Predicting the risk of road pavement premature destruction

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Abstract. The paper reveals the ideas of assessing the road condition on the basis of risk theory, which allows predicting the rate of the road structure destruction and its actual life. The regularities of the influence of physicomechanical parameters of road construction materials, as well as the coefficient of variation of the required modulus of elasticity of the subgrade on the value of the equivalent modulus of elasticity and the rate of destruction of pavement are established.

1. Introduction
Highways are one of the types of especially dangerous and technically complex capital construction projects. A large number of complex and often unique engineering structures, transport interchanges, retaining walls, and special protective structures are located on them. Design, construction and operation of such facilities are associated with increased risks [1-6]. New road-building materials are used in the design, construction, reconstruction of roads, innovative technical and technological solutions. The regulatory and technical base of road activities is being modernized, taking into account the use of innovations in the design, construction and operation of roads. National standards are updated and revised in order to improve road safety, increase the capacity of roads and turnaround times. Measures are being developed to ensure the safety of road surfaces and the environment, and resource-saving technologies. Considerable attention is paid to the introduction of new technical means of traffic management and the creation of intelligent traffic control systems in order to ensure its safety. Highways and vehicles are equipped with sophisticated computer vision technology; they are combined into a single integrated system. The technical complexity of such systems is the main reason for the need for a more detailed consideration of ensuring their reliability. These measures taken basing on the need to harmonize national standards with the international ones for technical regulation of road activities [7-9].

However, design, production and operational organizations as well as supervisory authorities do not have trustworthy forecasts about the dates of reliable operation of structural elements of roads built using new technical and technological solutions. There are no necessary statistics on changes in the operational properties of modern materials depending on the working conditions of structural elements of roads, changes in the intensity and composition of traffic flows. Moreover, the use of new road-building materials without normative and technical documentation is possible only if the results of experimental studies are available. These results should be scientifically substantiated and implemented in the organization’s standard. The validity of this standard has a limited duration and is
aimed at the accumulation of the necessary statistical data. To reduce the time and scientific justification for the introduction of innovative technologies, materials, structures, machines, equipment and technical solutions in order to ensure the longevity and safety of roads, as well as road safety and environmental safety, it is necessary to develop methods for modeling and assessing the risk of failure of road structures.

The situation is aggravated by the fact that the main parameters of the designed road structures (characterizing their carrying and bearing capacity) are determined based not on the existing transport conditions in the area of gravity, but, as a rule, based on a 20-year perspective. It significantly increases the requirements for the degree of validity of forecasts of their changes (taking into account the incompleteness and inaccuracy of information) in the future so distant from the moment of designing road objects [10-12]. Moreover, part of the roads may have significant wear, tear and insufficient throughput due to an increase in the level of motorization of the population. Moreover, there is insufficient funding for the construction, reconstruction and repair of roads [3]. Every fourth traffic accident occurs on the roads due to inadequate road conditions.

Safe (risk-free) and reliable operation of the road can be ensured only by its appropriate design, construction and operation. It is during the design and construction of roads that the level of risk of harm is laid, which may turn out to be more than the acceptable level during the operation of the structure. ensuring the quality of design, construction (reconstruction), overhaul, repair and maintenance of roads and artificial structures on them

Development of methodological aspects of modeling and assessing the state of the road is based on the theory of risks and patterns of influence of physical and mechanical parameters of road construction materials and construction technologies on the value of the equivalent modulus of elasticity and the rate of destruction of pavement.

2. Materials and methods
The increasing complexity of the construction of transport facilities, the use of new building materials and transport construction technologies, the growth in traffic and loads require the inclusion of an uncertainty factor in the justification of design decisions. Constructive eccentricity of transport infrastructure facilities, their elements and subsystems, as well as the probabilistic nature of the strength characteristics of structural materials and process parameters can cause hundreds of small individual failures and thousands of their combinations. Together, these factors sometimes lead to premature failure and destruction of the road structure, and become the causes of accidents and disasters on roads. It is no coincidence that one in five traffic accidents is caused by poor road conditions. In almost every second accident on highways, deficiencies in the transport and operational status of the urban road network are recorded [13-15]. The main ones are unevenness and defects in the coating, its low coupling qualities, lack of winter maintenance, narrowing of the carriageway and unsatisfactory condition of the dividing strip, malfunctions of technical means of organizing traffic according to global statistics on the causes of accidents.

