$\tau_1 = \tilde{R}_\tau - \varepsilon$; $\tau_2 = \tilde{R}_\tau + \varepsilon$; $\varepsilon =$

$$= k_\gamma \cdot (\tilde{R}_\tau \cdot (1 - \tilde{R}_\tau)/n)^{1/2}, \quad (18)$$

где k_γ – квантиль нормального закона для доверительной вероятности γ.

Для определения меры достоверности имитационной модели проверяется попадание математических ожиданий затрат по видам работ в их доверительные интервалы. Так, например, математическое ожидание затрат на ремонт после аварий:

$$M_z = \sum_{k=1}^{K} q_k \cdot M_k, \; M_k = \sum_{l=1}^{L_k} p_{lk} \cdot c_{lk}, \quad (19)$$

где $М_к$ – математическое ожидание затрат по k-й аварийной ситуации.

Значение (19) должно попасть с доверительной вероятностью γ в доверительный интервал (z_1, z_2):

$$z_1 = \tilde{z} - \beta; \; z_2 = \tilde{z} + \beta; \; \beta = k_\gamma \cdot s_z / \sqrt{I}, \quad (20)$$

где k_γ – квантиль нормального закона для доверительной вероятности γ; s_z – оценка среднеквадратического отклонения затрат; I – объем выборки, полученной имитационной моделью; $\tilde{z}$ – оценка математического ожидания затрат на ремонт по аварийным ситуациям:

$$\tilde{z} = \sum_{i=1}^{I} z_i / I, \quad (21)$$

где z_i – затраты для i-й аварийной ситуации, полученные по алгоритму Z(6).

ВЫВОДЫ

Направленность и экономический смысл исследования селективной технологии организации работ для верхнего строения пути заключается в следующем: имея статистические данные по периодичности и затратам на различные их виды, ставится задача методом имитационного моделирования подобрать параметры (1, 2) таким образом, чтобы значение показателя технологического риска (13) с учетом (14–18) было не выше заданного значения.

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FORMALIZATION OF SELECTIVE TECHNOLOGY OF INFRASTRUCTURE MAINTENANCE AND SAFETY FUND

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ABSTRACT

Any failure of technical means or abnormal operation situation reduces the intensity of rail traffic, significantly affects economic and operational performance of the transport market actors. In recent years, these complex processes have additionally been affected by threats caused by adverse changes in the economy and irregularities in the organization of transportation [1, 2]. So it is necessary to move from a traditional (situational) technology to a new one, «preventive», which is determined by means of monitoring and diagnostics based on a missed freight turnover and structural features of the track superstructure. The objective of the authors is to investigate a selective technology of repair and maintenance of the track superstructure.

The proposed technology is called selective because it is focused on repair of infrastructure on the fact (optionally, selectively). Selection implies the existence of an insurance or safety fund, which performs two functions: it collects payments with varying frequency to perform various types of repair work, and then as needed pays for these works. Cash flows related to the insurance fund, are structured and designed for a specific frequency of use, and the state of the fund itself is described by a random process of risk. Assessment of technological risk indicators and measures of reliability is given by simulation.

Keywords: *railway, insurance fund, payments, selective technology, repairs, track superstructure, simulation, risks, costs, cash flows.*

Background. *Any failure of technical means or abnormal operating situation reduces the intensity of rail traffic, significantly affects economic and operational performance of the transport market actors. In recent years, these complex processes have additionally been affected by threats caused by adverse changes in the economy and irregularities in the organization of transportation [1, 2].*

Way out of this situation can be seen through modernization of approaches to operation and maintenance of track, contact network and infrastructure complex as a whole. It is necessary to move from a traditional (situational) technology to repair and maintenance of infrastructure according to «actual condition». This technology allows the repair work not in the «emergency» mode, but in «preventive», which is determined by means of monitoring and diagnostics based on a missed freight turnover and structural features of the track superstructure, for example, the radius of curves.

Objective. *The objective of the authors is to investigate a selective technology of repair of the track superstructure, based on service on «actual state», to assess technological risk indicators and measures of reliability by simulation.*

Methods. *The authors use analysis, simulation, evaluation.*

Results. *The proposed technology is called selective because it is focused on repair of infrastructure on the fact (optionally, selectively). Selection implies the existence of an* ***insurance or safety fund****, which performs two functions: it collects payments with varying frequency to perform various types of repair work, and then as needed pays for these works. Cash flows related to the insurance fund, have the following structure:*

1) Payments for different types of work (accumulation of insurance fund): a) emergency; b) investment (modernization and development of the track); c) current. For each type of work frequency of insurance fund replenishment (days) and its cost (rubles) are set.

2) Costs planned for execution of works (decrease of insurance fund). For each type of work frequency of insurance fund use (day) and its cost (rubles) are set.

