

Optimality criteria for the process of technical operation of locomotives

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Abstract. The efficiency of a locomotive fleet as a complex system depends significantly on the mode and conditions of its operation, which, in many cases, are determined both by its own condition and by the state of the maintenance system. In reality, changes in the state of the system, and its further behaviour in most cases can be described by the Markov process. It should be noted the excessive rigidity of the hypothesis about the Markov character of the behaviour in the process of technical operation of the locomotive fleet that makes the resulting model insufficiently adequate. The article proposes a methodology to assess the efficiency in the functioning of the locomotive fleet as a semi-Markov system. Relationships for calculating the main statistical characteristics of the efficiency indicators in the process of technical operation of locomotives have been obtained. The choice of optimality criteria for the process is justified. A procedure for constructing an ordered sequence of enhancing maintenance and repair strategies, considering the condition of a particular locomotive has been offered. Determining the optimality criteria for the technical operation process of the locomotive fleet based on the research of stochastic estimates in the efficiency of the semi-Markov model. Obtaining a sequence of maintenance and repair strategies. The efficiency of locomotive fleet operation significantly depends on the quality of service. The quality of service is determined by the effectiveness of diagnostic tools for technical conditions. The process of operating a locomotive fleet is described by a semi-Markov model. The semi-Markov model used makes it possible to more fully take into account, in the general case, the diagnostic support of the locomotive and the restoration process. The unit cost function the average unit cost, the average unit loss coefficient the coefficient of average, and operating factor was selected as target functions. A procedure has been proposed for constructing an ordered sequence of improving maintenance and repair strategies, considering the condition of a particular locomotive.

1 Introduction

The reform of railway transport is connected with the development and implementation of a set of measures aimed at increasing the efficiency of the use of the locomotive fleet. Increasing the operational reliability of rolling stock is inextricably linked with the improvement of the maintenance and repair system. Recently, there has been a clear tendency to move to a rolling stock repair system based on the condition, the implementation of which is largely determined by the level of information support for the processes of operation, repair, technical control, and diagnostics.

Models of maintenance systems in most cases do not always fully take into account the operating modes of locomotives, design features and restoration (repair) technology. The task of selecting performance indicators

for the functioning of a maintenance and repair system that meets operating requirements is one of the main tasks that requires solutions in modern economic conditions.

In the process of operating the rolling stock, nodes and aggregates of locomotives are affected by increasing loads caused by the increase in the mass of trains, the increase in movement speeds and the average daily mileage of the locomotive.

The development and introduction into the production process of the operation of rolling stock of diagnostic tools and methods for the timely detection of failures and pre-failure states of nodes and aggregates is an urgent task.

Reliable diagnosis with diagnostic methods and tools is of particular importance in the conditions of a widespread transition from a planned and preventive system of technical maintenance and repair of

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locomotives to a maintenance system based on technical condition.

Taking into account the actual technical condition, as well as the constant increase in the costs of maintaining the traction rolling stock with an exceedingly long service life, which is operated by the railways of Ukraine, the planned and preventive maintenance system does not always meet the requirements for ensuring the transportation process and traffic safety. There are rare cases when, in accordance with the set duration of repair or maintenance, it is necessary to intervene in the work of a normally adjusted mechanism, although its technical condition does not require such intervention. The reliability of the work of such a node does not increase, but the costs of carrying out repairs increase. Taking into account the above and the general trend of transition to performing technical maintenance and repair according to the actual technical condition of traction rolling stock, it is appropriate to use the system of technical maintenance according to the actual condition or a combined system.

The number of unplanned repairs and failures during the execution of train work is the main indicator by which the reliability and quality of maintenance of locomotives, as well as the efficiency of the work of repair enterprises, is evaluated. With the help of diagnostics, it is possible to prevent failures during the execution of train work and to determine in advance the necessity of performing the appropriate types of repairs of locomotives in accordance with the actual technical condition. Today, non-destructive control and diagnostic methods are becoming more relevant and form the basis of modern monitoring and diagnostic systems.

Maintenance and repairs according to the actual technical condition will be possible only with the use of automated systems of non-disassembly diagnostics and technical condition control designed to assess the condition of the technical object, search for malfunctions and determine their causes, predict the residual resource of mechanisms and determine the term preventive maintenance without unnecessary disassembly.