These circumstances indicate that the problem of assessing technical risk in road construction is of great importance, manifested in the possibility of reducing socio-economic damage from road accidents. The annual loss from traffic accidents for most countries of the world is up to 3% of gross domestic product [15]. About 1.35 million people die due to traffic accidents. About 20 to 50 million people become disabled. Statistics show that the highest mortality from road accidents is observed in countries with a low level of economy (figure 1). Experts from the World Health Organization attribute this to a poorly developed infrastructure and poor roads. In addition, the large number of deaths in road accidents is explained by the lack of timely medical care [16].
A while ago engineers were not interested in risk accounting. It was believed that risk should be fundamentally excluded in engineering and design. However, with a more detailed study of the issue, it becomes clear that it is precisely in the adoption of design decisions and their subsequent implementation that the risk is often inevitable and should be taken into account [17]. In this regard, it is necessary to recognize the existence of technical risk and consciously refer to the conceptual foundations of its analysis, assessment and determination of measures to reduce risk in road activities. The risk, as a result of the influence of uncertainty on the achievement of the objectives for the construction of the facility, may correspond to the objectives of the project or the goals of the assets that are created as a result of the project. Assessment of the degree of risk in the design, construction and operation of transport facilities becomes the fundamental principle of technical regulation [18]. In this case, the basis of the principles of technical regulation is a refusal from the predominant satisfaction of the needs of owners of objects and structures (roads, bridges, objects of road infrastructure) through the apparatus of the theory of reliability (when standardizing integral indicators - service life). The need to move towards a more complete satisfaction of the needs of road users (drivers, pedestrians, freight forwarders) through a risk management methodology and consideration of dangers to the normal functioning of the facility becomes obvious [19-20]. Damage due to the implementation of a decision that was made taking into account the technical risk may turn out to be negligible compared to the cost of eliminating the consequences of such damage while ignoring the hazard factors [21].

The presence of technical risks in road construction is due to:

- the uncertainty of the data used in the design of roads (survey results, loads, traffic intensity, quality of materials, service life, etc.);
- the uncertainty of the construction conditions (weather conditions, the rhythmic supply of materials and structures, the reliability of the equipment, the human factor, financing, etc.);
- the uncertainty of operating conditions (weather conditions, loads, traffic, financing, etc.);
- the uncertainty of the conditions of repair and reconstruction, etc.

It is fundamentally necessary not to ignore the presence of risk in road construction, but to consciously minimize and take it into account.

In recent years, close attention has been paid to the assessment of technical risks in road construction and operation of roads. The work of I.A. Zolotar’, V.D. Kazarnovsky, A.P. Vasiliev, V.K. Apestin, S.K. Iliopolov, M.P. Klekovkina et al. [10, 22, 11, 12, 23]. The issues of technical regulation of the road sector and risk assessment were investigated in the works of V.V. Stolyarov, T. V. Samodurova, N. E. Kokodeeva, A.V. Kochetkova, L.V. Yanovsky, O.Yu. Moskalev et al. [4, 24, 22, 21].
11, 12, 23, 25]. However, it should be noted that in these studies, risk is considered as the probability of disruption of the normal operation of the road. Moreover, the risk value is calculated, as a rule, depending on one of the many factors ensuring the maintenance of proper road conditions. This approach does not allow us to assess the technical risk from the point of view of the systemic impact of road conditions on road safety and determine the most effective measures to increase it. A natural way out of this situation is either to establish the form of the probability distribution function for the occurrence of traffic accidents with victims as a multidimensional random variable, or to build a simulation model to determine the empirical probability density function.

It is known that the results of the design decisions made appear in the future, during the operation of transport facilities. At the design stage, some (and sometimes many) of the working conditions of the road structure are uncertain. In this regard, designers are forced and even doomed to make decisions in the conditions of uncertainty of the initial data (often this relates to traffic intensity). When developing design decisions, one has to take risks, since the possibility of undesirable events cannot be ruled out. However, it is possible to reduce the likelihood of their occurrence. For this, it is necessary to predict the further development of events, in particular, the consequences of the adopted design decisions and the possibility of failure during the operation of the road structure.

