

На основі описаної проблеми, пов'язаної з незадовільним технічним станом локомотивів на залізницях України, в статті запропоновано метод оновлення парку тягового рухомого складу, який заключається в модернізації існуючих тепловозів, що дозволить зекономити кошти на придбанні нових тепловозів. Ще одним з методів збереження низької вартості оновлення парку тепловозів є скорочення витрат на проведення випробувань, для чого запропоновано удосконалені методи експлуатаційних випробувань, які дозволяють проводити випробування згідно поставленої замовником випробувань мети, з контролем вузького кола параметрів роботи локомотива

Ключові слова: оновлення парку тепловозів, модернізація локомотивів, експлуатаційні випробування, класифікація випробувань

На основе описанной проблемы, связанной с неудовлетворительным техническим состоянием локомотивов на железных дорогах Украины, в статье предложены методы обновления парка тягового подвижного состава, которые заключаются в модернизации существующих тепловозов, что позволит сэкономить средства на приобретении новых тепловозов. Еще одним из методов сохранения низкой стоимости обновления парка тепловозов является сокращение расходов на проведение испытаний, для чего предложены усовершенствованные методы эксплуатационных испытаний, которые позволяют проводить испытания согласно поставленной заказчиком испытаний цели, с контролем узкого перечня параметров работы локомотива

Ключевые слова: обновление парка тепловозов, модернизация локомотивов, эксплуатационные испытания, классификация испытаний

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REFINING THE MODELS OF PERFORMING SERVICE TESTS OF UPGRADED LOCOMOTIVES

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1. Introduction

Admission to the operation of rolling stock provides for mandatory tests, as when buying a new, and in modernizing existing one. The issue of limiting the cost of the acquisition and improvement of existing technology also applies to reduce the cost of testing.

To be able to reduce the volume of tests modernized locomotives, while preserving the authenticity and accuracy of the results accomplished improvement models of operational tests of modernized locomotives.

2. Review of the literature and problem statement

Locomotive department Ukrzaliznytsia (UZ) provides the transportation process on the railways of Ukraine, who occupy the first place in passenger maintenance and second to ensure turnover. All work is done locomotive fleet belonging to the second generation. According to information of Ukrainian Railways (UR) [1], over 90 % of locomotives have

spent their service life. The increasing volume of carriage and the demand in locomotives, as well as natural processes of ageing and wear call for renovating the pool of locomotives.

Renovating the pool of traction rolling stock (TRS) demands vast investments. This is especially topical for cases when purchasing locomotives from abroad (Russia, Czechia, etc.) is considered [2]. Note that Ukraine has its own labour and research and production potential for organising and mastering the manufacture of locomotives at domestic production capacities [3, 4]. The progressive ageing of the pool of diesel locomotives and the inability of its rapid upgrading, as well as a significant reduction in financing the purchase of diesel-powered rolling stock forces major overhauls for upgrading [5].

Upgrading locomotives to extend their service life and improve performance has been practiced worldwide for many years [7–9]. When designing new generation TRS, it is assumed that the total cost of locomotive management facilities shall be reduced during the entire life cycle.

Renovation of the TRS pool in Ukraine's railways, with account of the available potentialities of domestic

research-and-engineering institutions and the industry, is suggested to be done stagewise [8, 9]:

- determine priority enterprises for manufacturing TRS, its completing assemblies and equipment, and managing servicing;
- develop on-board and stationary means for technical diagnostics; develop regulatory documents to change the time between overhaul and maintenance regulations, and to master manufacture of control and diagnostics devices;
- develop, manufacture and test new generation pilot TRS, and its assemblies and systems;
- develop modern systems for maintenance and servicing new generation TRS, and develop relevant regulatory documents (GSTU 32.0.08.001-97, GOST 15.005-86, GOST 15.309-98, GOST 16504-81, OST 32.53-96, OST 32.181-2001, [10]);
- develop a complex of basic technical solutions for new generation TRS assemblies and upgrade assemblies of existing rolling stock (superstructure, bogies, traction transmissions, traction engines, diesels, microprocessor control and diagnostics systems, etc.);
- establish an experts-managed test base at UR for acceptance of new and upgraded TRS, and its systems and assemblies;
- organise and manage TRS certification;
- organise purchase of modern imported TRS of certain types; and
- reform the system of personnel training for operating, servicing and repairing new generation TRS.

