Development of a methodology for automated control of the reliability indicators of the designed roads in the framework of the program-targeted approach

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Abstract. At present, the reliability of domestic roads in terms of their main indicators is significantly inferior to the reference indicators of the reliability of roads in advanced world countries. In this regard, in the field of modern road construction in the country, the task arises of strengthening the requirements for the reliability indicators of domestic roads and the transition from passive methods of ensuring these indicators to active methods of managing the reliability indicators of the country's roads at the stages of their design and stages of construction, reconstruction, overhaul, repair and maintenance. The work proposes a new program-targeted approach based on a functional model for managing the reliability indicators of roads, based on the implementation of procedures for forecasting, planning, rationing, accounting, control, analysis, regulation, and feedback, which are the initial components of the process of managing these reliability indicators of the designed roads. The main advantages of the proposed functional program-target approach to the management of the reliability indicators of roads are stated, which consist of its consistency and fairly complete development of the mathematical apparatus used in it.

1. Introduction
At present, the practical reliability of domestic roads [1] in terms of their failure-free, durability, maintainability, and preservation [2] is significantly inferior to the reference indicators of the reliability of roads in advanced world countries [3]. Therefore, the current situation in the field of modern road construction in the country raises the need to strengthen the requirements for indicators of the reliability of domestic roads and the transition from passive methods of managing these indicators to active methods [4]. This allows corrective actions to be made in the numerical values of these indicators at the design stages [5] and stages of construction, reconstruction, overhaul, repair, and maintenance of the country's roads [6].

Under the management of indicators of the reliability of roads in the framework of the program-target approach is understood as the establishment, provision, and maintenance of their required levels carried out through systematic and targeted control of the impact on these indicators of weather and climatic factors and operating conditions of roads [7].

To manage the reliability indicators of roads within the framework of the program-target approach, it is necessary to have appropriate mathematical models that reflect the causal and formal relationships of these reliability indicators with the main transport and operational conditions for the operation of
roads. That affects these indicators of their reliability in general, as well as their separate structural layers and elements [8].

2. Materials and research methods

Based on this point of view, one of the most noteworthy provisions of the solution to the problem outlined above should be considered an approach based on a functional model for managing the reliability of roads, based on the implementation of procedures for forecasting, planning, rationing, accounting, control, analysis, regulation and reverse connections. These are the initial constituent parts of any process of managing various objects [9].

The main feature of the proposed at the conceptual level of the functional scheme for managing the reliability indicators of roads [10] is that this model is focused on the management of specific indicators of the reliability of roads and constant monitoring of the scientific and technical level of design of roads according to their specific reliability indicators [11] regarding the reliability indicators of some design solutions for the reliability indicators of roads in the world's leading countries [12].

Taking into account the priority of the functional model for managing the reliability indicators of roads in comparison with other analytical models of automated regulation and management of various objects, in the material presented below, we will consider in detail the content of only the first three of the eight above-mentioned procedures for forecasting, planning and standardizing these indicators. We provide for the possibility of further presentation in new publications on the content of accounting, control, analysis, regulation, and feedback procedures. They are the initial components of the management of reliability indicators for new road design options.

The main advantage of the functionality of the program-targeted approach to the management of roads reliability indicators lies in its consistency and fairly complete development of the mathematical apparatus used in it. In addition, this approach fits well into the methodological concepts of the developed automated control systems for design and industrial enterprises, as well as computer-aided design system (CAD) of various technical objects [13]. The indicated important advantages of the approach proposed below make it very effective and promising in relation to the management of the reliability indicators of domestic roads in order to ensure the reliability indicators of these roads during their construction [14], reconstruction, and operation [15], exceeding the reliability indicators of roads of the world's leading countries.

3. Results of the study

Predicting the reliability indicators of roads means identifying the probabilistic tendencies of their behavior in the environment of disturbing factors (changes in the surface temperature, soil moisture of the road structure, characteristics of the inhomogeneity of the structure of road materials, etc.) [16] at a certain lead interval from the start to the end of the design of a given road option. It also includes obtaining probabilistic estimates (point and interval) of these trends. In a rather general setting, the prediction of the reliability indicators of roads can be carried out using the methods of regression analysis and the theory of random processes [17] in the following sequence.

