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Research paper

Justification of Statutory Service Life Extension of Locomotives on the Basis of Theory of Aging

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Abstract

The article is devoted to statutory service life extension of locomotives on the basis of mathematical methods and provisions of the following theories: reliability, games, probability, aging, pattern recognition, and others. Methods of reliability theory have been used to simulate a system of repairs and critical assessment of options for organization of maintenance and repair in excess of statutory service life of locomotives. Methods of game theory are used to determine the tactics of locomotive maintenance over normative term of use. Methods of probability theory and mathematical statistics are used for collecting and processing initial data, the laws of distribution of random variables of working properties and loads are determined in the calculation of the reliability of bearing structures of locomotives, as well as the effectiveness of replacing the old rolling stock with a new one. Methods based on the theory of aging to determine values of criteria for estimating boundary terms for various variants of the strategy of prolonging the operation of locomotives in excess of the normative term. Methods of pattern recognition theory are used to adjust the system of obtaining locomotives in excess of the normative lifetime.

Keywords: *Maintenance; Non-routine Maintenance; Statutory Service Life Extension; Theory of Reliability; Theory of Aging.*

1. Introduction

Increasing the efficiency of locomotive use in modern conditions is one of the prerequisites for the stable functioning of railways. There is a search for stocks in determining the limitation period for the use of locomotives. As experience of rolling stock in common industries shows, in some cases it is possible to obtain significant economic effect.

As was emphasized in the management documents of Ukrzaliznytsya that significant part of locomotives has expired the normative life. The age of the exploited fleet of locomotives has reached critical limit. The demolition of electric locomotives has reached 90% with an average age of locomotive of 36 years.

Due to the physical and moral depreciation of the rolling stock, in particular locomotive park, an important direction in ensuring operation of rail transport in the long run is the rational use of existing rolling stock within normative and extended (over normative) terms of service. Therefore, during the last years, according to the tasks of the State Administration of Railway Transport of Ukraine (Ukrzaliznytsya), scientific and technical developments are being intensively carried out to increase the service life of locomotives without worsening of traffic safety and reliability indicators.

Numerous studies in our country and abroad are devoted to the problems of increasing efficiency of locomotives. Priority in these studies was devoted to determining the optimal structure of repair cycles, the introduction of diagnostic tools in the technological processes of maintenance and repair and evaluation of technical condition before and after repair. Recently attention has been paid to the development of scientific measures to evaluate the effectiveness of lengthening life of locomotives after normative term of its operation. Unfortunately, in the railway transport of Ukraine, unified scientific direction concerning optimal life cycle of railway traction rolling stock is not substantiated. As the analysis shows, in different countries and organizations due to various economic and political situations, different concepts of life cycle are interpreted differently. One of the important measures is scientific justification of life of the bearing structures of the locomotives and practical measures to ensure fault-free and safe operation of them.

However, it should be noted that these should not outline approaches to the effective operation of locomotives in aftermath of statutory operating period.

Relevance is recorded depending on what you do, at the optimal cost of Maintanance and Repair, scientific examination in accordance with conditions and norms.

2. Literature Review

Determination of optimal service life of machines is directly related to the problems of wear aging of machines [16].

A number of authors believe that the optimal lifetime of machines is such that the total cost of repairs of the machine is approaching cost of the new machine [1, 15].

This approach can not be considered strictly scientific because in this case it is not analyzed the question of how effectively the means used to purchase and maintain the performance of the old machine.

More substantiated approaches to this issue are given in [6, 7, 18], where it is assumed that the depreciable service life, for example, of a vehicle, is conditionally determined by the life of the frame or the body of the carrier. However, these statements are not supplemented by analytical evidence.

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The contradiction in the decision of the problem of determining the optimal terms of the service of machines and equipment is stated in [6], which shows that the service life of the machine is determined ultimately by the profitability or disadvantage of their further exploitation and the possibility of replacement by new types of machines of advanced design.

