General issues of assessing the reliability of roads

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Abstract. The article describes the reasons for the interest in the problem of ensuring the reliability of roads, which consists in the fact that the maintenance of life safety of the population, material values and social conditions depend on their uninterrupted functioning. The author outlines a modern approach to the analysis of the state of the road pavement in terms of the rate (risk) of destruction and the actual duration of its service. The work substantiates the close connection between the failure of a road and the loss of working capacity or any of its structural elements (roadbed, pavement, road surface) failure. The necessity of improving the method of assessing the safety margin of the integrated 'pavement-roadbed' construction is associated with ensuring the reliability of this design, i.e. in terms of the occurrence of its failures. The problems of ensuring the operational reliability of the main structural elements of the road: the roadbed and pavement covering a wide range of issues. This should extend from the application of the theory of reliability and mathematical statistics to analyzing the influence of climatic and operating conditions on the work of the roadbed, improving the assessment of pavement, quality control of materials and justification of rational technology of work. It is shown that for the use in the design process of roads during the development of their pre-design, design and working documentation the authors proposed in this paper a probabilistic-statistical approach to assessing the reliability of roads and the risk of destruction of their pavement over time during road maintenance. This will contribute significantly to adjustment of these indicators in the direction of their improvement.

1. Introduction

The road is an object of transport infrastructure intended for the movement of vehicles [1]. It includes land plots within the boundaries of the road and structural elements located on them or under them [2] and road constructions that are its technological part. Each of the above structural elements [3] can be considered as an independent type of road production, obtained at a separate stage of the construction of roads [4]. In this regard, the level of quality of the road is a function of the quality of its elements - road structures [5].

It is known that both in the design [6] and in the construction [7] the aim is to achieve the required quality levels [8] and reliability when putting the road into operation [9].

The reason for the interest in the problem of reliability of roads [10] is, first of all, that their uninterrupted functioning during a certain time determines the preservation of life safety of the population, material values and social conditions [11].

In the general case, the reliability implies the property of the system to perform the functions assigned to it in specific operating conditions for a specified time (GOST 13377-75). Termination of at least one of the functions is called a failure. Thus, with respect to road pavement, reliability should be understood...
as the probability that it will withstand the effects of automobile loads and climatic factors under given conditions during the overhaul period. The failure with respect to road pavement is an event consisting of the appearance of damage and deformations in the pavement, reducing the average optimal speed of movement of cars. Thus, the reliability of the pavement can be considered as a property of ensuring its quality over time.

The relevance of assessing the reliability of the road arises due to the probabilistic nature of the various factors affecting the quality of road design and construction and the variability of operating conditions. The lack of information on such probabilistic factors is most often compensated by the introduction of certain compensation coefficients when designing [12]. However, the introduction of these coefficients often leads to unnecessary costs during construction. Therefore, the most promising is the use of probabilistic statistical methods for assessing the reliability of a road [13].

A number of valuable studies of eminent scientists, described in the works of Babkov V.F. [14], Zolotariya I.A. [15], Maltsev Yu.A. [16], Silyanov V.V. [17], Fedotov G.A. and Pospelov P.I. [18] and those of other prominent scientists are devoted to solving the problems of ensuring the required level of reliability of highways.

However, based on the studied literary sources on the problem of reliability of highways [9], it is revealed that the area of their reliability is still poorly studied [15].

The theory of reliability in the construction of roads has not yet been developed to the same extent as in instrumentation, mechanical engineering, and transport. The complexity of the analytical description of the diverse factors that must be considered when considering the reliability indicators at the design stages [19] and the construction of roads [4] was the reason for the absence of completed engineering methods for calculating them in road construction. In matters of evaluating the reliability of the designed and constructed roads, road science and practice are currently lagging behind the modern requirements.

Therefore, the aim of this work is to develop modern methods and mathematical models based on a probabilistic-statistical approach to assessing the reliability of roads during the stages of their construction and operation [13], as well as at the stages of development of pre-design, design and working documentation [19].

2. Materials and methods

One of the main indicators of the quality of the road is its reliability, which is manifested in time and reflects the changes that occur on the road throughout the entire period of its operation. In general, reliability is understood as the property of a road to perform the functions assigned to it under specific operating conditions for a stipulated time [17].