The mathematical description of the fund

Formalization of the organization of repair work on the example of the track superstructure was based on a random risk process [3, 4], which in our case describes the state of insurance fund at time t – R (t).

Originally, the volume of payments for the year is formed. Further, annual volume (X, mln rubles) is distributed by a type of activity:

$X^{(1)}=c_1 \cdot X,\ X^{(2)}=c_2 \cdot X,\ X^{(3)}=c_3 \cdot X;\ c_1+c_2+c_3=1.$ (1)

Here c_1 is a coefficient taking into account the proportion of the volume of payments for performing emergency operations; $X^{(1)}$ are annual payments to the insurance fund for emergency work; c_2 is a coefficient taking into account the proportion of the volume of payments for performing investment activities; $X^{(2)}$ are annual payments to the insurance fund for investment work; c_3 is a coefficient taking into account the proportion of the volume of payments for performing current repairs; $X^{(3)}$ are annual payments to the insurance fund for current repairs.

The cost of a single payment to the insurance fund for the j-th type of work with regard to (1):

$Y_j=365 \cdot X^{(j)}/h_j=c_j \cdot 365 \cdot X/h_j,\ j=1, 2, 3,$ (2)

where 365 is a number of days in the year; h_j is a frequency of payments to the insurance fund for the j-th type of work.

Total cumulative payments to the insurance fund to carry out repair work of the j-th type, taking into account (1, 2) and the assumptions made about the periodicity of its replenishment are

$YJ(t)=Y_j \cdot N_j(t)=(c_j \cdot 365 \cdot X/h_j) \cdot N_j(t),\ j=1, 2, 3,$ (3)

where $N_j(t)$ is a number of payment to the insurance fund during the time t for the j-th type of work.

Time of accomplishments of emergency situation is described by the process

$T_i=T_{i-1}+t_i,\ i=1,2\ldots,\ N_a(t),\ T_o=0,$ (4)

where t_i are time intervals between emergency situations; $N_a(t)$ is a number of emergency situations during the time t.

Under the conditions of uncertainty intervals t_i are values of a random variable with a given distribution function. Time T_i (4) corresponds to the costs for elimination of the i-th emergency situation – Z_i. These costs are also values of a discrete random variable.

The total cost of repair work on the emergency during the time t is equal to

$$YA(t)=\sum_{i=1}^{Na(t)} Z_i. \quad (5)$$

We emphasize that Z_i are taken from the insurance fund. Simulation of their values is proposed to be performed in two stages (algorithm Z):

1) We determine a category of emergency situation (a type of transport event: crash, accident, etc.). Category k is a value of a discrete random variable, k=1,…, K, where K is a number of categories of emergencies. For its modeling it is necessary to know a discrete law of probability distribution (k, q_k); q_k is probability of the situation of category k, $\sum_{k=1}^{K} q_k = 1$. The result of this stage is the category k.

2) We determine costs for recovery of the track after the emergency. For this K discrete laws on costs are set. The selection of a law's number is determined by the first stage. Every law has a form: (c_{lk}, p_{lk}), l=1,…, L_k. Here c_{lk} are costs for the case l of the category k; p_{lk} is a probability of this case; L_k is a number of possible cases on costs for the category k, $\sum_{l=1}^{L_k} p_{lk} = 1$, k=1,…, K. The values of costs:

$z_i= c_{lk}.$ (6)

For investment works there are three categories:

d=1 – rationalization and inventive activity;

d=2 – research and development activities (R & D);

d=3 – a program of cost- effective use of resources.

For the first two categories, the time interval between incurring of costs for the performance of investment works is a random variable with a known distribution function. The program of cost-effective use of resources provides for monthly (at the end of the month) costs.

The start time of the investment works for the category d and the i-th case:

$G_{id}=G_{i-1,\,d}+g_{id},\ i=1,2\ldots,\ NI_d(t),\ G_{o,\,d}=0,$ (7)

where g_{id} are time intervals between investment works of the category d of the i-th case; $NI_d(t)$ is a number of works of the category d during the time t. Time G_{id} (7) corresponds to the costs for investment activity of the category d for the i-th case – $U_{d,i}$. They have values of a random variable with a known distribution function.

In view of the assumptions made, the total cost for the investment works of the category d during the time t is

$$YU_d(t)=\sum_{i=1}^{NId(t)} U_{d,i},\ d=1,2,3. \quad (8)$$

Again, these costs are taken from the insurance fund. Referring to (8), they are equal to

$$YU(\mathrm{t})=\sum_{d=1}^{3} YU_d(t). \quad (9)$$

Similarly, we can find the total cost to perform current repairs:

$$YT(t)=\sum_{i=1}^{NT(t)} Yt_i, \quad (10)$$

where Yt_i is the amount of costs for the i-th current work; NT(t) is a number of types of these works during the time.

