The widespread introduction of information technologies in the systems that manage technical fleets, the use of maintenance and repair systems based on risk assessment, is based on the calculation of a large enough number of indicators. Modern locomotives are equipped with systems for monitoring and diagnosing technical condition. Combining these systems with the Internet of Things and Big Data technologies provides an opportunity to use completely new approaches to fleet management. At the initial stage of the construction of such systems, it is necessary to devise criteria that make it possible to automatically determine the technical condition of a locomotive and its components in order to identify the locomotive in the total fleet that requires maintenance or repair.

A procedure has been proposed for calculating the technical condition index of locomotives and their components based on data from monitoring systems. The procedure is based on the formation of latent diagnostic parameters employing the principal component method and on the subsequent calculation of the weight coefficients of these parameters applying the method of hierarchy analysis. The special feature of the proposed procedure is that when calculating the index, those latent diagnostic parameters are used that are derived from the group of control parameters whose weight coefficients are computed using the method of hierarchy analysis without involving experts.

This paper reports the results from calculating the informativeness of the diagnostic parameters of load, loss, input, as well as their weight coefficients. The highest information content, from 0.5 to 0.85, is demonstrated by the load parameter; the smallest (0.05–0.26) – the input parameter. The average value and the dependences of changes in the technical condition index of a hydraulic transmission during the tests have been determined. Analysis of the technical condition index makes it possible to assess the transmission's response to changes in test modes, the dynamics of changes in losses

Keywords: technical condition index, informativeness, diagnostic parameters, principal components, hydraulic transmission

UDC 629.083:
DOI: 10.15587/1729-4061.2021.242478

DEVISING A PROCEDURE FOR CALCULATING THE TECHNICAL CONDITION INDEX OF LOCOMOTIVE NODES BASED ON MONITORING RESULTS

Borys Bodnar
Doctor of Technical Sciences, Professor,
First Vice-Rector*

Oleksandr Ochkasov
Corresponding author
PhD, Associate Professor*
E-mail: abochkasov@gmail.com

Mykhailo Ochkasov
Department of Intelligent and Information Systems
Taras Shevchenko National University of Kyiv
Volodymyrska str., 60, Kyiv, Ukraine, 01033

*Department of Locomotives
Dnipro National University of Railway Transport
named after Academician V. Lazaryan
V. Lazariana str., 2, Dnipro, Ukraine, 49010

Received date 03.09.2021
Accepted date 07.10.2021
Published date 30.10.2021

How to Cite: *Bodnar, B., Ochkasov, O., Ochkasov, M. (2021). Devising a procedure for calculating the technical condition index of locomotive nodes based on monitoring results. Eastern-European Journal of Enterprise Technologies, 5 (3 (113)), 37–45. doi: https://doi.org/10.15587/1729-4061.2021.242478*

1. Introduction

The world's leading transport and industrial companies are investing heavily in the modernization of approaches to equipment maintenance. Intelligent management systems for the maintenance and repair of equipment are widely implemented in the industry. Such systems include EAM (Enterprise Asset Management) systems that manage fixed assets of an enterprise. The task of EAM systems is to reduce the cost of maintenance, repair, and logistics while maintaining a predefined level of reliability. The construction of fleet management systems should be guided by the RCM (reliability-centered maintenance) approaches. From the point of view of building a modern locomotive maintenance system, the introduction of the RCM approach involves the implementation of a differential approach to each element of the locomotive, managing the fleet of locomotives in order to minimize possible losses from failures, a predictive maintenance system based on forecasting the residual life of the nodes, assessing the risks from possible failures. Given the complexity of the models used and the significant amounts of information to process it, the main functions of the locomotive fleet management system must be automated. In this regard, there is a task to devise a series of procedures for managing the fleet of locomotives and determining criteria for assessing their effectiveness. Such tasks include the following issues:

– devising a procedure for ranking nodes according to the degree of their influence on the performance of the locomotive and traffic safety;

– devising a procedure for selecting a node that limits the entire locomotive repair based on the results from diagnosing;

– selecting a criterion according to which it is planned to repair the locomotive when choosing it from the total locomotive fleet.

To assess the technical condition of locomotives and their components, it is necessary to determine a series of criteria based on which fleet management procedures are to be devised.

Research aimed at replacing outdated approaches to the organization of the maintenance of the locomotive fleet is relevant for railroad companies around the world. The main areas of research are the adjustment of existing volumes and periodicity of repairs, the introduction of individual repair strategies, the introduction of adapted and flexible approaches to the maintenance of locomotives. World researchers distinguish the following approaches to managing the technical condition of technical objects: a system of maintenance to failure (reactive content), a planned preventive maintenance system (preventive maintenance), a condition-based maintenance system (predictive maintenance), an integrated management system of technical condition (a prescriptive maintenance system).

One of the most modern procedures used in the development of strategies for the management of fixed assets at enterprises is the RCM and RCM 2 methodologies. These procedures are fundamentally different from the methodology of preventive maintenance. The RCM procedures are based on the concept that the purpose of maintenance is not to maintain each piece of equipment in perfect condition but to ensure the reliability of production and technological processes critical to the activities of the enterprise.

Maintenance focused on the reliability of the equipment ensures minimization of the risks of emergencies with the maximum possible operational readiness of fixed assets, taking into consideration budget constraints and various risks.

2. Literature review and problem statement

The theoretical foundations and substantiation of the need to introduce the RCM methodology in the locomotive maintenance system are given in work [1]. The authors propose to use a differential approach to each element of the locomotive. For each such element, individual indicators have been determined such as design features, the impact on traffic safety, maintainability, possible consequences of failure. To form individual strategies for repairing locomotive units, the authors solve the problem of classification based on fuzzy algorithms. At the same time, when building an intelligent strategy for repairing locomotive units, one locomotive is considered without taking into consideration the analysis of the state of the locomotive fleet.

