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Control of the Railroad Bed by the Degree of Reliability of Operational State and the Degree of Hazard of Non-operational State

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ABSTRACT The railroad bed is subject to various destructive processes. Therefore, constant monitoring and control of the technical condition of railroad tracks is required. The existing literature examines a method, according to which special equipment is installed in one of the cars of the rolling stock, and an intelligent system is created to identify the railroad track sections that require extraordinary control. In this system, using a controller, the characteristics of the noise of the noisy vibration signal resulting from ground vibration are calculated, which are used as diagnostic informative attributes of the occurrence of malfunction on the railroad track in the initial latent period of inception, and a knowledge base of the technical condition is created. As a result of the analysis, a decision is made on the necessity or omission of off-schedule inspection of railroad tracks. In this paper, we propose to include new and more important diagnostic attributes into this knowledge base, which are estimates of the degree of reliability of operational and the degree of hazard of non-operational states of the railroad bed. To calculate these attributes, algorithms are proposed for calculating the probability of the useful component and the noise falling within given bounding intervals. Taking into account that the algorithms are rather complicated, the calculation of characteristics should be performed in the control center, where the noisy vibration signal is transmitted. As a result, a new final improved knowledge base is formed. The application of the proposed algorithms increases the reliability and adequacy of the control of the railroad bed.

KEYWORDS railroad bed; vibration noisy signal; useful signal; noise; reliability degree; hazard degree; operational state; non-operational state.

I. INTRODUCTION

It is known that rail transport, which enables the transportation of a large number of passengers and cargo over long distances, is a safer, more efficient, cost-effective and energy-efficient mode of transportation compared to other modes of transportation [1, 2]. As a rule, a railroad bed is designed for the movement of railroad traffic and consists of earth bed, sand cushion, ballast, sleepers, rails and track fasteners. The ballast layer provides vertical and horizontal stability of the railroad track [3]. The quality and design of the ballast layer determines the service life of the elements of the upper structure, i.e., sleepers, rails, fastenings and the condition of the railroad track as a whole [3-5].

Railroads operate in challenging conditions. These include such natural and climatic conditions as the impact of hurricane wind, torrential rain, seismic events, landslides, etc., as well as dynamic loads from the movement of rolling stock. Therefore, as a result of the operation of the railroad track, various faults occur in the above elements [6-7].

For uninterrupted movement of rolling stock, the technical condition of the elements of the railroad track is monitored [8-9]. For this purpose, special track-testing cars, geometry cars, flaw detector cars are used on railroads [9]. These testing cars control the technical condition of the railroad bed of each track section in turn as scheduled at certain intervals of time. However, in real life, under the influence of all kinds of factors, changes in the technical condition of the railroad bed elements can occur daily.

At the same time, it was noted in [10] that the vibration signals received from vibration sensors are characterized by a change in the spectrum depending on the occurrence of a malfunction of the railroad track. Due to this fact, an adaptive technology for forming informative attributes from estimates of vibration signals was proposed, which makes it possible to build intelligent systems of adaptive vibration control of malfunction.

In [10], an intelligent system for identifying railroad track sections requiring off-schedule inspection was proposed. The intelligent system consists of the following modules: vibration sensor, adaptive analog-to-digital conversion of vibration signals $G(t)$, determination of estimates of current informative attributes, formation of reference informative attributes, storage of reference informative attributes, identification of the beginning of the latent period of malfunction, formation and transmission of information via communication means.

It is shown in [10] that the noisy vibration signal received in the track-testing car from ground vibration as a result of railroad track movement consists of a useful component and a noise, which cannot be isolated from the noisy signal. The most important informative attributes of emergence of malfunction on the railroad track in the initial period are the estimates of the noise variance, cross-correlation function and relay cross-correlation function between the useful vibration signal and the noise, estimates of the useful signal variance, spectral characteristics of the noise, as well as coefficients characterizing the ratio of the noise variance to the useful signal variance. The values of these noise characteristics are calculated by means of the controller of the intelligent system installed in one of the cars of the rolling stock and transmitted via radio channel to the control room (or "system of establishing the presence of a malfunction in the section").