For the projected categories of roads, a representative retrospective of reliability indicators of the same type of roads is established. For the vast majority of motor roads of the same type, which are designed within the framework of traditional principles, the values of their reliability indicators change quite monotonously from development to development. At the same time, the changes in the average values of these indicators over time (regression curves) are close to linear (Figure 1).
Figure 1. Forecasting and planning the values of roads reliability indicators. 1. The regression line of the road reliability indicator obtained from retrospective test points of 2 roads of this category. 2. Line of regression of the road reliability indicator – the type representatives, obtained from retrospective test points 4 of the road for the advanced world model. 3. Line of regression of the program for the development of the indicator of the reliability of the road - the type representative in section \( t_k \), \( t_N \). 4. The zone of possible trajectories of the development program of the 5th indicator of the reliability of the road - the type representative. 5. Densities of distribution of probabilities of values of reliability indicators for roads - type representatives of the projected road and road of the advanced world standard.

Let for a given category of similar projects of roads a sufficiently representative retrospective be established, in which the values of the reliability indicators of roads - analogs at moments \( t_1, t_2, \ldots, t_N \) (Figure 1). Here \( t_1 \) is the moment of the beginning of the presentation of the retrospective of reliability indicators roads of the same type, \( t_N \) - the moment of the end of this retrospective (the beginning of the design stage). Taking into account the received retrospective information, a certain correlation field \( (x, t) \) of the presence of this information is established. Further, according to the available statistical data of retrospective information, the method of least squares establishes its regression dependence of form \( x = at + b \), \( x = at^2 + bt + c \) etc. The adequacy of the presented mathematical model of retrospective information is checked by \( F \) - Fisher's criterion [18]. The resulting dependence can be identified with an estimate of the mathematical expectation of a certain random discrete process that characterizes the statistical behavior of the reliability indicator \( x \) of a road in its specific design version. By the behavior of the correlation function of the random process \( x(t) \) (by the value of the decay of the correlation function), the correlation interval is found.

For a stationary random process, you can always indicate such a time moment \( t_0 \). in case of exceeding the time, that is, when the time moment \( t > t_0 \) occurs, the value of a certain indicator of the reliability of the road \( x \) at two adjacent points on the curve (see Figure 2) can be considered
practically uncorrelated if, for example, correlation function $r(t)$ decreases to a value of 0.05 (Figure 2).

The value of the time moment $t_0$ is called in this case the correlation interval. In practice [19], the correlation interval is usually taken as half the width of the base of a rectangle of unit height, the area of which is equal to the area under the curve of the modulus of the normalized correlation function $r(t)$, i.e.

$$t_0 = \frac{1}{2} \int_{-\infty}^{\infty} |r(t)| dt$$  \hspace{1cm} (1)

![Figure 2. Substantiation of the correlation interval.](image)

By the value of the found correlation interval, the action (extrapolation interval) of this random process is established, and, consequently, the correct use of the obtained correlation equation $x(t)$ on the lead interval $t_N$, $t_k$ (Figure 1).

Thus, the forecasting of the reliability indicator $x$ is carried out as a statistical extrapolation of the tendency of its change to the moment $t_k$ (Figure 1) of the completion of the development of the next version of the road of a certain category.

In a similar way, the forecast of the basic (reference) version of the road is carried out, which is taken as an advanced world model. As a result of the implementation of these procedures, point and interval estimates of the predicted values of the reliability indicator of the designed road are obtained. In the case when the retrospective information is not representative, the control of its regression dependence is in the form:

$$x = \varphi(z_1, z_2, ..., z_N),$$  \hspace{1cm} (2)

where $(z_1, z_2, ..., z_N)$ - tactical and technical characteristics of a road of a certain category.

The specific form of dependence (2) in a rather general case is determined in the form of regression polynomials, for example, of this form:

$$x = b_0 + \sum_{i=1}^{N} b_i z_i + \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} b_{ij} z_i z_j + \sum_{i=1}^{N-1} b_{ii} z_i^2 + ..., $$  \hspace{1cm} (3)

where $b_i = \left. \frac{dx}{dz_i} \right|_{z_i}$, $b_{ij} = \left. \frac{d^2x}{dz_i dz_j} \right|_{z_i z_j}$, $b_{ii} = \left. \frac{d^2x}{dz_i^2} \right|_{z_i}$ are the coefficients of equation (3).