Paper [2] provides an overview and analysis of approaches to the construction of intelligent fleet management systems for technical means of railroad transport. The authors propose to use the methods of fuzzy logic to build individual models of repair objects. A procedure for determining the optimal sequence of maintenance of the fleet of repair objects using the estimates of the Hearst indicator is considered in [3].

Issues of assessment of the technical condition of the equipment are relevant for various fields of technology. At the same time, it is important not only to categorize the technical condition of the equipment but also to devise criteria for building intelligent fleet management systems. The criteria used should be comprehensive while the results of the calculation should be easily interpreted.

For making management decisions and assessing traffic safety in railroad transport, the use of various types of indices is widespread. Thus, in work [4], an integrated coefficient of technical operation of locomotives is proposed, which characterizes the process of technical operation of the locomotive. The application of the proposed indicator for the choice of maintenance strategy of shunting diesel locomotives is considered in [5]. The use of the coefficient of technical operation makes it possible to justify the choice of a rational strategy for servicing locomotives when calculating the value of the coefficient, while the results of monitoring the condition of locomotive units are not used in calculating the coefficient. To assess the reliability of electrical equipment, work [6] proposes to use the concept of safety factor to perform individual forecasting of the operability and service life of the equipment. The proposed coefficient takes into consideration the operating conditions, parameters of probabilistic stress distributions in the structure. In the calculation of the coefficient values, reliability characteristics calculated on the basis of experience in the operation of electrical equipment are used, but the proposed procedure does not take into consideration the change in the characteristics of objects during operation.

To analyze the state of traffic safety, indicators of operation of the locomotive fleet, procedures for determining the traffic safety index [7], and the specific integrated index of operational traffic safety [8] are proposed. The special features of the considered indices are the use of methods for reducing the dimensionality to determine the contribution (weight coefficients) of the considered indicators to the total value of the index, as well as taking into consideration the operational parameters of the locomotive fleet. The integrated indicators proposed in papers [7, 8] are used to assess the state of the locomotive fleet and cannot be used to assess the condition of one locomotive or its unit.

In many branches of technology, the technical condition index is used to make management decisions in the systems of management of the technical condition of the equipment. The widespread use of the technical condition index for managing fleets of technical means is explained by the simple calculation of the index and the availability of interpretation of the results, the possibility of individual calculation of the index for each object from the group, and the subsequent comparison of values for the same type of objects.

In a general form, the Technical Condition Index H_{index} is defined as the ranked sum of the values of parameters (criteria) multiplied by their weight coefficients [9]:

$$H_{index}=\frac{\sum_{j=1}^{n} w_j \cdot K_j}{\sum_{j=1}^{n} w_j \cdot M_j}, \tag{1}$$

where j is the number of criteria used for evaluation; K_j – the value of the criterion; w_j is the weight coefficient corresponding to the criterion K_j; M_j is the maximum value of the criterion K_j.

The parameters used as criteria K are selected depending on the object. Such parameters include the diagnostic results, test results, operational indicators, service life of the object, etc. As a rule, these parameters are established by experts. Similarly, the values of weight coefficients are determined by experts.

For complex (multicomponent) objects, the technical condition index is determined according to [10] based on the degree of influence W_i of components on the possibility of functioning of a multi-component object. The level of significance of W_i is determined by experts.

$$H_{multi\_index}=\frac{\sum_{i=1}^{m} W_i \cdot I_i}{\sum_{i=1}^{m} W_i}, \tag{2}$$

where m is the number of structural units in the composition of the object; W_i is the level of importance of the i-th structural unit; I_i – the technical condition index of the i-th structural unit.

An alternative option for calculating the value of the technical condition index is the procedure given in [10]. In this case, when calculating the index, such components as the severity of the consequences of failure, the possible rate of development of the defect, the history of operation are taken into consideration.

$$H_{index} = \frac{\sqrt{\left(\sum_{i=1}^{n} x_n\right)^2 + \left(\sum_{i=1}^{n} y_n\right)^2 + \left(\sum_{i=1}^{n} z_n\right)^2}}{\sum_{i=1}^{n} M_{n\max}} \cdot 100\,\%, \qquad (3)$$

where $M_{n\max}$ is the maximum value of the coefficients of the i-th measurement; n – the number of measurements; x – the coefficient of assessment of severity, the danger of defect; y – the coefficient of the rate of development of the defect; z – the coefficient of evaluation of the history of operation and the duration of observation of the development of the defect.

The use of an expert approach can be justified at the initial stage of the implementation of intelligent technical condition management systems in the absence of a sufficient amount of information. An example of the use of procedures of expert assessments in the development of diagnostic support for locomotives is given in work [11]. The disadvantage of this approach is its labor intensity, the complexity of conducting a survey of a sufficient number of experts for the adequacy of the results, the duration of the procedure, as well as the possible subjectivity of experts. In addition, the procedure does not take into consideration the results of diagnosing and monitoring the technical condition of objects, the history of changes in the technical condition of the control object.

Paper [12] analyzes the procedures for determining the index of the technical condition of objects, taking into consideration the service life, the results of diagnosing, and the experience in the operation of such objects.

In the considered methods, the technical condition index is determined on the basis of expert estimates of weight coefficients and the further use of regression analysis methods or an assessment system using fuzzy logic.

The use of the technical condition index in combination with the use of risk management methodology is widespread. In work [13], the authors propose, to assess the reliability of the equipment, to use the deterministic and stochastic components to predict the value of the technical condition index. In addition, the concept of "degree of risk" was introduced – a dimensionless value in the range from 0 to 100, which is a quantitative measure of risk. In work [9], three categories are distinguished for ranking the magnitude of the risk depending on the value of the technical condition index. Depending on the risk category, the ranking of the setting of the object of control for repair is performed. The number of categories using which the risk value is ranked is different and depends on the type of task being solved.