According to this scheme, when the rolling stock moves along the damaged section of the railroad track, estimates of the characteristics of the noise $\mathrm{E}(t)$ of the vibration signal $G(t)$ differ from the reference ones. These characteristics are called informative attributes of malfunction initiation. This information is transmitted by radio channel to the control station. The control station registers the number of the section of the railroad track, where the difference between the values of the characteristics of the noise $\mathrm{E}(t)$ from the reference ones is detected. If any of the subsequent rolling stock on the same track section also shows a difference in characteristics from the reference ones, this is similarly transmitted to the control station. This is repeated for several days. A knowledge base is formed from the transmitted information collected in the control station over several days. As new information is received at the control station, the knowledge base is supplemented and a new knowledge base is formed and continuously analyzed. As a result of analyzing the knowledge base created on the basis of the proposed formulas, the number of the railroad section for which it is necessary to carry out unscheduled control with the help of the testing car is determined. In this way, the sections that are advisable to be inspected out-of-schedule by means of the track testing car are identified. Only testing cars determine the location of the malfunction and make the final decision.

In order to increase the adequacy of the control results of the sections requiring off-schedule control, we propose to add new additional informative noise-characteristics to the listed diagnostic attributes in the form of estimates of the degree of reliability of the operational state and the degree of hazard of the non-operational state of the railroad bed. These characteristics are determined as a result of calculating the probabilities of the useful component and noise of the noisy vibration signal resulting from the vibration during the rolling stock movement falling within predetermined intervals.

Since the algorithms of calculation of these characteristics are rather complex, they should be implemented on powerful computing facilities installed in the control center where the noisy vibration signal is received.

The use of estimates of reliability degree and hazard degree as additional informative diagnostic attributes is an extension of work [10]. As a result, the knowledge base of the intelligent system is supplemented with new, although quite complex, but much more significant characteristics, which allow a more adequate assessment of the technical condition of the railroad bed and the dynamics of changes in both operational and non-operational states at an early stage. Practical application of the combination of the algorithms proposed in [10], as well as the algorithms proposed in the following paragraphs, makes it possible to further increase the reliability of control.

II. PROBLEM STATEMENT

It is known that for effective and continuous monitoring of the technical condition of the railroad bed it is necessary to analyze the vibration signal caused by ground vibration resulting from the movement of rail vehicles [11-15]. As a rule, the vibration signal $G(t)$ consists of a useful component $X(t)$ and a noise component $\mathrm{E}(t)$ [10, 16-19]:

$$G(t) = X(t) + \mathrm{E}(t),$$

where $X(t)$ and $\mathrm{E}(t)$ are stationary ergodic signals, which have normal distribution law, mathematical expectation of the noise m_{E} =0.

The noise $\mathrm{E}(t)$ can be caused by changes in external factors and as a result of defects, malfunctions, etc. [20, 21]. We denote the noise caused by changes in external factors by $\mathrm{E}_1(t)$, and the noise caused by defects by $\mathrm{E}_2(t)$.

External factors are changes in train speed, sandstorms, heavy rainfall, hail, snow, landslides, seismic effects, etc. [4-8, 19]. When external factors change, the values of estimates of the characteristics of the useful signal $X(t)$ change. It is known that any signal (technological parameter) must vary within some limits (ranges):

$$x_1 \le X(t) \le x_2 . \tag{1}$$

This is called a positional constraint. As a rule, the minimum value of $X(t)$, and the maximum value of $X(t)$ are chosen as x_1 and x_2, respectively. If the signal (parameter) goes beyond these limits, it indicates a disruption in the course of the process under study.

