Economic efficiency of increasing the reliability of electric transport in urban transport systems

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Abstract. In this article, the authors propose a new approach to determining the efficiency of increasing the reliability of electric transport, based on the symbiosis of the effective implementation of a diagnostic technical set of measures and minimizing the cost of operating electric transport. As a result of its use, it was determined that increasing the reliability of electric transport systems can lead to a decrease in both specific operating costs and specific capital investments as a result of an increase in the annual productivity of electric transport. This is due to the reduction in the time it takes to take it out of operation to eliminate the consequences of failures and to carry out maintenance and repair.

1. Introduction

Currently, there are different views on determining the technical reliability of complex technical systems, including electric transport [1, 2]. One of the important approaches is the economic assessment of increasing the reliability of electric transport [2, 3]. In this article, the authors propose a new approach to determining the efficiency of increasing the reliability of electric transport, based on the symbiosis of the effective implementation of a diagnostic technical set of measures and minimizing the cost of operating electric transport. As a result of its use, it was determined that increasing the reliability of electric transport systems can lead to a decrease in both specific operating costs and specific capital investments as a result of an increase in the annual productivity of electric transport. This is due to the reduction in the time it takes to take it out of operation to eliminate the consequences of failures and to carry out maintenance and repair [4].

As mentioned earlier, one of the important problems in the operation of trolleybuses, which is a type of electric transport, at the present stage is to improve the quality of services for the transportation of passengers. Along with this, the task is to reduce the cost of operation and repair. These requirements are contradictory to a certain extent; therefore, it is more correct to speak about the joint solution of two problems by optimizing the level of quality of services in the transportation of
passengers [5]. At the same time, the minimum of total transportation costs was taken as the criterion of optimality [6].

The reliability of electric transport is one of the important components of quality, and the above tasks fully relate to this characteristic. To solve them in relation to the level of reliability of a trolleybus, mathematical models were developed that describe the dependence of the costs of creation $C_E$, operation $E_E$ and repair $P_E$ on the reliability indicators of units and parts of trolleybuses [7]. Two approaches to solving the problem were proposed: optimization of the reliability level of electric transport as a whole and optimization of the reliability of its elements with the subsequent determination of the structural reliability of the trolleybus as a whole.

2. Results
Let us consider an approach to determining the optimal level of trolleybus reliability. In the general case, the cost of a trolleybus $E_{c_1}$ with increased reliability can be expressed by the function

$$E_{c_1} = E(E_{c_0}, H_0, H_1),$$

where $E_{c_0}$ is the cost of a trolleybus of initial (basic) reliability; $H_0, H_1$ are trolleybus reliability levels, measured by some quantitative indicators, respectively, before and after the reliability improvement.

Since the cost of building a trolleybus also depends on its capacity, in equation (1), $E$ we mean the unit cost per unit of capacity. The function $E(E_{c_0}, H_0, H_1)$ must have the following properties:

1. $E(E_{c_0}, H_0, H_1) > 0$, since the costs are non-negative;
2. $E(E_{c_0}, H_0, H_1) > E_{c_0}$;
3. $\lim_{H_1 \to 1} E(E_{c_0}, H_0, H_1) = \infty$, since it is impossible to achieve absolute reliability in real design and production conditions;
4. $E(E_{c_0}, H_0, H_1) \leq E(E_{c_0}, H_0, H_2)$ if $H_0 < H'_0$ and, if $E(E_{c_0}, H_0, H_1)$, that is, $E(E_{c_0}, H_0, H_1)$ it does not decrease with respect to a fixed value and does not increase with $H_0$ respect to a fixed value $H_1$, because an increase in reliability is almost always associated with additional costs.

To quantify the level of reliability $H$ in expression (1), we use a complex indicator reflecting, if possible, all the components of reliability: reliability, durability, maintainability. Utilization and downtime ratios are often used as such an indicator under operating conditions $K_{pr}$, which depend on both uptime and recovery time.

