Проведено теоретичне та експериментальне дослідження контрольних параметрів агрегату трансмісії засобів транспорту. Виявлено, що для адаптації їх технічної експлуатації необхідно формувати діагностичну базу даних агрегату для подальшого аналізу і управління. Визначено, що критерій відносної чутливості дозволяє формувати діагностичну базу з подальшим контролем та управлінням технічним станом коробки переключення передач

Ключові слова: діагностичний параметр, показник надійності, відносна чутливість, засіб транспорту, агрегат трансмісії

Проведено теоретическое и экспериментальное исследование контрольных параметров агрегата трансмиссии средств транспорта. Выявлено, что для адаптации их технической эксплуатации необходимо формировать диагностическую базу данных агрегата для дальнейшего анализа и управления. Определено, что критерий относительной чувствительности дает возможность формировать диагностическую базу с последующим контролем и управлением техническим состоянием коробки переключения передач

Ключевые слова: диагностический параметр, показатель надежности, относительная чувствительность, средство транспорта, агрегат трансмиссии

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SUBSTANTIATION OF DIAGNOSTIC PARAMETERS FOR DETERMINING THE TECHNICAL CONDITION OF TRANSMISSION ASSEMBLIES IN TRUCKS

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1. Introduction

The most labor-consuming process at operation of transportation means is the process of diagnosis of systems and assemblies. It is difficult to automate a complex of operations in the diagnosis process of technical condition of transportation means in general. Very important in the control and management of technical condition is the development of tools for theoretical and informative support that ensure the formation of the required diagnostic information for specialists in the field of service and maintenance. Retrospective analysis of the practice of operation of transportation means under different conditions reveals that the average time to maintain and restore the technical condition of systems and assemblies of transportation means significantly exceeds the time claimed in the normative and technical documentation. The application of control system over a technical condition, based on statistical and diagnostic information, helps reduce service time of transportation means. This in turn leads to improved integrated performance indicators, such as coefficients of technical readiness and utilization rate. The time needed for the maintenance of systems and assemblies of transportation means is mostly taken by the execution of operations for technical diagnosis. This fact must be considered when compiling a diagnostic database on technical condition. The above confirms the importance of practical research aimed at reducing the time of technical diagnosis through the improvement of methods for generating and processing of diagnostic data base, which is an important scientific and technical task.

2. Literature review and problem statement

The improvement of express methods for the diagnosis of aligned units and assemblies, as well as addressing the issue of application of non-destructive control methods for the reducers of conveyor belts as a transportation means, is outlined in paper [1]. Special attention was paid by authors of the paper to such types of technical condition diagnosis as heat control and analysis of conditions of lubricants. The relevance of implementation of those types of non-destructive testing that are described in the work is defined by an increase in the energy efficiency of transportation systems under harsh operating conditions, specifically conveyors reducers. Periodic deep spectroscopic-emission diagnosis and monitoring of the temperature regime of utilization of the working oil during operation of control equipment and its technical condition makes it possible to control actual technical condition of the gearbox in a transportation vehicle. However, the authors failed to identify and form necessary diagnostic information and its periodicity. Testing the technical condition of the automatic transmission 4R by the deployment of sensors and by selecting their possible combinations of location is carried out to monitor their effectiveness and to detect a fault [2]. This work does not describe operations to coordinate diagnostic information with reliability indicators, which makes it difficult to estimate the given combinations of sensors. It was found that in transportation vehicles 30...33 % of the fuel energy is used to overcome friction forces in the transmission, engine and other systems and assemblies. Out of total amount, about 32...44 % of the fuel energy is used to move the automobile. The rest is spent on parasitic friction losses that make up 23...32 % of the fuel energy of transportation means related to the faults in their systems and units during operation [3]. The study conducted to establish the efficiency of consumption of fuel energy make it possible to compile a list of tribological joints of transportation means, which most of all lose their operational functions during use. Authors of the work, however, did not resolve the issue of their rational control.

The implementation of compiling a diagnostic base and a possibility to predict the technical condition of toothed gears was considered in [4], based on spectral emission, however, the authors failed to consider the diagnostic information during their work. Study of change in the diagnostic parameters of transmissions with the formation of Bayesian sensitivity was reported in paper [5], but the sensitivity in a work was considered to be absolute, applying which resulted in the problems of dimensionality that had to be additionally resolved. Substantiation of the system of diagnosing the transmissions of cars using the theory of fuzzy sets, taking into account the boundaries of diagnostic parameters, was performed in paper [6]. In a given work, the authors employed a mathematical apparatus of fuzzy logic, which makes it possible to vary the boundaries of change in diagnostic parameters, but this apparatus did not solve the problem when applying them at different intervals of run time.

Paper [7] considered the improvement and the development of the following directions in the application of the sensitivity theory, specifically to determine the degree of uncertainty in the input data of analysis, generation of the sample of database using the analysis, to overcome the uncertainty in the database. The authors' special attention is focused on the results of sensitivity analysis with descriptions and illustrations given for the following procedures: correlation and regression analysis, a two-dimensional test by Kolmogorov-Smirnov, the coincidence factor from top to bottom. Resolving the issues applying the considered procedures was based on using the absolute sensitivity; however, the authors could not implement them in practice to investigate technical condition of transmission assemblies.