Since in this case it is impossible to isolate the useful signal $X(t)$ from the noisy vibration signal $G(t)$ and to know its discrete values to check condition (1), we have to limit ourselves only to estimating the probability $P(x_1 \le X(t) \le x_2)$ with which the useful signal $X(t)$ falls into some admissible interval $x_1 \le X(t) \le x_2$. If the value of this probability is close to one, we can assume that condition (1) is satisfied. If it is close to zero, it means that condition (1) is not fulfilled. Thus, the reliability of the operational condition of the investigated section of the railroad track is estimated.

The probability $P\left(x_1 \le X\left(t\right) \le x_2\right)$, with which the useful signal takes values that allow the rolling stock to carry out safe movement, is determined by the expression [21-23]:

$$P\left(x_1 \le X\left(t\right) \le x_2\right) = \int_{x_1}^{x_2} N\left(x\right) dx \,, \quad (2)$$

where $N\left(x\right)$ is the normal distribution density function, D_X, σ_X, m_X are variance, standard deviation and mathematical expectation, respectively [22-24]:

$$N\left(x\right) = \frac{1}{\sigma_X \sqrt{2\pi}} e^{-\frac{(x-m_X)^2}{2(\sigma_X)^2}} \,, \quad (3)$$

$$\sigma_X = \sqrt{D_X} = \sqrt{\frac{\sum_{i=1}^{N}\left(X\left(i\Delta t\right) - m_X\right)^2}{N}} \,, \quad (4)$$

$$m_X = \sum_{i=1}^{N} X\left(i\Delta t\right). \quad (5)$$

The noise $\mathrm{E}\left(t\right) = \mathrm{E}_1\left(t\right)$ is not correlated with $X\left(t\right)$. The coefficient of correlation between $X\left(t\right)$ and $\mathrm{E}\left(t\right)$ [22-24]:

$$r_{X\mathrm{E}} = \frac{\sum_{i=1}^{N}\left(X\left(i\Delta t\right) - m_X\right)\left(\mathrm{E}\left(i\Delta t\right) - m_{\mathrm{E}}\right)}{\sqrt{\sum_{i=1}^{N}\left(X\left(i\Delta t\right) - m_X\right)^2}\sqrt{\sum_{i=1}^{N}\left(\mathrm{E}\left(i\Delta t\right) - m_{\mathrm{E}}\right)^2}} \quad (6)$$

is zero $r_{X\mathrm{E}} = 0$ or no greater than some threshold value $\left|r_{X\mathrm{E}}\right| < r_{X\mathrm{E}-p}$.

Knowing the probability $P\left(x_1 \le X\left(t\right) \le x_2\right)$, with which the rolling stock can safely perform the assigned functions, makes it possible to assess the degree of reliability of the operational state. If $P\left(x_1 \le X\left(t\right) \le x_2\right)$ is very low, it indicates that there is a high risk of transition to a non-operational state.

When defects and cracks appear on the rails, track fastenings and sleepers wear out, when the strength and stability of the subgrade, sand cushion, ballast, etc. decrease, the noise $\mathrm{E}_2\left(t\right)$ emerges. Then

$$\mathrm{E}\left(t\right) = \mathrm{E}_1\left(t\right) + \mathrm{E}_2\left(t\right).$$

In this case, the correlation coefficient is non-zero: $r_{X\mathrm{E}} \neq 0$. If $\left|r_{X\mathrm{E}}\right| \ge r_{X\mathrm{E}-p}$ is greater than some threshold value, it is an informative indication of an incipient malfunction.

In addition, the value of the probability $P\left(x_1 \le X\left(t\right) \le x_2\right)$ is much less than the threshold value characterizing the operational state.

Therefore, based on the value of the probability $P\left(x_1 \le X\left(t\right) \le x_2\right)$ it is possible to assess the degree of reliability of the operational state of the railroad bed and based on the value of the correlation coefficient $r_{X\mathrm{E}}$ it is possible to identify the initial latent period of malfunction occurrence.

