Locomotive Reliability Assessment Method

Pavel Gubarev[1,a*], Dmitry Glazunov[1,b] and Vladimir Krotov[1,c]

[1]Rostov State Transport University, Rostov-on-Don, 344038, Russia

[a]pavel.gybarev@yandex.ru, [b]glazunovdm@yandex.ru, [c]tehn_met@rgups.rul

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Abstract. The authors describe the analysis of the current state of the problem under consideration. A definition of "averaged failure flow parameter" is given. The periods of traction rolling stock life cycle are considered. The assumption of event distribution laws exponentiality is introduced, which makes it possible to obtain expressions of the main reliability indices in the analytical form. The work of depot service locomotives to ensure the required reliability and readiness of the rolling stock during their normal operation has been assessed. The introduction of the term "readiness" into the modern practice of traction rolling stock reliability estimation is considered. The initial data for calculating the indexes of locomotive uptime and readiness are presented. Calculated values of readiness and no-failure indices of electric locomotives in operation are obtained. The calculated values of internal and technical availability coefficients are compared with similar indicators established by technical specifications. Control procedures were performed to determine the compliance of each set of locomotives (EP1, 2ES4K) with the uptime requirements. As a result of comparing the calculated values of internal and technical availability factors (for electric locomotives EP1 and 2ES4K with analogous values set by specifications (EP1 and 2ES4K) it was determined that the surveyed locomotives comply with the established availability requirements. As a result of control procedures to determine the compliance of each set of EP1 and 2ES4K locomotives with the uptime requirements, it was determined that the set of 2ES4K electric locomotives for the run in question does not fully comply with the uptime requirement. And the set of EP1 electric locomotives meets the reliability requirements, but the error value is higher than 20%. To clarify both events, it is necessary to increase the mileage interval of the locomotives and repeat the procedure for determining compliance with the uptime requirements. The method of assessing the uptime and readiness of locomotives during their normal operation makes it possible to identify existing shortcomings in the operation of rolling stock and to form measures to improve the quality of rolling stock operation.

Introduction

In recent years, a lot of work has been done to improve reliability of locomotives and to improve their maintenance and repair [1-4]. However, ensuring the required level of reliability for complex equipment and apparatus with the existing means of control is a very difficult task. The majority of equipment failures nowadays are detected visually during direct external inspection. In this regard, the need has arisen to create methods and devices that allow detecting and eliminating defects before the failure of an individual unit or the entire locomotive. Technical diagnostics makes it possible to detect defects and predict the condition of a monitored unit or the whole system. The greatest effect can be achieved by creating and introducing computer-based diagnostic tools in each locomotive depot and improving the system of preventive maintenance [5-7].

Reliability of rolling stock is manifested as an objective result of a variety of acting random factors, the laws of change of which cannot be established only by classical methods of functional

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analysis or mathematical physics. These laws need special research methods. The existing methods of research and calculation of electric locomotive uptime can provide serious assistance in the operation of traction rolling stock for a comprehensive technical and economic assessment and development of measures to improve their quality [8-10]. Therefore, the use of special methods of calculating locomotives for reliability and non-failure is important. One of such methods is the assessment of reliability and readiness of locomotives during normal operation. This method consists in evaluating the impact on the reliability and readiness of the main parts and assemblies of a locomotive during its normal operation, the data on the reliability of which allows calculating the total reliability of a locomotive

Statement of the essence of the solution to the problem

After the locomotives have been built during the warranty period and subsequent operation, each of them experiences failures. Scheduled and unscheduled repairs restore their serviceability, and the locomotives continue their operational work. The alternating failures and restores of locomotives create some streams of failures and restores as a kind of streams of random events [11, 12]. As a quantitative indicator of the locomotive failure flow, the "averaged failure flow parameter" - the mathematical expectation of the number of failures N of locomotives per run - is used [13]. The averaged parameter of the flow of failures ω(L) is used as the main indicator of locomotive uptime. It characterizes the average number of locomotive failures over a sufficiently small run interval ΔL and is defined as:

$$\omega(L) = \lim_{\Delta L \to 0} \frac{\Sigma\{N(L+\Delta L)\} - \Sigma\{N(L)\}}{\Delta L} \tag{1}$$