The properties 1-4 of the function (1) are satisfied by an exponential function of the form

$$f(x) = k \cdot x^a.$$

Then we have

$$E_{c_1} = E_{c_0} \cdot \left(\frac{1 - K_{p00}}{1 - K_{p11}}\right)^a = E_{c_0} \left(\frac{K_{pr0}}{K_{pr1}}\right)^a,$$

where $K_{p00}, K_{pr0}$ are the coefficients of technical utilization and downtime of the trolleybus by the time of the start of measures to improve reliability; $K_{p11}, K_{pr1}$ are coefficients of technical utilization and downtime of the trolleybus after implementation of measures to improve reliability; $\alpha$ is a statistical coefficient, reflecting the degree of increase in reliability indicators from the funds invested in its increase. The statistical coefficient $\alpha$ is determined first as the mathematical expectation of the known distribution laws of a random variable for the investigated trolleybus node, and at subsequent
steps - according to the statistical data of observations after the implementation of measures [8, 9].

The costs of maintenance and repair of the trolleybus during operation will be

\[ E_{\text{op}} = E_{\text{to}} + E_p, \]

where \( E_{\text{to}} \) is the cost of maintaining a serviceable trolleybus; \( E_p \) - costs of repairing a trolleybus.

Expressing \( E_{\text{to}} \) and \( E_p \) in terms of the unit costs \( e_{\text{to}}, e_p \), respectively, per unit time of the trolleybus being in good and bad condition

\[ E_{\text{to}} = e_{\text{to}} \cdot K_u \cdot t = e_p \cdot (1 - K_{pr}) \cdot t, \]

\[ E_p = e_p \cdot (1 - K_u) \cdot t = e_{\text{to}} \cdot K_{np} \cdot t. \]

Considering that the costs of repairs during use are carried out at the moment \( t \) [10], they must be brought to the initial moment, that is, to the time of creation. Instead of the discrete reduction method by using the standard factor \( e_p \), the continuous reduction method is applied. Then the maintenance costs can be represented as

\[ E_{\text{to}}^{\text{np}} = e_{\text{to}} \cdot (1 - K_{np}) \cdot \frac{1}{\gamma} \left[ 1 - \exp(1 - \gamma \cdot t) \right] = e_{\text{to}} \cdot (1 - K_{np}) \cdot t_{np}, \]

where \( \gamma = \frac{1}{8760} \cdot \ln(1 + E_{\text{to}}); t_{np} \) - conditional time, taking into account the reduction of costs to the initial moment, that is

\[ t_{np} = \frac{1}{\gamma} \left[ 1 - \exp(-\gamma \cdot t) \right] \]

Similarly, for the second component of formula (8), taking into account (2)

\[ E_p^{\text{np}} = e_p \cdot K_{np} \cdot t_{np} \]

The total costs in the field of creating and using a trolleybus of increased reliability, taking into account the diagnostic complex according to equations (2) (5), will be

\[ E_{\Sigma 1} = E_{\text{co}} \cdot \left( \frac{K_{np0}}{K_{np1}} \right)^\alpha + E_{\text{to}}^{\text{np}} + E_p^{\text{np}} = E_{\text{co}} \cdot \left( \frac{K_{np0}}{K_{np1}} \right)^\alpha + e_{\text{to}} \cdot (1 - K_{np1}) \cdot t_{np} + e_p \cdot K_{np1} \cdot t_{np} \]

From (9) it can be determined that at the minimum value \( \frac{dE_{\Sigma 1}}{dK_{np1}} = 0 \) the optimal level of reliability corresponds

\[ K_{np1}^{\text{opt}} = \left[ \frac{\alpha \cdot E_{\text{co}}}{(e_{\text{to}} - e_{\text{to}}) \cdot t_{np}} \right]^{\frac{1}{\alpha+1}} \cdot \left( K_{np0} \right)^{\frac{\alpha}{\alpha+1}} \]

According to equation (10), it is possible to determine, per one trolleybus, the optimal level of reliability, characterized by the downtime coefficient \( K_{np1}^{\text{opt}} \) or the coefficient of technical utilization \( K_{ni1}^{\text{opt}} = 1 - K_{np1}^{\text{opt}} \), and also determine the corresponding total costs \( E_{\Sigma 1}^{\text{min}} \) by expression (9), as well as the magnitude of the effect per one trolleybus with the optimal level of reliability, equal

\[ E_{\text{eff}} = E_{\Sigma 0} - E_{\Sigma 1}^{\text{min}} \]