The analysis of sensitivity was addressed by authors of paper [8] who created a scale of disturbances for the examined parameters that can be defined as a preset size of the neighboring region of sensitivity around the parameters. The authors note that the scales of disturbances are intrinsic to any local and global sensitivity analysis. It is shown how approaches based on derivatives (the Morris method) focus on small disturbances, while the approaches based on variations (the Sobol method) focus on large-scale disturbances. The proposed analysis with different actual models of the examined processes demonstrates significant consequences of subjectivity in the choice of scales of disturbances and the need to develop strategies to address these problems. The authors also unambiguously characterized the dependence of the scale of disturbances and developed procedures that cover the entire database, but they did not solve the problem related to the relative sensitivity of parameters in the full spectrum of disturbance scales.

The theory of sensitivity was further developed in the form of a theory of relative sensitivity of functions (sensitives), described in paper [9]. The theory of sensitives was used when solving the tasks on assessing the accuracy of mathematical models of friction and wear processes and measurement of tribotechnical characteristics [10]. The analysis of the theory of relative sensitivity of functions revealed significant advantages and broad aspects of its application as compared with the absolute sensitivity. Authors of the above works did not form a description of change in diagnostic information concerning reliability indicators, but only suggested the estimate of entropy of tribo-coupling.

Using the theory of relative sensitivity makes it possible to solve the task on technical operation. The following tasks need to be solved: estimation of technical condition and the evolution of its development, determining the parameters of reliability of systems and assemblies in the transportation vehicles based on diagnostic information and relations between them. The mathematical apparatus for studying and generating diagnostic parameters has not been fully utilized up to now. The main methods used are: methods of theory of reliability, information, theory of errors, automated control, and others. At the same time, quality change and the relationship between indicators of reliability and diagnostic parameters have not been formed. It is possible to create such a relationship applying the methods of theory of relative sensitivity.

3. The aim and objectives of the study

The aim of present study was to determine and establish the character of change in the examined indicators of reliability and diagnostic parameters of technical condition of the transmission assembly in transportation vehicles. Based on them, it would be possible to develop a process of creation of rational diagnostic base with the formation of a theoretical apparatus for choosing informatively significant diagnostic parameters.

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

– to develop theoretical provisions for the description of a technical condition of the assembly using the diagnostic parameters based on the theory of relative sensitivity;

– to identify a relationship between the diagnostic parameters and indicators of reliability of systems and assemblies of transportation vehicles;

– to propose a criterion for choosing diagnostic parameters for the formation of rational diagnostic database.

4. Materials and methods for examining a technical condition of the gear box of a truck

Observation under operational conditions is the process that makes it possible to obtain reliable information about a technical condition of the examined systems and assemblies of transportation vehicles. When planning the observations, one determines the required amount of information for obtaining the estimates of parameters of reliability with preset accuracy and authenticity. The study into probability of the occurrence of failures implies a number of objects of observations N.

We used as the initial data for calculating the minimum amount of observations: confidence probability γ, that is, the probability that the confidence interval covers a valid parameter value for the sample data, which is chosen from a range of 0.80; 0.90; 0.95; 0.99 and is a characteristic of reliability of the indicator; boundary relative error δ, which characterizes the interval, which with a preset probability covers the unknown value of parameter estimate, which is selected from a range of 0.05, 0.10, 0.15, 0.20 and is a measure of accuracy of the indicator estimate.

In this case, confidence interval I_y is the interval that covers the unknown diagnostic parameter with a preset reliability γ.

In line with a known law of distribution of a random magnitude (the likelihood of the occurrence of failure), by assigning the boundary relative error $\delta=0.15$ and confidence probability $\gamma=0.8$ at variation coefficients of 0.3; 0.6; 1 (plan NUn), we determine the number of observations. In this case, for the normal distribution law, it is necessary to explore not less than five objects of observation; for the exponential law – not less than fifteen, and for the Weibull-Gnedenko distribution – not less than forty. The number of objects of observation for the exponential law of distribution is set by tables [11] and at $P(L)=0.9$ with confidence probability $\gamma=0.8$ will equal $N\geq 12$, which is why it was decided that the minimum sample size is $N=12$.

In the course of research we determined diagnostic parameters of the samples of fresh and working transmission oils of varying degree of contamination based on operation time. During operation of the transportation vehicles, we used the transmission oil Agrinol TSp-15K, which, according to international classifications, meets ARI GL-3; SAE 90. The samples of oil were taken every 2,000 km of runtime of transportation vehicles, the volume of the sample was 600 ml of the working transmission oil needed for five cycles of determining the examined diagnostic parameters at each sample selection.

Diagnostic parameters of transmission oil were determined by methods accepted by DSTU: alkaline number – DSTU 5094:2008, content of mechanical impurities – DSTU GOST 6370-83 (valid in Ukraine).

The obtained values of diagnostic parameters and derived indicators were compared to the maximal permissible values. In addition to the estimation of physical-chemical characteristics and properties, we performed, according to DSTU, express-analysis using EraSpec Oil, the microscope «Biolam-11». Micro photographs were taken at a magnification resolution of the microscope of ×500 on the samples of oil under conditions of chemical laboratory. Dispersed composition of the working transmission oil was determined, using a personal computer, employing digital photographs, using a microscope. Working transmission oil gets darker over time because of the formation of finely dispersed and other polluting substances. We determined the percentage of these impurities using the software package Adobe Photoshop CC 2016 followed by the processing and analysis of digital images at PC. Employing this software package enables the investigation of the percentage of impurities that obscure the color of oil. It was performed on the selected samples of oils using digital images. Digital information is added to the environment of graphics software that support the function of the histogram distribution of colors. Next, it is required to convert the colors into black and white gamma and to choose sample distribution from 0...132-color gamma. As a result, we obtain in a given interval the value of percentage for impurities, the amount of polluting and acting particles in a transmission oil.

