Research of improved mathematical models at operational tests of diesel locomotives

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S u m m a r y . This paper presents the application of mathematical simulation studies at new locomotives operational testing.
The basic specification is determined that defines conditions, procedures, and amount of operational tests. The general procedure of operational tests is defined on the basis of which the ways of models improvement is described. Group of parameters is proposed and formed that describe the operation of traction rolling stock and have to be determined at operation. Goals of operational testing operation are defined, that allows range of control parameters and volumes of works for the gathering of statistical data narrowing. The possibility of improved models using for modernized locomotives operation in concerning new locomotives is determined. The possibility of replacing certain stages of operational tests implementation by mathematical simulation, which provides possibility of the total cost of operation reducing, is determined. The dependence between operational testing goals and control parameters is defined, which are determined during their operation. The dependence between the volume range of control parameters determined during the test and the reliability of their results, which also determines the operation cost, is defined. Benefits of improved operation models application comparing with existing developing diesel traction rolling stock are defined.
K e y w o r d s : diesel locomotives, operational tests, mathematical model, control parameters, test results.

INTRODUCTION

To ensure the transportation process on the railway network of Ukraine and maintaining the technical condition of traction rolling at a high level it is necessary to supply the rolling stock of railway enterprises [1]. It is also necessary to carry out tests after its manufacturing or upgrading. For operational characteristics of the rolling stock determining and verification of the specified values in the technical documentation operational tests are carried out (operational tests - tests carried out at operation [2]). For traction rolling stock they are power consumption, trains weight norms at concrete area, reliability, maintainability etc. Thus, entire group testing, and appropriate corrective actions results are key elements of any development. Undoubtedly, testing is technological process that is planned and provided by all necessary resources and strict technology compliance is quality guarantee, meeting deadlines is the key to success. Technology development and operational on the basis of experience is creative process based on analysis of carried out scientific researches and experimental operations, knowledge of standard base and scientific development trends and forecasts [2, 3]. Without passing the entire test cycle, including maintenance, in accordance with the regulations on the creation, development and production of products, vehicles may not be admitted to regular use, which is associated with the possibility of occurrence of situations that can lead to disastrous consequences, both for locomotive teams, and the entire surrounding space.

In terms of public sector financing and upgrading of rolling stock reducing and the growing trend of railways electrification in Ukraine, the actual question of diesel locomotive buying reduction that by-turn complicates tests financing. However, diesel locomotives are still necessary for rail traffic on diselectrified areas and switching services. With the development of intelligent control hardware and implementation of on-board diagnostic systems and predicting changes of technical condition in new locomotives becomes possible when tested using the accumulated information for further modeling of their work. Way out of this situation is the use of mathematical modeling in the performance tests. This procedure, using mathematical tools of mathematical and statistical methods and forecasting expertise allows forming a mathematical description of physical processes of normal operation test locomotive, or allows you to make assumptions about the acquisition of a test object technical condition stipulated in consequence of his actions. In this case, mathematical simulation makes possible replacing some stages of testing that simplifies and reduces their implementation cost.

MATERIALS AND METHODS

One of the methods proposed for the upgrading of railway rolling stock is existing diesel upgrading with partial or full technical retooling and conduct a number of technical operations for checking and confirmation possible extension of the object. Thus, to assess changes in its condition over the extended life, the various methods those are based on accumulated data for the entire operation and different methods of assessment using various technical and software, both known and individually designed are used [4-6].

According to regulative documents [2, 7-9], which regulate products development and production, locomotives without fail must pass through number of tests, which include operational tests. This type of testing provides verification or identification of all operating parameters established or modernized locomotive that can be achieved at the locomotive work. Testing necessity is noted in [3, 6, 10, 11], which defines the basic principles of General Assessment complex testing and performance testing for critical components including new and modernized rolling stock using control systems to extend their service. In these works is considered in addition to the technical aspects of testing, from the point of view of the changes of the vehicle and the change in value of the life cycle, depending on technical service and operational needs.

As it is shown in publications [11-14], determining the parameters of new locomotives will not necessarily require control of all working parameters list, some of which are fixed at the stage of preliminary tests or using mathematical simulation.