In [14], 7 categories for estimating the technical condition index are offered. The index value varies from 0 to 100. To simplify the analysis of the results, the original 7 categories are combined into three intervals of index values: sufficient, degraded, not sufficient. To assess the development of risk in transport systems, the authors of [15] proposed the concepts of *a priori* and *a posteriori* risk, as well as a procedure for assessing their values.

An example of assessing the reliability of locomotives using the risk management methodology is given in [16]. The authors introduced 7 categories of risk assessment based on the calculated risk values. In [17], to assess the technical condition of locomotives, a risk matrix is used, as well as the fuzzy sets of risk levels.

Our review of research in the field of application of the technical condition index of equipment in technology reveals the relevance of this approach for ranking technical objects to manage their fleets. It should be noted that in most cases, expert estimates are used to determine the weighting coefficients of the parameters. This approach is rational with a small number of parameters used in the calculation of the index. With an increase in the number of parameters, the procedures for determining weight coefficients become more complicated since experts need to choose from a significant number of parameters.

One of the disadvantages of the existing approach is that interrelated control parameters, once they accept high values of weight coefficients, could lead to distortion of information reflected in the technical condition index. In addition, in most of the procedures considered, a linear relationship between the index and the constituent criteria (parameters) is accepted.

The active development of technical diagnostics, the rapid transition to the technologies of the industrial revolution 4.0 (Industry 4.0), the introduction of Internet of Things and Services technology in the industry put forward the requirements for increasing the speed of decision-making. In addition, it is necessary to formalize the procedures of expert assessments as much as possible, reducing the time for their implementation, and minimize the subjective components in decision-making.

Our analysis of approaches and procedures to the calculation of the technical condition index showed that their use for technical objects equipped with monitoring and diagnostic systems would not be effective. This is due to the fact that in most cases, expert assessments are used in determining the weighting coefficients of the parameters whose determining requires considerable time. In addition, expert assessments are focused on taking into consideration the importance of the node and the severity of the consequences of possible failures; these factors are usually taken into consideration when choosing installation sites and the number of sensors of diagnostic systems. In this regard, it is necessary to improve the procedure for calculating the technical condition index based on the results from monitoring and diagnosing the technical condition of objects.

3. The aim and objectives of the study

The purpose of this study is to devise a methodology for calculating the index of the technical condition of the equipment using the results of diagnosing, which would enable the selection of the most informative parameters and the calculation of their weight coefficients without the involvement of experts.

To accomplish the aim, the following tasks have been set:

– to suggest a methodology for calculating the weighting coefficients of the selected parameters without the involvement of experts;

– to validate the procedure based on the calculation of the index of the technical condition of hydraulic transmissions.

4. The study materials and methods

The practical significance of the automated calculation of the technical condition index is the possibility to rank repair objects when choosing them from the total fleet.

Applying the technical condition index in the maintenance and repair of locomotives could make it possible:

– to devise a procedure for identifying a unit that limits the repair of the entire locomotive based on the results of diagnosing;

– to use the technical condition index as a criterion according to which it is planned to repair the locomotive when choosing it from the total locomotive fleet.

For operating organizations, the priority task is the interpretation and analysis of diagnostic information in order to manage the technical condition of the equipment fleet. Diagnostic information should be analyzed continuously in an automated mode. As an object of our research, consider the diagnostic system that performs continuous monitoring of the parameters of a diagnosed object (a locomotive or other technical object). The result of the diagnostic system operation is an array of unstructured data acquired from the diagnosed object in real-time. To manage the fleet of technical means, it is proposed to use the index of the technical condition of the equipment.

At the first stage of resolving the task, it is necessary to select the most informative, non-correlated diagnostic parameters. To this end, it is proposed to use mathematical methods for reducing dimensionality. Paper [18] substantiates the expediency of using the principal component method as a mathematical apparatus that allows for the analysis of diagnostic parameters. As a result of using this procedure, the initial set of diagnostic parameters is converted into a set of latent diagnostic parameters of smaller dimensionality. At the same time, the latent diagnostic parameters obtained as a result of the transformation do not correlate with each other and make it possible to keep the amount of diagnostic information at least as specified.

To determine the technical condition index according to [19], we perform a linear convolution of latent diagnostic parameters by the method of hierarchy analysis. As weight coefficients w for the obtained diagnostic parameters g, it is proposed to use the proportion of variances of the principal components since the values of the variances reflect the informativeness of the component.

Mathematically, determining the technical condition index based on the monitoring results is described as follows:

The results of monitoring the technical condition of the control object are represented by an n-dimensional vector (a set of control parameters acquired from the sensors installed at the object):

$$X = \left(x_1, \dots, x_n\right). \quad (4)$$

To apply the principal component method properly, the values of the control parameters are normalized. As a result of using the principal component method, the original vector is converted to the vector $G=\{g_1, g_2, g_3, \dots, g_n\}$. In further analysis, the dimensionality of the vector G decreases to m (where $m \le n$) most informative components.

To determine the significant number of components, the following condition is used:

$$\sum_{i=1}^{m} D\left(g_i\right) \le \alpha, \quad (5)$$

where α – the necessary percentage of preservation of the original information; $D(g_i)$ – the amount of information per component.

Applying condition (5), we obtain the vector $G' = \left\{g_i\right\}_{i=1}^{m}$ representing a set of significant diagnostic components g_i, each of which is determined from (6):

$$g_i = \sum_{i=1}^{m} x_i \cdot a_i, \quad (6)$$

where x_i is the value of the diagnostic parameter; a_i is the factor load of the parameter.

The contribution (informativeness) of the parameter x_i is greater, the greater the absolute value of $|a_i|$. The factor load sign a_i indicates the direction of change in the initial diagnostic parameter x_i relative to the axis of the principal component. The number of initial diagnostic parameters x_i, which are part of each component, is determined based on the values of the factor load of the parameters and the physical essence of the parameters [18].

At the next stage of calculation, according to [7, 19], we perform a linear convolution of the formed latent diagnostic parameters using the method of hierarchy analysis.

