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On the task of allocating investment to facilities preventing unauthorized movement of road vehicles across level crossings for various statistical criteria[1]

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Aim. *Railway transportation is affected by a whole range of transportation incidents, both related to rolling stock, i. e. vehicle-to-vehicle collisions, derailments, broken cast parts of bogies, etc. , and infrastructure, i. e. broken rail, fires at railway stations and terminals, broken catenary, etc. Among the above incidents, collisions at level crossings are the most likely to cause a public response, as collisions between trains and road vehicles often cause multiple deaths that are reported in national media, which entails significant reputational damage for JSC RZD. Additionally, collisions often cause derailment of vehicles, which may cause deaths and major environmental disasters, if dangerous chemical products are transported. Beside the reputational damage, collisions at level crossings cause significant expenditure related to the repair of damaged infrastructure and rolling stock, as well as damage caused by trains idling due to maintenance machines operation at the location of incident. That brings up the issue of optimal allocation of investment to facilities preventing unauthorized movement of road vehicles across level crossings (hereinafter referred to as protection systems). This problem is of relevance, as replacing level crossings with tunnels and viaducts is not going fast and does not imply the eventual elimination of all level crossing. Hence is the requirement for rational allocation of funds to the installation of protection systems over the extensive railway network. Given the above, the aim of this paper is to develop decision-making guidelines for the reduction of the number of transportation incidents in terms of statistical criteria, i. e. quantile and probabilistic.* **Methods.** *The paper uses methods of deterministic equivalent, of equivalent transformations, of the probability theory, of optimization.* **Results.** *The problem of maximizing the probability of no incidents is reduced to integer linear programming. For the problem of minimizing the maximum number of incidents guaranteed at the given level of dependability, a suboptimal solution of the initial problem of quantile optimization is suggested that is obtained by solving the integer linear programming problem through the replacement of binomially distributed random values with Poisson values.* **Conclusions.** *The examined models not only allow developing an optimal strategy with guaranteed characteristics, but also demonstrate the sufficiency or insufficiency of the investment funds allocated to the improvement of level crossing safety. Decision-making must be ruled by the quantile criterion, as the probability of not a single incident occurring may seem to be high, yet the probability of one, two, three or more incidents occurring may be unacceptable. The quantile criterion does not have this disadvantage and allows evaluating the number of transportation incidents guaranteed at the specified level of dependability.*

Keywords: *level crossing, collision, probability, quantile, integer programming.*

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1. Introduction

According to [1], the value of risk is a functional that associates the probability (and frequency) of an event and the expectation of the aftermath (damage) of such event. The general method of evaluation of risks associated with the above and other adverse events was addressed in [2, 3].

Most research dedicated to disasters in level crossings deals with either regressive models of correlation between the number of incidents and various factors [4, 5], or obtaining a certain cumulative index that characterizes the level of hazard/safety of a level crossing [6, 7]. A general concept of development of a strategy for protection system deployment is set forth in [7-9]. In [7], various approaches are discussed to the evaluation of the efficiency of installation of specific protection systems at specific level crossings that was based on a set of average characteristics. In order to solve the problem related to the deployment of protection systems throughout the railway network, it was suggested to use a deterministic number that characterizes the number of transportation incidents per year at a specific level crossing. However, the number of railway incidents is a random value, while the problem of rational allocation of funds was described only verbally. In [8], the problem of rational allocation of funds to protection systems installation was defined mathematically, yet as the measure of the value of a system's installation the average profit is used. However, average characteristics cannot be used to obtain any guaranteed characteristics that play a very important role in railway processes that may cause harm to people. In [9], the unit of the utility of installation of a protection system is a certain deterministic value that is obtained from an expected number of incidents at a level crossing.

This paper examines the problem related to the allocation of funds to the installation of protection systems over a railway network. Each crossing may have a unique number of protection systems available for installation, while their number may be random. It is assumed that the set of protection systems already installed at a crossing is specified. In order to define the optimal strategy of protection systems deployment, the probability is examined of not a single transportation incident occurring over a period of time. The maximum number of transportation incidents that will occur at the given level of dependability is studied as well.