3. Purpose and research problems

To reduce the cost of the implemented modernized traction rolling stock necessary to reduce the costs of the operational tests by improving the methods and models of their conduct. Rationalization of the array of control parameters that are monitored during the test, gives an opportunity to reduce the amount of work and the value of their holding.

Operational testing modernized locomotives associated with necessary substantiation their admission to the operation of the railways of Ukraine on certain parameters of reliability and efficiency of TPS. Tests are also carried out for comparison the existing model locomotive with its modernized version, or those which are supposed to be replaced. To achieve this goal were as follows:

1. Conduct an analysis of existing methods and procedures for testing locomotives.
2. Determine the range of technical and economic parameters characterizing the performance tests.
3. Develop measures for rational choice of the range of indicators to monitor the technical condition of locomotives in tests.
4. Improve methods for conducting operational tests of modernized locomotives.

4. Improvement of test methods

Requirements to developing and testing all types of traction rolling stock are set forth in the following regulatory documents and standards: GSTU 32.0.08.001-97,

GOST 15.309-98, OST 32.181-2001, GOST 15.005-86, GOST 3.1507-84, GOST 16504-81, GOST 34.603-92, OST 32.53-96, OST 32.55-96, and Guidelines for preparing and holding acceptance tests of traction rolling stock and its components [10].

The issue of performing service tests of locomotives and assessing their technical level is presently lacking due regard. TRS tests, including service ones in Ukraine, are performed by rolling stock test organisations and at manufacturing plants. The tests per se are supervised by the Interagency Test Commission for acceptance tests (by kinds) of TRS and the task group of the Interagency Commission.

Service tests are performed, as a rule, after acceptance tests of a pilot lot of products have been performed. They are also included in full-scale reliability tests.

Service tests are governed fully or partially by regulatory documents specifying the procedure and conditions for their performance. At the same time, there is no clear definition of types of service tests for upgraded TRS. Using analytical and expert methods, the authors have refined the classification of service tests by their functional purpose. According to the classification target feature, it has been divided in three types with subtypes (Fig. 1). Such classification was done with account of possible requirements of test customers, who can be both manufacturers and consumers of products, for a concrete definition of the objective of performing service tests and their outcome.

The classification suggested shows the classification of service tests into three basic lines of determining characteristics with refinement of objectives for more precise and specific analysis of operation of the upgraded locomotive being tested. According to GOST 16504-81:

- Comparative service tests are tests of two or more characteristic-similar identical objects, which are performed in identical conditions to compare the characteristics of their properties;
- Determinative service tests are tests for determining the values of characteristics of an object with preset accuracy and/or validity;
- Reliability service tests are tests for determining (evaluating) reliability parameters with preset service modes and conditions.

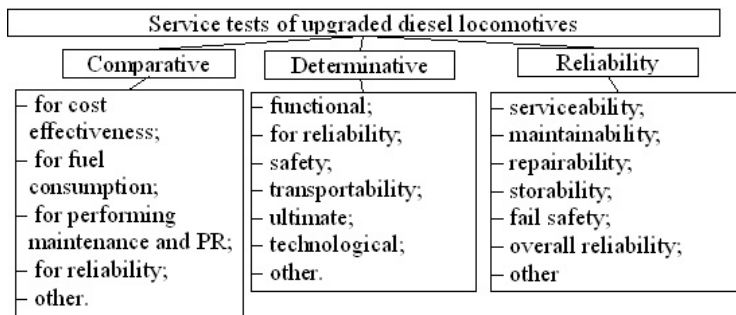


Fig. 1. Classification of service tests for upgraded TRS

This classification meets the requirements to determining relevant performance indicators of locomotive service in running conditions. The set of key check parameters to be controlled during tests has been refined.