If there is noise $\mathrm{E}\left(t\right)$ correlated with the useful signal $X\left(t\right)$, it is necessary to calculate with the probability $P\left(\varepsilon_1 \le \mathrm{E}\left(t\right) \le \varepsilon_2\right)$ with which the noise falls within the inadmissible range

$$\varepsilon_1 \le \mathrm{E}\left(t\right) \le \varepsilon_2 .$$

If the probability $P\left(\varepsilon_1 \le \mathrm{E}\left(t\right) \le \varepsilon_2\right)$ is low, then it can be considered that the malfunction is insignificant. The higher the value of the probability $P\left(\varepsilon_1 \le \mathrm{E}\left(t\right) \le \varepsilon_2\right)$, the more dangerous the malfunction.

Thus, in addition, based on the estimates of the characteristics of the noise $\mathrm{E}\left(t\right)$ and the probability $P\left(\varepsilon_1 \le \mathrm{E}\left(t\right) \le \varepsilon_2\right)$, with which the noise takes threshold values exceeding the preset values, it is possible to determine the degree of danger of the latent initial period of malfunction occurrence and the dynamics of its development [10, 19, 21-24]:

$$P\left(\varepsilon_1 \le \mathrm{E}\left(t\right) \le \varepsilon_2\right) = \int_{\varepsilon_1}^{\varepsilon_2} N\left(\varepsilon\right) d\varepsilon \,, \quad (7)$$

where $N\left(\varepsilon\right)$ is the normal distribution density function of the noise $\mathrm{E}\left(t\right)$; D_{E}, σ_{E} are variance and standard deviation [19, 22, 25]:

$$N\left(\varepsilon\right) = \frac{1}{\sigma_{\mathrm{E}} \sqrt{2\pi}} e^{-\frac{(\varepsilon)^2}{2(\sigma_{\mathrm{E}})^2}} \,, \quad (8)$$

$$\sigma_{\mathrm{E}} = \sqrt{D_{\mathrm{E}}} = \sqrt{\frac{\sum_{i=1}^{N}\left(\mathrm{E}\left(i\Delta t\right) - m_{\mathrm{E}}\right)^2}{N}} . \quad (9)$$

Thus, the estimates of the reliability degree of the operational state, calculated by expressions (2)-(6) for the useful signal $X\left(t\right)$, as well as the estimates of the hazard rate of the incipient non-operational state, calculated by expressions

(7)-(9) for the noise $\mathrm{E}(t)$, are the most important additional diagnostic informative attributes, which should be added to the knowledge base of the intelligent system for identifying the railroad track sections requiring off-schedule inspection, presented in [10].

III. CALCULATING THE ESTIMATES OF THE DEGREE OF RELIABILITY OF THE RAILROAD TRACK OPERATIONAL STATE WHEN EXTERNAL FACTORS CHANGE

When external factors, such as changes in train speed, sandstorms, heavy rainfall, hail, snow, landslides, seismic effects, etc. change, so do characteristics (2)-(5) of the useful signal $X(t)$. At the same time, the characteristics of the noise $\mathrm{E}(t)=\mathrm{E}_1(t)$ change, as the effects of external factors change.

In this case, the noise $\mathrm{E}(t)$ is not correlated with $X(t)$

$$r^*_{X\mathrm{E}}=0.$$

Therefore, the first step is to calculate the correlation coefficient $r_{X\mathrm{E}}$ [11]. To use the known formula (6), it is necessary to know the values of discrete samples $X(i\Delta t)$, $\mathrm{E}(i\Delta t)$, that cannot be separated from the discrete reference sample $G(i\Delta t)$ of the vibration signal $G(t)$.