Detection and search for defects are processes of determining the technical condition of the object and are combined by the general term "diagnosis". Thus, the tasks of diagnosis are the task of checking the serviceability, operability and correct functioning of the object, as well as the task of searching for defects that disrupt the serviceability, operability or correct functioning. The strict formulation of these tasks involves, firstly, a direct or indirect task of a class of possible (considered, given, most likely) defects and, secondly, the presence of formalized methods of constructing diagnostic algorithms, the implementation of which ensures the detection of defects from a given class with the necessary completeness.

The efficiency of a locomotive fleet as a complex system depends significantly on the mode and conditions of its operation, which, in many cases, are determined both by its own condition and by the state of the maintenance system. In reality, changes in the state of the system, and its further behaviour in most cases can be described by the Markov process. It should be noted the excessive rigidity of the hypothesis about the Markov

character of the behaviour in the process of technical operation of the locomotive fleet that makes the resulting model insufficiently adequate. Another obvious drawback of this model is in the simplified description of the evolution of the process under research on a set of possible states: in the adopted model, transitions are only possible to neighbouring states.

Seeking to take into account a larger number of factors in the mathematical model in the real process of operating a locomotive fleet leads to an increase in the number of Chapman-Kolmogorov differential equations regarding the probabilities of states. The numerical solution of such a system of differential equations imposes significant restrictions on the developing Markov model of the simulated process. In this regard, the analysis of the functioning of the locomotive fleet as a system with more general premises is of theoretical and practical interest.

2 Literature review

The determining factors influencing the operation process, which in turn depends on the reliability and efficiency of its functioning as a restored system, are the organization of maintenance and the availability of a sufficient number of spare elements. Models in systems where various methods of carrying out emergency, preventive, planned-preventive, and other types of repairs are described in [1-3], where the mathematical apparatus of Markov and semi-Markov processes with a finite set of states is used.

To compare maintenance strategies, technical and economic indicators of the quality of system functioning are calculated. Paper [4] analyses models in which the development of a system is described by a semi-Markov process with an uncountable set of states and a controlled semi-Markov process with a finite set of states [4]. The main method for studying complex stochastic systems is queuing theory.

The objectives of queuing theory are to develop recommendations for ensuring high efficiency of the system. To achieve this goal, objectives are set consisting of establishing the dependencies of the system's efficiency on its organization [5-7]. The research of stationary characteristics is not only of particular interest but also the possibility of changing the structure of the system and obtaining certain (optimal) results, for example, increasing profits from the system operation [8, 9].

Stochastic models of operation and maintenance are used in analysing the quality of functioning of computer systems and technological processes [10, 11], the functional safety of railway automation equipment [12], and in assessing the reliability of software [13, 14].

3 The purpose of the article (research)

Determining the optimality criteria for the technical operation process of the locomotive fleet based on the research of stochastic estimates in the efficiency of the semi-Markov model. Obtaining a sequence of maintenance and repair strategies.

4 Basic assumptions

Let us assume that the process of technical operation of a locomotive fleet is a random sequence of transitions from the current phase state S_i to the next one S_j . The staying time in each state can be either a random variable with a given (arbitrary) distribution law, or a constant. Under this assumption, the described process can be approximated by a model of a semi-Markov process, also called in the literature the embedded Markov chain (EMC), and specified by the following parameters:

– an initial state vector EMC

$$P_0 = \{P_i^0\}, i = \overline{1, N},$$

where N is a number of possible process states;

– square matrix of transition probabilities from state to state

$$\|P_{ij}\|, i = \overline{1, N}; j = \overline{1, N};$$

– row matrix of distribution densities of staying time in a state S_i before transition to the next state S_j

$$F = \{F_i(t)\}, i = \overline{1, N}.$$

5 Justification for choosing optimality criteria

Representation of the process under study by an EMC model makes it possible to apply fairly convenient techniques used in stochastic modelling. Statistical processing of experimental data in simulating the process of operating locomotives allows to calculate the values of complex reliability indicators of economic operational indicators, which can be used as criteria.

An arbitrary distribution of the staying time in each of the possible states leads to a semi-Markov process, a formal description of which is presented, for example, in [15]. In addition to one-step transition probabilities, the work considers the probabilities R_{ij} of transition from state i to state j in finite $n > 1$ steps.

Using the total probability formula

$$R_{ij} = \sum_{k=1}^N P_{ik} R_{kj}$$

or

$$R_{ij} = \sum_{k \neq (j, i)}^N P_{ik} R_{kj} + P_{ij} R_{ij}.$$

We rewrite the last expression in matrix form

$$R = \|R_{ij}\| = PR = P(R - R_{dg}) + PR_{dg},$$

where R_{dg} is the diagonal matrix obtained from the matrix R by replacing the diagonal elements with zeros.