The dielectric permittivity of transmission oil in this work was measured based on the capacity of capacitors applying a voltmeter method – by using an ammeter (Fig. 1), which is used for measuring relatively large capacities.

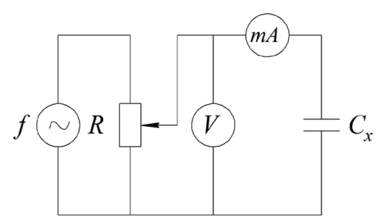

Fig. 1. Measuring method of dielectric permittivity of oil by using voltmeter-ammeter

The power supply of the measuring circuit was typically enabled from the source of current with low frequency: $f=50...1{,}000$ Hz and therefore we disregarded active losses in capacitors and the influence of reactive parameters of measuring devices and harmful relationships.

The examined capacitor C_x is included in the circuit of alternating electric current of known frequency f; by using a rheostat (potentiometer) R, we set the value, required under testing conditions, or suitable for reference count, of current I or voltage U. The readouts from the AC devices were used to calculate full impedance of the capacitor:

$$Z = \left(R^2 + X^2\right)^{1/2} = U / I, \quad (1)$$

where R and $X_C = (2\pi f C_x)^{-1}$ are, accordingly, the active and reactive components of its resistance. If the losses are not significant, that is, $R \ll X_C$, the measured capacity is derived from the following formula:

$$C_x = (2\pi f U)^{-1}. \quad (2)$$

At the same time, we switch sequentially with the source of alternating current f a source of DC whose voltage at the electric contacts U_0 should exceed the amplitude of alternating voltage. Then a pulsating voltage will act in the circuit, safe for the capacitor under condition of the correct polarity of its inclusion in the circuit. The pulsating voltage can also be obtained at the consistent inclusion of a diode in the measuring circuit. Note that in all cases the voltmeter V and the milliammeter mA should measure only a change in the components of voltage and current. This explains why the input circuit is closed. In a given method of measuring, we used a multimeter and a capacitive cell. The laboratory multimeter MASTECH MS8040 serves as a measuring device while the capacitive cell represents a capacitor with dielectric environment, which in this case is a working transmission oil. Capacitive cell is the two electrodes that are connected by a dielectric and have a cavity to be filled with the working oil.

The procedure for monitoring a technical condition of the gear box was devised and developed based on acting DSTU (GOST) and technical conditions for the operation of commercial vehicles. We have examined the following trucks: KamAZ 4310 (5 units), KamAZ 43105 (6 units), KamAZ 43114 (4 units).

5. Results of studying and creating a rational diagnostic database on the technical condition of transmissions in transportation vehicles

In the process of operation, the execution of a certain work leads to a change in the diagnostic parameters of systems and assemblies of transportation vehicles. It is an important task of technical operation to take into consideration the development or patterns of change. Vectors of parameters that characterize transportation vehicles as a technical system in operation are represented in the form of a functional relationship diagram (Fig. 2).

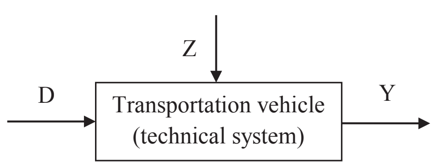

Fig. 2. Functional diagram of the relationship between totalities of parameters of transportation vehicles: D – totality of internal (diagnostic) parameters, $Z = Z_1 + Z_2$ – totality of parameters of operational conditions Z_1 and technical influences Z_2, Y – totality of parameters of the functional designation of conjugations of parts, systems and assemblies of transportation vehicles

Inextricably linked totalities of various parameters in the functional scheme requires a mathematical interpretation and generalization of possible relations, as well as a more qualitative control and monitoring of the technical condition of transportation vehicles [12]. It was found that the generalized functional dependences of parameters in the mathematical models of systems and assemblies can be represented in the form of functions of totalities of direct links:

$$y_i = f(D_i, \alpha_i, z_i, \delta_i), \quad i = \overline{1,n}, \quad (3)$$

as well as by totalities of feedback related to a certain level of reliability and conducting operations of technical maintenance:

$$y_i = f(D_i, \beta_i, \tilde{z}_i, \gamma_i), \quad i = \overline{1,n}, \quad (4)$$

where D_i is the totality of diagnostic parameters of the technical condition of systems and assemblies in TV, $\tilde{z}_i$ are the disturbances in parameters of control over technical condition at feedback, γ_i are the parameters of decision making related to technical operation.

Under conditions that mathematical models (3), (4) are fixed, technical condition is determined by the choice of the totality of diagnostic parameters – α_i, operating conditions parameters β_i, error in the measurement of diagnostic parameters δ_i, parameters of decision making γ_i.

A totality of technical and operational parameters, as well as a set of functional states of transportation vehicles, can be merged in one vector $\vec{Y}$. Under different conditions of operation, the technical condition will be determined by a complex vector function:

$$\vec{Y} = (\vec{\alpha}, \vec{\beta}, \vec{\gamma}, \vec{\delta}). \quad (5)$$

A condition of normal functioning of TV, with respect to a given vector function (5), can be represented in the form of the ratio of sets:

$$R(\vec{Y}) \subset M_y, \quad (6)$$

where $R(\vec{Y})$ is the vector space of values for technical condition $\vec{Y}$ of conjugations of parts, systems and assemblies in transportation vehicles in general, which they may accept during operation; M_y is the set of valid states. Ratio (6) indicates that in order to ensure the working state of transportation vehicles, it is necessary to constantly control the parameters that describe the technical condition of systems and assemblies of a transportation vehicle under specified operational conditions. To control operational conditions of transportation vehicles, to consider and manage a dynamic change in the technical condition is difficult hard and energy-intensive. It was established that systems and assemblies of transportation vehicles can at a certain period of operation be under different operating conditions [11]. The value of error in a diagnostic parameter is also very important factor that affects technical maintenance of systems and assemblies of transportation vehicles. Given this, decision making and application of strategies for restoring the working state of transportation vehicles require theoretical substantiation. Based on this, such factors are identified and taken into consideration that significantly affect, during operation, the character of change in the technical condition of systems, assemblies, and transportation vehicles in general.