To this end, we build a matrix of random comparisons, in which the number of columns of the matrix is equal to the number of principal components selected in the previous calculation step. To determine the elements of the first line, we accept:

$$a_{11} = 1; \quad a_{12} = \frac{s_2}{s_1}; \quad a_{1i} = \frac{s_i}{s_1}, \quad (7)$$

where s_i is the variance of the i-th principal component.

The weights of the components are determined as follows:

$$w_i = \frac{a_{1n}}{a_{1i}}, \quad i = \overline{1,n}. \quad (8)$$

By normalizing the weights of the components by (9), we obtain the relative weights of the components:

$$w_i^* = \frac{w_i}{\sum_{k=1}^{n} w_k}. \quad (9)$$

The value of the technical condition index of the equipment at any time can be determined on the basis of the monitoring results:

$$h_{index\_diagn} = \sum_{i=1}^{n} w_i^* \cdot \frac{\sum_{j=1}^{m} \left|a_j\right| \cdot x_j}{\sum_{j=1}^{m} \left|a_j\right| \cdot x_j^{\max}}, \quad (10)$$

where x_j is the value of the diagnostic parameter measured at time t; $x_j^{\max}$ – the maximum permissible value of the diagnostic parameter based on the design of the diagnostic object and operating conditions; n – the number of latent diagnostic parameters (principal components); m – the number of diagnostic parameters x_j used in the calculation of the principal component.

Each term in expression (10) is an index of the state h_i corresponding to the components. Expression (10) can be written as

$$h_{index\_diagn} = \sum_{i=1}^{n} h_i. \quad (11)$$

Depending on the modes of operation of the technical object and the conditions of monitoring, the average value of the technical condition index $\bar{H}_{index\_diagn}$, the analysis of the plot of changes in the technical condition index of the $h_{index\_diagn}(t)$ over the period of observations $[0, T]$ can be used to analyze the technical condition.

The obtained average value of the index $\bar{H}_{index\_diagn}$ for the period can be used to rank the same type of diagnostic objects when planning their maintenance and repair. In addition, the value of the index can be used to assess the technical condition of the object of diagnosis while as a criterion for evaluation, it is proposed to use rule (12):

$$\bar{H}_{index\_diagn} - k \cdot \sigma_{H_{index\_diagh}} \leq H_{index\_diagn} \leq$$
$$\leq \bar{H}_{index\_diagn} + k \cdot \sigma_{H_{index\_diagh}}, \quad (12)$$

where $\bar{H}_{index\_diagn}$ – the average value of the technical condition index of the same type of objects operated under the same conditions; $\sigma_{H_{index\_diagh}}$ – standard deviation $\bar{H}_{index\_diagn}$; k – the coefficient used to assess the technical condition.

At the initial stage, it is proposed that the diagnostic objects for which the value of the index H_{index_diagn} is in the range k=[0…1] should refer to the group that does not require additional technical activity (green level). Such equipment is operated and maintained in accordance with the adopted strategy. The equipment k=(0…1] requires enhanced control, adjustment of the adopted service strategy (yellow level). Equipment units that take a coefficient value in the range k=(2…3] refer to the orange zone and require additional maintenance and repair of increased volume. Equipment with the index $k>3$ refers to emergency-prone; its operation is not allowed. The boundary values of the coefficient k and the number of intervals for assessing the technical condition of the diagnosed objects can be specified on the basis of operational experience.

To calculate the values of the technical condition index, we used the C# and Python programming languages to develop a computer program that makes it possible to select the number and calculate the values of the principal components, calculate the information content and weight coefficients of diagnostic components, as well as statistical indicators of index values for a group of controlled objects.

The proposed approach for calculating the technical condition index based on the diagnostic results was implemented on the basis of results from the bench tests of hydraulic transmissions of the UGP750/12000 type.

After the overhaul, hydraulic transmission is tested on a specialized bench; a series of control parameters are then measured. One of the issues related to testing the hydraulic transmissions of diesel locomotives and other high-power vehicles over the entire range of specifications loads is the need to use special high-power equipment to drive the input shaft. This results in more energy costs and increased test costs. A feature of the equipment used on a typical test bench is that the technical condition of the hydraulic transmission is assessed under the mode of its not full load. This is due to the technical limitations of the power of drive and load motors. In the process of running in and testing, the drive motor simulates the operation of a diesel engine. The load from the wheelsets is simulated by a generator, the energy of which is extinguished on a water rheostat. As a drive motor and load generator, DC machines with independent excitation are used. The bench makes it possible to measure the temperature and pressure of the oil in the hydraulic valves, current strength, voltage, speed of the drive motor and load generator. Characteristics of technical means for testing, the procedures for processing and analyzing results are given in works [18, 20, 21].

Paper [18] report the results of selecting the most informative parameters at bench tests of hydraulic transmissions. During the tests, the following diagnostic parameters are registered: the voltage U_m and the current of the armature I_m of the drive electric motor, the voltage U_{gen} and the current of the armature I_{gen} of the load electric motor. For hydraulic transmission, the input parameters are the speed w_m and the torque M_m on the drive motor shaft, the speed w_{ci}, and the torque of the pump wheel M_{ci}. The output parameters of the hydraulic transmission during the tests are the speed w_{ct} and the torque of the turbine impeller M_{ct}, which corresponds to the rotation frequency and torque of the load generator armature. The oil temperature at the inlet and outlet t_{out} of the hydraulic transmission, the temperature t_{tcf}, and the oil pressure p_{tcf} in the hydraulic apparatus are also registered. In addition, the design parameters were taken into consideration. The power of the drive motor P_m and the power of the load generator P_{gen}. The ratio of oil temperature in the hydraulic unit to the power of the generator t_{tcf}/P_{gen}. The gear ratio of speeds (w_{ci}/w_{ct}) of the turbine w_{ct} and pump w_{ci} impellers.