In work [18] it is suggested to consider three criteria for the evaluation of the technical state of the machine parts or their combinations and nodes: technical, technological and economic.

An essential disadvantage of research [19, 20] is that they lack universality. Modern machines are quite complicated and it is not known how to determine these characteristics in a certain ratio to find the optimal service life in general.

Most foreign authors [3-5, 21], on the basis of practical materials, set average terms of operation of machines within the limits of 15 to 20 years.

The task of constructing an optimal system of repair using cost information was solved by R.N. Kolehaiev [9]. In the considered model, the vehicle (machine) during the service life goes through a number of planned repairs, according to which the optimal service life "T" and the optimal periods between capital repairs, the number of which can be any [9, 10].

In research article [11] it is considered problem within the framework of a stochastic model, which introduces probabilities of machine transitions from one state to another as functions of its age and other factors. In general, the developed model has certain interest, however, with the increase in the number of elements forming the machine, the solution to the problem is complicated.

The research article [2] is solved the task of determining such volumes of repairs, their frequency and service life of the system, in which the required probability of failure-free operation is ensured with a minimal total cost of the means. In doing so, the following assumptions are made that the time for repair and prevention, ignoring the small; in the event of system failure during period of work, a penalty for the refusal is charged; refusals occur with a constant in time intensity.

The diversity of the studies examined shows that there is no single approach to the definition of a strategy beyond the normative exploitation of locomotives [8, 14, 22].

3. Materials and Methods

It is necessary to determine the justification of an effective system of maintenance of locomotives with lengthening of their exploitation period [12, 13, 16]. The research objective is to determine such an option, which corresponds to the minimum cost of maintenance. In this case, the efficiency indicator is the sum of the costs of maintenance (TO), repair (PR) and capital repair (KR), taking into account the cost of energy during the period when it reaches the total output.

Accepted the following values of run-time after the VR (L_{VR}) before the write-off, having graduations L_{VR} = 360, 420, 450, and 500 thousand km. The number of PR-3 before write-off should be 1 ÷ 2; the number of PR-2 in the period up to PR-3 - 0 ÷ 1; the work between the current repairs of the PR-2 and the PR-3 should be reduced with the increase of their serial numbers in the repair cycle before the write-off (ie, instead of the traditional principle of equality and multiplicity of normative developments, the principle of their "differentiation" should be used), since the technical condition of the locomotive tends to deterioration with the growth of its development; standard mileage between TO-3 and PR-1 also need to be reduced with the growth of the time of the locomotive from the VR.

In Table 1, there are eight variants of periodicity and alternations of PR-2 and PR-3 for the adopted four variants of LRP = 360, 420, 450, 500 thousand km.

Table 1: Overhaul runs for different repair arrangements

Type of maintenance variant	PR - 3(I)	PR - 3(II)	PR - 2(I)	PR - 2(II)	PR - 2(III)	∑L, 10^3km
1	180		100	100		360
2	150	110	80	60	55	360
3	150	140	80			360
4	170	140	90	80	60	420
5	170	170		90		420
6	170	150	90	80	70	450
7	180	170	100	90		450
8	210	180	120	100	60	500

Features of the options: II - with the usual alternation of repairs, that is, with two PR-3 and three PR-2; III - with two PR-3, but in the period from the LBP to the first PR-3 absent PR-2; I - with one PR-3 and two PR-2 for the run from VR to write-off. Options with L_{VR} > 360 ths. km provide for two repairs of PR-3 and 2σ3 repairs of PR-2. The largest mileage to the PR-3 in variants corresponds to the period from VR to I PR-3 (with L_{VR} = 500 thousand km) and makes 210 thousand km, and the smallest - 110 thousand km (from I PR-3 to II PR -3 at L_{VR} - 360 thousand km).

