operating life [total mileage], km		0	295	3385	25744	53897	65216	…	212870	230670	244300	269551	285603	295534
1	1	861	861	861	861	861	861	…	860,9	860,8	860,7	860,7	860,5	860,5
	2	861	861	861	861	861	861	…	860,9	860,8	860,7	860,6	860,5	860,5
2	1	860,5	860,5	860,5	860,5	860,5	860,5	…	860,4	860,3	860,2	860,2	860,2	860,2
	2	860,5	860,5	860,5	860,5	860,5	860,5	…	860,5	860,4	860,3	860,3	860,3	860,3
3	1	861	861	861	861	861	861	…	860,4	860,3	860,2	860,2	860,2	860,1
	2	861	861	861	861	861	861	…	860,8	860,8	860,7	860,7	860,7	860,7
4	1	861	861	861	861	861	861	…	860,5	860,5	860,4	860,3	860,3	860,2
	2	861	861	861	861	861	861	…	860,6	860,5	860,5	860,4	860,4	860,2
5	1	860,5	860,5	860,5	860,5	860,5	860,5	…	860	859,9	859,8	859,7	859,7	859,6
	2	860,5	860,5	860,5	860,5	860,5	860,5	…	859,9	859,8	859,7	859,7	859,7	859,6
6	1	861	861	861	861	861	861	…	860,4	860,3	860,2	860,1	860	859,9
	2	861	861	861	861	861	861	…	860,5	860,4	860,3	860,2	860,2	860,1

Table 2

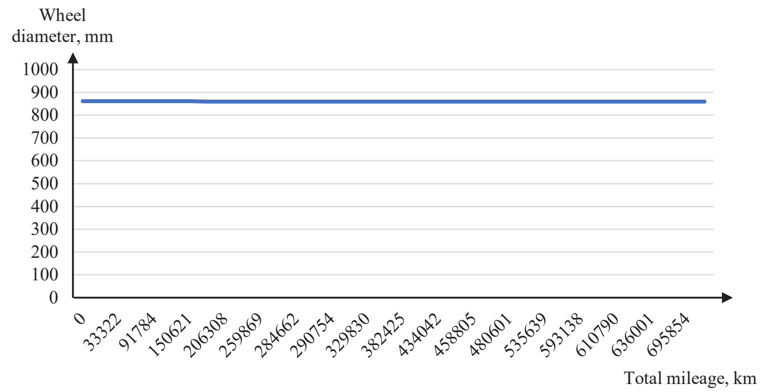
The values of flange thickness of the wheelsets of car No. 0291 of the «Rusich» series [compiled by the authors]

Flange thickness		Initial mileage	TM-3	TM-3	TM-3	TR-1	TM-3		TM-3	…	TM-3
Mileage before next maintenance/repair, km		0	0	8665	24656	28807	29655		26763	…	27028
Operating life [total mileage], km		0	0	8665	33321	62129,1	91784		259868	…	722882
1	1	33	33	33	33	33	33		32,8	…	30,5
	2	33	33	33	33	33	33		32,8	…	31
2	1	32	32	32	32	32	32		32	…	29
	2	32,5	32,5	32,5	32,5	32,5	32,5		32,3	…	29,5
3	1	32,5	32,5	32,5	32,5	32,5	32,5		32,5	…	31
	2	32,5	32,5	32,5	32,5	32,5	32,5		32,5	…	31
4	1	32	32	32	32	32	32		32	…	30,5
	2	32	32	32	32	32	32		31,8	…	31
5	1	32,5	32,5	32,5	32,5	32,5	32,5		32,4	…	29,5
	2	32,5	32,5	32,5	32,5	32,5	32,5		32,3	…	30
6	1	32,5	32,5	32,5	32,5	32,5	32,5		32,4	…	26,8
	2	32	32	32	32	32	32		31,8	…	28,5

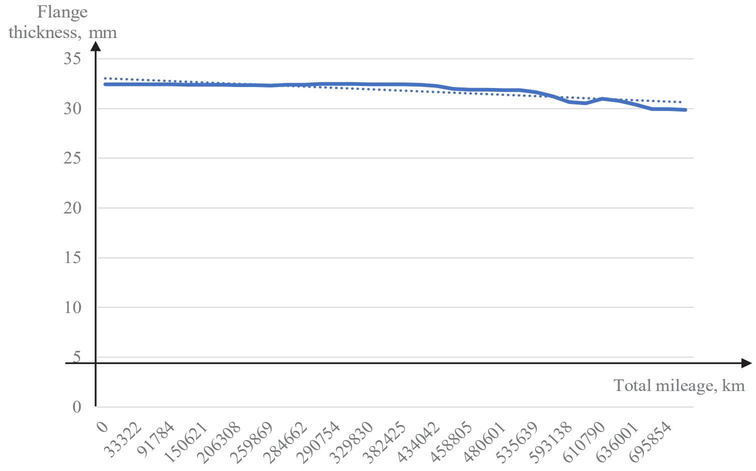
Table 3

Examples of approximation of the wear of the tread of wheelsets for car No. 0293 [compiled by the authors]