When processing the experimental data obtained from the tests, the data compliance with the normal distribution law was checked and the data set was cleaned of emissions by the 3σ method. For the correct use of the principal component analysis, the data were normalized by the maximum-minimum method.

Using the principal component method, three latent diagnostic features were obtained: “load”, “losses”, “input”.

The results of the application of the methodology set out in [18] for five hydraulic transmissions when choosing the most informative non-correlating diagnostic parameters during bench tests are given in Table 1.

Table 1

Factor load of the diagnostic parameters for hydraulic transmissions

Transmission	Component	Factor load of the diagnostic parameter									
		U_{gen}	I_{gen}	U_m	I_m	w_{ct}	t_{tcf}	p_{tcf}	t_{inp}	t_{out}	P_m
tr 1	Load	0.35	0.81	–	–	–	–	0.33	–	–	–
	Losses	–	–	–	–	–	0.51	–	0.55	0.53	–
	Input	–	–	0.46	0.47	–	–	–	–	–	–
tr 2	Load	0.37	0.36	–	–	0.35	–	0.35	–	–	0.37
	Losses	–	–	–	–	–	0.49	–	0.10	0.27	–
	Input	–	–	0.13	0.10	–	–	–	–	–	–
tr 3	Load	0.45	0.48	–	–	–	–	0.03	–	–	0.39
	Losses	–	–		–	–	0.54	–	0.42	0.44	–
	Input	–	–	0.44	0.51	–	–	–	–	–	–
tr 4	Load	0.24	0.27	–	–	–	–	0.39	–	–	–
	Losses	–	–	–	–	–	0.56	–	0.39	0.45	–
	Input	–	–	0.60	0.05	0.44	–	–	–	–	–
tr 5	Load	0.13	0.63	–	–	–	–	0.46	–	–	–
	Losses	–	–	–	–	–	0.77	–	0.60	–	–
	Input	–	–	0.15	0.46	–	–	–	–	–	–

Using the tr1 transmission as an example, the equations of the latent diagnostic parameters (components) are as follows:

$$\begin{cases} \text{load} = 0.35 \cdot U_{gen} + 0.81 \cdot I_{gen} + 0.33 \cdot p_{tcf}, \\ \text{losses} = 0.51 \cdot t_{tcf} + 0.55 \cdot t_{inp} + 0.53 \cdot t_{out}, \\ \text{input} = 0.46 \cdot U_m + 0.47 \cdot I_m. \end{cases} \quad (13)$$

Based on Table 1, a system of equations similar to (13) can be constructed for each hydraulic transmission. The system of equations characterizes the state of transmission from the point of view of three components: load, loss, input.

To further calculate the technical condition index of a transmission, it is necessary to determine the weight coefficients of the components of the load, loss, input.

5. Results of calculating the technical condition index based on the results of diagnosing a hydraulic transmission of the diesel locomotive

5. 1. Calculating the weight coefficients of diagnostic parameters

When calculating the technical condition index, a weight coefficient corresponding to the diagnostic parameter is used.

When performing an automated calculation of the index, the information content (variance) of the component is used as the initial data. Values of informativeness characterize the contribution of each of the parameters to the value of the technical condition index. Based on the treatment of the test results for hydraulic transmissions, we derived the values of informativeness, given in Table 2. The values of the parameters in the table are normalized using expression (9).

Table 2

Informativeness of latent diagnostic parameters

Transmission	Parameter informativeness		
	Load	Losses	Input
tr 1	0.60	0.31	0.09
tr 2	0.84	0.10	0.06
tr 3	0.70	0.22	0.08
tr 4	0.51	0.39	0.10
tr 5	0.61	0.13	0.26

The distribution of values of the informativeness of diagnostic parameters is shown in Fig. 1.

Using expressions (7) to (9), the weights of the components for each transmission have been determined. The results of the calculation of the weight coefficients of latent diagnostic parameters are given in Table 3. Graphically, the distribution of weight coefficients is shown in Fig. 2.

A feature that distinguishes weight coefficients from the informativeness of a diagnostic parameter is that the weight coefficient characterizes the influence of the diagnostic parameter on the technical condition index, as well as shows how accurately the technology (modes) of the tests were observed. The informativeness of the parameter reflects how significantly the parameter changed during the monitoring process. In other words, the load parameter (Load), when changing widely according to the test program, has high informativeness while its contribution to the assessment of the technical condition (weight) is reduced compared to such a parameter as losses.