For each of the eight variants, two types of periodicity of the PR-1 were used in the studies: A - for the period of the diesel locomotive from VR to I, PR-3 - 40 thousand km, for the period from I PR-3 to II PR-3 - 35 thousand. km, from II PR-3 to the end of operation - 30 thousand km; B - respectively, for the specified periods of 35, 30 and 25 thousand km. Thus, frequency of PR-1 is also adopted by a differentiated-decreasing period from period to period.

Whereas each of the eight periodic variants has two PR-1 periodic cushions (A and B), 16 repair cycles are subject to review. For each of them, in turn, three varieties of periodicity M-3 are considered: a - in the period from BP to I PR-3 - 40 days, from I PR-3 to II PR-3 - 30 days, from II PR-3 to end of operation - 25 days; b - for the specified periods periodicity TO-3 is respectively 35, 25 and 20 days; in - 30, 25 and 20 days.

During operation, the suitability of the locomotive, as well as its individual elements, is reduced due to wear during operation, transportation and storage. The suitability of locomotive is partially restored periodically by the use of new equipment or the restoration of some parameters of old equipment. This occurs in the general case as many times as the construction provided by the change of non-durable equipment of the locomotive is carried out, as well as the restoration of parameters of repairable units for maintenance and repair.

Locomotives belong to the category of vehicles (category IV), which consist of unalterable structural elements of initial suitability, as a result of which, in addition to periodic repairs, maintenance is expected.

In general, the initial suitability of a locomotive is equal

$$E_{\text{мIV}} = \sum E_{\text{iIV}} + \sum G_{\text{jIV}} = \sum E_{\text{iIV}} + \sum G_{\text{1IV}} + G_{\text{2IV}} + G^0_{\text{3IV}}, \quad (1)$$

where E_{IV} is the suitability of all structural elements, $\sum G_{\text{1IV}}$ is the suitability that corresponds to the long-term active assembly and fitting of structural elements, $\sum G_{\text{2IV}}$ is the part of suitability of locomotive, which corresponds to a lack of long-acting processing and installation of structural elements, which must be fully restored in terms of repair times during the life of the locomotive, $\sum G^0_{\text{3IV}}$ is the part of suitability of non-constructive elements of the locomotive, which corresponds to the short-acting lubrication and regulation, which, should be periodically restored in use due to partial maintenance of the service life of locomotives.

In the analysis depending on structural components of fitness locomotives and their changes over the lifetime considered that the structure of eligibility locomotive in the opposite during operation is somewhat reduced value life structural elements and simultaneously decreasing suitability long-acting non-constructive

elements, then renewed the repair of non-constructive elements and, finally, reconditioned in maintenance of non-structural elements, in which consistently introduced a number of renewable usability: $G_{3IV}^{0}, g_{3IV}^{1}, g_{3IV}^{2}, g_{3IV}^{3}, ..., g_{3IV}^{l}, ..., , g_{3IV}^{m_j-1}$.

In determining the appropriate values used to construct graphs, part of suitability g_{2IV}^{L} has periodicity of change τ_{2IV}^{L}, part g_{3IV}^{l} - periodicity τ_{3IV}^{l}, and in the repair of locomotive, since these periodicities are taken multiple, they are introduced simultaneously as components that complement each other.

Following coefficients are used to quantify the suitability.

The coefficient of uniformity is determined by the ratio of the total value of the suitability of the original constructive elements of the locomotive to the total suitability of all structural elements that wear out during the service life

$$K_p = \frac{\sum E_i}{\sum n_i E_i}, \tag{2}$$

where n_i is the total number of corresponding structural elements that wear out in the locomotive during its operation.

Practically with sufficient accuracy, coefficient of steadiness is determined from the correlation of corresponding values, that is

$$K_{stead} = \frac{\sum E_i}{\sum n_i E_i} \approx \frac{\sum Q_i}{\sum n_i Q_i}, \tag{3}$$

where Q_i is the cost of corresponding constructive element.