The reliability of road $P$ is closely related to the likelihood of a general failure [20], or the risk of an undesirable event $r$, which means an event characterizing the loss of working capacity or the failure of any structural element of the road (roadbed, pavement, paving) [12]:

$$P = 1 - r.$$  \hspace{1cm} (1)

Along with the concept of a general failure of a road [21], it is necessary to distinguish the particular failures constituting its structural elements.

As a private failure in strength, one or other defects of individual structural layers should be considered, which reduce their strength (for example, obliteration of the sand or frost destruction of a crushed-stone base).

In each case of the occurrence of such a private failure, the operational characteristics of the structural element of a road go beyond the permissible limits, for example, the evenness of the coating and, accordingly, the speed at this section becomes less than the permissible values. Private failures can also include the failure of the deformation and destruction of the road surface, which was not promptly repaired by the road service [22].

In this regard, one can quantitatively consider the partial reliability of individual road elements as the probability of ensuring a given (required) strength or a given (required) speed of traffic safety (for example, on curves, slopes, etc.).
The pavement and roadbed have the greatest influence on the level of quality and reliability of the road.

Currently, the most detailed questions of reliability are designed for pavements. The basis of this approach is the consideration of random variation of the strength of the pavement condition.

A general failure in strength is the corresponding defects of the pavement as a whole (mesh cracks, subsidence, etc.), leading to a decrease in the calculated strength for a period less than stipulated by the calculation.

In the general case, a pavement failure is an event in which the ability of a traffic stream to perform certain specific work (in ton-kilometers per hour or day) is impaired. The failure of the pavement may occur when its strength decreases, the flatness and adhesion of the road surface deteriorated.

The occurrence of road failures is due to many reasons. There are gradual and sudden failures. Gradual failures are caused by the accumulation of irreversible deformations and minor damages as a result of repeated applications of loads, mechanical wear, creep and other causes. Sudden failures are caused by loss of strength or stability of the structure, accompanied by its destruction. The causes of sudden failures of the highway may be natural disasters, which, it was impossible to foresee. However, in some cases, natural disasters include massive destruction of roads, in which you can set the blame and the designers, and builders, and operators, but it should be noted that events in which there is a sudden and complete failure of the road are quite rare.

In case of failures, there is a malfunction of the road, that is, it cannot perform the specified functions with the parameters established by the regulations. The failure of the road as a whole is a gradual decrease in the average annual speed of movement below the permissible limits. However, sudden failures affect the value of the average annual speed, which should be the main parameter of the annual assessment of the reliability of the road in operation.

In the process of developing modern road construction, the improvement of the method for assessing the failure-free of the road pavement - roadbed structure, which is related to ensuring the reliability of this structure, especially in the initial period of road operation, i.e. in terms of the occurrence of its failures.

Failures caused by deformations and destruction of the subgrade, mainly occur under the influence of natural and climatic influences, which often contribute to design errors and poor quality construction work.

For a roadbed, the following causes of its deformation and destruction are typical:
- precipitation arising from insufficient compaction, over-wetting of soils and inconsistencies between the design load and the actual load;
- subsidence, formed in areas with weak underlying soils - in swamps, subsidence soils, karst, etc.;
- creeping of slopes, arising from over-wetting of soils, the use of low-strength materials, non-compliance with technology in the construction of the embankment (under-compaction of the lower layers, exceeding the slope steepness norms);
- destruction of slopes in the form of cracks and washouts, resulting from water and wind erosion when the roadbed was erected from low-strength or non-cohesive soils with little compaction and consolidation;
- deformations of the uncompacted part of the shoulders in the form of holes, cracks, ravines due to the incompatibility of measures for their operation.

Analysis of the causes of deformations and destruction of the roadbed shows that the result of their occurrence is the failure of the roadway.

These failures are expressed in the form of washouts of its embankments, creeping slopes of embankments and excavations, creeping of the entire roadbed on landslide areas, landslides on the roadbed and mudflows in mountainous areas, over-moistening of the roadbed and loss of bearing capacity, surficial swellings, unacceptable in terms of flooding of low landings, water, snow drifts, avalanches, etc.