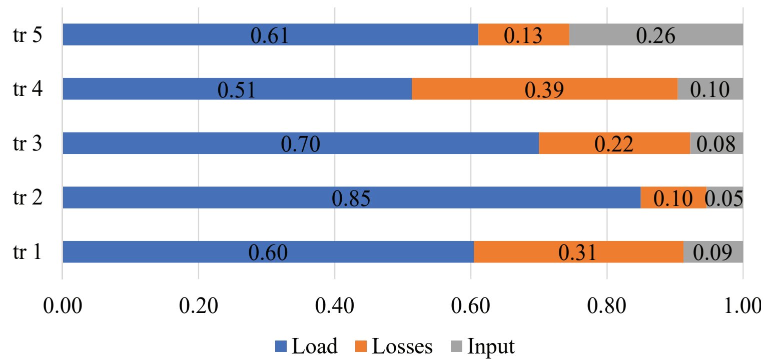

Fig. 1. Informativeness of diagnostic parameters

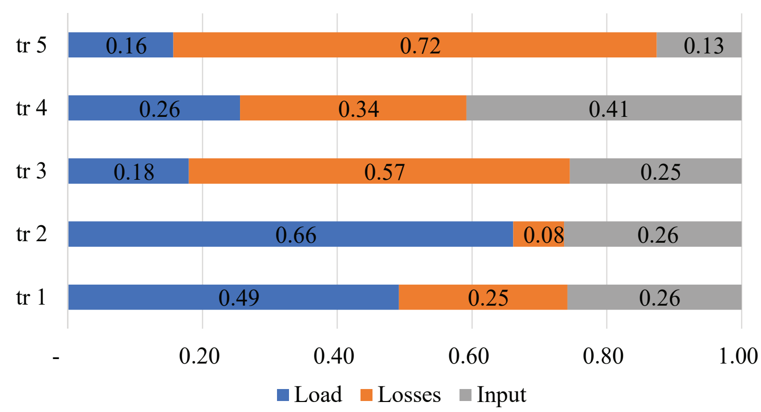

Fig. 2. Weight coefficients of diagnostic parameters

Table 3

Weight coefficients of latent diagnostic parameters

Transmission	Weight coefficient		
	Load	Losses	Input
tr 1	0.49	0.25	0.26
tr 2	0.66	0.08	0.27
tr 3	0.18	0.57	0.25
tr 4	0.26	0.34	0.41
tr 5	0.16	0.72	0.13

5. 2. Validating the procedure based on the calculation of the technical condition index of hydraulic transmissions

We calculated values for the technical condition index of a hydraulic transmission based on monitoring during bench tests by using expression (10). When determining the technical condition index for each moment of measurement, the values of the diagnostic parameters of the load, losses, input are calculated. The results of calculating the average value of the technical condition index for the considered hydraulic transmissions are shown in Fig. 3.

The results of the calculation of the index of the technical condition of hydraulic transmissions and the values of its terms corresponding to the components “load”, “loss”, “input” are shown in Fig. 4.

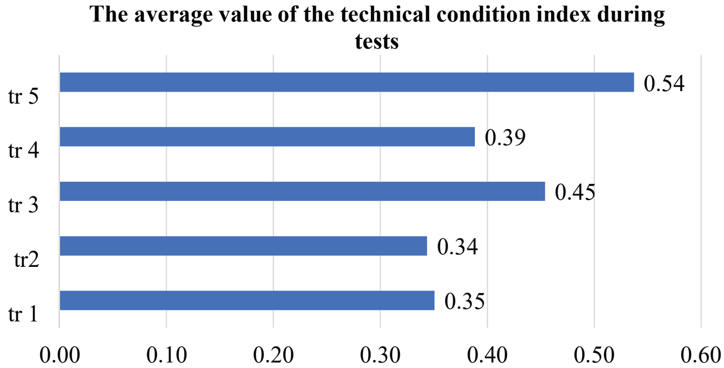

Fig. 3. The average value of the technical condition index for hydraulic transmissions during testing

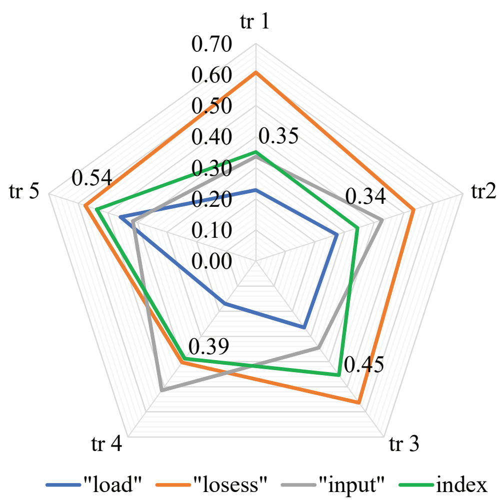

Fig. 4. Technical condition index and its components for tested transmissions

The value of the technical condition index, derived from processing the monitoring results, characterizes both the technical condition of the hydraulic transmission and the completeness of information about its technical condition. When assessing the technical condition, it is necessary to take into consideration the values and ratios between the components of the index, as well as the weight coefficients of the components. A significant excess of the coefficient of one of the parameters over the others indicates a violation of operating modes or the presence of a malfunction.

6. Discussion of results of calculating the technical condition index of hydraulic transmissions based on the monitoring results

The key point of the current study is the use of latent diagnostic parameters in the calculation of the index of the technical condition of the monitoring object, as well as determining the weight coefficients of diagnostic parameters using the method of hierarchy analysis.

Latent diagnostic parameters were obtained using the principal component method. Thus, of the total set of parameters controlled when monitoring the technical condition of hydraulic transmissions, the most informative components have been identified, while the control parameters that make up the components do not correlate with each other.

Bench tests of the hydraulic transmissions of diesel locomotives were chosen as the object to validate the proposed procedure; in this case, the methodology suggested can be used to calculate the index of the technical condition of any components of the locomotive or a locomotive in general. When using the proposed procedure for calculating the technical condition index for another type of locomotive equipment, the number of latent parameters characterizing the state of the control object may differ. The number of latent parameters depends on the percentage of preservation of the initial information taken in the calculation, the design features of the monitoring object, and the number of sensors installed at the object.

The process of calculating the index of the technical condition of the monitored object includes three main stages:

1. Define a system of equations (13), which characterizes the state of transmission in terms of three components: load, loss, input.

2. Determine the weight coefficients and informativeness of latent diagnostic parameters using the method of principal components and a hierarchy analysis.

3. Calculate values for the technical condition index based on expression (10).

A feature of the proposed procedure, unlike other methods, is that latent diagnostic parameters are used in the calculation of the index, which are derived from the group of control parameters. At the same time, the control parameters included in the group characterize the monitored object from one of the technical sides.

When analyzing the calculation results, it is necessary to separate the concepts of a weight coefficient and the informativeness of a parameter. The informativeness of the parameter reflects how significantly the parameter changed during the monitoring process. The informativeness of the parameter to a greater extent characterizes the testing process (operation, control, etc.) while the weight coefficient characterizes the technical condition of the control object. The difference between the concepts of informativeness and weight coefficient is illustrated by Fig. 1, 2. The value of the weight coefficient of the parameter is influenced by the ratio of the informativeness of all the constituent parameters used in the calculation. For example, for the tr2 transmission, the “load” parameter has an informative value of 0.85, the informativeness of the “loss” and “input” parameters is 0.10 and 0.05, respectively. This distribution of the information content of the parameters distinguishes the transmission tr2 from other transmissions in the study group. The weight coefficient of the “loss” parameter for the transmission tr2 is 0.08, which indicates the need to monitor its technical condition. When comparing the weights for other transmissions, one can also see the difference between the tr2 transmission and the tested ones.