Coefficient of stability K_s of locomotive regulation characterizes the required volumes of work during maintenance and repair and their repetition for the period of operation. Coefficient K_s is determined by the ratio of the initial suitability of non-structural elements necessary for the normal operation of the locomotive during its full service life.

$$K_s = \frac{\sum G_j}{\sum n_j G_j}. \tag{4}$$

In practice, stability coefficient of locomotive regulation is determined with sufficient accuracy due to the corresponding cost indicators, i.e.

$$K_s = \frac{\sum Q_j}{\sum n_j Q_j}. \tag{5}$$

In case of inequality of the initial and renewable suitability of non-structural elements $(g_j \neq G_j)$ coefficient K_c is determined from the expression

$$K_c = \frac{\sum G_j}{\sum G_j + \sum (n_j - 1) g_j} \approx \frac{\sum Q_j}{\sum Q_j + \sum (n_j - 1) q_j}, \tag{6}$$

where G_j and Q_j is the suitability and cost of output and renewables with adequate maintenance and repair of the structural elements of the locomotive, $n_j - 1$ is the the number of relevant maintenance and repairs of the locomotive for the entire service life, g_j i q_j is the respectively, suitability and cost, entered in the locomotive when updating the corresponding non-constructive element.

For a certain non-constructive element of locomotive it is also possible to determine a partial stability factor with respect to the suitability or cost, taking into account the repetition of the renewal of the suitability of this non-constructive element

$$k_{sj} = \frac{G_j}{G_j + (n_j - 1) g_j} = \frac{Q_j}{Q_j + (n_j - 1) q_j}. \tag{7}$$

The durability coefficient can be determined by expression

$$K_d = \frac{K_r K s E_м}{K s \sum E_i + K_r \sum G_j}, \tag{8}$$

or, using value ratios, according to the formula

$$K_d = \frac{K_r K s Q_м}{K_c \sum Q_i + K_r \sum Q_j}, \tag{9}$$

where $E_м$ i $Q_м$ is the accordingly the suitability and cost of the locomotive, E_i i Q_i is the suitability and cost of constructive elements of a locomotive, G_j i Q_j is the suitability and cost of non-constructive elements of locomotive.

The specific suitability of a locomotive is determined by expression

$$П_n = \frac{E_м + \sum (n_i - 1) E_i + \sum (n_i - 1) G_i}{T}, \tag{10}$$

where T is the lifetime of locomotive in excess of the normative term.

From the analysis of the structure of the change of suitability of the locomotive during its period of operation, it is possible to make significant adjustments to the existing valuation characteristics.

4. Results and Discussion

For 8 variants of lengthening the life of the locomotives after the last KP, the total costs for all types of maintenance, TO, PR and possible unscheduled repairs (HP) were calculated. The amount of TO, PR was calculated according to the accepted variants and is given in Table 2. The costs for TO-3, PR-1, PR-2, PR-3 were taken by the average on the railways and are also shown in Table 2. As practice shows, with As the runway increases, the component of overtime work on TO, PR is increasing. In calculations according to the option of lengthening the life of this component, this component varied in the range of 0.26 ÷ 0.33 of the total costs of TO, PR. Accordingly, the mandatory volume of regulatory work in these conditions decreased in opposite to the normative term.

Total costs incurred in unscheduled repairs were taken at 25% more than over regulatory costs for planned maintenance, maintenance and repair. The factor for increasing the lifetime was taken into account with an increase in the volume of repairs in the range of 1.0 ÷ 1.25. Residual price of the locomotive at the start of operation after the CD was adopted in the amount of SL = 5 · 106 UAH.

On the basis of the above calculations carried out, summarized in Table 2, K_{stead} coefficient of steadiness due to planned TO, PR was stable in the range of 0.76 ÷ 0.73. Moreover, its least value was the 7th version of the organization of maintenance, PR in after the normative term of exploitation. This testifies that, in compliance

with the technology of TO, PR is achieving a stable level of equipment maintenance.