The authors of [15-20] offer wide range of technical state criterions based on multivariate analysis of components using, diagnosing business processes, and mathematical simulation individual processes of interaction and simulation of cost reducing operations. Based on said above and also existing methods that anticipate monitoring and analyzing the full range of traction rolling stock parameters during the operational test, the improved model of their carrying out is formulated [21].

OBJECT OF INVESTIGATION AND PROBLEMS

It is necessary to determine the applicability of advanced mathematical models of operational tests of modernized locomotives for testing new or modernized locomotives to test their technical parameters before admission to regular operation.

From the point of view of necessity of locomotives tests carrying out we need to determine the operational tests types, the volume of sample benchmarks locomotives and models of their carrying out for the possibility of testing the first sample of rolling stock and then sending it into operation. This problem is solved by control parameters optimization using the information obtained from on-board intelligent system management and diesel diagnostics system.

The analysis of procedures for operational testing of locomotives indicates on necessity of determination changes in performance parameters at locomotive run. During any type of performance testing provides total control specified parameter list of the engine according to the established procedure.

To determine the performance of the new traction rolling stock during the type test performance we recommend to use their implementation improved methods. Its feature is the use of a rational nomenclature benchmarks that will control the parameters of the test object changes depending on the test purpose. Thus to evaluate the nodes that are used on other types of rolling stock may use the collected statistical base with regard to design locomotive and operation area.

The following methods were used at locomotive operational tests:

a) methods of statistical information analysis and calculation of their uptime probability and methods of mathematical statistics and probability theory are used to analyze and collect statistics on locomotives work during trials to determine the effectiveness of their use in freight movement on the main railway tracks of Ukraine,

b) numerical methods are used for solving equations of modeling and optimization theory for refinement of structural formulas classification and development to create models operational tests. Analytical and expert methods of comparison are used for targets selection. Methods of heuristic forecasting, iterative and variational calculus are used to fulfill the criteria comparing the results of performance tests of TRS. Methods of statistical results analysis are applied to determine the results of the developed mathematical model of testing performance.

Expert methods of reasonably estimating the operational parameters, methods of predicting resource and diagnostics are used for the task of improving the process of modernized locomotives operational testing.

Methods of statistical simulation based on accumulated statistical data are applied at improving the operational test operation.

Conditional methods of optimization and nonlinear programming methods are used at constructing and verifying the mathematical models correctness (verifying mathematical model adequacy) [22].

Methods of mathematical statistics, theory of locomotive traction and traction calculations are used to determine the fuel and oil discharge for traction trains at operational tests.

Empirical assessing methods for the technical object condition examination are used at assessing locomotive operation working ability.

Existing procedure of operational tests are improved and can be generally described as the next logical consistent steps:

- determining of purpose of TRS operational tests. At this step, the test's customer (the manufacturer or product's consumer) determines the desired testing result,

- choosing of type of operational tests. This step involves the installation of concrete type of operational tests according to the conducting purpose,

- evaluation criteria and TRS benchmarks range depending on the purpose choosing. The choice of evaluating test results criteria is made after defining the purpose and determining the operational tests type. The nomenclature of control indexes, which will be monitored and recorded during their implementation, is defined to get data about operational tests and criteria calculation. This procedure provides choosing by qualified expert team the necessity list of work parameters of diesel locomotive examination by exhausting and assessing the impact of each parameter on the total range of tests outcome, which is defined by their purpose,

- creation of operational model, formulating of objective function. Step provides mathematical model of operational testing creating, based on the purpose and definition of criteria for evaluating the test results. Also in mathematical model there is the plan of observing test progress, which will determine the accumulation of reliable data,

- setting limits taking into account control indexes, operational tests operation, statistic data collecting. This step of operational tests operation provides limiting operation according to the purpose of carrying out the test and the plan of observations. After all conditions are provided, tests themselves are carrying out, in which the locomotive is performing certain types of work on the railroad and areas of statistical database is forming,

- analysis and data processing, test results evaluating. After all tests are carried out the evaluation and calculation of indexes starts, which according to the established purpose will give detailed data about the results of their implementation and customer response as for the further effective work of the tested locomotive.