Fig. 3, 4 show that the greatest value of the technical condition index is accepted by the transmission tr5. The load component (Fig. 4) reflects the completeness of the load and the transmission response to the change in load; similarly, the terms of loss and input reflect the losses and changes in test modes. The tr5 transmission was tested in the fullest load volume; in this case, the loss level does not exceed the loss levels for other transmissions, the test modes correspond to other transmissions.

The value of the loss component for the tr3 transmission corresponds to the tr5 transmission value while the value of the tr3 transmission condition index is lower than that of the tr5 transmission. This is due to the fact that when testing tr3 transmission, the input and load mode ranges are narrower; which affected the values of the load and input terms.

The tr4 transmission was tested in a wide range of input modes; in this case, the load modes were not complete – given this, the information about the technical condition of the tr4 transmission does not sufficiently reflect its technical condition. This is evidenced by a decrease in the value of the technical condition index.

Of the considered transmissions, tr1 and tr2 have the lowest index value. This is due to the fact that the level of losses by these transmissions corresponds to the group of transmissions while the components characterizing the loading conditions and input modes accept lower values.

The advantage of the proposed approach is the possibility of using, simultaneously with the average value of the index, when analyzing the graphical dependences of the index and latent parameters during the monitoring period. In view of the above, the average value of the index can be used as an indicator of the state of the object of control. For a more detailed analysis, graphical dependences of the index and latent parameters during the monitoring period are used.

Certain limitations in the use of the proposed procedure refer to constraints inherent in the application of the principal component method, namely, the approximation of the initial set of parameters by straight lines and planes. If the initial set of diagnostic features is better approximated by nonlinear dependences, it is rational to use the method of principal manifolds or nonlinear principal components.

For comparative estimation of the obtained values of the index for the group of transmissions, expression (10) employs the normalization of values for control parameters. When calculating latent diagnostic parameters, absolute values of factor loads $|a_j|$ are used.

The complexity of ranking the same type of technical objects in the management of the technical condition of the fleet is associated with the need to ensure the same conditions and modes of operation of the controlled objects. To eliminate this disadvantage, it is desirable to use specific indicators attributed to the unit of work, production, etc. When using the proposed method during control and bench tests, the controlled objects should be tested under the same conditions.

In the examples considered, the calculation of the technical condition index was performed every 0.4 seconds, which corresponded to the frequency of polling sensors during monitoring. The test mode of 10 minutes was considered. At the same time, the proposed approach could be used to calculate the index of the technical condition of objects with an arbitrary registration periodicity of control parameters, from fractions of seconds to several days and months.

Debatable and requiring further research is the issue of using the average value of the technical condition index H_{index_diagn} as an assessment of the state of the object of control. To avoid errors in the interpretation of the results inherent in the average values, it is possible to use additional statistical indicators.

A further continuation of the research is to study the relationship between the values of the weight coefficients of latent parameters and the technical state of transmission, and the quality of the tests. It is necessary to take into consideration the values of the weight coefficients of diagnostic parameters. A significant excess of the weight coefficient of one of the parameters over the others may indicate a violation of the operating modes or the presence of a malfunction.

Additional studies are needed to determine the number and boundary values of the index change ranges during bench tests of hydraulic transmissions.

The value of the technical condition index could be used as a criterion for optimization (or part of it) in the construction of locomotive fleet management systems.

7. Conclusions

1. The proposed methodology has been used to determine the informativeness and weight coefficients for the formed latent diagnostic parameters. The informativeness and weight coefficients were determined automatically using the method of principal components and the hierarchy analysis without the involvement of experts. Thus, the values of the weight coefficients can be calculated in real-time, which makes it possible to use these values to control the technical condition of the monitored object and calculate the technical condition index. The tr2 transmission was used as an example to show that the ratio of information content and weight coefficients of the parameters "load" (0.66), "loss" (0.08), "input" (0.26) distinguishes this transmission from other transmissions of the group and indicates the need to control its technical condition. This conclusion was confirmed by the test results.

2. Based on the calculated weight coefficients of latent parameters and the test results of hydraulic transmissions, we determined the values of the technical condition index. As a result of the analysis of the values of the technical condition index, three groups of transmissions were identified: "green level" – transmissions tr5 and tr3 – the index values are 0.45÷0.54; "yellow level" – transmission tr4 – the index value is 0.39; "orange level" – transmissions tr1, tr2 – the index values are 0.34÷0.35. The ranges given are preliminary and can be refined based on further experience in using the methodology.

References

1. Tartakovskyi, E., Ustenko, O., Puzyr, V., Datsun, Y. (2017). Systems Approach to the Organization of Locomotive Maintenance on Ukraine Railways. Studies in Systems, Decision and Control, 217–236. doi: https://doi.org/10.1007/978-3-319-51502-1_5
2. Skalozub, V., Osovik, V. (2014). Individual intelligent models for operating a number of unified railway engineering systems based on the current state parameters. Informatsiyno-keruiuchi systemy na zaliznychnomu transporti, 6, 8–12. Available at: http://eadnurt.diit.edu.ua/bitstream/123456789/3434/1/Skalozub_Osovik.pdf
3. Skalozub, V. V., Klymenko, I. V. (2018). Method for planning non-determined operation processes of railway technical system park. Science and Transport Progress. Bulletin of Dnipropetrovsk National University of Railway Transport, 5 (77), 7–18. doi: https://doi.org/10.15802/stp2018/141430