Depending on the volumes, these destructions can cause complete or partial closure of traffic for a period of several hours to several months, a decrease in the speed of movement caused by the need to
bypass the destroyed site, regular road closures for the winter period due to snow drifts, which is observed on many mountain roads [22].

Road cover is the upper part of the pavement, which is directly affected by the wheels of cars and weather and climatic factors.

Failures caused by deformations and destruction of pavements are mainly due to poor quality work. For example, when an unsatisfactory selection of asphalt-concrete mixtures forms waves, and shifts (with an excessively plastic mixture) or gouges (with an excessively rigid mixture) on a coating. Mass destruction of coatings can cause the impossibility of driving on them and the transition of moving cars to the roadsides or parallel dirt roads.

Types of defects in covering the roadway of a road, which is the topmost part of the pavement, are presented in GOST 33180-2014 Public roads (Table 1).

Table 1. Types of defects in covering the carriageway

| Quality indicator (type of defect) of the carriageway | Describing of defects |
|------------------------------------------------------|-----------------------|
| Pot holes                                            | The destruction of the coating in the form of depressions of various shapes with sharply defined edges (more than 3 cm deep and an area of more than 200 cm) |
| Bracks                                               | Destruction of pavement for its entire thickness with a sharp distortion of the transverse profile, accompanied by a grid of cracks |
| Untreated sections of the roadway with bleeding of bonding material | Surplus of bonding material on the surface of the coating with a change in its texture and color, area of more than 1 m |
| Cracks                                               | Violation of the integrity of the coating without removing the material with the formation of narrow slits. Cracks of arbitrary outline and location with a width of opening more than 3 mm on the carriageway |
| Temperature cracks                                   | Cracks caused by temperature fluctuations and stress concentrations in the coating layers |
| The grid of cracks along the bands of rolling        | The destruction of the coating without significant distortion of the profile and accompanying with small longitudinal and transverse an arbitrary outline cracks, characteristic of insufficient pavement strength |
| Destroyed and not filled with mastic deformation seams on cement concrete coating | Damage of joints and materials near them, presence of debris in damaged joints and inclusions of armoring elements |
| Strips of dirt at the edges of the coating           | The presence of contamination of the coating of dirt and debris at the edges |

Failures caused by destructions and deformations of pavements (subsidence, breaks, etc.) often occur during the periods of spring and autumn thaws during over-wetting of the subgrade soil and loss of bearing capacity by them, not strong enough (proper thickness and stiffness) road pavement.

Road clothes should be considered as a complex object and approach this problem in two ways. First, the object “pavement” can be taken as a system of simple objects - materials of structural layers. In turn, the material (for example, asphalt concrete) can be considered as a complex object made up of a system of simple objects - particles of rubble, sand, powder, and bitumen. Bitumen can also be considered as a
complex object, which is a system of subprimary structures and associations of various structural elements.

Secondly, road pavement can be considered as a system characterized by separate parameters - evenness, strength, adhesion, and defectiveness. The theory of reliability allows you to justify the general techniques and methods that should be followed in the design, construction, and operation of roads to ensure maximum efficiency of their use.

One of the objectives of the theory of reliability - the development of methods for calculating the reliability of complex objects based on the reliability of the components of their simple objects. For all calculations of the reliability of road structures, there is one general condition: the reliability of the main elements forming the individual layers of this structure must be known. Therefore, to determine the reliability of asphalt concrete coatings, it is necessary to take into account the reliability of materials of structural layers, in particular, asphalt concrete.

It should be borne in mind that road pavement is also a complex structure, the reliability of which largely depends on the degree of reliability of its individual layers and the roadbed. You can not talk about the reliability of the pavement as a whole without taking into account the reliability of its individual layers, differing in the level of a location, a degree of compaction and moisture, the type of soil and many other factors.

When vehicles are moving on a road, static and dynamic loads act on road pavements, from which various types of deformation and destruction can occur on the surface of the pavement and the entire pavement design.