Under operating conditions, the reliability of the equipment is characterized by its reliability, durability and maintainability. The economic effect of increasing the level of reliability can be defined as the sum of the economic effects of increasing reliability, durability and maintainability, excluding additional costs that were required to increase the reliability of the trolleybus, that is
\[
E_{n} = \left( E_{b} + E_{d} + E_{p} \right) - E_{n} \cdot K \cdot N, \text{ rub / year,}
\]

where \( E_{n} \) is the standard payback ratio; \( K \) - one-time costs to improve the reliability of the trolleybus; \( N \) - the number of operated trolleybuses.

The annual economic effect of increasing the reliability of the trolleybus can be defined as

\[
E_{b} = \frac{L_{g1}}{L_{sp1}} \cdot U_{1} - \frac{L_{g2}}{L_{sp2}} \cdot U_{2} + \frac{\Delta \tau_{pb} \cdot E_{n} \cdot C_{t}}{8760}, \text{ rub / year,}
\]

where \( L_{g1}, L_{g2} \) - the annual runs of the trolleybus before and after the increase in reliability, km; \( L_{sp1}, L_{sp2} \) are the reliability of the trolleybus, characterized by the mean time between failures of the trolleybus before and after the increase in reliability, km / failure; \( U_{1}, U_{2} \) - damage from trolleybus failure before and after the safety increase, rubles / refusal; \( C_{t} \) - trolleybus price; 8760 - annual working time fund, h; \( \Delta \tau_{pb} \) - saving time as a result of the reliability of the trolleybus electrical equipment. Time saving is defined as

\[
\Delta \tau_{pb} = \frac{L_{g1}}{L_{sp1}} \cdot \tau_{v1} - \frac{L_{g2}}{L_{sp2}} \cdot \tau_{v2}, \text{ rub / year,}
\]

where \( \tau_{v1}, \tau_{v2} \) are the average downtime of the trolleybus under repair due to failure before and after the increase in reliability, h.

The annual economic effect from increasing the durability of the trolleybus is defined as

\[
E_{d} = \sum_{i=1}^{k} \left( \frac{L_{g1}}{L_{pi1}} \cdot c_{i1} - \frac{L_{g2}}{L_{pi2}} \cdot c_{i2} \right) + \sum_{i=1}^{k} \left( \frac{L_{g1}}{L_{pi1}} \cdot \tau_{i1} \cdot c_{im} - \frac{L_{g2}}{L_{pi2}} \cdot \tau_{i2} \cdot c_{im} \right) + \sum_{i=1}^{k} \frac{\Delta \tau_{mi}}{8760} \cdot E_{n} \cdot C_{t},
\]

where \( L_{pi1}, L_{pi2} \) - trolleybus runs between types of repairs before and after increasing durability, km; \( c_{i1}, c_{i2} \) - the cost of the \( i \) -th type of repair before and after increasing the durability of the trolleybus, rubles; \( \tau_{i1}, \tau_{i2} \) - the duration of the downtime of the trolleybus in the \( i \) type of repair before and after increasing the durability, h; \( c_{im} \) - cost of 1 hour of trolleybus downtime for repair, rubles; \( \Delta \tau_{mi} \) - saving trolleybus hours during repairs as a result of increasing the durability of the trolleybus [11, 12].

The calculation according to expression (15) is carried out only for those types of repairs, the runs between which, as a result of increased durability, have changed taking into account the cyclicity coefficient [13, 14].

The annual economic effect from improving the maintainability of trolleybus equipment will be

\[
E_{p} = \frac{L_{g1}}{L_{sp1}} \cdot \tau_{v1} \cdot c_{im} - \frac{L_{g2}}{L_{sp2}} \cdot \tau_{v2} \cdot c_{im},
\]

where \( \tau_{v1}, \tau_{v2} \) are the average downtime of the trolleybus under repair due to failure before and after the increase in reliability, h.
Figure 1. Change in serviceable and faulty technical conditions of the electrical complex of the trolleybus (SPTS): a - before the implementation of the SPTS; b - after the implementation of the SPTS.