In this notation, the insurance fund state is described by a random process of risk:

$R(t) = X_0 + Y1(t) + Y2(t) + Y3(t) - YA(t) - YU(t) - YT(t)$, (11)

where X_0 are primary assets of the insurance fund; $YJ(t)$ are total accumulation payments by type of activity (3), (j=1, 2, 3); $YA(t)$ are total costs for emergency situations (5); $YU(t)$ are total costs for investment works (8); $YT(t)$ are total costs for the current works (10). To investigate the process (11) a simulation is required [5, 6].

Technological risk assessment

For a random risk process (11) time τ is determined, when the condition $R(t) < 0$ is met for the first time:

$\tau = \min_t \{t: R(t) < 0\}$. (12)

It is proposed that it should be considered as a technological risk and be assessed by the indicator r_τ as a probability of a special event $\tau < T\tau$:

Time moment (12) demonstrates the effectiveness of the organization of work in terms of the distribution of payments by their types (1). It is proposed to be considered as a technological risk and to be estimated by an indicator r_τ as a probability of a special event $\tau < T_\tau$:

$r_\tau = P(\tau < T_\tau)$, (13)

where T_τ is a set value.

When using simulation the indicator (13) is characterized by a point ($\tilde{R}_\tau$) and interval (τ_1, τ_2) estimates:

$\tilde{R}_\tau = k_\tau / n$, (14)

where k_τ is a number of realizations of the random process of risk (11), for which $\tau < T_\tau$, n is a total number of simulated realizations.

The calculation of the confidence interval is recommended within three models, depending on the value (14) [7, 8]:

1) $\tilde{R}_\tau$ <0,01 («rare event») – only the upper limit is found:

$\tau_2 = 1 - (1-\gamma)^{1/n}$. At $\gamma = 0,95$ $\tau_2 = \approx 3/n$, $\tau_1 = 0$; (15)

2) $0,01 \le \tilde{R}_\tau \le 0,15$ («relatively rare event»):

$\tau_1 = k_\tau / [k_\tau + (n - k_\tau + 1) \cdot F_1(p_1, p_2)]$, (16)

where $F_1(p_1, p_2)$ is a critical value for the F-distribution at p_1 and p_2 freedom degrees and confidence probability γ; $p_1 = 2 \cdot (n - k_\tau + 1)$, $p_2 = 2 \cdot k_\tau$;

$\tau_2 = (k_\tau + 1) \cdot F_2(p_1, p_2) / [n - k_\tau + (k_\tau + 1) \cdot F_2(p_1, p_2)]$, (17)

where $F_2(p_1, p_2)$ is a critical value for the F-distribution at p_1 and p_2 freedom degrees and a confidence level γ; $p_1 = 2 \cdot (k_\tau + 1)$, $p_2 = 2 \cdot (n - k_\tau)$;

3) $\tilde{R}_\tau$ >0,15 («usual frequency event»), for a sufficiently large sample of n size, approximation by the normal law is possible:

$\tau_1 = \tilde{R}_\tau - \varepsilon$; $\tau_2 = \tilde{R}_\tau + \varepsilon$; $\varepsilon = k_\gamma \cdot (\tilde{R}_\tau \cdot (1 - \tilde{R}_\tau)/n)^{1/2}$, (18)

where k_γ is a quantile of the normal law for the confidence probability γ.

To determine the measure of the reliability of the simulation model it is verified whether mathematical expectations of costs by type of works fall within their confidence intervals. For example, the expectation of costs for the repair after the accident:

$$M_z = \sum_{k=1}^{K} q_k \cdot M_k \ , \quad M_k = \sum_{l=1}^{L_k} p_{lk} \cdot c_{lk} \ , \qquad (19)$$

where $M_к$ is a mathematical expectation of costs on the k-th emergency situation.

The value (19) should hit with the confidence probability γ the confidence interval (z_1, z_2):

$$z_1 = \tilde{z} - \beta; \quad z_2 = \tilde{z} + \beta; \quad \beta = k_\gamma \cdot s_z / \sqrt{I} \ , \qquad (20)$$

where k_γ is a quantile of the normal law for a confidence probability γ; s_z is an estimate of the standard deviation of costs; I is a size of the sample, obtained by the simulation model; $\tilde{z}$ is an evaluation of the mathematical expectation of costs for repairs in emergency situations:

$$\tilde{z} = \sum_{i=1}^{I} z_i \, / \, I \ , \qquad (21)$$

where z_i are costs for the i-th emergency situation, obtained by the algorithm Z (6).

Conclusion. *Selective technology of the organization of works on the track superstructure has the following vector and economic sense. Having statistics on the frequency and costs of various types, there is a task to select the parameters (1, 2) by the simulation method so that the value of the index of the technological risk (13) with account of (14–18) should not be above a predetermined value. The implementation of selective technology will lead to more cost-efficiency of track maintenece works.*

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