2. Primary designations and assumptions

Let us consider a railway network that consists of N level crossings, in which i-th crossing may be equipped with any available M_i different protection systems, $i=\overline{1,N}$. Note that the number of protection systems available for installation may vary depending on the crossing due, for example, to the geographical features of the crossing location. Hence, it might turn out that M_1=8, while M_2=9. A protection system is understood as set of measures aimed at preventing transportation incidents (e. g. automatic level crossing signalling with automatic barriers, automatic level crossing signalling with automatic barriers and rising barrier, etc.). Let the j-th system at the i-th level crossing be characterized by the probability P_i,j of collision between an automotive vehicle and railway rolling stock, $i=\overline{1,N},\ j=\overline{1,M_i}$. Let us assume that the protection systems are sorted based on the safety level, i.e. $\forall i \in \{1,2,\dots,N\}$ and $\forall j \in \{1,2,\dots,M_i-1\}$ the following is true

$$P_{i,j+1} \le P_{i,j}. \tag{1}$$

Let us assume that over a long time period (month, year) T the i-th level crossing is crossed by n_i trains, $i=\overline{1,N}$. On a line section with 2 or more tracks 2 or more trains can simultaneously be on a level crossing. Without loss of generality, further we will omit this case that can be taken into consideration within the given model, if we understand n_i as the number of cases when a level crossing was occupied by trains.

Let the variable u_i^0 designate the number of the protection system currently installed at the i-th level crossing, while the variable $u_{i,j}^0$ characterize whether a protection system with the number j is installed at the i-th level crossing: 0 if not installed, 1 if installed. Let us introduce control variables: let the variable u_i designate the number of the protection system currently installed at the i-th level crossing, while the variable $u_{i,j}$ characterize whether a protection system with the number j is installed at the i-th level crossing: 0 if not installed, 1 if installed.

Also, let the cost of installation of the j-th system at the i-th level crossing be $c_{i,j}$ currency units $i=\overline{1,N},\ j=\overline{1,M}$, while the total investment fund of protection systems installation is C^0 currency units. As the i-th level crossing is already equipped with the protection system with the number u_i^0, it is not required to install it again, i. e. $c_{i,u_i^0}=0$, $i=\overline{1,N}$. Further, in virtue of (1) the installation at the i-th level crossing of the protection system with the index u_i^0 is impossible, so we can assume $c_{i,j}=0$ for $1\le j<u_i^0, i=\overline{1,N}$. It must be noted that the remaining coefficients $c_{i,j}$ also depend on u_i^0, $i=\overline{1,N},\ j=\overline{1,M_i}$. Further, we will assume that

$$\sum_{i=1}^{N} \max_{1\le j\le M_i} c_{i,j} > C^0,$$

as otherwise the cost of a set of the most expensive protection systems does not exceed the investment fund, which makes the problem of optimization related to the resource distribution trivial.

Let us introduce the following designations:

$$u^0 \overset{\text{def}}{=} \begin{pmatrix} u_1^0, u_2^0, \dots, u_N^0, u_{1,1}^0, u_{1,2}^0, \dots, u_{1,M_1}^0, u_{2,1}^0, \\ u_{2,2}^0, \dots, u_{2,M_2}^0, \dots, u_{N,1}^0, u_{N,2}^0, \dots, u_{N,M_N}^0 \end{pmatrix},$$

$$u \overset{\text{def}}{=} \begin{pmatrix} u_1, u_2, \dots, u_N, u_{1,1}, u_{1,2}, \dots, u_{1,M_1}, u_{2,1}, \\ u_{2,2}, \dots, u_{2,M_2}, \dots, u_{N,1}, u_{N,2}, \dots, u_{N,M_N} \end{pmatrix}.$$

Then the set of acceptable strategies $U(u^0)$ that depends on the initial system state, i.e. already installed set of protection systems, consists of various vectors u to which restrictions are applied:

$$u_i \in \{1,2,\ldots,M_i\}, i=\overline{1,N},$$

$$u_{i,j} \in \{0,1\}, i=\overline{1,N}, j=\overline{1,M_i},$$

$$\sum_{j=1}^{M_i} u_{i,j} = 1, i=\overline{1,N}, \quad (2)$$

$$\sum_{j=1}^{M_i} j u_{i,j} = u_i, i=\overline{1,N}, \quad (3)$$

$$u_i \geq u_i^0, i=\overline{1,N}, \quad (4)$$

$$\sum_{i=1}^{N}\sum_{j=1}^{M_i} c_{i,j} u_{i,j} \leq C^0. \quad (5)$$

Restrictions (2) – (3) guarantee that each level crossing can be equipper with only one protection system. Restriction (4) in virtue of (1) guarantees that the selection and installation of new protection systems will not increase the probability of collision between trains and automotive vehicles. Restriction (5) regards the maximum amount of funds that can be directed towards the installation of new protection systems, i.e. is a budget restriction.