No.	Mileage before turning l_n	Mathematical expectation of diameters of wheelsets of the car	Product of mileage and diameter $l_n \cdot d_n$	Square of mileage l_n^2
1	0	860,92	0	0
2	117 554	860,85	101 196 360	13818942916
3	143 351	860,83	123 400 841	20549509201
4	175 644	860,67	151 171 521	30850814736
5	202 728	860,56	174 459 607	41098641984
6	228 222	860,36	196 353 079	52085281284
7	240 874	860,17	207 192 588	58020283876
8	246 054	860,07	211 623 663	60542570916
9	265 552	859,97	228 366 753	70517864704
10	292 689	859,89	251 680 344	85666850721
11	322 539	859,81	277 322 257	104031406521
Σ	2 235 207	9 464,10	1 922 767 018	537182166859
Trend	k = -0,000004147	b = 860,92		
1	350 000	859,47		
…	…	…		
239	12 250 000	810,12		
240	12 300 000	809,92		



Pic. 1. Dependence of the wheel diameter on total mileage of the car No. 0883 [developed by the authors].



Pic. 2. Dependence of wheel flange thickness on total mileage of the car No. 0291 [developed by the authors].

when the wheelset was rolled under the car and during periodic technical maintenance and repairs of cars.

To determine the relationship between the mileage and the diameter and thickness of the wheel flange, we will construct the operational characteristics of the wheelsets using the indicated values (Pics. 1, 2).

As can be seen from Pics. 1 and 2, the numerical values of the diameter and thickness of the wheel flange, depending on the total mileage, have linear dependences of the form $y = k \bullet x + b$. This allows finding the coefficients k, b and predicting the residual life of wheelsets by approximating numerical values with analytical expressions using the least squares method.

Forecasting the Residual Life of a Wheelset by Wheel Diameter

Table 1 shows an example of wheel centre wear data as by diameter. To predict the residual life, it is necessary to regularly measure the geometric parameters of the wheelsets from the very beginning of its operation. Let us denote the number of measurements as N and approximate the wear of the wheel tread based on 11 available values obtained during the measurements.

Let, as a result of measuring $n = \{1, N\}$ of the diameter or thickness of the wheelset flange at different mileages l_n, the diagnosed parameter takes the values d_n. Then the linear trend function will be calculated by the least squares method using formulas (1) and (2):

$$k = [N \cdot \sum_{n=1}^{N}(l_n \cdot d_n) - \sum_{n=1}^{N} l_n \cdot \sum_{n=1}^{N} d_n] / [N\left(\sum_{n=1}^{N} l_n \,\hat{}\, 2\right) - (\sum_{n=1}^{N} l_n)\,\hat{}\,2], \quad (1)$$

$$b = [\sum_{n=1}^{N}(d_n) - k \cdot \sum_{n=1}^{N} l_n] / N . \quad (2)$$

Using formulas (1) and (2), the coefficients k and b were calculated for an equation of the form $y = k \bullet x + b$, then the equation for forecasting the value the diameter of the wheelsets of car No. 0293 takes the form indicated in the formula (3):

$$d = -0{,}000004147 \bullet l + 860{,}92. \quad (3)$$

Examples of the results of forecasting the residual life of wheelsets by their diameter for car No. 0293 are summarised in Table 3.

Thus, by summing the values of the products of the mileage and the wheel diameter ($l_n \bullet g_n$), the square of the mileage l_n^2 indicated in Table 3, substituting them into expression (1) ($\sum_{n=1}^{N}(l_n\, d_n)$ and $\sum_{n=1}^{N} l_n^{\,2}$), it becomes possible to find the coefficient k of the expression $y = k \bullet x + b$.

Forecasting the service life of wheelsets based on the diameter for car No. 0293 shows that the change of wheelsets for the specified car must be done when the mileage reaches 12,25 million km.

Having made similar calculations for the remaining cars of train No. 0291–0293, the mileage values given in Table 4 were obtained.