The main types of deformation and destruction of pavement are:
- deformations and damages caused by the abysses occurring in springtime when the soil of the roadbed thaws in areas with unfavorable drainage conditions and the protection of the roadbed from temperature effects. The reasons for such destruction can be errors in the estimation of the perspective intensity of movement and loads; substandard materials and their heterogeneity, poor compaction of the subgrade and pavement, as well as the overwetting of the roadbed;
- loss of strength of the pavement caused by the continuous influence of the wheels of cars and weather-climatic factors. Loss of strength is greatly influenced by errors made in the design, construction, and operation of pavements, as well as thermal deformations;
- subsidence of non-rigid pavements in the form of depressions resulting from local subsidence of under-compacted soil or layers of pavement. Especially often this type of deformation appears at the entrances to the bridge, at the places of laying under existing roads of culverts and pipelines;
- cross-cutting cracks characteristic of cement concrete coatings, when subsidence forms on them. Cracks appear most often in places of subsidence of the roadbed and are associated with untimely repairs;
- breaks - the destruction of the pavement in the form of long slits along the wheel tracks. These destructions are characteristic of road pavements of the transitional type when passing very heavy cars and reducing the bearing capacity of the pavement base. The destruction of the entire pavement structure is preceded by the deformation and destruction of pavements.

The term reliability has a well-defined quantitative meaning: this is the probability of failure-free operation for a given period of time under certain operating conditions. The notion of failure means a change in the state of an object, as a result of which its normal operation is disturbed in accordance with specified norms. Operation of an object within tolerances is considered normal, and going beyond tolerances is considered a failure. Thus, the level of reliability of an object operating in certain conditions depends on the level of technical requirements determining the failure criteria.

Thus, failures of roads, characterizing the loss of performance of the roadbed, pavement, and paving, are caused by their deformations, defects and damage, which occur mainly under the influence of design errors, poor quality construction work, natural influences, and repeated loads from cars [23].

As stated above, at present, the most detailed issues of reliability are designed for pavements, taking into account random changes in the strength of state of the pavement (grid of cracks, subsidence, etc.) [15].
The level of reliability of the road structure for the period of time $t$ is determined by the formula [13]:

$$P_t = 0.5 + F \left( \frac{E_{eq} - E_m}{\sqrt{\sigma_{eq}^2 + \sigma_m^2}} \right),$$

(2)

where $P_t$ is the probability of failure-free operation for a period of time $t$; $E_{eq}$ – the equivalent (total) modulus of elasticity on the pavement in the year $t$ from the beginning of the operation of the road or after major repairs, MPa; $E_m$ – the maximum modulus of elasticity of the pavement at which the risk of destruction is 50%, MPa; $\sigma_{eq}$ – the mean square deviation of the equivalent modulus of elasticity set taking into account the time of operation of the pavement $t$, MPa; $\sigma_m$ – the mean square deviation of the maximum modulus of elasticity, MPa; $F \left( \frac{E_{eq(t)} - E_m}{\sqrt{\sigma_{eq(t)}^2 + \sigma_m^2}} \right)$ – probability integral (Laplace function).

A modern approach to analyzing the state of pavement in terms of the rate (risk) of destruction and the actual duration of its service is predictable. This approach is based on risk theory formulas and quality control applied in road construction [13].

The risk (rate) of the destruction of the pavement over time is a qualitative engineering characteristic of the structure and, in accordance with the theory of probability, is determined by the expression

$$r_t = \frac{S_{des}}{S_{tot}},$$

(3)

where $S_{des}$ is the area of destruction of part of the structure on the road section for the period of time $t$, m²; $S_{tot}$ – the total area of road construction on the site, m².

The risk of destruction of pavement at the time of the survey, as well as after $t$ years, is determined by the following dependency:

$$r = 0.5 - F \left( \frac{E_{eq} - E_{cr}}{\sqrt{\sigma_{eq}^2 + \sigma_{cr}^2}} \right)$$

(4)

where $E_{eq}$ and $\sigma_{eq}$ – see formula (2); $E_{cr}$ – critical (limiting) modulus of elasticity of the pavement, in which the risk of destruction is 50%, MPa; $\sigma_{cr}$ – the mean square deviation of the critical (limiting) modulus of elasticity, MPa; $F \left( u \right)$ – Laplace function.