The operation of transportation vehicles, from a theoretical point of view, should be represented in the form of a mathematical model of cause-effect relationships between the totality of factors and parameters that represent the cause, and by the objective function that characterizes the result. Note that in this case a large number of elements in the systems and assemblies of transportation vehicles interact both between themselves and the environment.

Information about the processes that occur in them during operation, as well as on the technical condition, is acquired by various physical methods. To efficiently process a database obtained, it is proposed to use methods of a generalized graph theory and the theory of function sensitivity. Examining a change in the function of technical condition due to a change in the essential factors and parameters by using the criterion of relative sensitivity (sensitive) has significant advantages in comparison with the methods of absolute sensitivity, which are based on the content of the derivative. First, it is the fact that the criterion of relative sensitivity is a dimensionless quantity, and has several other characteristic properties [7], which should be respected and employed when analyzing a database on the technical condition of systems, assemblies, and transportation vehicles in general.

The mathematical essence of the criterion implies the construction of the ratio of relative increment in the objective state function to the relative increment of the factor:

$$sen\,y_i(x)=\frac{dy_i(x)}{y_i(x)}\cdot\frac{x}{dx}=\frac{dy_i(x)}{dx}\cdot\frac{x}{y_i(x)}. \tag{7}$$

This form of representation of the criterion of relative sensitivity (sensitive) is proposed to use for optimum assessment of any diagnostic parameter that needs to be controlled when determining a technical condition of systems and assemblies in transportation vehicles. Based on expression (7), the criterion of relative sensitivity of each diagnostic parameter relative to the ideally-represented function of technical condition of transportation vehicles takes the form:

$$sen\,D_i(\alpha_i)=\frac{D_i'(\alpha_i)}{D_i}\cdot\alpha_i=$$

$$=f_{\alpha_i}'(\alpha_i,\beta_i,\gamma_i,\delta_i)\cdot\frac{\alpha_i}{f(\alpha_i,\beta_i,\gamma_i,\delta_i)}, \tag{8}$$

where $D_i(\alpha_i)$ is the value of diagnostic parameters of the systems and assemblies of transportation vehicles; α_i is the idealization of the entire totality of diagnostic parameters; β_i is the idealization of parameters of operational conditions of transportation vehicles; δ_i is the idealization of measurement error of diagnostic parameters; γ_i is the idealization of parameters for decision making on technical operation of transportation vehicles; $f_{\alpha_i}'(\alpha_i,\beta_i,\gamma_i,\delta_i)$ is the function of technical condition of transportation vehicles based on the developed parameters.

The focus of attention is a general character of examining the functions of technical condition of systems, assemblies, and transportation vehicles in general, as well as patterns of its relative changes. In this case, a relative change in the increment of function due to the relative increment in the totality of diagnostic parameters reflects a change in the relative sensitivity of state functions over operation period. The required mathematical apparatus is constructed using the properties of the absolute and relative sensitivities of functions of technical condition. The most common measure of absolute sensitivity of the state functions to a change in factors and diagnostic parameters is their resulting gain or differential. For the state function $S(D)$ of one factor (diagnostic parameter) D, we have:

$$dS(D)=\frac{dS(D)}{dD}dD. \tag{9}$$

Absolute sensitivity of the state function, that is, the derivative from the state function typically has a dimensionality of the absolute sensitivity of a diagnostic parameter:

$$\frac{dS(D)}{dD}=S'(D). \tag{10}$$

If a state function depends on the vector of diagnostic parameters $\bar{D}=(D_1, D_2,..., D_n)$, then there is an entire system of partial absolute sensitivities of state functions:

$$\frac{\partial S(D_1,D_2,...,D_n)}{\partial D_1}=S_{D_1}'(D_1,D_2,...,D_n);$$

$$\frac{\partial S(D_1,D_2,...,D_n)}{\partial D_2}=S_{D_2}'(D_1,D_2,...,D_n);...;$$

$$\frac{\partial S(D_1,D_2,...,D_n)}{\partial D_n}=S_{D_n}'(D_1,D_2,...,D_n). \tag{11}$$

The criterion of relative sensitivity of the objective function of technical state $S(D)$ is equal to:

$$senS(D)=S^s(D)=\frac{dS(D)}{S(D)}\Big/\frac{dD}{D}=S'(D)\cdot\frac{D}{S(D)}, \tag{12}$$

where $dS(D)/S(D)$, dD/D are the relative increments in the objective function and a diagnostic parameter.