The concept of failure means a change in the state of structural elements, as a result of which the normal operation of a road structure is violated in accordance with specified standards. The operation of the road within tolerances is considered normal, and going beyond tolerances is considered a failure. Thus, the level of safety and reliability of a structure operating under certain conditions depends on the level of technical requirements that determine the criteria for failure.

Engineering, physical and economic considerations serve as the basis for designating permissible boundaries for changing parameters beyond which should be considered a failure. For roads, the most important failure criteria underlying the determination of safe operation of the entire road are violations of the evenness and strength of the coating, a decrease in the coefficient of adhesion of the automobile wheel to the coating below the required value, and the appearance of a significant number of defects.

As a result of the effects of climatic factors and traffic loads, a gradual change in time occurs in terms of strength, flatness and coefficient of adhesion of the car wheel to the road surface. The rate of change of these indicators over time also depends on the physicomechanical properties of the materials used and on the quality of the production of road construction and road repair work. In this regard, the speed provided by the road conditions of the mixed traffic flow changes in time (usually decreases) until the next repair is made, after which the speed value can be brought back to its original value or even exceed it (in the case of reconstruction of the road with its translation to a higher category). The dynamics of this process is shown in figure 2.

Bearing structural elements of the road are at risk when exposed to loads. If at the same time the limit is exceeded, for example, in strength, the pavement will be destroyed.

Design technical risk here is characterized by the probability of exceeding the load with respect to $p_k$ strength. If $X$ and $Y$ are random variables, moreover, $X$ characterizes the load, and $Y$ characterizes bearing capacity, then for the technical risk, the following relation is true:

$$R_t = p_k = p(X,Y)$$

(1)

If the load and bearing capacity are described by discrete distributions, namely, as it is shown in tables 1 and 2,

Table 1. $X$ random variable distribution series.

| $X$ | $X_1$ | $X_2$ | $X_n$ |
|-----|-------|-------|-------|
| $p_x$ | $p_1$ | $p_2$ | $p_n$ |
Table 2. $Y$ random variable distribution series.

| $Y$ | $Y_1$ | $Y_2$ | $\ldots$ | $Y_n$ |
|-----|-------|-------|-----------|--------|
| $q_y$ | $q_1$ | $q_2$ | $\ldots$ | $q_n$ |

and harmful effects are characterized by $a \left( x_i, y_j \right) = a_{ij}, i = 1, \ldots, n; j = 1, \ldots, m$ values, then instead of (1) we will get:

$$R = \sum_{i=1}^{n} \sum_{j=1}^{m} a_{ij} p_i q_j.$$  \hspace{1cm} (2)

Figure 2. The dynamics of the reliability of the road structure.

So, for example, it is known that when designing pavements, tabular values of the deformation (elasticity) moduli of subgrade soils $E_0$ and materials of pavement layers $E_i$ are used.

For a specific climatic zone, depending on the design of the road, drainage conditions, regulatory and methodological documents for the calculation of pavement give unambiguous module values. Obviously, both $E_0$ and $E_i$ are the probabilistic characteristics of the soil and materials of the layers of the pavement, having a certain scatter relative to their average values. Neglecting this, it is impossible to characterize the absence of risk in the design decisions [26].

Then, during the construction of the subgrade and the construction of pavement, certain deviations of the density of soil and materials from standard values are possible. In addition, when accepting finished layers of pavement, deviations from the design thickness are allowed.

If a combination of adverse circumstances occurred on a certain section of the road, i.e., the actual modules and thicknesses of a number of layers turned out to be lower than the normative ones, it can lead to the appearance of deformations and destruction of pavement.

Obviously, when approaching the design of roads taking into account risks, such cases can be excluded with a predetermined certainty or the level of acceptable risk. To this end it is possible to use the theoretical developments of I A Zolotar as a methodological basis in the field of assessing the reliability of roads [10].

As it has been previously noted, the failure of the road (as a technical system) can be considered a random event occurring under the influence of many random factors. Accordingly, quantitative indicators of random events are calculated on the basis of a probabilistic measure. Therefore,
Probability theory and mathematical statistics are the main apparatus that is used to study the risk of failure in the operation of roads, and the characteristics of failures themselves should be selected from among the indicators adopted in probability theory. It should be remembered that the complete characteristic of any random variable is its distribution law, i.e. the relationship between the possible values of a random variable and the probabilities corresponding to these values.