It was proved in [10, 19, 22] that the correlation coefficient between $X(t)$ and $\mathrm{E}(t)$ can be calculated from the following formula:

$$r^*_{X\mathrm{E}}=\frac{R^{r*}_{X\mathrm{E}}(0)}{\sqrt{\frac{2}{\pi}}\cdot\sigma^*_{\mathrm{E}}}, \tag{10}$$

where $R^{r*}_{X\mathrm{E}}(0)$ is the relay cross-correlation function between $X(t)$ and $\mathrm{E}(t)$, σ^*_{E} is the standard deviation of $\mathrm{E}(t)$, $R^r_{GG}(\mu)$ is the relay correlation function of the noisy vibration signal $G(t)$, $R_{GG}(\mu)$ is the correlation function of $G(t)$, $sgnG(i\Delta t)$ is the sign function of $G(t)$:

$$R^{r*}_{X\mathrm{E}}(0)=R^r_{GG}(0)-2R^r_{GG}(1)+R^r_{GG}(2), \tag{11}$$

$$\sigma^*_{\mathrm{E}}=\sqrt{R_G(0)-2R_G(\Delta t)+R_G(2\Delta t)}, \tag{12}$$

$$R^r_{GG}(\mu)=\frac{1}{N}\sum_{i=1}^{N}sgn\left(\overset{\circ}{G}(i\Delta t)\right)\overset{\circ}{G}((i+\mu)\Delta t), \tag{13}$$

$$sgnG(i\Delta t)=\begin{cases}+1, & \overset{\circ}{G}(i\Delta t)>0\\ 0, & \overset{\circ}{G}(i\Delta t)=0,\\ -1, & \overset{\circ}{G}(i\Delta t)<0\end{cases} \tag{14}$$

$$R_{GG}(\mu)=\frac{1}{N}\sum_{i=1}^{N}\overset{\circ}{G}(i\Delta t)\overset{\circ}{G}((i+\mu)\Delta t), \tag{15}$$

centered values $\overset{\circ}{G}(i\Delta t)=G(i\Delta t)-m_G$, m_G is the mathematical expectation of $G(t)$.

If the condition $r^*_{X\mathrm{E}}=0$ is really satisfied, then the probability with which the useful signal falls within the predetermined permissible intervals is determined $P(x_1\le X(t)\le x_2)$. For this purpose, the standard deviation and mathematical expectation of the useful signal $X(t)$ are calculated using the expressions:

$$\sigma^*_X=\sqrt{D^*_X}=\sqrt{D_G-D^*_{\mathrm{E}}}, \tag{16}$$

$$m^*_X=m_G-m_{\mathrm{E}}=\frac{\sum_{i=1}^{N}G(i\Delta t)}{N},$$

where $D_G=R_{GG}(0)$ is the variance of the noisy vibration signal $G(t)$.

Then the distribution density function is constructed [26] as follows:

$$N^*(x)=\frac{1}{\sigma^*_X\sqrt{2\pi}}e^{-\frac{(x-m^*_X)^2}{2(\sigma^*_X)^2}}. \tag{17}$$

After that, the probability $P^*(x_1\le X(t)\le x_2)$ of the useful signal $X(t)$ falling within the permissible intervals is determined:

$$P^*(x_1\le X(t)\le x_2)=\int_{x_1}^{x_2}N^*(x)dx=p_x. \tag{18}$$

Thus, the probability p_x of the useful signal $X(t)$ falling within the permissible intervals, calculated by formula (18), is another informative diagnostic attribute in addition to those described in [10] and characterizes the degree of reliability of the operational state of the railroad bed.

IV. CALCULATING THE ESTIMATES OF THE DEGREE OF HAZARD OF THE RAILROAD BED NON-OPERATIONAL STATE BASED ON THE CHARACTERISTICS OF THE VIBRATION SIGNAL NOISE

When the railroad bed is in the ultimate operational state (21), the correlation coefficient $r^*_{X\mathrm{E}}$ should be recalculated using (10). If

$$r^*_{X\mathrm{E}}\neq 0, \tag{19}$$

it means that as a result of changes in external influences, defects and cracks appeared on rails, track fastenings and sleepers were worn out, strength and stability of earth bed, sand cushion, ballast, etc. decreased.