In case a state function depends on the vector of diagnostic parameters, partial criteria of relative sensitivity (sensitives) are equal to:

$$Sen\,S_{D_1}(D_i)=S_{D_1}'(D_i)\cdot\frac{D_1}{S_{D_1}(D_i)};$$

$$Sen\,S_{D_2}(D_i)=S_{D_2}'(D_i)\cdot\frac{D_2}{S_{D_2}(D_i)};...;$$

$$Sen\,S_{D_n}(D_i)=S_{D_n}'(D_i)\cdot\frac{D_i}{S_{D_n}(D_i)}. \tag{13}$$

At graphical representation of the dependence of criterion, it is appropriate to use the rule of differentiation of a logarithmic function:

$$senS(D)=S^s(D)=\frac{d(\ln S(D))}{d\ln D}=\frac{(\ln S(D))'S(D)}{(\ln D)'D}. \tag{14}$$

Given such a representation, the criterion is represented as the ratio of the derivative (partial derivative) from the logarithm of state function to the derivative from the logarithm of diagnostic parameters. Note that in practice it makes sense to apply absolute and relative sensitivity of the first and second orders. Absolute sensitivity of the first order from a state function is the rate of change in the increment of state function due to a change in the values of diagnostic parameters. Absolute sensitivity of the second order is the rate of speed of change in the state function or the acceleration of change in the increment of function with a change in the increment of diagnostic parameter. Absolute sensitivity of second and higher orders can be used to analyze the convergence of calculation algorithms. As the relative sensitivities of the first and second order of state function due to diagnostic parameters are dimensionless, it can be effectively used as the criterion of relative sensitivity when analyzing a database of information technology and PC processing methods.

When considering a totality of diagnostic parameters, the criterion of relative sensitivity is generalized for the case of an arbitrary number of the sum or difference in the functions of change in diagnostic parameters that make up the function of state of systems and assemblies in transportation vehicles:

$$S(D)=U_1(D)+U_2(D)+ +U_3(D)+U_4(D)+U_5(D)+....=\sum_{i=1}^{n}U_i(D); \quad (15)$$

$$Sen(S(D))=Sen(S(U_1(D)))\frac{U_1(D)}{\sum U_i(D)}+ + Sen(S(U_2(D)))\frac{U_2(D)}{\sum U_i(D)}+ + Sen(S(U_3(D)))\frac{U_3(D)}{\sum U_i(D)}+...+ + Sen(S(U_5(D)))\frac{U_5(D)}{\sum U_i(D)}+..., \quad (16)$$

where $Sen(S(D))$ is the general criterion of relative sensitivity of the state function for diagnostic parameters D; $Sen(S(U_i))$ are the partial criteria of relative sensitivity; $U_i(D)$, $i=1,N$ are the functions of change in the corresponding diagnostic parameter for various systems and assemblies of transportation vehicles.

By using the procedure of implementation of analysis of the theory of sensitivity of state functions, it is possible to obtain partial criteria of relative sensitivity for each diagnostic parameter at different periods of runtime. In this case, the function of diagnostic parameter and the general function of reliability (probability of failure-free operation) of a transportation vehicle or its systems and assemblies can be considered to be assigned parametrically:

$$\left.\begin{array}{l} x_i=D_j(L), \\ y_i=P_i(L), \end{array}\right\} \quad (17)$$

where i is the index of a system or an assembly, j is the index of diagnostic parameter of the technical condition of systems and assemblies, P_i is the probability of their failure-free operation.

Using the rules for finding the criterion of relative sensitivity and its properties regarding the reliability of systems or assemblies, as well as a transportation vehicle in general, one can obtain the criterion of relative sensitivity of a diagnostic parameter as a function of TV runtime:

$$sen\,D_j(L)=\frac{P_i(L)'}{D_j(L)'}\cdot\frac{D_j(L)}{P_i(L)}=\frac{\frac{dP_i}{dL}\cdot D_j(L)}{\frac{dD_j}{dL}\cdot P_i(L)}. \quad (18)$$

Note that equation (18) describes dependences of the relative sensitivity of diagnostic parameters on the function of reliability of systems and assemblies and transportation vehicles in general, but it needs clarification of the trend of change in the function of diagnostic parameter $D_j(L)$ on the runtime. It is known [5] that the methods of extrapolation are employed for this purpose, which are the most affordable methods among the entire totality when constructing the examined functions of diagnostic parameters. The use of extrapolation is based on the assumption that a given process of change in the diagnostic parameter is a combination of two components: regular and random:

$$D_j(L)=D_j(\vec{a},L)+d_j(L). \quad (19)$$

It is believed that the regular component of diagnostic parameter $D(\vec{a},L)$ is a function of the runtime, which is described by vector of parameters $\vec{a}$, which retain their values over the extrapolation period. This component is a trend or a tendency. In this case, there is an intuitive idea of disturbances, cleared of accidental impacts of noise, which affect the essence of the process of change in a diagnostic parameter. At the same time, for most technical, natural processes one cannot clearly separate a tendency from accidental influences because the random component $d_j(L)$ is typically considered to be a non-correlated process with a zero mathematical expectation. The estimation of a component is required for further determining the accuracy of the obtained function of diagnostic parameter $d_j(L)$. Extrapolation methods are based on the selection of the best, in some sense, description of the tendency, and on determining the examined values of diagnostic parameters by means of extrapolation.

Specific features of extrapolation are considered to be the methods of preliminary processing of an existing database. The goal of the transformation is the reduction to a more convenient form for the application in order to analyze logic and the physics of processes of change in the diagnostic parameters. This affects the choice of type of an extrapolation function and determining the range of change in parameters.

Thus, examining the function of technical condition of systems, assemblies, and transportation vehicles in general, based on a series of diagnostic parameters, is possible through the use of the theory of relative sensitivity. The advantage of applying the criterion of relative sensitivity in the analysis of technical condition is its dimensionlessness. In addition, it reflects actual relative change in a diagnostic parameter and a reliability indicator (the probability of a failure-free operation) for systems, assemblies, and transportation vehicles in general with respect to runtime.