The procedure of operational tests operation is developed as for evaluation criteria and control TRS indexes choosing according to the purpose (Fig. 1). The method of determining the nomenclature of control parameters in order to get the results of operational tests operation of diesel locomotives is improved for this reason, which unlike existing methods considers determining the parameters influence.

It is necessary to define technical and economic parameters in order to describe various parameters of the tested locomotives. Let's grouped them into the corresponding arrays:

$$\Pi_{lok} = \{M_l^{nad}, M_l^{f \cdot pr \cdot}, M_l^{ekspl.}, M_l^{TO,PR}\}, \quad (1)$$

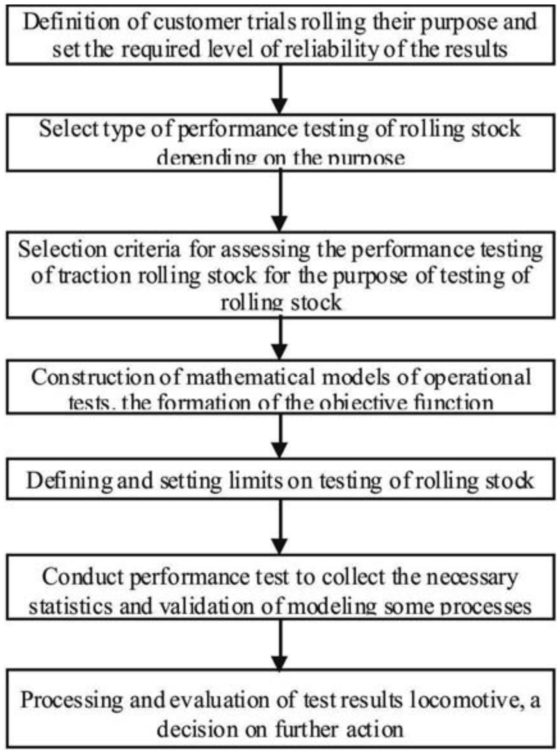

Fig. 1. Scheme performance testing procedure of rolling stock

where: Π_{lok} is the total array of locomotive factors at operational,

M_l^{nad} is array of locomotive reliability. This array includes the next factors: reliability factor, durability factor (average resource, assigned resource, average durability, assigned durability, gamma -percent factor, gamma percent durability), maintainability factor (probability of recovery working condition, average recovery time working condition, intensity recovery), safety indicators (average safety term, gamma-term safety term), complex reliability (coefficient of readiness, operational readiness rate, rate of technical use),

$M_l^{f \cdot pr \cdot}$ is array of functional locomotive purpose. This array includes the following factors: structural speed, power, service weight, changing the load from the axis of the wheel pair on the track, speed of prolonged regime, continued tractive force,

$M_l^{ekspl.}$ is array of operational locomotive factors. This array includes the following factors: the operational locomotive speed, technical speed, operating type works, specified locomotive weight, fuel-power recourses discharge (PER) for locomotive traction, average daily locomotive efficiency, specific PER discharge per unit of performed work, mileage, tractive force,

$M_l^{TO,PR}$ is array of technical operational and repair locomotives factors. This array includes: time cycles of service and operational (TO) and routine repairs (PR), the number of TO and PR cycles, run cycles between TO and PR.

Evaluation of operational TRS tests is performed by composed nomenclature of control work parameters according to the the purpose, tasks and test type. The analytical base of statistic data of tested locomotives is formed on this basis.

The current method of determining the nomenclature of control indicators is based on their definition according to the type of tests by regulations. Improvement of the method of obtaining complete data during operational TRS testing sequence seems necessary processes and consists in determining the range of indicators that are included in the comparison criterion.

Expert ranking methods are used to determine rational nomenclature indicators. Owing to this, their quantitative characteristics are determined normalized to one ordinal grading scale, which determines their order and importance. The ponderability of indexes is determined by the values of ranks that are set by qualified experts at control parameters analyzing, which form the general nomenclature. This procedure consists in determining the priority of indicators monitoring for the type of operational test by experts.

Data collection during the service tests modernized locomotives performed using a combination of statistical methods for input and control methods for quantitative traits, which involves the use of appropriate sampling quality control, based on the application of mathematical statistics to verify compliance with the requirements of product quality and action, and also measure and record the numerical values of the trait for each unit of this group are designed to match with some continuous scale.