For an ergodic embedded chain, there is a unique solution vector. If we denote, then $R = R_{dg} + R_0$, then

$$R_{dg} = (P - I)R_0 + P, \quad (1)$$

I is an identity (unit) matrix of dimension $N \times N$. Multiplying both sides of expression (1) by the vector π , we get

$$\pi R_{dg} = \pi P = \pi,$$

π is a vector, stationary probability distribution of states. Consequently, $R_{dg} = I$ and we can finally write

$$R = P(R - I) + P.$$

In particular, $R_{ij} = \sum_{k \neq (j, i)}^N P_{ik} R_{kj} + P_{ij}$. This result is

also true for embedded circuits with communicating states. If a process has no absorbing states and the total number of states is finite, then it is always possible to specify a route of finite length, following which the process can move from one state to another in a finite number of steps.

The average number of steps m_{ij} before the first transition from state i to state j satisfies the renewal equation

$$m_{ij} = \sum_{k \neq (j, i)} P_{ik} (m_{kj} + 1) + P_{ij}.$$

From this expression it follows that the average number of steps required to return the process to state i ,

$$m_{ii} = \frac{1}{\pi_i}.$$

Timing function of unconditional staying of a process in a state i

$$F_i(t) = \sum_{k=1}^N P_{ij} F_{ij}(t). \quad (2)$$

If μ_{ij} is the average time, corresponding to the distribution $F_{ij}(t)$, then from expression (2) one can obtain the average time μ_i of the unconditional staying of the process in the state i , namely

$$\mu_i = \sum_{k=1}^N P_{ik} \mu_{ik}.$$

Let l_{ij} is the average time until the process first gets from state i to state j , then

$$L = \|l_{ij}\| = P(L - L_{dg}) + M, \quad (3)$$

where M is a matrix whose elements are unconditional averages μ_i ; L_{dg} is a diagonal matrix obtained from a matrix L by replacing non-diagonal elements with zeros.

Expression (3) can be written as

$$l_{ij} = \sum_{k \neq i}^N P_{ik} l_{ij} + \mu_i.$$

Accordingly, for the average time to return to the state i

$$l_{ij} = \frac{1}{\pi_i} \sum_{k=1}^N \pi_k \mu_k. \quad (4)$$

For the average operating time of a locomotive in the state j of a process between two subsequent entering into the state i

$$\varphi_{ji} = (\pi_j / \pi_i) \mu_i,$$

where $\frac{\pi_j}{\pi_i}$ is the number of transitions in to state j . It

follows that $l_{ij} = \sum_{j=1}^N \varphi_{ij}$.

Let us introduce the probability of transition from state i to state j in a time not exceeding the time t

$$P_{ij}(t) = P_{ij} F_{ij}(t).$$

Smith's theorem [16] for finite processes with communicating states says that

$$\lim_{t \rightarrow \infty} P_{ij}(t) = \frac{\mu_i}{l_{ij}}. \quad (5)$$

For any $\mu_i < \infty$ and arbitrary functions

$$F_i(t) = \sum_{j=1}^N P_{ij}(t).$$

Expression (5) represents the operating factor in state j . In particular, if the state j is the target one of the

operation process, then $\frac{\mu_i}{l_{ii}}$ can be defined as the target

function of the technical operation process. It can be considered as an operating factor, and its maximum can serve as an optimality criterion for the process of technical operation of locomotives.

Denoting the operating factor $K_j = \frac{\mu_j}{l_{jj}}$, and using expression (4), we can write down

$$K_j = \frac{\mu_j}{\mu_j + \frac{1}{\pi_j} \sum_{k \neq j}^N \pi_k \mu_k}. \quad (6)$$

From here it follows that $K_j > 0$ for all D_j and

$\sum_{j=1}^N K_j = 1$. Therefore, K_j there is a possibility. Since

K_j is a probability function P_{ik} , then it is a characteristic of the process of technical operation of locomotives and hence can serve as its target function. Formally, this means that the maximum K_j can be accepted as one of the optimality criteria for the process of technical operation of locomotives.