In the process of a database analysis we determined statistical probability of non-failure operation P_j of the gear box in the family of trucks KamAZ; the models and their number were specified in chapter 4. Operational conditions, type and modification of the examined assembly in transportation vehicles are the same for the entire fleet of the examined trucks. The minimum sample size for examining technical state of the gear box with a confidence probability of 0.9, a confidence interval of 10 %, a general totality of the fleet of transportation vehicles of 15, as specified in chapter 4, was 12 units. The calculation of statistical probability of the examined assembly at run intervals was conducted using operational simplifications. We studied 8 main conjugations of the gear box, specifically toothed gear, synchronizers, bearings. The total number of conjugations in the examined sample was 96 units. The occurrence of a sign of fault in the conjugations of assemblies under study over the run interval was registered as a failure. Statistical probability of a non-failure operation was calculated as an event opposite to a failure; under such conditions, the following formula can be used:

$$P_j = 1 - \frac{n_{fo}}{N_!}, \quad (20)$$

where n_{fo} is the number of failures over a specific run interval; N_C is the total number of conjugations in the examined assemblies.

The number of failures that occurred in the run interval of 0...60 thousand km, and a series of distribution of indicator P_j for the tested assembly, are given in Table 1.

Table 1

Distribution of the number of failures and the probability of a non-failure operation of the gear box depending on the run of transportation vehicles

Number of failures and probability of non-failure operation	Run intervals, thousand km				
	0...12	12...24	24...36	36...48	48...60
Gear box					
N	1	2	11	12	14
P	0.989	0.979	0.885	0.875	0.854

Summarized data from Table 1 allow us to analyze the reliability of a transmission assembly in more detail. Based on data on the probability of a non-failure operation, we constructed a mathematical model in the form of a regression equation:

$$P_{GB}(L) = 7.26 \cdot 10^{-15} \cdot L^3 - $$
$$- 7.094 \cdot 10^{-10} \cdot L^2 + 1.64 \cdot 10^{-5} \cdot L + 0.8839, \quad (21)$$

where $P_{GB}(L)$ is the statistical probability of a non-failure operation of the gear box depending on the run of a transportation vehicle.

Graphical interpretation of this model is shown in Fig. 3.

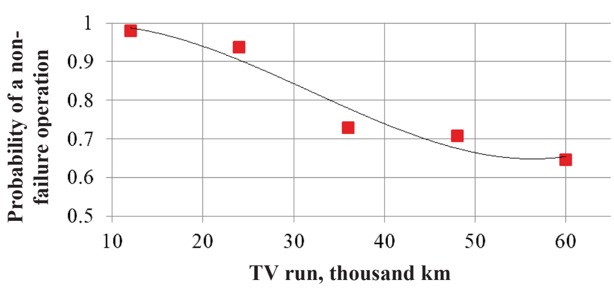

Fig. 3. Change in the probability of a non-failure operation of the gear box on the run of TV

The minimum sample size for examining technical condition of the gear box with a confidence probability of 0.9, a confidence interval of 10 %, a general totality of the fleet of transportation vehicles of 15, as specified in chapter 4, was 12 units. A general totality of sampling at each run interval, for each diagnostic parameter, was 30, based on the procedure for examining the diagnostic parameters of oil, as specified in chapter 4. The minimum sample size of diagnostical parameters of the gear box with a confidence probability of 0.9, a confidence interval of 10 %, a general totality of 30, was 21 units. Mean values of data from express analysis of the actual technical condition of the gear box are given in Table 2.

Table 2

Change in the diagnostic indicators of transmission oil due to the run of transportation vehicles

Parameter	Run intervals, thousand km				
	0...12	12...24	24...36	36...48	48...60
Content of mechanical impurities, %	0.1	0.3	0.8	1.2	1.9
Dielectric permittivity of oil	2.47	2.50	2.54	2.57	2.61
Oil alkaline number, mg KOH/g	0.02	0.12	0.27	0.32	0.4

Results of digital images of the samples of transmission oil for different run of a transportation vehicle are shown in Fig. 4.

Graphical interpretation of the dependence of content of mechanical impurities in transmission oil on the run of transportation vehicles is shown in Fig. 5.

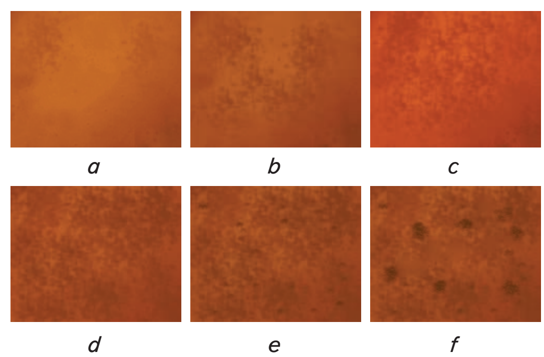

Fig. 4. Digital images of examination of the samples of transmission oil for the content of mechanical impurities depending on the run of transportation vehicles: *a* – fresh oil; *b* – after 12 thousand km; *c* – after 24 thousand km; *d* – after 36 thousand km; *e* – after 48 thousand km; *f* – after 60 thousand km

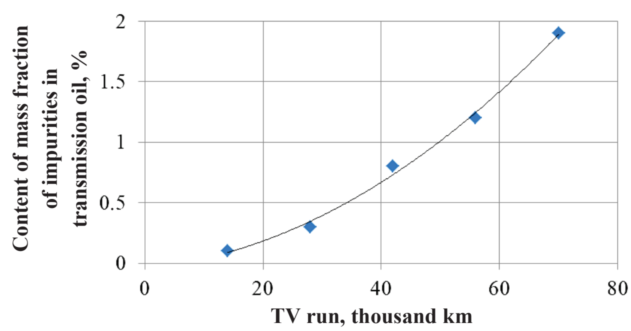

Fig. 5. Mean value of change in the content of impurities in transmission oil depending on the run of a transportation vehicle

One can see the non-linear character of the specified dependence. This indicates the intensification of processes of friction and wear of heavy-loaded parts of the gear box. Moreover, wear particles can act as abrasive particles that localize stresses on the working surfaces of toothed gears, which in turn leads to the wear and destruction of parts during operation and the deterioration in transmission oil.