The locomotive life cycle period is divided into two periods. The first, established between the Supplier and the Recipient, is the period of warranty operation of the locomotive. The second is the period of normal post-warranty operation. Failure flow during the period of post-warranty operation is assumed to correspond to the simplest Poisson flow of failures, in which the distribution of operating time between failures is quite close to the exponential one. The simplest Poisson flow is characterized by constancy of density of distribution of failures, mutual independence of failures, the failures come not in groups, but one by one. Introduction of an assumption about exponentiality of event distribution laws allows us to get expressions of the main reliability indices in an analytical form. The exponential law plays the same role in reliability theory as Ohm's law in electrical engineering [14,15]. Most electric circuits contain non-linear elements, which complicates the calculation of such circuits. However, the assumption of a linear character of the current-voltage relationship for all circuit elements, which reflects Ohm's law, greatly simplifies the calculations. Of course, the results of such calculations will be approximate. It will require more detailed specification of the results by other methods and circuits and reliability indicators [16].

A characteristic sign of exponentiality of locomotive failure distribution law will be:

$$T = \sigma_t$$

where T - is the mean value of the locomotive's operating time before failure, $T = 1/\lambda$;

σ_t -is the mean square deviation of failures, $\sigma_t = \sqrt{D}$;

λ - failure rate;

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D_t - dispersion of operating time to failure, $T = 1/\lambda^2$.

The statistical estimation of the parameter of failure flow for changing number of locomotives during the run interval ΔL is defined as [3, 6]

$$\acute{\omega} = \Delta N \Big/ \sum_{i=1} L_i \qquad (2)$$

- ΔN - the number of failures of all M locomotives in the interval ΔL ;

L_i - total mileage of the set of locomotives;

The upper bound of the one-way interval for the parameter of the failure flow

$$\omega_{1-\beta} = \omega \cdot \frac{x_\gamma^2}{2 \cdot \Delta N}, \qquad (3)$$

where x_γ^2 - value of the "xu-square" function of the distribution at a confidence probability γ and number of degrees of freedom $n-1$.

The error of an estimation of parameters of a stream of failures

$$\varepsilon = \frac{\omega_{1-\beta} - \omega}{\omega} \cdot 100\%, \qquad (4)$$

where $\omega_{1-\beta}$ - is the value of the locomotive failure flow parameter, corresponding to the upper boundary of the one-sided confidence interval.

The conditions for making a decision on the compliance of locomotives with the established requirement of no-failure performance

$$\omega_{1-\beta} \le \omega_\beta \text{ and } \varepsilon \le \varepsilon_3,$$

where $\omega_\beta = \omega_{TY}$ is the rejection value of the locomotive failure rate parameter according to the technical specifications (TS);

ε_3 - estimation error for making a decision on compliance of locomotives with the established requirement of no-failure performance.

According to RD 50-690-89 [19]

-error of parameter estimation ; $\omega \le \varepsilon_3 \le 20\%$ (5)

-confidence probability ; $\gamma = 0,8$ (6)

The term "readiness" is widely used in the modern practice of locomotive reliability assessment. Before 2011, domestic normative documents on terminology in the field of technical reliability and reliability of traction rolling stock (TCS) did not contain the term "readiness" [17,18]. According to the "Methodological provisions..." [13], introduced in 2008 in Russia, the readiness of locomotives, taking into account the European practice, is defined as the ability of a locomotive to perform a required function within a given time interval (year, half a year etc.) on condition it

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is provided with required resources (materials, spare parts etc.). Quantitatively, the readiness of a locomotive, in general terms, can be defined through the readiness factor k_g

$$k_g = T_{pc} / \left(T_{pc} + T_{nc}\right) \quad (7)$$

where T_{pc} - is the dwell time of the locomotive in an operable condition;

T_{nc} - is the time of the stay of the locomotive in a non-operational state;

$\left(T_{pc} + T_{nc}\right)$ - time fund of the period under consideration.

The readiness of a locomotive is characterized by statistical estimates of values of three coefficients - internal k_{vp}, technical k_{tg} and operational (logistical) $k_{во}$ readiness. If the summand in the time $\left(T_{pc} + T_{nc}\right)$ budget T_{nc} corresponds to the downtime of the locomotive for scheduled repairs, then $k_g = k_{vg}$; if the summand T_{nc} includes the downtime for scheduled and unscheduled repairs, then $k_g = k_{tg}$; if the logistic delays of the locomotives are added to the mentioned downtime, then $k_g = k_{vO}$. Coefficients of internal k_{vg} and technical k_{tg} readiness in accordance with requirements of Russian Railways are normalized and specified in technical specifications (TS) for the locomotive. For example, for freight locomotives 2ES4K, 2ES5K the coefficient of internal availability in accordance with TS is 0,97 and the coefficient of technical availability k_{tg} for passenger electric locomotives (EP1, EP2K) must not exceed 0,96. Let's use the initial data in Table 1 to calculate readiness indicators.