To refine service tests, mathematical modelling of the test process [11–13] has been suggested. When building the mathematical model of service tests of upgraded rolling stock, the key tasks are as follows:

1. Determining the optimal number of parameters for observation and finding certain technical characteristics of TRS operation in good condition during a preset time period, and for further usage to determine object reliability;

2. Possibility of forecasting the results of testing new or upgraded rolling stock prior to completion to detect and eliminate ‘weak spots’ in assemblies and systems of the object being tested [11, 12, 14] with the help of the model developed;

3. Reliability forecasting means representing the trends in changes of earlier evaluated reliability of analogous objects or their components with account of design and service conditions changes (DSTU 3004-95);

4. Mathematical modelling of separate kinds of service tests to determine a rational set of TRS performance indicators and the possibility of forecasting test results [10, 13, 15–18]. The objective of service tests is determined with account of manufacturer-specified admissible values of tested object service parameters.

The algorithm of building a mathematical model of service tests of upgraded locomotives ready to run is shown in Fig. 2.

Determining the test type and objective implies offering advantage to the type of service tests, for which parameters and characteristics will be determined or comparison with rolling stock to be replaced will be done. The mathematical model target functions are minimising the cost of tests by rational selection of the number of check parameters, and consequently, cutting costs of determining and calculating these parameters. Constraints on the functions consist in determining test conditions and instantiating the ultimate conditions of rolling stock service during service tests and further service in main railway lines pursuant to regulatory documents. The stage of presenting the method of solving the problem stated envisages submitting a substantiated calculation with the use of source data and data obtained by rolling stock service tests to determine and check predefined parameters pursuant to regulatory documents. The next stage provides for rejection or confirmation of evaluated parameters specified in engineering documentation for TRS manufacture.

Should the model meet adequacy requirements, the solution method is used for producing results. Otherwise, detection, checking and elimination of the cause of incompliance are carried out. After statistical data have been processed and key parameters have been calculated, the results are checked for compliance to regulatory documents with account of errors and tolerances. In the event of compliance, the test results are submitted to the interagency commission, which considers the issue of launching the tested rolling stock into series production. Should the results fail to comply, the level of tolerances is checked and calculations are repeated.

To perform service tests, a test plan (basic requirements) is drawn up. It is the basis of the model and contains the following elements: scope of experiment; content of single experiment and parameters of its completion; experiment procedure; methods for reducing the required scope of experiment based on accounting for a priori information; and solving rule (findings and recommendations).

By comparing problems solved during service tests, their procedure was refined and presented as a logically sequential process of determining stages and the procedure of performing tests with account of selecting the check parameters of operation of upgraded locomotives (Fig. 3).

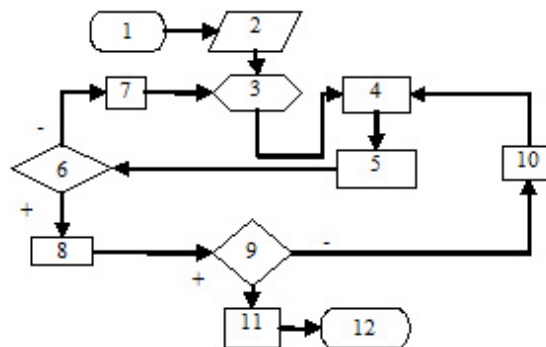


Fig. 2. Service test algorithm: 1 – start; 2 – determining the objective of service tests and determining source data; 3 – specifying the target function; 4 – introducing function constraints; 5 – presenting the problem solution method; 6 – checking test model adequacy; 7 – adjusting possible incompliance causes; 8 – applying the problem solution method; 9 – checking compliance of calculated parameters to standards and engineering documentation for the object being tested; 10 – checking the values of errors and constraints; 11 – making a decision on permitting commissioning and series production of the object being tested by compliance of its parameters to customer’s requirements and the test objective; 12 – end

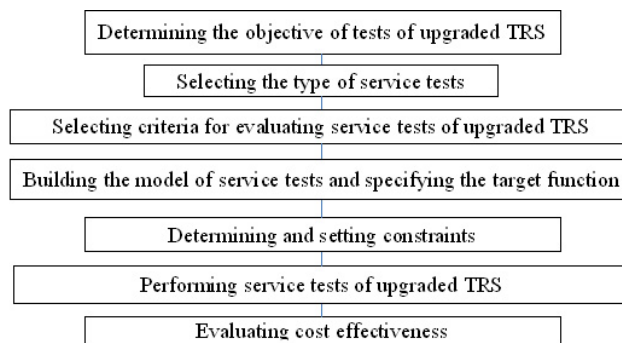


Fig. 3. Procedure for service tests of upgraded locomotive

The procedure developed allows for in-depth consideration of the objective and essence of performing service tests to meet customer’s requirements, establishing the test procedure, collecting information, and determining its volume and result evaluation priorities.