For fundamentally new options for roads, the predicted values of their reliability indicators (point and interval) are found by expert methods.

Prediction of reliability indicators using the described procedures is carried out at the stage of development of pre-design documentation [20]. At subsequent design stages, the results of the existing
forecast are constantly updated as new information becomes available on similar projects and on the basis of the results of the accumulated information on a fundamentally new design option.

With incomplete (not representative) information, in some cases, it is possible to use data on roads-analogs to obtain representative retrospective information; however, in this case, the specific main transport and operational conditions of their operation should be considered.

Planning refers to the development of models of the future state of roads based on predictive information. Since the objects of their control are indicators of reliability, then a plan for its practical implementation is developed for a certain category of roads in relation to a specific indicator. That is, the procedure for planning the values of the reliability indicators of roads is carried out on the basis of information obtained from the results of their predictive estimates (point and interval) for the newly designed and basic versions of roads. Let curve 1 (Figure 1) describe the behavior of the index for new development, and curve 3 for the reference one (some advanced world sample). Then, if the task is set by the end of development (that is, by the moment of time \( t_k \), Figure 1) to reach the level of the advanced world standard for this indicator, it is necessary to develop a certain plan (development program) in the form of curve 5 (Figure 1).

In accordance with it for the time period \( t_N, t_k \) the output of indicator \( x \) will be ensured at the end of the time period \( t_k \) of the end of development at the level of the advanced world standard. Consequently, in the development process, it is necessary to implement such a design solution (or a set of solutions.) Along the projected road, so that by time \( t_k \) we go to point \( x_2 \) (Figure 1). For this purpose, in order to practically realize the value of the indicator of level \( x_2 \), it is necessary to consider a certain set of possible plans in the form of probabilistic network models (probabilistic graphs with backtracks [21]). In this case, the edges of the directed graphs characterizing the dominant processes of the development program for the reliability indicator \( x_2 \) should be represented in the form of some growth models. Their parameters are set according to similar design options with the subsequent forcing these parameters to execute the development program in order to reach the value of indicator \( x \) to level \( x_2 \) (Figure 1). An indicator that in the process of developing the next modification of a road of a certain category is the movement of the reliability indicator \( x \) along a certain "tube" of possible development programs (Figure 1), the quantitative measure of N.S. Streletsky [22].

The planning function of reliability index 1 is carried out at the stage of development of pre-design documentation with the subsequent refinement of plans at the stages of development of an engineering project and working documentation as new information becomes available and the development of options for design and technological solutions for a projected road of the corresponding category.

The rationing of the reliability indicators of roads is understood as the determination of such areas of their values, at which the efficiency of the operation of roads is maximum at a given cost of the main types of resources. Or the costs of the main types of resources are minimal at a certain specified efficiency of the operation of roads. When rationing indicators of the reliability of highways, two main tasks are solved. The solution to the first problem involves the establishment of optimal values of the reliability indicators of the road as a whole. When solving the second problem, the reliability indicators are distributed (normalized) for all composite structural layers and elements of the road. At the same time, the issue of rationing the reliability indicators of structural layers and elements, which are typical design solutions for roads, is of great importance.

One of the possible formulations for solving the problem is reduced to the following.

Let \( M_{ijk}^{(z)} \) be the number of operations of \( k \)-types performed in the process of construction of a \( j \)-road. In this case, the concept of a road is understood as its generalized concept. This can be a structural layer or an element that is part of the road structure of a road. Let the construction of a road be carried out according to \( l \)-technology and be intended for operation in \( Z \)-natural-climatic zone
and \( t \) - calendar period. And \( R_{ijk}^{(z)}(B_{1j}, B_{jr}, N_j, T_j) \), \( q_{ijk}^{(z)}(B_{1j}, B_{jr}) \), \( W_{ijk}^{(z)}(B_{1j}, B_{jr}) \) are respectively specified costs associated with the maintenance of road construction equipment \((B_{1j})\), carrying out its repair and preventive work \((B_{jr})\). Its annual operation is in the amount of \( T \) hours and the volume of the fulfillment of the shifting task for the construction of a highway by \( N_j \) percent, including labor costs for its construction, and some useful effect associated with the implementation of the construction of a road, with parameters \( B_{1j}, B_{jr} \) measured in conditional units.