A change in the values of dielectric permittivity of transmission oil due to the run of transportation vehicles is shown in Fig. 6.

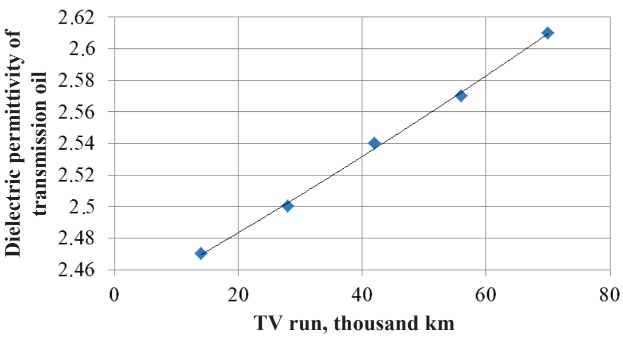

Fig. 6. Change in the values of dielectric permittivity of transmission oil due to the run of transportation vehicles

There is almost a linear character of dependence of change in the average value of dielectric permittivity of transmission oil on the run of a transportation vehicle. Note that the dielectric permittivity reflects the process of arrival of electrically conductive particles of metal during operation of parts of the gear box.

The character of change in the alkaline number of transmission oil due to the run of a transportation vehicle is shown in Fig. 7.

We register the non-linear character of dependence of the magnitude of alkaline number of transmission oil on the run. A diagnostic parameter in this case reflects the level of maintaining the properties of oil that protect the parts of transmission assemblies at wear during operation.

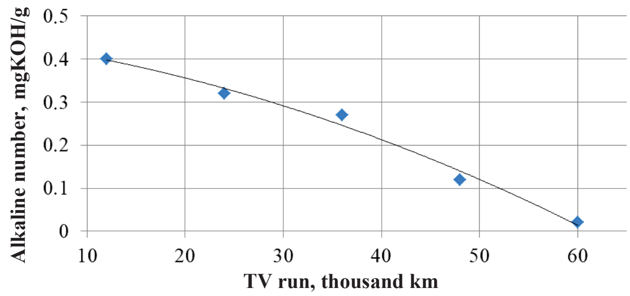

Fig. 7. Change in the values of alkaline number of transmission oil due to the run of transportation vehicles

According to data from experimental research into diagnostic parameters of transmission oil, we obtained regression models of their change due to the run of transportation vehicles, which are summarized in Table 3.

Table 3

Regression mathematical models of change in the diagnostic parameters of transmission oil due to the run of a transportation vehicle

Content of mechanical impurities	
$D_{CMITO}(L)=3.28\cdot10^{-10}L^2+4.59\cdot10^{-6}L-0.04,\ \%$	(22)
Dielectric permittivity	
$D_{DPTO}(L)=3.64\cdot10^{-12}L^2+2.19\cdot10^{-6}L+2.438$	(23)
Alkaline number	
$D_{ANTO}(L)=-5.1\cdot10^{-11}L^2+1.12\cdot10^{-5}L-0.132$, mgKOH/g	(24)

We used the software package Mathcad 14, in which, based on formula (19), we substitute expression $P(L)$ with dependence $P_{GB}(L)$, expression $D_j(L)$ is alternately substituted with $D_{CMITO}(L)$, $D_{DPTO}(L)$, $D_{ANTO}(L)$, for obtaining appropriate dependences of their relative sensitivity. The obtained dependences of relative sensitivity (sensitives) of express significant diagnostic parameters of the gear box of transportation vehicles are summarized in Table 4.

Table 4

Mathematical models of relative sensitivity of informatively significant diagnostic parameters of the examined assembly

Gear box	
Content of mechanical impurities of transmission oil	
$senD(L)_{CMITO}=\dfrac{\left(4.59\cdot10^{-6}L+3.28\cdot10^{-10}L^2-0.04\right)\left(-1.04\cdot10^{-9}L+1.37\cdot10^{-14}L^2+14.1\cdot10^{-6}\right)}{\left(6.56\cdot10^{-10}L+45.9\cdot10^{-7}\right)\left(1.14\cdot10^{-5}L-5.21\cdot10^{-10}L^2+4.57\cdot10^{-15}L^3+0.884\right)}$	(25)
Dielectric permittivity of transmission oil	
$senD(L)_{DPTO}=\dfrac{\left(-1.042\cdot10^{-9}L+1.37\cdot10^{-14}L^2+14.1\cdot10^{-6}\right)\left(2.19\cdot10^{-6}L+3.64\cdot10^{-12}L^2+2.44\right)}{\left(7.28\cdot10^{-12}L+21.9\cdot10^{-7}\right)\left(1.41\cdot10^{-5}L-5.21\cdot10^{-10}L^2+4.57\cdot10^{-15}L^3+0.884\right)}$	(26)
Alkaline number of transmission oil	
$senD(L)_{ANTO}=\dfrac{\left(1.11\cdot10^{-5}L-5.1\cdot10^{-11}L^2-0.132\right)\left(-1.04\cdot10^{-9}L+1.37\cdot10^{-14}L^2+14.1\cdot10^{-6}\right)}{\left(-1.02\cdot10^{-10}L+1.11\cdot10^{-6}\right)\left(1.41\cdot10^{-5}L-5.21\cdot10^{-10}L^2+4.57\cdot10^{-15}L^3+0.884\right)}$	(27)

Based on the mathematical models of relative sensitivity (sensitives) of informatively significant diagnostic parameters, it is possible to obtain specific values in the range of run of transportation vehicles. A value of the criterion of relative sensitivity makes it possible to establish a relationship between diagnostic parameters and indicators of reliability. Note that the criterion lacks measurements units. This advantage is utilized when studying heterogeneous diagnostic parameters. A mathematical apparatus of the theory of relative sensitivity is an effective tool for solving applied technical tasks.