From expression (6), through simple algebraic transformations, one can obtain a series of specific criteria for the efficiency of the technical operation process that are widespread in practice, in particular the specific costs for technical operation. From expression (6) one can, for example, obtain,

$$K_j = \frac{1}{1 - \frac{1}{\pi_j \mu_j} \sum_{k \neq j}^N \pi_k \mu_k}. \quad (7)$$

The expression in the denominator (7) is often called the coefficient of average specific losses and is denoted

$$\tau_i = \frac{1}{\pi_j \mu_j} \sum_{k \neq j}^N \pi_k \mu_k. \quad (8)$$

To maximize K_j in (7) it is enough to perform minimization τ_i . Reducing the value τ_i is possible primarily due to the redistribution of probabilities π_j and π_k , as well as the reduction of μ_k .

In the case when, instead of average times μ_k average costs C_k of staying in states $k = 1, 2, \dots, N$ are introduced, from expression (7) it is possible to obtain an economic optimality criterion for the process of technical operation and repair of locomotives.

$$\begin{aligned} K_{jc} &= \frac{\pi_j C_j}{\pi_j C_j + \sum_{k \neq j}^N \pi_k C_k} = \\ &= \frac{1}{1 + \frac{1}{\pi_j C_j} \sum_{k \neq j}^N \pi_k C_k}. \end{aligned} \quad (9)$$

If we assume that each hour of use of the locomotive in the target state gives an average specific income d_j , then we can say that the incomes in the target state are $C_j = d_j \mu_j$. Substituting this expression into (9), we get

$$K_{jc} = \frac{1}{1 + \frac{1}{d_j} \sum_{k \neq j}^N \frac{\pi_k C_k}{\pi_j \mu_j}} .$$

The expression determined by the factor for the element $\frac{1}{d_j}$, is called the average unit cost C_j for the technical operation and repair of an object. If $d_j = \text{const}$, then the maximum K_{jc} is achieved by minimizing the expression

$$C_j = \frac{1}{\pi_j \mu_j} \sum_{k \neq j}^N \pi_k C_k . \quad (10)$$

As the optimality criteria for the process of technical operation of locomotives expressions $\max K_j (\min \tau_j)$ and (or) $\min C_j$, (6), (8) and (10) can be selected. In accordance with these criteria, optimal maintenance and repair strategies are determined in relation to individual nodes and assemblies of locomotives.

The idea of getting the most profitable strategy is as follows. For some initial process of technical operation of an object, it is assumed that the corresponding maintenance and repair strategy does not consider the technical condition of a particular object.

The value of the target function in this case will determine the quality of the initial strategy. Then a maintenance and repair strategy is defined, partially including the technical conditions of specific objects, and a new value of the target function is found. If it turns out that it is better than the original one, then it can be argued that the second strategy is preferable to the first one.

Next, using the second strategy as the initial one, a new strategy is determined, which already fully takes into consideration the technical states of the objects, i.e., each of its component elements. If this strategy is preferable to the second, then of the three strategies considered it will be optimal. Thus, it seems possible to obtain an ordered sequence of strategies in which one strategy has advantages over others (Fig. 1, 2, 3).

Using diagnostics, one can:

- identify faulty units and subject them to maintenance and repair;
- in faulty units, locate faulty nodes and subject them to inspection and maintenance;
- identify faulty parts and repair only them, etc.

The more deeply the technical condition is assessed, the more effective the strategy will be. However, in practice, the implementation of a more effective strategy is associated with additional costs for technical diagnostics [17]. With regard to these costs, the distribution of strategies according to their degree of effectiveness may change significantly. In this case, the optimal maintenance and repair strategy will be the one at which the total reduced costs will be the least [18].

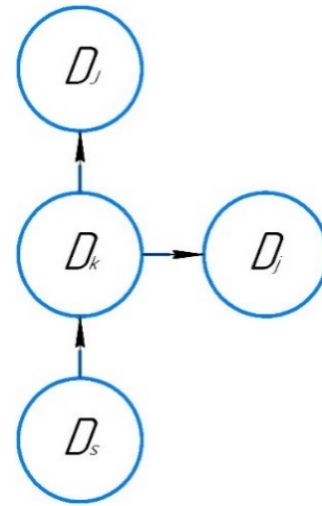


Fig. 1. Graphical representation for the principle of obtaining an optimal strategy for technical operation without taking into consideration the technical condition of the unit