In the process of determining the risk of destruction of pavement at the time of the survey ($r$), the coefficient of variation of the required modulus of elasticity ($C^{req}_V$) is established, which depends on the accuracy of the prediction of the composition and intensity of movement.

To determine the coefficient of variation of the required modulus of elasticity ($C^{req}_V$), the following studies were conducted. For a number of years, on the roads, the actual intensity and composition of the traffic were established. Of the projects stored in the archives of road organizations, the prospective intensity and composition of the movement at the time of observation of the intensity and composition of the movement were written out. The actual and taken from the draft intensity and composition of the
movement to the calculated cars, for which two values of the required and reduced elastic modules were established, were brought.

With the accumulation of statistical data, using the method of the difference of double measurements, the mean square deviations ($\sigma_{req}$) and coefficients of variation ($C_{req}^V$) of the required elastic modules were determined. It is found that:

- for pavements of the capital type, the deviation from the required modulus of elasticity ranges from 0.13 to 0.19;
- for lightweight road pavements $C_{req}^V=0.06\pm0.15$;
- for pavements of the transition type $C_{req}^V=0.03\pm0.09$.

Thus, it can be assumed that the longer the road is maintained and the higher its durability, the more $C_{req}^V$.

Parameter $C_{req}^V$ was taken depending on the duration of the forecast period and the type of pavement in Table 1.

Table 2. The calculated values of the coefficient of variation of the required modulus of elasticity

| Duration of the forecast period, years | Values $C_{req}^V$ for pavement of type |
|--------------------------------------|---------------------------------------|
|                                       | transition | lightweight | capital |
| 1-3                                   | 0.03-0.05  | -           | -        |
| 4-6                                   | 0.06-0.07  | 0.06-0.07   | -        |
| 7-9                                   | 0.08-0.09  | 0.08-0.10   | -        |
| 10-13                                 | -          | 0.11-0.15   | 0.13-0.15|
| 14-17                                 | -          | -           | 0.16-0.17|
| 18-22                                 | -          | -           | 0.18-0.19|

Note: for the left values of the parameter $t$, the left values of the parameter should be taken; $C_{req}^V$; for the right values of the parameter $t$ - right values $C_{req}^V$; for intermediate values of $t$, the values of parameter $C_{req}^V$ should be interpolated.

The algorithm for determining the risk of destruction of the pavement at the time of the survey and $t$ years after its examination ($r_F$) is presented in Figure 1.

The results of the analysis of the pavement strength state for two characteristic sections of a category II road are presented graphically depending on the change in the equivalent elastic modulus (Figure 2) and the change in the rate of pavement destruction over time ($r_{(F)}=F(t)$) on these sections of the road (Figure 3).

Analysis of the graphical dependences shows that in the first section of the road for the last year of prediction, the destruction area reaches 15.4 m$^2$ out of 100 m$^2$ coverage, that is, a decrease in the equivalent elastic modulus in the first section of the road during the last year of operation from 122 MPa to 115 MPa is observed. In the second section of the road for the last year of forecasting, the area of destruction reaches 7.93 m$^2$ from 100 m$^2$ of coverage, which indicates a decrease in the equivalent elastic modulus in the second section of the road for the last year of its operation from 122 MPa to 113 MPa only (fig. 2). At the same time, the pace of destruction of pavement after 10 years of operation of the road in the second section will be less than the rate of destruction of the structure in the first section (0.0793 <0.0918) (figure 2).
Begin

$E_{eq} \cdot E_{a} \cdot E_{req} \cdot \sigma_{eq}$

Selected value

$C_{V}^{\text{req}} = 0.08 + 0.18$

$\sigma_{eq} = C_{V}^{\text{req}} \cdot E_{req}$

$C_{V}^{\text{req}} \neq 0, 2$?