Further calculation of the value of relative sensitivity of diagnostic parameters is carried out using the software package Mathcad 14. To calculate, we shall build a vector of the run of transportation vehicles from 0 to 60 thousand km with a step of 12 thousand km, and next substitute it in the obtained dependences (25)–(27). The calculated values of relative sensitivity of diagnostic parameters of the technical condition of the gear box in transportation vehicles are given in Table 5.

Table 5

Estimation of relative sensitivity of informatively significant diagnostic parameters of the transmission assembly due to the run of TV

Run, thousand km	Sensitive of the content of mechanical impurities in oil	Sensitive of dielectric permittivity of oil	Sensitive of alkaline number of oil
0	–0.139	–0.013	–0.046
12	0.014	–0.018	0.037
24	–0.067	–0.101	0.106
36	–0.139	–0.17	–0.098
48	–0.045	–0.103	–0.035
60	0.352	0.223	0.076

One can see, based on data from Table 5, that the criterion of relative sensitivity at different intervals of the run has a different value that can be used later in the analysis and selection of informative values of diagnostic parameters.

6. Discussion of results of examining the diagnostic parameters of technical condition of the gear box

Changing the sign of the criterion of relative sensitivity reflects the relationship between the examined indicators of reliability of the gear box and diagnostic parameters of technical condition. Forming a criterion of relative sensitivity and conducting further analysis based on it makes it possible to investigate and control, as well as substantiate, the required diagnostic parameters, and to determine the time of control during operation under certain conditions. It was found that the positive value of the criterion of relative sensitivity reflects robustness of the dependence, while a negative value – insignificance of reliability indicators and diagnostic parameters. In addition, the criterion in turn enables the automation of the technical maintenance service of operation of transportation vehicles under different conditions.

By analyzing the obtained values for the criterion of relative sensitivity of the informatively significant diagnostic parameters of technical condition of the transmission assemblies depending on the run of transportation vehicles, we determined the possibility of forming such ranges of run, over which we should control diagnostic parameters. The research has found that the content of mechanical impurities in transmission oil is advisable to control at intervals of 0...12 and 48...60 thousand km of the run of transportation vehicles; the dielectric permittivity of oil – 48...60 thousand km. As regards control over the alkaline number of transmission oil, it should be executed at intervals of 12...24 and 48...60 thousand km of the run of transportation vehicles.

Based on the developed procedures for analysis and creation of a diagnostic database, it is possible to establish the required control operations for the technical condition of the examined assemblies of transportation vehicles. The implementation of procedures developed for the technical operation of transportation vehicles would reduce the time for carrying out control operations, as well as more carefully define their faulty technical condition.

The advantage of present research in comparison with analogues for determining technical condition is the fact that the developed method possesses a flexible apparatus for the analysis of diagnostic parameters and allows the automation of forming diagnostic information during technical operation of trucks. The solutions proposed make it possible to achieve this goal by combining two criteria, such as the value of a diagnostic parameter and the statistical probability of a non-failure operation of assemblies in transportation vehicles, into the criterion of their relative sensitivity. One of the main benefits of using the criterion of relative sensitivity is also the absence of dimensionality that makes it universal in technical operation. The drawback of present study is the time needed for compiling statistical information, as well as the mandatory use of computer technology and software for calculations, which are not always in the public domain.

The prospect of further development of this study is the analysis, selection of diagnostic information and, based on it, prediction of technical condition of systems and assemblies in transportation vehicles. Since during forecasting of technical condition each piece of diagnostic information significantly adjusts the process of determining future technical condition of transportation vehicles, creating its rational amount is a required step.

7. Conclusions

1. We have substantiated the use of the criterion of relative sensitivity, to analyze diagnostic parameters, based on the parametrical relationship between an indicator of a failure-free operation of systems and assemblies of transportation vehicles and the diagnostic parameters that describe actual technical condition.

2. Experimental research was undertaken, which allowed us to establish a change in the indicator of a failure-free operation of the gear box and diagnostic parameters dependent on the run of transportation vehicles. A change in the reliability indicator over a 60-thousand-km run changed by 0.135. The examined diagnostic parameters of the quality of working oil in the gear box of trucks over a 60-thousand-km run changed in the following way: the content of mechanical impurities in oil – 0.1...1.9 %, dielectric permittivity of oil – 2.47...2.61, alkaline number – 0.02...0.4 mgKOH/g.

3. Based on experimental data and an analysis of indicator of relative sensitivity, we created a rational diagnostic database when examining a technical condition of the gear box. Therefore, the content of mechanical impurities in transmission oil is advisable to control at intervals of 0...12 and 48...60 thousand km of the run; the dielectric permittivity of oil should be controlled within 48...60 thousand km of the run; the alkaline number of transmission oil should be controlled within 12...24 and 48...60 thousand km of the run of transportation vehicles.

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