***Table 1**. Input data for calculating indicators of locomotive uptime and readiness*

No	Parameter name	EP1	2ES4K
1	Annual stock of the locomotive Tf, h 1	32334	187133
2	Idle time on scheduled repairs Tpl, h	4589.2	2824,4
3	Average idle time of one locomotive on unscheduled repairs Tpr, h	247	2564
4	Number of locomotives in operation M, units	83	41
5	Number of refusals (unscheduled repairs)	20	99
6	Total mileage Li, million km	2.519	1.859
7	Internal readiness coefficient by specifications,	0.98	0.96
8	Technical readiness coefficient by specifications,	0.97	0.95

Initial data were provided by Locomotive Technologies group of LLC TMH-Service branch "North-Caucasus". The calculation is made by expressions (1)...(4) with regard to (5) and (6). Criterion x^2 (K. Pirsov) was defined according to Appendix A in [14] by confidence probability $\gamma = 80\%$. The results of the calculations are summarized in Table 2.

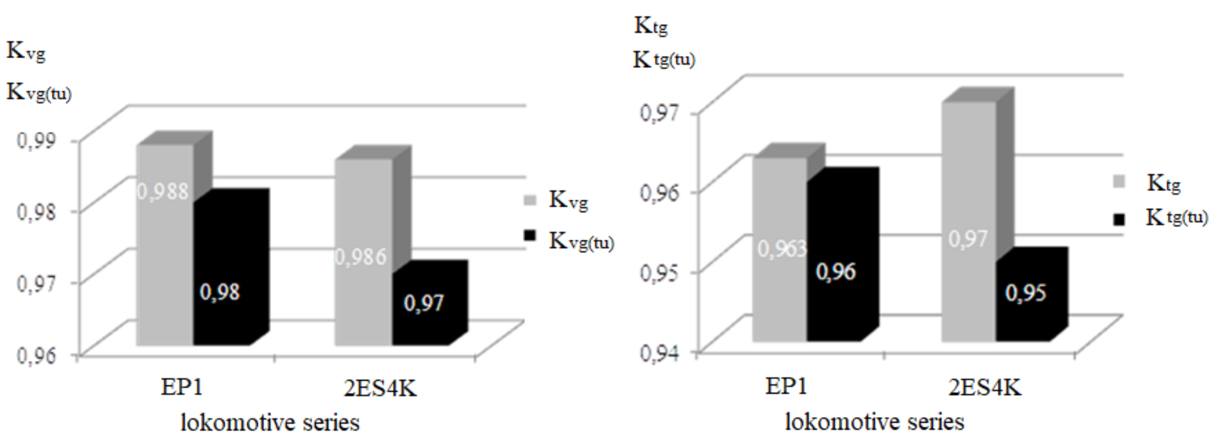
***Table 2**. Calculated values of availability and uptime indicators of electric locomotives in operation*

No	Parameter name	EP1	2ES4K
1	Total operating time of the locomotive in serviceable condition , h	127497.8	181744.6
2	Internal availability coefficient of electric locomotive	0.998	0.986
3	Technical readiness coefficient	0.963	0.97
4	Failure rate of electric locomotives in operation (unscheduled failures), km-1	7.94	47.9
5	Upper limit of confidence interval of failures flow, km-1	9.82	52.67
6	Error in evaluation of failure flux parameter	23.7	10

Let's compare the calculated values of internal and technical readiness coefficients (Table 2) with similar indicators established by technical specifications (TS). The conditions for deciding whether the EP1 and 2ES4K locomotives meet the established readiness requirement [19-20] are met if

$$K_{vg} \geq K_{vg}^{tu}; \mathrm{K}_{tg} \geq K_{tg}^{tu} \quad (8)$$

The calculated values of the internal and technical readiness coefficients of the EP1 and 2ES4K locomotives with similar values set (TU) are shown in Figure 1.



a) b)

***Fig. 1.** Calculated values of internal (a) and technical availability (b) coefficients of EP1 and 2ES4K locomotives with similar indicators established (TU)*

For electric locomotive EP1 $K_{vg} = 0,988$, $K_{vg}^{tu} = 0,98$, $\mathrm{K}_{tg} = 0,963$, $K_{tg}^{tu} = 0,96$ for electric locomotive 2ES4K $K_{vg} = 0,986$, $K_{vg}^{tu} = 0,97$, $\mathrm{K}_{tg} = 0,97$, $K_{tg}^{tu} = 0,95$.