Obtaining such distribution laws is possible by determining the type of analytical dependencies, or by using simulation modeling of the processes of changing indicators during the operation of the road. As a result of simulation, it is possible to construct empirical functions of the distribution density of random variables characterizing the reliability, durability and maintainability of the road and its structural elements.

If we take a relative value of the acceptable risk of 5%, then the formula for determining the probability of an undesirable event (destruction of pavement) will take the following form:

\[ Q(t) = 1 - P(t) = 1 - 0.95 = 0.05. \]

Since the destruction of pavements can occur at a strength factor

\[ k_n \leq \frac{E_e}{E_{rp}}, \]

where \( E_e \) and \( E_{rp} \) are the equivalent and required elastic moduli respectively, then the risk-free condition can be written as follows:

\[ P(k_n > \frac{E_e}{E_{rp}}) = 0.95. \]  \( (3) \)

(3) is followed by the need to disclose the distribution law as a probabilistic characteristic and establish its quantitative characteristics (mathematical expectation of variance, etc.), which will make it possible to determine whether equality (3) is satisfied with possible deviations of \( h_i \) layer thicknesses and their \( E_i \) elastic moduli from the design ones.

In solving the problem, one can use the simplified methodology for calculating the elastic modulus of \( E_e \) multilayer pavement, the essence of which is as follows.

First, the average elastic modulus \( E_{cp} \) of all layers of the pavement is calculated, and then, taking into account the elastic modulus of the soil \( E_0 \), the subgrade \( E_e \) is determined.

\[ E_{cp} = \frac{\sum_{i=1}^{n} h_i E_i}{\sum_{i=1}^{n} h_i}. \]  \( (4) \)

The value \( E_e \) is determined by the known approximate dependence

\[ E_e = \frac{E_0}{1 - 2 \left(1 - \frac{1}{n^{3.5}} \right) \arctg \left( \frac{h}{D} n \right)}, \]  \( (5) \)

where \( n = \sqrt[25]{\frac{E_{cp}}{E_0}}, \ h = \sum_{i=1}^{n} h_i. \)
From formula (5) it is clear that the elastic modulus of the road structure \( E_e \) is a function of three quantities \( E_0, E_{cp} \) and \( h \), each of which is probabilistic in nature and has its own distribution law.

If we assume that these laws, according to the central limit theorem, are the laws of normal distribution, then the problem arises of determining the distribution law for a function of several random variables. We will not consider the procedure for determining such a function, but we will also assume that \( E_e \) also has a normal distribution law. It is necessary to determine the quantitative characteristics of this quantity (mathematical expectation and variance), which fully characterize the law of normal distribution.

In probability theory it is proved that in this case the approximate quantities \( \bar{E}_e \) and \( \sigma_{E_e}^2 \) can be calculated from the following relations:

\[
\bar{E}_e = f(\bar{E}_0, \bar{E}_{cp}, \bar{h}),
\]

\[
\sigma_{E_e}^2 = f(\sigma_{E_0}^2, \sigma_{E_{cp}}^2, \sigma_h^2) = \left( \frac{df}{dE_0} \right)^2 \sigma_{E_0}^2 + \left( \frac{df}{dE_{cp}} \right)^2 \sigma_{E_{cp}}^2 + \left( \frac{df}{dh} \right)^2 \sigma_h^2,
\]

where \( \bar{E}_0, \bar{E}_{cp}, \bar{h} \) are mathematical expectations of random variables;

\( \sigma_{E_0}^2, \sigma_{E_{cp}}^2, \sigma_h^2 \) are variance of random variables.

To find \( \sigma_{E_e}^2 \) it is necessary to first determine the partial derivatives and variances of the right-hand side of the dependence (7).

We will find the variance \( \sigma_{E_0}^2 \) from the condition that the scatter of the actual values of the quantities \( E_0 \) relative to the standard value \( \bar{E}_0 \) does not exceed three sigma.

The variance \( \sigma_h^2 \) can be found from the relation

\[
\sigma_h^2 = \sigma_{h_1}^2 + \sigma_{h_2}^2 + \ldots + \sigma_{h_n}^2.
\]

This requires a preliminary determination of the quantities \( \sigma_{h_i}^2 \). The latter can also be found by the rule of “three sigma”.