At this time the noise $E_2(t)$ emerges. Therefore, for this situation it is necessary to calculate the characteristics of the noise $E(t)$. This makes it possible to identify the degree of danger at an early stage of the onset of a malfunction and to determine the dynamics of its development.

First, the standard deviation σ_E^* is calculated by formula (12) of the noise, and the normal distribution density function is constructed:

$$N^*(\varepsilon)=\frac{1}{\sigma_E^*\sqrt{2\pi}}e^{-\frac{(\varepsilon)^2}{2(\sigma_E^*)^2}}. \qquad (20)$$

Then the probability $P(\varepsilon_1 \le E(t) \le \varepsilon_2)$, with which the noise takes on values that estimate the degree of hazard, is determined:

$$P^*(\varepsilon_1 \le E(t) \le \varepsilon_2)=\int_{\varepsilon_1}^{\varepsilon_2} N^*(\varepsilon)d\varepsilon = p_\varepsilon. \qquad (21)$$

Thus, the probability p_ε of the noise $E(t)$ falling within the permissible intervals, calculated by formula (23), is another informative diagnostic attribute in addition to those described in [10] and algorithm (18), and characterizes the degree of hazard of the non-operational state of the railroad bed.

V. TECHNOLOGIES OF CONTROL OF THE RAILROAD BED BASED ON THE INDICATORS OF THE DEGREE OF RELIABILITY OF THE OPERATIONAL STATE IN CASE OF CHANGES IN EXTERNAL FACTORS AND INDICATORS OF THE DEGREE OF HAZARD OF THE NON-OPERATIONAL STATE IN CASE OF DEFECT INITIATION

In [10], it is noted that the railroad track monitoring tool is an inexpensive and quite simple device that consists of a vibration sensor, a sampling tool and a controller. The controller is used to calculate the estimates of the noise variance $D_E^*=(\sigma_E^*)^2$, cross-correlation function $R_{XE}^*(\mu)$

$$R_{XE}^*(\mu)=\frac{1}{N}\sum_{i=1}^{N}\overset{\circ}{G}(i\Delta t)\overset{\circ}{G}((i+\mu-1)\Delta t)-$$

$$-2\overset{\circ}{G}(i\Delta t)\overset{\circ}{G}((i+\mu)\Delta t)+,$$

$$+\overset{\circ}{G}(i\Delta t)\overset{\circ}{G}((i+\mu+1)\Delta t), \qquad (22)$$

relay cross-correlation function $R_{XE}^{r*}(\mu)$ between the useful vibration signal and the noise, estimates of the variance of the useful signal D_X^*, coefficients characterizing the ratio of the noise characteristics to the characteristics of the useful signal:

$$K_1=\frac{D_E^*}{D_X^*},\ K_2=\frac{D_E^*}{D_G},\ K_3=\frac{D_X}{D_G},$$

$$K_4=\frac{R_{XE}^*(\mu)}{D_E^*},\ K_5=\frac{R_{XE}^*(\mu)}{D_X^*},$$

$$K_6=\frac{R_{XE}^{r*}(\mu)}{D_E^*}\ \ K_7=\frac{R_{XE}^{r*}(\mu)}{D_X^*}, \qquad (23)$$

as well as spectral characteristics of the noise a_{nE}, b_{nE}.

According to [10], the controller calculates current estimates of characteristics (10)-(12), (22), (23), which are compared with the reference ones obtained as a result of training. If on each rolling stock the current estimates differ significantly from the reference ones, then a signal is formed about a malfunction in this railroad track section. This information is transmitted to the control center (or "system for establishing the presence of a malfunction in the railroad section") via "means of communication".

At the same time, the estimates of the degree of reliability of operational (18) and the degree of danger of non-operational (21) states of the railroad track, proposed in this paper, cannot be calculated in the rolling stock car by means of a controller, because the algorithms of their calculation are quite complex. Therefore, the vibration signal $G(t)$ itself is sent to the control center simultaneously with the estimates of characteristics (10)-(12), (22), (23) for the same observation time.