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Requirements (19) are met - this is a sufficient condition for making a consistent assessment of locomotive compliance in terms of reliability. However, a necessary condition is that the locomotives meet the established requirement for reliability. We perform control procedures to determine whether each set of locomotives (EP1, 2ES4K) meets the reliability requirement according to the inequalities given in [14].

There are three compliance events:

-full compliance $\left(\omega_{1-\beta} \le \omega_{\beta}\right) \wedge \left(\omega \le \omega_{\beta}\right) \wedge \left(\varepsilon \le \varepsilon\right)$; (9)

- nonconformance $\left(\omega_{1-\beta} > \omega_{\beta}\right) \wedge \left(\omega > \omega_{\beta}\right) \wedge \left(\varepsilon > \varepsilon\right)$; (10)

- "limited" mismatch $\left(\omega_{1-\beta} > \omega_{\beta}\right) \wedge \left(\omega \le \omega_{\beta}\right) \wedge \left(\varepsilon > \varepsilon\right)$; (11)

where $\wedge$ - reads as "AND"

ω_{β} - the failure flow parameter according to the TU, $\omega_{\beta} = 10 \cdot 10^{-6}$ km (EP1),

$\omega_{\beta} = 11 \cdot 10^{-6}$ km (2ES4K).

Let us use the data of table 2 and for each set of electric locomotives in accordance with inequalities (8)...(11) determine the conformity of requirements for no-failure rate.

For the set of electric locomotives EP1: $\left(9{,}82 < 10\right)^{-6} \wedge \left(7{,}94 < 10\right) \cdot 10^{-6} \wedge \left(23{,}7 > 20\right)$

For the set of electric locomotives 2ES4K: $\left(52{,}67 > 11\right)^{-6} \wedge \left(47{,}9 > 11\right) \cdot 10^{-6} \wedge \left(10 < 20\right)$

Thus, the control procedures to determine the compliance of each set of EP1 and 2ES4K locomotives with the reliability requirements according to the inequalities (8)...(11) showed that the set of 2ES4K electric locomotives for the considered run does not fully meet the reliability requirement. In order to clarify this event, it is necessary to increase the interval of the locomotives' run and repeat the procedure of determining compliance with the reliability requirements, as well as to develop and implement measures to improve the reliability of the considered set of 2ES4K electric locomotives. The EP1 set of electric locomotives meets the reliability requirements, but the error value is higher than 20% . This means that the tabulated value of the chi-square distribution function at confidence probability is not 80%, but 76.3%. In this case, an increase in the mileage L of the locomotives is required. And then the error of the estimate of the failure flow parameter can be refined . The reliability of the 2ES4K electric locomotives was significantly affected by the number of unscheduled repairs. Unscheduled repairs increased the flow of failures, from which the value of the upper limit of the one-sided interval was higher than the rejection value of the parameter of the flow of failuresv . The most informative is the availability factor , which characterizes such reliability properties of EP1 and 2ES4K electric locomotives, as fault tolerance and maintainability. These characteristics can be increased by reducing downtime before, during and after maintenance and repairs, advance training of operating and maintenance personnel, saturation of locomotive facilities with modern equipment, devices and technologies, increasing the role of transport science, etc.

The results of research and their discussion

Taking into account the importance of the research and calculation of the electric locomotives uptime, as well as the absence of a universal method for assessing the work of service locomotives in depots to ensure the required uptime, the sequence of assessing the uptime and readiness of locomotives during their normal operation is given. As a result of comparing the calculated coefficient values of the internal and technical readiness (for electric locomotive EP1 ; for electric locomotive 2ES4K) with the analogous values, established by the technical conditions (EP1 corresponds ; ; 2ES4K corresponds), it is determined that the investigated locomotives meet the established readiness requirements.

Conclusions

As a result of the control procedures to determine the compliance of each set of locomotives EP1 and 2ES4K with the reliability requirements, it was determined that the set of electric locomotives 2ES4K for the run in question does not fully comply with the requirement for uptime. And the set of EP1 electric locomotives meets the reliability requirements, but the error value is higher than 20%. To clarify both events, it is necessary to increase the mileage interval of the locomotives and repeat the procedure for determining compliance with the uptime requirements. The method of assessing the uptime and readiness of locomotives during their normal operation makes it possible to identify existing shortcomings in the operation of rolling stock and to form measures to improve the quality of rolling stock operation.

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