3. Problem definition

Under the made assumptions we conclude that when one passenger or freight train passes over a level crossing the probability of its collision with automotive vehicles is

$$P_i = \sum_{j=1}^{M_i} u_{i,j} P_{i,j}. \quad (6)$$

Therefore, the number of collisions X_i within the time period T between automotive vehicles and passenger/freight trains is described with a binomial random value with the parameters n_i and P_i, i.e. $X_i \sim \mathrm{Bi}(n_i, P_i)$.

Let us introduce a new random value X that has the meaning of the total number of collisions throughout the railway network over the time period T:

$$X(u) \stackrel{\text{def}}{=} X_1(u) + X_2(u) + \ldots + X_N(u).$$

Let us consider the probability function

$$P_\phi(u) \stackrel{\text{def}}{=} P\{X(u) \leq \phi\}, \phi \in \mathbb{Z}_+,$$

and quantile function

$$\phi_\alpha(u) \stackrel{\text{def}}{=} \min\{\phi : P_\phi(u) \geq \alpha\}, \alpha \in (0,1).$$

Function $P_\phi(u)$ characterizes the probability that within the time period T not more than φ transportation incidents occur throughout the railway network. Function $\phi_\alpha(u)$ characterizes the maximum number of incidents at the specified level of dependability α. As the given problem concerns the improvement of system dependability, further we will be considering only the case $\alpha > 1/2$.

Using probability and quantile functions, let us formulate two problems

$$u_0^* = \arg\max_{u \in U(u^0)} P_0(u), \quad (7)$$

$$u_\alpha^* = \arg\min_{u \in U(u^0)} \phi_\alpha(u). \quad (8)$$

Problem (7) concerns the search for the optimal strategy that would ensure the maximum probability of not a single incident occurring over the given period of time. Note that a similar problem was researched in [11], where the problem of the probability of at least one collision between shunting consists and passenger/freight trains within a given period of time was examined. However, [11] examined the analysis problem, while this paper looks at the synthesis problem. Problem (8) concerns the search for the strategy that would allow minimizing the maximum number of incidents guaranteed at the given level of dependability.

4. Solution of the problem

4. 1 Probability function optimization problem

Let us find the value of the probability of not a single incident occurring over the given period of time T. Due to the fact that the number of transportation incidents cannot be negative, we obtain

$$P_0(u) = P\{X(u) \leq 0\} = P\{X(u) = 0\} = \\ = P\{X_1(u) + X_2(u) + \ldots + X_N(u) = 0\}. \quad (9)$$

As the number of transportation incidents at each level crossing cannot be negative either, out of (9) follows

$$P_0(u) = P\{\{X_1(u)=0\} \cdot \{X_2(u)=0\} \cdot \ldots \cdot \{X_N(u)=0\}\}.$$

Given that the number of transportation incidents at one level crossing does not affect the number of transportation incidents at the others, the random values $X_1(u)$, $X_2(u)$, …, $X_N(u)$ are independent in total, therefore according to the formula of multiplication of probabilities [10]

$$P_0(u) = P\{X_1(u)=0\} \cdot P\{X_2(u)=0\} \cdot \ldots \cdot P\{X_N(u)=0\}. \quad (10)$$

Out of (6) and (10) follows that

$$P_0(u) = (1-P_1)^{n_1} \cdot (1-P_2)^{n_2} \cdot \ldots \cdot (1-P_N)^{n_N} = $$
$$= \left(1-\sum_{j=1}^{M_1} u_{1,j} P_{1,j}\right)^{n_1} \cdot \left(1-\sum_{j=1}^{M_2} u_{2,j} P_{2,j}\right)^{n_2} \cdot$$
$$\cdot \ldots \cdot \left(1-\sum_{j=1}^{M_N} u_{N,j} P_{N,j}\right)^{n_N}. \qquad (11)$$