Table 2: Calculation of locomotive parameters of suitability

Run variant	Amount / total cost TO,PR $\left(K_i / \sum K_i C_i\right)$				Over normal lifetime T, 10^3	Total, $Q_{TO,PR}$, 10^3	Regulated costs, Q_1, 10^3	Over regulatory costs, Q_2, 10^3	Unforeseen expenses, Q_3, 10^3	Total costs of TO,PR, after the normative term of exploitation, 10^3	Coefficient of resistance, K_r	Coefficient of regulation stability, K_s	Coefficient of durability, K_d	Specific capacity, S_c
	TO – 3 ($C_{TO\text{-}3}$ = 5000)	PR – 1 ($C_{PR\text{-}1}$ = 15000)	PR – 2 ($C_{PR\text{-}2}$ = 85000)	PR – 3 ($C_{PR\text{-}3}$ = 190000)										
1	46 / 230000	9 / 1350000	2 / 170000	1 / 190000	360	1940	1429.1	510.9	459.8	2399.8	0.76	0.53	0.73	19.28
2	51 / 255000	8 / 1200000	3 / 255000	2 / 380000	360	2090	1518.7	571.3	542.7	2632.7	0.74	0.51	0.71	19.69
3	47 / 235000	10 / 1500000	1 / 85000	2 / 380000	360	2200	1576.7	623.3	623.3	2823.3	0.74	0.50	0.69	20.00
4	49 / 245000	8 / 1200000	3 / 255000	2 / 380000	420	2080	1469.9	610.1	640.6	2720.6	0.75	0.49	0.70	16.86
5	45 / 225000	10 / 1500000	1 / 85000	2 / 380000	420	2190	1525.7	664.3	730.7	2920.7	0.74	0.48	0.69	17.12
6	50 / 250000	9 / 1350000	3 / 255000	2 / 380000	450	2235	1534.7	700.3	805.4	3040.4	0.74	0.47	0.68	16.08
7	47 / 235000	10 / 1500000	2 / 170000	2 / 380000	450	2285	1546.2	738.8	886.6	3171.6	0.73	0.45	0.67	16.19
8	49 / 245000	9 / 1350000	3 / 255000	2 / 380000	500	2230	1486.7	743.3	929.2	3159.2	0.74	0.44	0.67	14.46

However, when normative term of using locomotives is exceeded, the coefficient of stability of the regulated works K_c with the increase of the life of the operation decreases. The range of changes in K_c s is observed within the range of 0.55 ÷ 0.44. This confirms that when wearing out and aging the equipment is increasingly difficult to maintain the technical condition of the locomotives, especially when there are no special works related to lengthening of service life.

Such nature of change of coefficients K_r and K_s has formed the dynamics of the change in the coefficient of durability K_d. Fluctuation range K_d is in range of 0.73 ÷ 0.67, which is largely due to the coefficient K_r.

The processes of aging of locomotives in excess of the normative term of operation affect the coefficient of specific suitability S_c. With an increase in lifetime S_c is gradually decreases with the growth of total costs in support of the technical condition of locomotives. From this it can be stated that only due to correction of inter-repair runs can not stably maintain the technical condition of locomotives, even with the increase in the cost of scheduled maintenance, PR, which are required by the regulations. As follows from the practice of locomotive operation, it is necessary to adjust the scope of work with each of the following TO, PR due to additional diagnostic testing of equipment, which should be exploited further.

5. Conclusion

1. Existing approaches and models of rolling stock maintenance in Ukraine are based on the criteria based on minimization of specific costs per life cycle, which does not fully take into account the peculiarities of the operation of locomotives that continue to use in excess of the normative term.

2. In order to ensure the effective use of locomotives in any period of its operation, the technical operation system should ensure its adaptability to the production sectors in order to optimize the repair base and technology of TO, PR of locomotives.

3. Formed models allow us to determine the suitability of locomotive equipment and its corresponding estimation, which in turn allows us to further adjust the technology TO, PR with allowance for the limiting period of their use in the repair cycle.

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