4. Falendysh, A. P., Chyhyryk, N. D., Sumtsov, A. L., Kletska, O. V. (2019). The choice of the strategy of technical operation of modernized shunting locomotives. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 2, 43–50. doi: https://doi.org/10.29202/nvngu/2019-2/7
5. Falendysh, A., Sumtsov, A., Artemenko, O., Klecka, O. (2016). Simulation of changes in the steady state availability factor of shunting locomotives for various maintenance systems. Eastern-European Journal of Enterprise Technologies, 1 (3 (79)), 24–31. doi: https://doi.org/10.15587/1729-4061.2016.60640
6. Babyak, M., Keršys, R., Neduzha, L. (2020). Improving the dependability evaluation technique of a transport vehicle. Proceedings of 24th International Scientific Conference. Transport Means 2020, 646–651. Available at: https://www.researchgate.net/publication/345710826_Improving_the_Dependability_Evaluation_Technique_of_a_Transport_Vehicle
7. Bodnar, B., Bolzhelarskyi, Y., Ochkasov, O., Hryshechkina, T., Černiauskaite, L. (2018). Determination of integrated indicator for analysis of the traffic safety condition for traction rolling stock. Intelligent Technologies in Logistics and Mechatronics Systems (ITELMS'2018): The 12th International Scientific Conf., 45–54. Available at: http://eadnurt.diit.edu.ua/jspui/handle/123456789/10806
8. Bodnar, B., Ochkasov, O., Bodnar, E., Hryshechkina, T., Keršys, R. (2018). Safety performance analysis of the movement and operation of locomotives. Proceedings of 22nd International Scientific Conference, 839–843. Available at: http://eadnurt.diit.edu.ua/bitstream/123456789/10780/1/Bodnar.pdf
9. Davidenko, I. V., Halikova, E. D. (2014). Uchet riskov pri vybore ocherednosti meropriyatiy tehnicheskogo obsluzhivaniya silovyh transformatorov. Elektro. Elektrotehnika, elektroenergetika, elektrotehnicheskaya promyshlennost', 6, 32–37. Available at: https://www.elibrary.ru/item.asp?id=22768160
10. Jürgensen, J. H., Scheutz Godin, A., Hilber, P. (2017). Health index as condition estimator for power system equipment: a critical discussion and case study. CIRED - Open Access Proceedings Journal, 2017 (1), 202–205. doi: https://doi.org/10.1049/oap-cired.2017.1174
11. Bodnar', B. E., Ochkasov, A. B. (2001). Ispol'zovanie metoda ekspertnyh ocenok pri razrabotke diagnosticheskogo obespecheniya lokomotivov. Nauchnye trudy Kremenchugskogo gosudarstvennogo politehnicheskogo universiteta, 1 (10), 217–220.
12. Kuzina, T. S., Davidenko, I. V. (2016). The analysis of foreign methods for estimation of the health index of power transformers. Energo- i resursosberezhenie. Energoobespechenie. Netradicionnye i vozobnovlyaemye istochniki energii: materialy Vserossiyskoy nauchno-prakticheskoy konferencii studentov, aspirantov i molodyh uchenyh s mezhdunarodnym uchastiem. Ekaterinburg: UrFU, 158–162.
13. Gavrilyuk, E. A., Mantserov, S. A., Panov, A. Y. (2015). The failure prediction of automatic gas-compressor unit control systems on basis of technical state index and measure of risk. Fundamental research, 7, 309–313. Available at: https://fundamental-research.ru/ru/article/view?id=38691
14. Wesołowski, M., Iwanowski, P. (2020). APCI Evaluation Method for Cement Concrete Airport Pavements in the Scope of Air Operation Safety and Air Transport Participants Life. International Journal of Environmental Research and Public Health, 17 (5), 1663. doi: https://doi.org/10.3390/ijerph17051663
15. Bulakh, M., Okorokov, A., Baranovskyi, D. (2021). Risk System and Railway Safety. IOP Conference Series: Earth and Environmental Science, 666 (4), 042074. doi: https://doi.org/10.1088/1755-1315/666/4/042074
16. Lakin, I. K., Abolmasov, A. A., Melnikov, V. A. (2013). Risk management model to prevent locomotive malfunction. World of Transport and Transportation, 4, 130–136. Available at: https://mirtr.elpub.ru/jour/article/view/427/684
17. Datsun, Y. (2015). The choice of the strategy of the technical service and repair of locomotives based on the methods of fuzzy logic. Visnyk Skhidnoukrainskoho natsionalnoho universytetu imeni Volodymyra Dalia, 1 (218), 77–80. Available at: http://nbuv.gov.ua/UJRN/VSUNU_2015_1_17
18. Bodnar, B., Ochkasov, O. (2021). Devising a procedure to form the diagnostic parameters for locomotives using a principal components analysis. Eastern-European Journal of Enterprise Technologies, 2 (1 (110)), 97–103. doi: https://doi.org/10.15587/1729-4061.2021.230293
19. Bosov, A., Loza, P. (2014). Creation of an index of arbitrary process. Zbirnyk naukovykh prats Donetskoho instytutu zaliznychnoho transportu, 38, 68–73. Available at: http://nbuv.gov.ua/UJRN/znpdizt_2014_38_13
20. Bodnar, B., Ochkasov, O., Bobyr, D., Korenyuk, R., Bazaras, Z. (2018). Using the Self-Braking Method when the Post-Overhaul Diagnostics of Diesel-Hydraulic Locomotives. Proceedings of 22nd International Scientific Conference, 914–919. Available at: https://transportmeans.ktu.edu/wp-content/uploads/sites/307/2018/02/Transport-means-II-A4-2018-09-25.pdf
21. Zhukovyts'kyy, I., Kliushnyk, I. (2018). Development of a selfdiagnostics subsystem of the informationmeasuring system using anfis controllers. Eastern-European Journal of Enterprise Technologies, 1 (9 (91)), 11–19. doi: https://doi.org/10.15587/1729-4061.2018.123591