Through equivalent transformations let us reduce the resulting nonlinear programming problem to a linear programming problem. For this purpose, let us consider a new function

$$\hat{P}_0(u) \overset{\text{def}}{=} \ln(P_0(u))$$

and define the problem

$$\hat{u}_0^* = \arg \max_{u \in U(u^0)} \hat{P}_0(u). \qquad (12)$$

Note, that the solutions of problems (7) and (12) will be identical, as the logarithm is a monotonic increasing function. Let us consider in detail the structure of function $\hat{P}_0(u)$:

$$\hat{P}_0(u) = \ln\left(\begin{array}{c}\left(1-\sum_{j=1}^{M_1} u_{1,j} P_{1,j}\right)^{n_1} \cdot \left(1-\sum_{j=1}^{M_2} u_{2,j} P_{2,j}\right)^{n_2} \cdot \\ \cdot \ldots \cdot \left(1-\sum_{j=1}^{M_N} u_{N,j} P_{N,j}\right)^{n_N}\end{array}\right) =$$
$$= n_1 \ln\left(1-\sum_{j=1}^{M_1} u_{1,j} P_{1,j}\right) + n_2 \left(1-\sum_{j=1}^{M_2} u_{2,j} P_{2,j}\right) + \ldots +$$
$$+ n_N \ln\left(1-\sum_{j=1}^{M_N} u_{N,j} P_{N,j}\right) = \sum_{i=1}^{N} n_i \ln\left(1-\sum_{j=1}^{M_i} u_{i,j} P_{i,j}\right).$$

Function $\hat{P}_0(u)$ is nonlinear again, yet due to the fact that according to the problem's definition under a certain fixed i out of all variables $u_{i,j}$ only one takes on the value equal to one, while all the others equal to zero, by making the change of variables

$$\hat{P}_{i,j} = \ln\left(1-P_{i,j}\right),$$

we obtain a representation of function $\hat{P}_0(u)$ linear in the controllable variables:

$$\hat{P}_0(u) = \sum_{i=1}^{N} n_i \sum_{j=1}^{M_i} u_{i,j} \hat{P}_{i,j}. \qquad (13)$$

Thus, the optimization of nonlinear function (11) is reduced to the problem of optimization of linear function (13) in the set of acceptable strategies $U(u^0)$, and the problem of integer linear programming is obtained that can be solved in IBM ILOG Cplex and belongs to the class of knapsack problems [12].

4. 2. Quantile function optimization problem

Let us now find the expression for quantile function $\phi_\alpha(u)$. By definition we obtain

$$P_\phi(u) = P\{X(u) \le \phi\} = P\{\{X(u)=0\} +$$
$$+\{X(u)=1\} + \ldots + \{X(u)=\phi\}\}.$$

As for $k_1 \neq k_2$ the events $\{X(u)=k_1\}$ and $\{X(u)=k_2\}$ are incompatible, due to the fact that within one given period of time T different numbers of incidents cannot occur, using the formula of composition of probabilities [10] we obtain

$$P_\phi(u) = P\{X(u)=0\} + P\{X(u)=1\} + \ldots + P\{X(u)=\phi\}. \quad (14)$$

As shown above, identifying the probability of not a single incident $P\{X(u)=0\}$ occurring over the given period of time T itself is not trivial, let alone identifying other probabilities in formula (14). Thus, in finding the quantile function let us use the Poisson approximation, as n_i is a large number, while due to P_i being close to zero, out of the problem definition we obtain

$$\mathbf{M}[X_i] = n_i P_i \approx n_i P_i - n_i P_i^2 = n_i P_i (1-P_i) = \mathbf{D}[X_i],$$

i.e. let us consider new random values

$$\tilde{X}_i(u) \sim \Pi(n_i P_i),\ \tilde{X}(u) \overset{\text{def}}{=} \tilde{X}_1(u) + \tilde{X}_2(u) + \ldots + \tilde{X}_n(u)$$

and new functions

$$\tilde{P}_\phi(u) \overset{\text{def}}{=} P\{\tilde{X}(u) \le \phi\},$$

$$\tilde{\phi}_\alpha(u) \overset{\text{def}}{=} \min\{\phi : \tilde{P}_\phi(u) \ge \alpha\}, \alpha \in (0,1).$$

Let us define a new problem

$$\tilde{u}_\alpha^* = \arg \min_{u \in U(u^0)} \tilde{\phi}_\alpha(u). \qquad (15)$$

Note, that the solutions of problems (8) and (15) may not be identical, yet the solution of problem (15) will be suboptimal for problem (8).