In the control center, using known methods, first, on the basis of characteristics (10-12), (22), (23) described in [10], a database of informative attributes obtained from all rolling stock over a day, two days, three days, etc. is formed:

$$Wo=\begin{bmatrix} Z_{11} & \dots & Z_{1n} \\ Z_{21} & \dots & Z_{21} \\ \dots & \dots & \dots \\ Z_{l1} & \dots & Z_{ln} \end{bmatrix}, \qquad (24)$$

$$Z_{ij}=\left(D_E^*, D_X^*, R_{XE}^*(\mu), R_{XE}^{r*}(\mu), a_{nE}, b_{nE}, K\right)_{ij},$$

$i=1,l$ is the section number, $j=1,n$ is the number of the rolling stock that has passed through the i-th section.

At the initial stage in the control room, the technical condition of the railroad track is tentatively assessed using knowledge base (24).

Then, the knowledge base Wo in the "system for establishing the presence of a malfunction in the railroad section" is supplemented with new estimates, which are developed in the proposed work. These include estimates of the reliability degree of operational (18) and hazard degree of non-operational (21) states of the railroad track.

Thus, knowledge base (24) is supplemented by the following two new knowledge bases: Wi, Wn – the knowledge base of estimates of indicators of the degree of reliability of operational and the degree of hazard of non-operational technical states of the railroad track.

The first new knowledge base Wi of the estimates of indicators of the degree of reliability of the operational technical state of the railroad track contains estimates of probabilities (18) calculated for each section during the movement of rolling stock cars over a day, two days, three days, etc.:

$$Wi = \begin{bmatrix} p_{x-11} & p_{x-12} & \cdots & p_{x-1n} \\ p_{x-21} & p_{x-22} & \cdots & p_{x-2n} \\ \cdots & \cdots & \cdots & \cdots \\ p_{x-l1} & p_{x-l2} & \cdots & p_{x-ln} \end{bmatrix}. \quad (25)$$

Knowledge base (25) supplements knowledge base (24) with such new characteristics as the degree of reliability of the operational state. As a result, a new knowledge base is formed:

$$W = Wo + Wi . \quad (26)$$

If during the day n rolling stock passed through the i-th section and m of them recorded the probability of p_x

$$0,7 \le p_x \le 1 \quad (27)$$

with the ratio of the coefficient

$$M_a = \frac{m}{n} \ge 0,5 , \quad (28)$$

indicating the degree of absence of necessity (optionality) of off-schedule control of the section, then it can be considered that the external impact had an insignificant effect on the technical condition of the railroad bed. In this case, no off-schedule inspection of the railroad bed is required.

If the value of the coefficient M_a at the same value of the probability p_x, equal to (27), is

$$0,1 \le M_a < 0,5 , \quad (29)$$

then it means that the degree of reliability of the operational state of the railroad bed is not so high, and it is necessary to carry out preventive control.

Then the analysis of the probabilities p_x that fell in the following threshold interval begins:

$$0,5 \le p_x < 0,7 . \quad (30)$$

If during the day n rolling stock passed through the i-th section and m of them recorded the probability of p_x corresponding to condition (30) at the value of the coefficient M_a, corresponding to condition (28), it means that, as a result of the external influence, the technical condition of the railroad track has reached the threshold operational state requiring an off-schedule inspection.

If condition (30) was recorded for the number of trains satisfying condition (29), then it means that, as a result of the external influence, the technical condition of the railroad bed has reached the threshold operational state, requiring an off-schedule more serious inspection.