Yes

Yes

$E_{\sigma} = \sqrt{E_{eq}^2 + 25\sigma_{eq}^2}$

$E_{\sigma} = \sqrt{E_{eq}^2 + 25\sigma_{eq}^2 - 1\left(E_{eq}^2 + 25\sigma_{eq}^2\right) - E_{\text{mean}}}$

$E_{\sigma} = \frac{1}{25\sigma_{eq}^2 - 1}$

$\sigma_{\text{req}} = C_{V}^{\text{req}} \cdot E_{req}$

$r = (E_{\text{max}} - E_{\text{min}}) \frac{0.5 - \sigma}{\sqrt{\sigma^2 + \sigma^2}}$

End

Figure 1. Algorithm for determining the risk of destruction of pavement ($R$) at the time of the survey and $t$ years after its examination.
3. Conclusions
The study found that one of the main indicators of the quality of the road is its reliability, which manifests itself in time and reflects the changes that occur on the road throughout the entire period of its operation. These changes are associated with the likelihood of a general failure or the risk of an undesirable event, which is understood as an event characterizing the loss of working capacity or breakdown of any structural element of the road (roadbed, pavement, paving, etc.).

The concepts of the general failure of a road and private failures of the components of the structural elements of a road caused by the accumulation of irreversible deformations and minor damage as a result of repeated loads, mechanical wear, plastic flow and natural disasters that could not be foreseen are formulated.

The analysis of the causes of the deformations and destruction of the roadbed, which shows that the consequences of their occurrence are the failures of the roadbed.

These failures are expressed in the form of erosion of its embankments, plastic flow slopes of embankments and excavations, plastic flow of the entire roadbed on landslide areas, landslides on the roadbed and mudflows in mountainous areas, over-moistening of the roadbed and loss of bearing capacity, surficial swellings. They are unacceptable in terms of flooding of low landings by water, snowdrifts, avalanches, etc.

Detailed information on the main causes and types of formation of deformations and destruction of pavement, which are:
- deformations and damages caused by the abysses occurring in springtime when the soil of the roadbed thaws in areas with unfavorable drainage conditions and the protection of the roadbed from temperature effects. The reasons for such destruction can be errors in the estimation of the perspective intensity of movement and loads; substandard materials and their heterogeneity, poor compaction of the roadbed and road pavement, as well as waterlogging of the roadbed;

- the loss of strength of the pavement caused by the continuous influence of the wheels of cars and weather-climatic factors. Loss of strength is greatly influenced by errors made in the design, construction, and operation of pavements, as well as thermal deformations;

- subsidence of non-rigid pavements in the form of depressions resulting from local subsidence of under-compacted soil or layers of pavement. Especially often this type of deformation appears at the entrances to the bridge, at the places of laying under existing roads of culverts and pipelines;

- cross-cutting cracks characteristic of cement concrete coatings, when subsidence forms on them. Cracks appear most often in places of subsidence of the roadbed and are associated with untimely repairs;

- breaks – the destruction of the pavement in the form of long slits along the wheel tracks. These destructions are characteristic of road pavements of the transitional type when passing very heavy cars and reducing the bearing capacity of the pavement base. The destruction of the entire pavement structure is preceded by the deformation and destruction of pavings.

An analytical expression is proposed for determining the level of reliability of road construction for a period of time $t$, which is determined by the formula (2).

Analysis of the graphical dependences shows that in the first section of the road for the last year of prediction, the destruction area reaches 15.4 m$^2$ out of 100 m$^2$ coverage, that is, a decrease in the equivalent elastic modulus in the first section of the road during the last year of operation from 122 MPa to 115 MPa is observed. In the second section of the road for the last year of forecasting, the area of destruction reaches 7.93 m$^2$ from 100 m$^2$ of coverage, which indicates a decrease in the equivalent elastic modulus in the second section of the road for the last year of its operation from 122 MPa to 113 MPa only (fig. 2). At the same time, the pace of destruction of pavement after 10 years of operation of the road in the second section will be less than the rate of destruction of the structure in the first section ($0.0793 < 0.0918$).

The theory of reliability of highways allows you to justify the general techniques and methods that should be followed in their design, construction, and operation to ensure maximum efficiency in the use of roads. Therefore, one of the tasks of reliable operation of highways is to develop methods for calculating their trouble-free operation based on the reliability of the components of their simple elements.

The probabilistic-statistical approach is used in the design of roads during the development of their pre-design, design and working documentation proposed in this work. A probabilistic-statistical approach aims to assess the reliability of roads, and the risk of destruction of their pavement over time during road operation will contribute to a significant adjustment of these indicators towards their improvement.

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