The accumulation of statistics and performance sampling test results performed formed range of indicators used to create any expert methods of weight parameters, given that their composition is described by the theory of sets, and then determine their quantitative characteristics for both uniform criteria and carry them to bring one ordinal grading scale, which is determined by the order and the importance of determining characteristics. For installation of a rational nomenclature according to the types of performance tests to determine the weight coefficient of performance. Definite weight ratio would indicate the need for inclusion of quality products (benchmark) to the respective nomenclature.

The methods of determining the weight coefficient of performance include analytical, expert and sociological methods, and methods based on the analysis of the impact of quality products on the effectiveness of its creation and use or consumption.

Determination of parameters of importance in this case is the expert ranking methods. This procedure will determine a rational number of control parameters in a higher weight factor that will influence the result of start-up and will reduce labor content operations to collect data in their testing. Expert ranking method is also used for the distribution parameters into groups according to their importance.

This method consists in placing expert performance engine in order of importance or advantages in weight. Attention is paid to so called rank. It is assigned the highest rank for a more meaningful indicator relating to conduct this type of test.

All involved experts who established the benefits of monitoring indicators in tests in accordance with their beliefs consider the following list of parameters : the duration of the tests of experimental trips , the probability of failure-free operation , technical speed (in loaded , empty and average per trip), volume work (Freight), the total mileage engine during testing average mileage of locomotives during trials, the total fuel consumption, average fuel consumption of the train (train loaded, empty, average per trip), the total consumption of oil, the average weight of the train (in loaded condition, empty , for the trip), productivity (in the loaded condition, empty, on average per trip), the total consumption of sand (for travel and all-time studies), duration of TO-2, the number of TO-2, ran to the TO-2, the coefficient of availability, MTBF, the probability of recovery, the recovery of working locomotive labor content recovery medium term of safety, failure rate, the rate of operational readiness rate of technical applications, construction speed, engine power, mass locomotive change in axle load locomotive speed long regime thrust long mode, normalized weight train duration TO-3, the number of TO- 3, run to the TO-3, duration of PR-1, the number of PR-1 to PR mileage-1, the duration of the PR-2, the number of PR-2, PR mileage to 2, the duration of the PR-3, the number of PR -3, PR mileage to 3.

The procedure for selecting the control parameters of the engine, taking into account the objective function of operational testing - reducing the overall cost of their implementation, can narrow the range of control parameters to the minimum required by the exclusion from the number of parameters that do not appear to meet the primary goal of operational testing and indirectly their characterize and call themselves enough time for a significant portion control and processing parameters that affect the length, volume, which specifies the observation plan and a list of restrictions on the type of operational test in comparison with the existing method, which made establishing a list of all range performance of the engine during testing.

The basic data defining the number of parameters that are relevant groups (range), and the value of the degree of reliability is the weight factor and the number of parameters corresponding to the specified limit entry to the group, respectively. Valuation tests performed on these same parameters.

Forming groups of indicators to determine the degree of reliability indices is as follows:

- Set the value of the weight ratio of control parameters, which should not be exceeded,

- As defined by the coefficient determined by the number of control parameters, perform this condition,

Of the obtained number of indicators and the level of significance of the coefficient determined by the degree of reliability of test results.

Cost of comparative performance tests of serial and modernized locomotive type M62 on economic efficiency is based on the received range of control parameters, test length and the number of people involved.

The calculation of the ranks sum for each object of the assessment is carried out to determine the ponderability coefficients of tested diesel locomotive performance engine performed as follows:

$$S_{ij} = \sum_{i=1}^{n} \sum_{j=1}^{m} x_{ij} \, , \tag{2}$$

where: S_{ij} is sum of ranks of the *i*-th parameter by *j*-th expert,

n is number of considered parameters,

m is number of experts,

x_{ij} is evaluation of *i* factor given by *j* expert.

Determination of weight coefficients *g* of locomotive working factors for testing is based on defined sum of ranks by the well-known formula:

$$g_i = \frac{\sum_{i=1}^{n} x_{ij}}{\sum_{\substack{i=1 \\ j=1}}^{n,m} x_{ij}} \, . \tag{3}$$

The excess of the ponderability coefficient value of the specified value is the condition getting of control indicators to the group.