The following efforts are executed according to the stages of the service tests procedure (Fig. 3):

- Analysis of tested TRS data specified in engineering documentation, and establishing objectives for determining the actual parameters of its operation within customer-defined limits;
- Determining the kind of service tests based on the classification developed for reducing the set of operational parameters being determined for the object being tested;
- Selecting evaluation criteria and the set of check parameters depending on the objectives of service tests and determining the impact of selected parameters on test analysis results, and the possibility of reducing their cost;
- Building the mathematical model of service tests, depending on the classification-defined type, for acquisition, analysis and treatment of test information. Specifying the test target function with a detailed statement of the goals

and tasks of tests, and determining means for actualising the given problem;

– Determining constraints on the set of test check parameters and composite evaluation criteria, which define admissible values of parameters;

– Investigation trips to the test site while observing service conditions according to service documentation; and

– Calculating results for evaluating the cost effectiveness of a locomotive; making conclusions and recommendations on the expediency of commissioning the given locomotive and applying the given service test method.

– To generalise the selection of the array of check parameters during TRS service tests, a common array has been formed to describe locomotive operation. With account of that certain locomotive parameters (weight on working order and weight on drivers, load on wheel set axle, and minimal radius of curve run by the locomotive) are constant, they need no continual checking during service tests.

$$\Pi_{loc} = \left\{ \begin{array}{l} P(t), T_m, T_o, T_y, \lambda(t), f(t), \Pi^L, \Pi^M, \Pi^{St}, \Pi^{IRC}, \\ g_e, S, P_{loc(max)}, V_{(max,c,s,o)}, F(v)_{(c,max)}, W_w, G_{FER}, \\ J_{PROD}, Q_{(max,rated)}, (t, n, l)_{(M-2, M-3, RR-1, RR-2, RR-3)} \end{array} \right\} \quad (1)$$

$P(t)$ – no-failure probability; T_m – mean time to failure; T_o – mean time between failures; T_y – gamma-percentile time to failure; $\lambda(t)$ – failure rate; $f(t)$ – time-to-failure density function.

Π^L – life characteristics: mean life, assigned operation time, mean service life, assigned lifetime, gamma-percentile life, and gamma-percentile service lifetime; Π^M – maintainability characteristics (probability of restoration, mean time to restore normal operation, and renewal rate); Π^{St} – storability characteristics (mean storage time and gamma-percentile storage time); Π^{IRC} – integrated reliability characteristics (availability factor, operational availability factor, and steady state availability factor); g_e is specific consumption of fuel and energy resources (FER) per unit work done, kg/tkm gross; S – locomotive run, km; $P_{loc(max)}$ – locomotive power (maximum), kW; $V_{(max,c,s,o)}$ – locomotive speed (maximum, continuous, service, operative), km/hr; $F(v)_{(c,max)}$ – locomotive traction force (continuous, maximum), kN; W_w – kind of work performed by the locomotive; G_{FER} – FER consumption for hauling operations, kg/kW×year; J_{PROD} – average daily locomotive capacity, tkm gross; $Q_{(max,rated)}$ – train weight (maximum, rated), t; $(t, n, l)_{(M-2, M-3, RR-1, RR-2, RR-3)}$ – respectively, time, quantity and locomotive run for performing requisite maintenance and routine repair cycles.