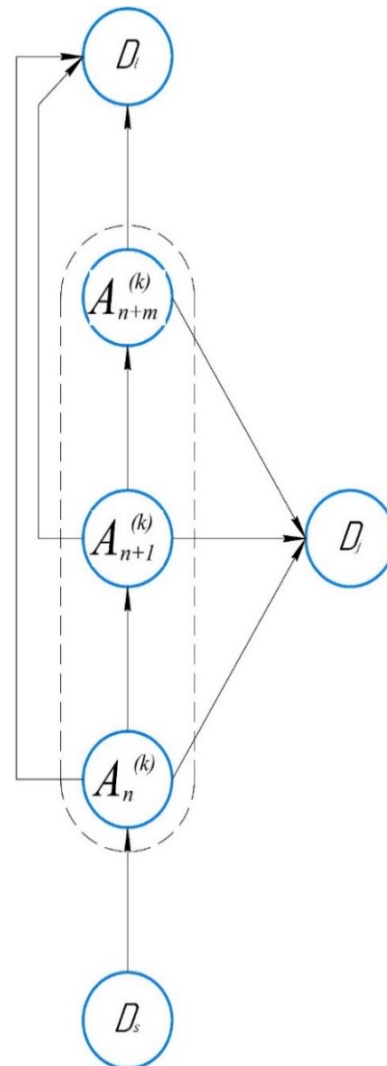


Fig. 2. Graphical representation for the principle of obtaining an optimal strategy for technical operation considering the technical condition of the unit

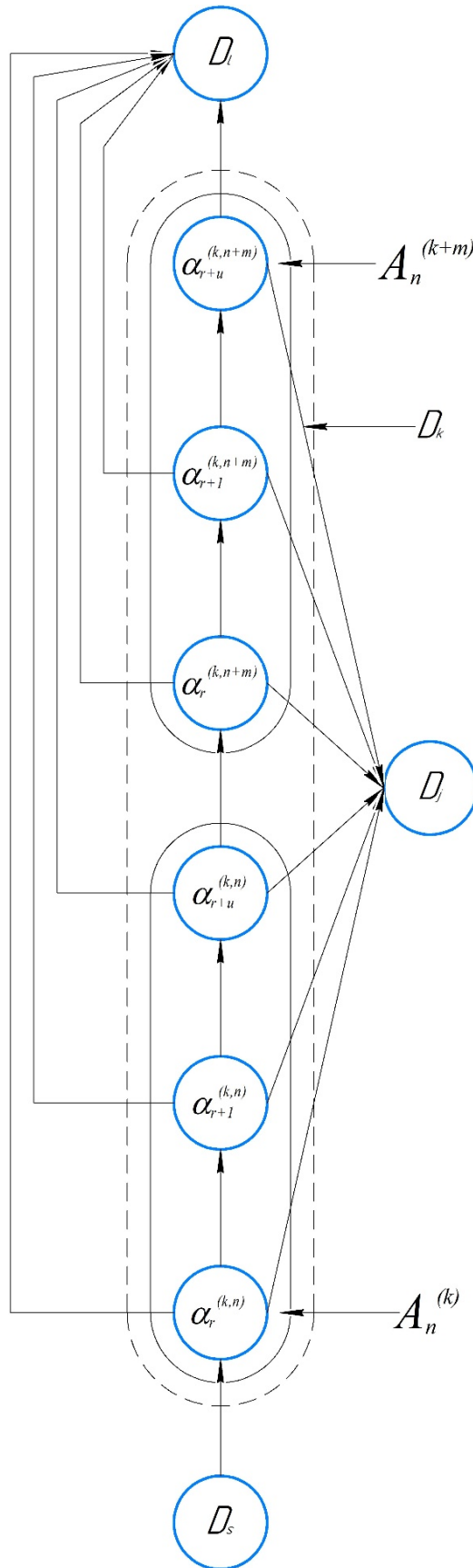


Fig. 3. Graphical representation for the principle of obtaining an optimal strategy for technical operation considering the technical condition of the unit elements

6 Conclusions

The efficiency of locomotive fleet operation significantly depends on the quality of service. The quality of service is determined by the effectiveness of diagnostic tools for technical conditions. The process of operating a locomotive fleet is described by a semi-Markov model. The semi-Markov model used makes it possible to more fully take into account, in the general case, the diagnostic support of the locomotive and the restoration process.

The unit cost function (10), the average unit loss coefficient (8), and operating factor (6) were selected as target functions. A procedure has been proposed for constructing an ordered sequence of improving maintenance and re-pair strategies, considering the condition of a particular locomotive.

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