We use known formula to determine the degree of test results reliability:

$$m = \frac{\sigma}{\sqrt{n}}, \tag{4}$$

where: σ is standard deviation,

n is number of control parameters during operational tests operation, which are in group.

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \overline{x})^2}{n}}, \tag{5}$$

where: x_i – analyzed index (the weight coefficient parameter),

$\overline{x}$ – mean values of the group.

The procedure of control parameters choosing of the diesel locomotive work, taking into account the objective function of operational testing – reducing the overall cost of their implementation, allows narrowing the control parameters nomenclature to the minimum required by excluding the number of parameters that do not appear to meet the primary goal of operational testing and characterize them indirectly and need much time for significant portion control and processing parameters that affect the continuity, volume, which specifies the observation plan and list of restrictions on the type of operational test in comparison with the existing method, which made establishing list of all nomenclature of diesel locomotive work indicators at testing.

The results of calculations for convenience has been kept to a Table. 1 and shown in Fig. 2.

Table 1. Determining the reliability of test results and the cost of their implementation by the number of targets

Factor of importance, at least	Number of parameters	Dispersion	Mean-square deviation	The reliability of test results
≥ 0,04	4	9,17×10^{-07}	9,57×10^{-04}	0,10
≥ 0,035	10	6,06×10^{-06}	2,46×10^{-03}	0,12
≥ 0,03	14	1,92×10^{-05}	4,38×10^{-03}	0,25
≥ 0,025	18	3,11×10^{-05}	5,58×10^{-03}	0,59
≥ 0,0225	20	3,84×10^{-05}	6,20×10^{-03}	0,89
≥ 0,02	21	4,45×10^{-05}	6,67×10^{-03}	0,89
≥ 0,015	31	8,11×10^{-05}	9,01×10^{-03}	0,89
≥ 0,01	41	1,02×10^{-04}	1,01×10^{-02}	0,91
≥ 0,005	43	1,12×10^{-04}	1,06×10^{-02}	0,92
≥ 0	45	1,26×10^{-04}	1,12×10^{-02}	0,92

The dependence of the cost changes of the operational test on volume of control indicators nomenclature is shown by diagram considering the results reliability in these tests (Fig. 2).

The nomenclature of control indicators influence on tests results reliability, which determines their cost and is the reference value at analyzing the results of operational tests and presenting conclusions.

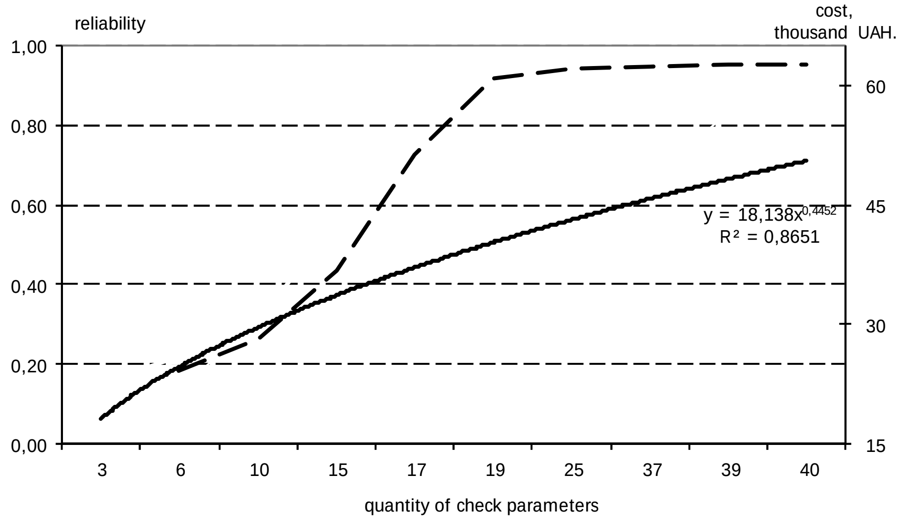

Fig. 2. Dependence of the cost changes of the operational test on volume of control indicators nomenclature

Taking into account the operational tests purpose (definition of technical and economic characteristics of locomotives in operational), and using expert methods, criterion of tests evaluation is chosen. This criterion forms the function of control indicators of tested locomotives and depends on the fuel and oil discharge of diesel locomotives.