Let us find the analytic expression of function $\tilde{P}_\phi(u)$. As random values $X_1(u), X_2(u), \ldots, X_N(u)$ are independent in total, random values $\tilde{X}_1(u), \tilde{X}_2(u), \ldots, \tilde{X}_N(u)$ are independent in total as well. Therefore,

$$\tilde{X}(u) \sim \Pi\left(\sum_{i=1}^{N} n_i P_i\right),$$

$$\tilde{P}_\phi(u) = \exp\left\{-\sum_{i=1}^{N} n_i P_i\right\}\sum_{k=0}^{\phi}\frac{\left(\sum_{i=1}^{N} n_i P_i\right)^k}{k!} =$$

$$= \exp\left\{-\sum_{i=1}^{N} n_i \sum_{j=1}^{M_i} u_{i,j} P_{i,j}\right\}\sum_{k=0}^{\phi}\frac{\left(\sum_{i=1}^{N} n_i \sum_{j=1}^{M_i} u_{i,j} P_{i,j}\right)^k}{k!}.$$

As in order to find strategy $\tilde{u}^*_\alpha$ functions $\tilde{P}_\phi(u)$ must be optimized for different φ, in order to simplify the optimization let us introduce a new function

$$L_\phi(u) = \ln(\tilde{P}_\phi(u)) = -\sum_{i=1}^{N} n_i \sum_{j=1}^{M_i} u_{i,j} P_{i,j} + \ln\sum_{k=0}^{\phi}\frac{\left(\sum_{i=1}^{N} n_i \sum_{j=1}^{M_i} u_{i,j} P_{i,j}\right)^k}{k!}.$$

and define new problems

$$u^*_{L_\phi} = \arg\max_{u\in U(u_0)} L_\phi(u), \qquad (16)$$

where $\phi = 0,1,2,\ldots$. Note, that (16) are problems of mixed integer nonlinear programming and can be solved using Opti Toolbox. Let

$$\phi^* = \min\{\phi \in Z_+ : \exp\{L_\phi(u^*_{L_\phi})\} \geq \alpha\},$$

then $\tilde{u}^*_\alpha = u^*_{L_{\phi^*}}, \tilde{\phi}_\alpha(\tilde{u}^*_\alpha) = \phi^*$.

5. Example

Let a railway network comprising 10 level crossings be equipped with the following systems preventing unauthorized movement of road vehicles across level crossings:

(i) signs warning of the approach to a level crossing

(ii) automatic signalling

(iii) automatic signalling with blinking lunar white aspect

(iv) automatic signalling with semi-automatic barriers

(v) automatic signalling with automatic barriers

(vi) automatic signalling with rising barriers

(vii) automatic signalling with a full barrier that creates a physical obstacle to unauthorized movement of road vehicles across the crossing when a train approaches

(viii) viaduct.

Let us define a set of protection systems installed on the railway network, the number of trains travelling across a crossing every 24 hours, as well as the cost of various protection systems and the probability of collision according to information from publicly available sources, expert evaluations and [7].

Let us comment on the choice of collision probability numbers in Table 2. According to [1], "when calculating event probabilities, it is assumed that according to expert data 5 percent of pedestrians do not evaluate the danger caused by the approaching train, 10 percent of pedestrians evaluate the danger incorrectly (believing they will be able to cross the track before the approaching train, etc.)", while according to [13, 14] the probability of signal violation by a shunting engine driver is around 10^{-4}, therefore in real life the numbers given in Table 2 below may turn out to be higher. Let us also note that this example refers to cases when all level crossings are equipped with identical protection systems with identical collision probabilities.

In Table 3, highlighted in grey are those protection systems that definitely will not be installed at level crossings due to condition (1).

Let us assume that total funds allocated for the installation of protection systems are C^0=2 mil. rubles, while the time T of observation of transportation incidents is one year. Let us find optimal strategies of maximizing the probability function, as well as the suboptimal strategy of optimizing the quantile function if α = 0,95.

Before finding the solution of the optimal protection system installation problem let us note that the example under consideration cannot be fully interpreted as real-life example, as a real railway network has much more level crossings than ten, while data regarding collision probability is confidential.