Depending on the kind of service tests and tasks, a rational array of characteristics M_i^p has been defined, which are checked during service tests. It includes the characteristics of standard locomotive operation stated in the TOR, which should be maintained during service tests and further operation:

$$M_i^p = \{V_i, P_{loc}, F(v)_i, g_e, S_i, Q_i, t_{M-2}, t_{M-3}, t_{RR-1}, t_{RR-2}, t_{RR-3}\}. \quad (2)$$

The array of characteristics of a locomotive undergoing service tests takes the form:

– for serviceability:

$$M_{loc}^{serv} = \left\{ \begin{array}{l} V, P_{loc}, F(v), g_e, S, Q, \Pi^M, \Pi^{St}, \Pi^{IRC}, \\ W_w, G_{FER}, J_{PROD}, t_{M-2, M-3, RR-1, RR-2, RR-3} \end{array} \right\}; \quad (3)$$

– for reliability:

$$M_{loc}^{rel} = \left\{ \begin{array}{l} V, P_{loc}, F(v), g_e, S, Q, t_{M-2, M-3, RR-1, RR-2, RR-3}, \\ P(t), T_m, T_o, T_y, \lambda(t), f(t), \Pi^L, \Pi^M, \Pi^{St}, \Pi^{IRC} \end{array} \right\}; \quad (4)$$

– for comparative service tests and cost effectiveness tests:

$$M_{loc}^{comp} = \left\{ \begin{array}{l} T_m, T_o, \Pi^L, \Pi^M, \Pi^{IRC}, V, P_{loc}, F(v), W_w, Q, \\ G_{FER}, J_{PROD}, g_e, S, (t, n)_{M-2, M-3, RR-1, RR-2, RR-3, M-2} \end{array} \right\}; \quad (5)$$

– for determinative service tests:

$$M_{loc}^{det} = \left\{ \begin{array}{l} V, P_{loc}, F(v), W_w, \\ G_{FER}, g_e, S, Q_{max} \end{array} \right\}. \quad (6)$$

Refining the given method for obtaining exhaustive information when performing service tests of an upgraded TRS is presented as a sequence of requisite processes. It consists in determining the set of parameters included in the comparison criterion.

The check parameters for a certain type of service tests are determined from the general set of locomotive performance indicators with account of the goal defined by the test customer.

Statistical data are accumulated and tests are monitored according to the generated set of parameters. To create a rational set, expert methods were used to assign weights to parameters with account of the theory of sets and quantitative characteristics as for non-uniform criteria, and reducing to one ordinal scale of evaluation specifying the sequence and priority of determining the characteristics. To establish the composition of a rational set for respective types of service tests, the parameters weight factor should be determined. A definite weight factor will point to the necessity of including the check parameter in the respective set.

In this case, the parameters weight factor is determined by expert exhaustive methods. This procedure allows determining a reasonable number of check parameters by a higher weight factor, which will affect the result of a service test and reduce labour input for data acquisition during tests. The expert ranking method is also used for arranging parameters by groups according to their significance.

The method implies that experts arrange locomotive performance indicators in order of their importance or significance ranking. The position thus specified is called a rank. In so doing, the highest rank is assigned to a more significant indicator related to the given kind of test.

To determine the weight factors for the performance indicators of the locomotive being tested, the sum of ranks for each evaluation object is calculated:

$$S_{ij} = \sum_{i=1}^n \sum_{j=1}^m x_{ij}, \quad (7)$$

S_{ij} – sum of ranks of i -th parameter specified by j -th expert;
 n – number of parameters considered; m – number of experts;
 x_{ij} – evaluation of factor i by expert j .

Based on definite total ranks, weight factors g of locomotive performance indicators for performing tests are found:

$$g_i = \frac{\sum_{j=1}^m x_{ij}}{\sum_{j=1}^m \sum_{i=1}^n x_{ij}} \tag{8}$$

To obtain results of calculating weight factors by their values, check parameters are grouped to establish the degree of validity of test results. This evaluation parameter depends on the number of parameters included in groups by the weight factor value.

The degree of validity of test results is found using the formula:

$$m = \frac{\sigma}{\sqrt{n}} \tag{9}$$

σ – root-mean-square deviation; n – number of check parameters for service tests, which are included in groups.

$$\sigma = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n}} \tag{10}$$

x_i – analysed indicator (parameter weight factor value);
 \bar{x} – mean indicator value in the group.