Table 4

Forecasting the condition of wheelsets for the train No. 0291–0293 [compiled by the authors]

No. of the car	Mileage from beginning of operation to minimal diameter of 810 mm, mln km
0291	17
0883	19,45
0888	4,8
0293	12,25
Average value	13,375

Thus, the calculation of the average value of the wheelset mileage according to the limited value of the diameter [5] of the wheel fixed at 810 mm for the train No. 0291–0293 amounted to 13,375 million km, which, with a daily run of a metro car of 700 km, is equal to 52,3 years of service of the wheelsets without considering downtime for TMR. The obtained value of the service life indicates that such a parameter as the diameter of the wheel is subject to increased requirements in accordance with the operation and repair manual for metro wheelsets. This is due to the need to keep the values of diameters of the wheels of one wheelset, of the wheels of the wheelsets on the same bogie and of the wheels of the wheelsets of one car as close to the same value as possible.

However, besides such a controlled value as the wheel diameter, there are dozens of other quantities (ridge thickness, tyre width, tyre thickness, etc.) that have a limited value. This indicates that it is impossible to determine the actual service life of individual elements of wheelsets, considering only one of the controlled parameters (for example, wheel diameter). Therefore, there is a need to apply the least squares method to other controlled parameters of wheelsets to find vulnerabilities and increase the service life of individual elements of wheelsets, which is currently 31 years.

Table 5

Examples of approximating the thickness of the wheelset flange for car No. 0291 [compiled by the authors]

No.	Mileage before turning l_n	Mathematical expectation of wheel flange of the car	Product of mileage and flange thickness $l_n \cdot g_n$	Square of mileage l_n^2
1	0	32,42	0	0
2	120 000	32,38	3885600	14400000000
3	240 000	32,32	7756800	57600000000
4	360 000	32,32	11635200	129600000000
5	480 000	31,85	15288000	230400000000
6	600 000	30,66	18396000	360000000000
7	720 000	29,86	21499200	518400000000
Σ	2 520 000	221,81	78 460 800	1310400000000
Trend	k = -0,000003449	b = 32,42		
1	840 000	29,52		
2	960 000	29,11		
3	1 080 000	28,69		
4	1 200 000	28,28		
5	1 320 000	27,87		
6	1 440 000	27,45		
7	1 560 000	27,04		
8	1 680 000	26,63		
9	1 800 000	26,21		
10	1 920 000	25,80		
11	2 040 000	25,38		
12	2 160 000	24,97		

Forecasting the Residual Life of the Wheelset by Flange Thickness

Table 2 shows examples of data on the wear of wheel centres along flange thickness, where the number of measurements of geometric parameters of whellsets $N = 7$. Using formulas (1) and (2), the coefficients k and b were calculated for an equation of the form $y = k \cdot x + b$, then the equation for predicting the thickness of the wheel flange of car No. 0291 takes the form indicated in formula (4):

$$g = -0{,}000003449 \cdot l + 32{,}42. \quad (4)$$

Examples of the results of forecasting the service life of wheelsets by their diameter for car No. 0291 are summarised in Table 5.

Thus, by summing the values of the products of the mileage and the thickness of the flange ($l_n \cdot g_n$) indicated in Table 5, the square of the mileage l_n^2, substituting them into expression (1) ($\sum_{n=1}^{N}(l_n \cdot d_n)$ and $\sum_{n=1}^{N} l_n^2$), it becomes possible to find the coefficient k of the expression $y = k \cdot x + b$.

Forecasting the resource of wheelsets based on the thickness of the wheel flange for car No. 0291 shows that the change of wheelsets for the specified car must be done when the mileage reaches 2,04 million km, since at the specified mileage, the thickness of the wheel flange will be closest to the minimum (25 mm). In most cases, the cause of increased wear of the flange part of the wheel is the wheel slip as a result of creeping and (or) slipping relative to the rail [6].

Having made similar calculations for the remaining cars of the train No. 0291–0293, the mileage values given in Table 6 were obtained.

It should be noted that for cars No. 0883 and No. 0888, the estimated mileage from the beginning of operation to the minimum flange thickness of 25 mm was 1,2 million km, while the value of the flange thickness for both cars was 25,1 mm, which indicates the accuracy of the applied method.

For head cars No. 0291 and No. 0293, the mileage was 2,04 million km and 1,8 million km, respectively, which is more than for intermediate cars. This is explained by the fact that for head cars with a stall valve installed, increased requirements are imposed to ensure traffic safety.