As it follows from Table 4, a criterion in the form of probability identifies the most "vulnerable" spot of the railway network, that is level crossing no. 3, as it has the

Table 1. Data regarding the preinstalled protection systems at level crossings and trains going across them used in solving the problems (7) and (8)

Crossing number	1	2	3	4	5	6	7	8	9	10
Number of trains running across the level crossing (per 24 hours)	11	20	100	35	9	8	5	20	50	60
Preinstalled protection system	i	ii	i	ii	i	i	i	ii	iv	iv

Table 2. Data regarding the probability of collision at the moment of train going across various level crossings equipped with various safety solutions

Crossing number	Possible protection systems (probability of collision)							
Any	i ($5\cdot10^{-4}$)	ii (10^{-5})	iii ($8\cdot10^{-6}$)	iv ($6\cdot10^{-6}$)	v ($2\cdot10^{-6}$)	vi (10^{-6})	vii ($5\cdot10^{-7}$)	viii (0)

Table 3. Data regarding the cost of installation of various protections systems at various level crossings

Crossing number	Possible protection systems (probability of collision)							
1	i (0)	ii (0.6)	iii (0.7)	iv (0.9)	v (1)	vi (1.2)	vii (1.5)	viii (800)
2	i	ii (0)	iii (0.1)	iv (0.3)	v (0.4)	vi (0.6)	vii (0.9)	viii (800)
3	i (0)	ii (0.6)	iii (0.7)	iv (0.9)	v (1)	vi (1.2)	vii (1.5)	viii (800)
4	i	ii (0)	iii (0.1)	iv (0.3)	v (0.4)	vi (0.6)	vii (0.9)	viii (800)
5	i (0)	ii (0.6)	iii (0.7)	iv (0.9)	v (1)	vi (1.2)	vii (1.5)	viii (800)
6	i (0)	ii (0.6)	iii (0.7)	iv (0.9)	v (1)	vi (1.2)	vii (1.5)	viii (800)
7	i (0)	ii (0.6)	iii (0.7)	iv (0.9)	v (1)	vi (1.2)	vii (1.5)	viii (800)
8	i	ii (0)	iii (0.7)	iv (0.9)	v (1)	vi (1.2)	vii (1.5)	viii (800)
9	i	ii	iii	iv (0)	v (0.1)	vi (0.3)	vii (0.6)	viii (800)
10	i	ii	iii	iv (0)	v (0.1)	vi (0.3)	vii (0.6)	viii (800)

Table 4. Optimal strategies of protection systems installation

Problem \ Crossing number	1	2	3	4	5	6	7	8	9	10
Maximization of probability function	ii	ii	iii	ii	ii	i	i	ii	iv	v
Minimization of quantile function	ii	ii	ii	ii	ii	i	i	ii	v	v

highest rate of trains travelling across it and the installed protection system allows for a high probability of collision. Both criteria are characterized by the fact that the strategies they produce “suggest” maximizing the quality of the level crossings equipped with protection systems no. 1, but not maximizing the quality of the level crossings with high traffic volume (nos. 9 and 10). It should be noted that in this example when substituting the quantile-optimal strategy into function $P_0(u)$ we obtain practically the same value as $P_0(u_0^*)$. Decision-making must be ruled by the quantile criterion, as the probability of not a single incident occurring may turn out to be high, while the probability of one, two, three or more incidents occurring may be unacceptable. The quantile criterion does not have this disadvantage and allows evaluating the number of transportation incidents guaranteed at the specified level of dependability. $\tilde{\phi}_\alpha(\tilde{u}_\alpha^*) = 6$, while $P_0(u_0^*) = 0{,}0422$, which means that the investment fund in this example is not sufficient for satisfactory operation (from the safety point of view) of level crossings.

6. Conclusion

The paper considers the problem of allocating investment to facilities preventing unauthorized movement of road vehicles across level crossings. It also examines the feasibility of both installing protection systems at an unequipped level crossing and improving the existing protection systems. The problem of maximizing the probability of no collisions occurring is reduced to the problem of integer linear programming (this result, as well as problem definition, were obtained with the support of the Russian Science Foundation (project no. 16-11-00062)). For the problem of minimizing the maximum number of transportation incidents occurring at the specified level, a suboptimal solution was proposed that is obtained by solving integer linear programming problems (this result, as well as the results of computational modeling, were obtained with the support of RFB and JSC RZD as part of research project no. 17-20-03050 ofi_m_RZD). The obtained optimal strategies allow making a range of managerial solutions that can be later used by a decision-maker. Additionally, the value $P_0(u_0^*)$ of the probability of no collisions occurring allows judging the sufficiency of investment funds, while the value $\tilde{\phi}_\alpha(\tilde{u}_\alpha^*)$ characterizes the number of transportation incidents that will occur in the future with the predefined probability α, which allows judging the level of risk of collision at level crossings.

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