The procedure of selecting locomotive performance check parameters, with account of the service tests target function – reducing the total cost of testing – allows reducing the set of check parameters to the requisite minimum by excluding from the set some parameters, which are irrelevant for meeting the objectives of the service tests.

Selecting a reasonable number of check parameters is considered a nonlinear programming optimisation problem. This involves a big number of parameters and their nonlinear change with respect to duration of tests and work performed, and forming a system of constraints on performing tests based on an array of check performance indicators. These actions have been done to obtain valid test data. Since service tests are described by the functional dependence of test costs on the scope of check parameters and test constraints, the given problem is an optimisation one with constraints. In general form, the service tests target function takes the form:

$$E_i^{bump} = f(X_i, \Pi_i^{loc}, K_i^{bump}) \Rightarrow \min, \tag{11}$$

i – type of service test for traction rolling stock; X_i – performance indicators selected for checking and monitoring during tests; Π_i^{loc} – array of parameters describing the locomotive technical condition

$$X_i \in \Pi_i^{loc}, \tag{12}$$

K_i^{bump} – service tests evaluation criterion.

In explicit form, the target function can be written as follows:

$$E_i^{bump}(X_i) = C_{(X_i)}(\text{rasch.param.}) + C_{(X_i)}(\text{spost.param.}) \cdot T_{mon} + LC_{(X_i)}(\text{ispit.org.}) \cdot T_{bump} \Rightarrow \min, \tag{13}$$

$C_{(X_i)}(\text{rasch.param.})$ – cost of calculating the operational parameters of the tested locomotive, the cost being dependent on the size of the array of check parameters; $C_{(X_i)}(\text{spost.param.})$ – cost of monitoring check parameters (array of check indicators) during service tests; T_{mon} – time of monitoring and registering values of locomotive performance check parameters; $LC_{(X_i)}(\text{ispit.org.})$ – labour costs and payments to piece-rate workers of a testing organisation engaged in locomotive service tests; and T_{bump} – duration of locomotive service tests.

To make more specific the defining of performance indicators and ensuring calculations, several constraints are imposed on the test procedure, including check indicators. These constraints specify the conditions when the service tests shall be considered invalid with results being calculated with insufficient accuracy:

$$\begin{cases} T_j \leq T_{max}; P'(t) > P'(t)_{min}; \\ K_{TA} > K_{TAmin}; n_{loc.cr.}^s = n_{loc.cr.}^u \end{cases} \tag{14}$$

The constraints are as follows: T_j, T_{max} – times of performing tests, respectively, time of testing with locomotive and maximum full time of testing, days; $P'(t), P'(t)_{min}$ – locomotive no-failure probability, respectively, actual and minimal; K_{TA}, K_{TAmin} – locomotive technical availability coefficient, respectively, actual and minimal; $n_{loc.cr.}^s, n_{loc.cr.}^u$ – number of locomotive crews servicing the locomotives during comparative service tests, respectively, with a series-production locomotive and an upgraded one.

To solve the target function, nonlinear programming dual methods were used. They allow for easy problem solution when realising an iteration process and optimising the array of check parameters for performance of upgraded locomotives. They also reduce the cost of monitoring and calculating performance indicators and, consequently, reduce testing costs.

Test results are validated provided two conditions are met:

- Sufficient accuracy of test results;
- Results non-repudiable by any other calculations.

5. Conclusions

The results of the research provide an opportunity to solve the scientific problem of improving the process of operational tests of modernized locomotives through the choice of a rational number of parameters monitored during the operations.

Established methods used in the refinement of the classification performance test methods and improvement of their holding. The basic principles of mathematical models and the choice of nomenclature benchmarks by type of performance tests.

The dependence of the degree of reliability of the results of operational tests of modernized locomotives on the number of control parameters, which allowed the development of

a model of operational tests of modernized locomotives on the basis of a rational nomenclature performance tests.

Refined classification performance tests modernized CBP purposes for. Determine the purpose and need for the performance test, which consists in evaluating the tests identified in the technical parameters, developed according

to the type of classification and admission to regular operation on the railway network of Ukraine modernized locomotives as the test object.

To determine the range of rational parameters during performance tests designed corresponding mathematical model. Its objective function is to minimize the cost of the tests.

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