Then the analysis of the probabilities p_x that fell in the following threshold interval begins:

$$0,1 \le p_x < 0,5 . \quad (31)$$

If the probability p_x satisfying condition (31) was observed for the number of rolling stock satisfying condition (28), then it means that from the change of external influences further operation of the railroad bed is inexpedient, because the danger of transition from an operational condition to a non-operational one is high. In such cases, an urgent off-schedule inspection should be conducted, which includes protective measures to prevent the occurrence of malfunctioning of the railroad bed. The final decision in choosing the values of probability intervals (30), (31) is made in the testing car during unscheduled control.

In this case, knowledge base (25) is also supplemented with new characteristics such as the degree of hazard of the non-operational state. This results in the final knowledge base

$$W = Wo + Wi + Wn , \quad (32)$$

where final knowledge base Wn of the estimates of indicators of the degree of hazard of non-operational technical state of the railroad track contains estimates of probabilities (21) calculated for each section during the movement of rolling stock cars over a day, two days, three days, etc.:

$$Wn = \begin{bmatrix} p_{\varepsilon-11} & p_{\varepsilon-12} & \cdots & p_{\varepsilon-1n} \\ p_{\varepsilon-21} & p_{\varepsilon-22} & \cdots & p_{\varepsilon-2n} \\ \cdots & \cdots & \cdots & \cdots \\ p_{\varepsilon-l1} & p_{\varepsilon-l2} & \cdots & p_{\varepsilon-ln} \end{bmatrix}. \quad (33)$$

If the probability p_ε is low, e.g.,

$$0,1 \le p_\varepsilon \le 0,3 , \quad (34)$$

then it can be considered that the malfunction in the rail track, rails and fasteners, sleepers and transfer beams, etc. are minor, and it is necessary to carry out preventive off-schedule inspection of the railroad track, aimed at preventing significant wear of the railroad track superstructure.

If the probability p_ε is medium, e.g.,

$$0,3 < p_\varepsilon \le 0,7 , \quad (35)$$

it means that the malfunction is significant. In this case, recommendations should be given to conduct an off-schedule inspection aimed at eliminating non-critical faults, which, although they allow the track to be operated, can become dangerous without repairs.

If the probability p_ε is high, e.g.,

$$0,7 < p_\varepsilon \le 0,99\,, \qquad (36)$$

it means that there is severe deterioration and damage, which does not allow further operation of the railroad bed. Therefore, it is necessary to issue recommendations for urgent off-schedule inspection aimed at carrying out major repairs of the railroad bed and replacement of the rails and sleepers or other element of the track superstructure.

To check the dynamics of the malfunction development it is necessary to recalculate the probability p_ε after a certain period of time. If after some sufficiently large interval of time Δt_{max} the value of the probability p_ε remains unchanged, it means that the malfunction is developing non-intensively. If after a small period of time Δt_{min} the value of the probability p_ε increases significantly, this means that the malfunction is developing intensively.

Numerous examples of modeling of a useful signal, noise, noisy signal, computational experiments and results of comparative analysis were given in [19], as well as in other works of the authors.

It should be noted that in order to further improve the reliability of operation of the intelligent system for identifying railroad track sections requiring off-schedule control, base of informative attributes (32) can also be supplemented with other characteristics of the noise and the useful signal.

VI. CONCLUSIONS

The paper proposes to supplement the knowledge base of the intelligent system for identifying railroad track sections requiring off-schedule control, proposed in earlier literature, with two such important characteristics as the estimate of the degree of reliability of the operational state and the estimate of the degree of hazard of the non-operational state of the railroad track. The use of these estimates, combined with the estimates of the noise characteristics, allows the traffic safety center to receive in a timely manner signals from trains in the sections that should undergo off-schedule control. As a result of application of the proposed technology, the degree of adequacy and reliability of the results of control of the railroad track increases, which increases the degree of safety and continuity of train traffic and reduces the degree of hazard in the operation of rail transport. The knowledge base of the intelligent system for detecting railroad track sections requiring unscheduled inspection can also be supplemented with such characteristics as high-order moments of the noise and the useful signal, as well as their ratios.

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