The value \( \sigma_{E_{cp}}^2 \) can be calculated using the following relation:

\[
\sigma_{E_{cp}}^2 = \left( \frac{\bar{h}_1}{h} \right)^2 \sigma_{E_1}^2 + \bar{E}_{E_1}^2 \sigma_{h_1}^2 + \left( \frac{\bar{h}_2}{h} \right)^2 \sigma_{E_2}^2 + \bar{E}_{E_2}^2 \sigma_{h_2}^2 + \ldots + \left( \frac{\bar{h}_n}{h} \right)^2 \sigma_{E_n}^2 + \bar{E}_{E_n}^2 \sigma_{h_n}^2.
\]

The variance \( \sigma_{h_i}^2 \) can be determined on the basis of the dispersion theorem of the product of independent random variables

\[
\sigma_{h_i}^2 = \frac{\sigma_{h_i}^2 + \bar{h}_i^2}{\sigma_h^2 + (h)^2} - \frac{\bar{h}_i^2}{(h)^2}.
\]

At the final stage of calculations, formula (3) determines the probability of the absence of the risk of premature destruction of pavement during the calculation period.
3. Results and discussion

In recent years, the issues of road safety and reliability have received increasing attention both in the theoretical, organizational, technological, and regulatory aspects of road activities [15, 27]. However, despite the measures taken, the state of the state road infrastructure requires a radical improvement in the quality of design, construction, reconstruction, repair and maintenance of roads. Low durability, premature failure and failure due to underestimation of the role of reliability and risk indicators in the design and construction of roads. At the current level of development of road science, the provisions of the theory of risks and its quantitative requirements are conceptually determined only for individual elements of the road structure or in relation to individual measures of road activity.

At the same time, the reliability, durability and safety of the road depends on the proper operation of the entire road structure: subgrade, protective artificial structures, construction elements, drainage, retaining and reinforcing elements. The described methodological approach to assessing the risk of premature destruction of pavement makes it possible to assess the complex impact on the road structure of the quality of road building materials and technological factors, increase the validity of the design decisions and determine a system of measures to improve road conditions aimed at improving road safety. At the same time, it is possible to increase the maximum safe speed of movement and the degree of protection of its participants while taking into account road conditions and traffic management activities.

4. Conclusion

Improving the management of road activities in order to implement plans for the development of the network of roads, ensuring the required level of their transport and operational condition and road safety requires a thorough analysis of the problems of theory and practice of risk management in the design, construction, reconstruction, repair and operation of road infrastructure, and also the development of risk management methods in road activities. It requires the development of methods and models for determining the optimal balance between cost and road safety, monitoring and quality management of road pavements, and ensuring environmental safety of road activities. The necessary reliability and safety of roads should be laid down in design decisions, ensured by their high-quality implementation during the construction process and maintained during the operation of the road.

The basis for assessing risk (total risk) during the life cycle of road sections is the function that relates the frequency (probability) of occurrence of dangerous events and the harm from these dangerous events. The basis for safe operation of the road includes design decisions that are justified taking into account the influence of uncertainty. As a source of information for risk assessment at the design stage, all available source data and information should be used: results of engineering and soil-geological surveys; data on the functioning of analogous facilities; forecasting results of research organizations; information from automated information databases of the road industry; information about road insurance; data of statistical reports of state bodies and risk registers of road organizations; the results of the experimental verification of innovations, atypical designs in testing laboratories (centers); results from forensic examinations based on risk assessment.

A further direction in the development of methodological principles for forecasting and assessing the risks of failure in the operation of road structures is the development of simulation models. This will overcome the difficulties associated with obtaining analytical dependencies for reliability indicators of road structures and highways in terms of strength, taking into account the complex influence of many probability factors. The development of simulation models will make it possible to predict the rate of destruction of the road structure and its actual service life. Simulation of all the main factors affecting the reliability of road structures will provide an opportunity to identify patterns of influence of physical and mechanical parameters of road construction materials, as well as the coefficient of variation of the required modulus of elasticity and soil moisture of the subgrade on the value of the equivalent modulus of elasticity and the rate of destruction of pavement. The use of simulation will become an indispensable and effective means of studying the work of the road as a complex technical system consisting of "aging elements".
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