The payback period of the one-time costs $K$ for improving the reliability of the electrical equipment of the trolleybus is defined as

$$T_{ok} = \frac{K}{E_b + E_d + E_p} = \frac{3200000}{2000000} = 1.6 \text{ years}. \quad (17)$$

Thus, according to the presented method, the payback period of the proposed diagnostic system is $T_{ok} = 1.6$ years.
3. Conclusion

As a result of the analysis of the collected statistics on trolleybus equipment failures, it was determined that the number of failures decreased over the year from 30% to 17% on average, that is, almost 2 times (Figure 1). Of these, equipment failures decreased in 2 times, and failures of mechanical equipment decreased by 60%, which is a confirmation of the dependence of the serviceability of mechanical equipment on the serviceability of equipment. The remaining 7% of equipment failures were attributed to random, which depend on external operational factors. Further studies should be devoted to the determination of these factors.

References

[1] Nazarova M N and Palaev A G 2017 Diagnostics and repair of centrifugal oil transfer pump rotor shaft IOP Conf. Ser.: Earth Env. 87 092016

[2] Gabov V V and Romanova V S 2017 Investigation of Layer-by-layer Destruction of Rocks in High-frequency Cone Crusher IOP Conf. Ser.: Earth Env. 87 022006. DOI:10.1088/1755-1315/87/2/022006

[3] Strizhenok A V and Korelskiy D S 2016 Assessment of the state of soil-vegetation complexes exposed to powder-gas emissions of nonferrous metallurgy enterprises J. of Ecological Engineering 17(4) 25-29

[4] Grosse K U 2012 Non-destructive testing and technology for monitoring the technical condition of structures for quality control and supervision of construction sites ALITinform: Cement. Concrete. Dry mixes 6 62-77

[5] Ardashkin I B, Yakovlev A N and Martyushev N V 2014 Evaluation of the resource efficiency of foundry technologies: Methodological aspect Advanced Materials Research 1040 912-916. DOI: 10.4028/www.scientific.net/AMR.1040.912

[6] Loshkarev I Yu and Chernyshov A S 2013 Unbrakable control. Features of methods of nondestructive testing, in: Actual problems of power engineering of agrarian and industrial complex: Mater. of IV Int. sci. and pract. conf. (Ed A V Pavlova) pp 184-186

[7] Malozyomov B V, Babaeva O V and Andreev A I 2014 Posteriori analysis of the reliability of transport systems Scientific problems of transport in Siberia and the Far East 1 93-95

[8] Vorfolomeev G N, Evdokimov S A, Malozyomov B V, Schurov N I and Shalnev V O 2004 Reliable sources of a feed of the direct current, in: 8th Korea-Russia Int. Symp. on Science and Technology Proc.: KORUS 2004. sponsors: Tomsk Polytechnic University, University of Ulsan, Novosibirsk State Technical University pp 316-320

[9] Daimer J, Graphite electrode for electrothermal reduction furnaces, electrode column and method for making graphite electrodes Patent for invention RUS No. 2374342 (12 May 2005)

[10] Shabalina A V, Lapin I N and Belova K A 2015 Graphite electrodes for electric arc furnaces Black metals 12(1008) 20-21

[11] Malozyomov B V, Wilberger M E and Kulekina A V 2015 The most typical damage and methods of diagnosing the traction motor Transport: science, technology, management 10 60-65

[12] Nikolaev A A, Nikolaev A V, Kirpichev D E and Tssetkov Yu V 2008 Formation of a diffuse cathode spot on a graphite electrode with an arc discharge Physics and chemistry of material processing 43-48

[13] Shchurov N I, Porsev E G and Vil'berger M E 2009 Asymmetrical and nonsinusoidal operation modes of multipulse rectifiers Russian Electrical Engineering 80(12) 680-684

[14] Borisenkov S, Votintsev A and Roth H 2003 Quality control: non-destructive testing of brazed joints using X-ray radiation Components and technologies 28 168-170