The mathematical model adequacy of operational tests on economical efficiency is verified against their implementation cost, shows the error value (Eq. 6) and is less than 0.08:

$$\beta = \frac{1}{N} \cdot \sum_{M^{pot}_{por},\lim} \frac{\left| E^{ekspl.vypr.}_{por.\,M^{opt}_{por}} - E^{ekspl.vypr.}_{por.\,\Pi^{isn}_{por}} \right|}{E^{ekspl.vypr.}_{por.\,\Pi^{isn}_{por}}}, \qquad (6)$$

where:

β is indicator of mathematical model adequacy,

N is number of tested locomotives,

$E^{ekspl.vypr.}_{por.\,M^{opt}_{por}}$ is cost of comparative operational tests on the economic efficiency of the developed model, UAH,

$E^{ekspl.vypr.}_{por.\,\Pi^{isn}_{por}}$ is cost of comparative operational tests on the cost-effectiveness according to Program-methodology, UAH.

In such a way we show the steps of mathematical model improving of operational tests operation. Mathematical model universality is confirmed by possibility of its application for a similar locomotives testing of various types, conditions, purposes and limitations, when they match given in the paper purposes.

The advantage of the improved model for new locomotives testing is possibility to use the accumulated statistical database of management systems and locomotive diagnostics, which seems to be very effective data for simulation of standard operational in different modes and determine possible results.

Also very important reason for the use of advanced models is the possibility of purposeful design tests to determine specific, predetermined characteristics that required the customer to decide whether to implement this type of rolling stock.

CONCLUSIONS

1. Using the rational nomenclature of control indicators at operational tests for new or modernized locomotives make it possible to reduce their implementation cost, which also influence on the overall locomotive life cycle cost at the initial stage.
2. The results of investigation make it possible to establish the possibility to use the improved models of operational testing for new locomotives by choosing rational number of controlled parameters, which are determined and monitored according to the testing purpose.
3. The dependence of the accuracy degree of the locomotives operational tests results on the number of control parameters that are allows developing models of operations on the basis of rational nomenclature indicators tests.
4. Operational tests procedure is improved, which takes into account choosing the rational nomenclature of control indicators as well as collection and processing the statistical data on testing itself and its terms.

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ИССЛЕДОВАНИЕ ПРИМЕНЕНИЯ УСОВЕРШЕНСТВОВАННЫХ МАТЕМАТИЧЕСКИХ МОДЕЛЕЙ ПРИ ПРОВЕДЕНИИ ЭКСПЛУАТАЦИОННЫХ ИСПЫТАНИЙ ТЕПЛОВОЗОВ

Анатолий Фалендыш, Артем Зиньковский, Никита Брагин

Аннотация. В статье представлено исследование применения математического моделирования при проведении эксплуатационных испытаний новых тепловозов.
Установленный основной перечень нормативной документации, определяющей предпосылки, порядок и объемы проведения эксплуатационных испытаний. Определена общая процедура проведения эксплуатационных испытаний, на основе которой установлены пути совершенствования моделей их проведения. Предложен и сформированы группы параметров, описывающих работу тягового подвижного состава и должны определяться в ходе испытаний. Определены цели проведения эксплуатационных испытаний, что позволило сузить номенклатуру контрольных параметров и объемы выполняемых работ по сбору статистических данных. Определена возможность применения усовершенствованных моделей проведения испытаний модернизированных

тепловозов в отношении вновь созданных локомотивов. Установленная возможность выполнения замены некоторых этапов эксплуатационных испытаний математическим моделированием, что обеспечивает возможность сокращения общей суммы затрат на проведение испытаний. Исследована зависимость между целью эксплуатационных испытаний и контрольных параметров, которые определяются во время их проведения. Установленная зависимость между объемом номенклатуры контрольных параметров, определяемых в ходе испытаний и достоверностью их результатов, также определяет цену проведения испытаний. Определены преимущества применения усовершенствованных моделей проведения эксплуатационных испытаний над существующими при применении для дизельного тягового подвижного состава, который разрабатывается.

Ключевые слова: эксплуатационные испытания тепловозов, математическая модель, параметры управления, результаты испытаний.