The task is to determine such a number of roads, the values of their design parameters (indicators of functional purpose), as well as the required amount of their construction in a certain time period so that the total reduced costs for the design, construction, and operation of roads would be minimal.

In relation to the formulated conditions, the mathematical model of the problem is presented in the form of a functional:

\[
\sum_{z=1}^{q} \sum_{s=1}^{n} \sum_{i=1}^{m} \sum_{j=1}^{k} R_{ijk}^{(z)}(B_{1j}, B_{jr}, N_j, T_j) M_{ijk}^{(z)}
\]

under the following restrictions:

\[
0 < B_{1j} \leq B_{1j}^\lim, 0 < B_{jr} \leq B_{jr}^\lim, \ldots, 0 < B_{jr}^\lim, \quad \sum_{j=1}^{m} \sum_{i=1}^{n} M_{ijk}^{(z)} = \phi_k^{(z)};
\]

\[
\sum_{i=1}^{n} \sum_{j=1}^{m} \sum_{k=1}^{a} W_{ijk}^{(z)}(B_{1j}, B_{jr}) \leq Q_j^{(z)};
\]

\[
\frac{1}{\sum_{k=1}^{a}} \sum_{j=1}^{m} \sum_{i=1}^{n} q_{ijk}^{(z)}(B_{1j}, B_{jr}), M_{ijk}^{(z)} \leq q_{lim};
\]

\[
\sum_{z=1}^{q} \sum_{s=1}^{n} \sum_{i=1}^{m} \sum_{j=1}^{k} \max_{i=1}^{n} \sum_{k=1}^{a} W_{ijk}^{(z)}(B_{1j}, B_{jr}) = N_j;
\]

\[
\frac{1}{N} \sum_{z=1}^{q} \sum_{s=1}^{n} \sum_{i=1}^{m} \sum_{j=1}^{k} M_{ijk}^{(z)} = T
\]

where \( \tau^{(z)} \) - total operating time in hours \( t \) - period \( z \) - zone;

\[
M_{ijk}^{(z)} \geq 0, N_j \geq 0, T_j \geq 0.
\]

The obtained ratios make it possible to ensure the prevention of exceeding the maximum permissible limits by the values of the indicators of failure-free and durability of roads (5); compliance with the specified deadlines for the implementation of all technological operations of their construction (6). It provides the prevention of exceeding the required number of roads and a certain number of their design solutions (7); the impossibility of exceeding the average labor costs for performing one typical operation by a motor road or certain (preset) values (8); calculation of construction volumes during the year with known values of \( M_{ijk}^{(z)} \) (9) and (10).

The mathematical model for solving the problem under consideration in the form of relations (4) - (11) is, in general, rather complicated, nonlinear, and multi-extreme. However, as applied to specific roads for which the necessary initial data are available, the problem in this formulation is solved by
decomposing it, i.e. by dividing them into a number of simpler problems and solving them in the framework of an iterative computational procedure.

4. Conclusions
1. As a result of the research, a method of automated control of the reliability indicators of the designed roads was developed within the framework of the program-targeted approach. This approach is based on the implementation of a functional model for managing the reliability indicators of roads, based on the implementation of procedures for forecasting, planning, rationing, accounting, control, analysis, regulation, and feedback, which are the initial components of any process for managing various objects.

2. The proposed functional model for managing the reliability indicators of roads is focused on managing their specific indicators and constantly monitoring the scientific and technical level of the design of roads for specific indicators of their reliability relative to the reliability indicators of some design solutions for the reliability indicators of roads in the world's leading countries.

3. The expediency of the creation of an automated performance management system reliability projected roads has been substantiated. Such a structure of an automated control system fits into the generally accepted methodology of automated control systems to CAD of new equipment and technologies for its manufacture created in our country, both at the level of individual enterprises and at the industry level.

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