Intensive wear of the flange is provoked by a large difference in the diameters of the wheels in the rolling circle. Measuring the diameters of wheels mounted on one axle is necessary to ensure the correct location of the wheelset in the track, since with different diameters of the wheels their slippage increases, and misalignments of the wheelset occur during movement [7].

Thus, the calculation of the average value of the wheelset mileage according to the limited value of the flange thickness [8] of 25 mm of the train No. 0291–0293 amounted to 1,56 mln km, which with daily mileage of a metro car of 700 km is equal to 6,1 years of service of wheelsets without considering downtime for TMR. This, in turn, requires optimisation in terms of increasing reliability [9] of wheelsets, since this unit has the greatest impact on train traffic safety.

Results of Calculation of Mileage Values

Data on the mileage for the wheels of cars of the «Rusich» series with a DMeTI profile [a type of wheel profile allowed for use for metro cars of this series] and a minimum wheel diameter of 810 mm are summarised in Table 7.

It can be seen from Table 7 that the service life of wheelsets with calculated mileage up to the minimum wheel diameter, considering downtime for technical maintenance and repair, is 50,8 years, which is 63,8 % more than the designated service life for individual elements of wheelsets (31 years). This refers to timely replacement of wheelsets to maintain the same diameter for all wheel centres mounted on one car and, consequently, to reduce dynamic loads on the wheels of one car.

Another reason for replacing the wheelset may be associated with the discrepancy between its controlled parameters and the permissible values. In this case, the dismantled wheelset is sent for scheduled repairs, turning or for inspection to bring its controlled parameters back to acceptable values and further put wheelsets on the car for further operation.

«Wheelsets are part of the running gear and are one of the most important elements of the car. Therefore, they are subject to special, increased requirements of the state standard, the Rules for technical operation of railways, the Instructions for survey, repair, and assembling of car wheelsets, as well as of other regulatory documents during their design, manufacture, and maintenance» [10].

Table 6

Forecasting the condition of wheelsets for the train No. 0291–0293 [compiled by the authors]

No. of the car	Mileage from the beginning of operation to minimal value of flange thickness of 25 mm of wheels of the car, mln km
0291	2,04
0883	1,2
0888	1,2
0293	1,8
Average value	1,56

Let us summarise the data on the mileage for the wheels of the «Rusich» series cars with DMeTI wheel profile and the minimum value of the wheel flange thickness of 25 mm in Table 8.

Table 8 shows that the service life at the calculated mileage to the minimum thickness of the wheel flange, considering downtime for technical maintenance and repair, is 5,9 years, which is 5,2 times less (19,1 % of the assigned mileage) than the designated service life for separate elements of wheelsets (31 years). This is due to the fact that the least squares method must be applied starting with a flange thickness of 30 mm. With a flange thickness of 33 mm to 30 mm, intensive wear occurs, which was proved using the methods for calculating service life indicators in the article [11].

CONCLUSIONS

Analysis of the results of the study has shown that the estimated mileage when using the least squares method and approximating respectively the values of:

- Wheel diameters is 13,375 mln km.
- Wheel flange thickness is 1,56 mln km.

The use of wheelsets with the current wheel profile for metro rolling stock is not advisable, since intensive wear of the wheel flange thickness is the limiting factor in terms of reducing the mileage between unscheduled maintenance (turning of wheelsets) [12].

Structurally, there are the following ways to improve reliability of wheelsets:

Table 7

Calculation results [compiled by the authors]

Mileage of a car per day, km	Estimated value of mileage, days	Estimated value of mileage, years	Estimated value of mileage with account for downtime, years	Assigned service life for elements of wheelsets of DMeTI profile and diameter of 862 mm, years	Percentage of assigned mileage of the train No. 0291–0293, %
700	19107	52,3	50,8	31,0	163,8

Table 8

Calculation results [compiled by the authors]

Mileage of a car per day, km	Estimated value of mileage, days	Estimated value of mileage, years	Estimated value of mileage with account of downtime, years	Assigned service life for elements of wheelsets of DMeTI profile and flange thickness of 33 mm, years	Percentage of assigned mileage of the train No. 0291–0293, %
700	2229	6,1	5,9	31,0	19,1

• Improvement of mechanical properties through the use of new grades of steel.

• Calculation of optimal dimensions of the wheel centre.

• Improvement of the technology of their manufacture [13].

Due to the large number of curved track sections on the lines of the Moscow Metro, and, as a result, to the increased wear of the wheel flange from 33 to 30 mm due to the effect of lateral forces [14], it is advisable to use the DMeTI VR wheel profile with a 30 mm thick flange for metro car rolling stock.

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