THE IMPACT OF CLIMATE CHANGE ON THE FUNCTIONAL RELIABILITY OF ROAD TRANSPORT NETWORKS

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Abstract

The article considers the problem of taking into account the impact of climate change on the functional reliability (FR) of regional road networks. An algorithm and methodology for assessing the FR of a road are proposed, which are based on assessing the durability and residual life of the road surface structure according to deformation criteria: (1) the maximum permissible residual deflection of the road surface, (2) the maximum permissible reduction of the road surface material elasticity modulus as a result of multiple elastic-plastic deformation of the road surface under the action of traffic, (3) the appearance of unacceptable longitudinal track(s) and/or potholes in the road surface.

Keywords: functional reliability, transport network, climate change, durability, residual resource

I. Introduction

The problem of assessing the reliability of a developed road network is very relevant, especially in light of the increasing complexity of transport and logistics chains, the constant growth of transport traffic, the degradation of the road surface from the impact of transport, temperature changes, adverse weather conditions, climate change, frost upheaval, earthquakes, mudflows, landslides, avalanches, destruction and demolition of bridges due to floods, insufficient funds for repairs, etc. The criterion for the road network failure is road surface deformation.

The functional reliability (FR) of a regional road network is understood as the reliability of the main route for which this network is intended. The main route FR is equal to the product of the reliabilities of the network sections that form it.

In the case where the main route consists of several equivalent routes, its reliability is calculated using the formula:

$$R_n = 1 - Q_1 \cdot Q_2 \cdot \ldots \cdot Q_n, \tag{1}$$

Where $Q_1 \cdot Q_2 \cdot \ldots \cdot Q_n$ are the probabilities of failure (POF) of paths n in number that make up the main route.

Calculation of network reliability shows that the more equivalent paths the selected route is organized by, the higher its reliability and, accordingly, the higher is the entire transport network the reliability.

II. Mathematical model of the road network

When assessing the functionality of a transport network, its mathematical model is used, with the help of which each driver of a vehicle selects a route, calculates the travel time and the traffic flow on each road. The stationary distribution of traffic is found as the solution of the optimization problem of the transportation network functioning [7]:

$$min\ Z(x) = \sum_i \int_0^{x_i} t_i(w)dw, \tag{2}$$

Where x_i is the volume of traffic on the road *i*; t_i is the travel time on the road *i*:

$$t_i(x_i) = t_0(1+\alpha \left[\frac{x_i}{C_0 \cdot N_L}\right]^{\beta}), \tag{3}$$

where t_0 is the time of unimpeded passage on the *i-th* road; C_0 is the capacity of one traffic lane; N_L is the number of lanes of the *i-th* road; α and β is the variable parameters defined as 3.0 and 4.0 respectively for design speeds of 20 km/h and 30 km/h and 4.5 for design speeds of 40 km/h and above [7].

The total travel time of the road is determined as follows:

$$C_i = \sum_i t_i(x_i)\delta_i, \tag{4}$$

Where δ_i is a logical function that indicates whether the selected route passes along the *i-th* road.

III. Simulation of real-time traffic flow after an accident using an agent-based model

Agent-based modeling is a powerful method for analyzing distributed complex systems, suitable for modeling systems under three conditions: the problem domain is spatially distributed; subsystems exist in a dynamic environment; subsystems must interact with each other with greater flexibility [7].

IV. Initialization of the agent-based model [7]

With continuous monitoring of road traffic (including with the help of video cameras and drones), information is accumulated about the travel time of each vehicle and the volume of traffic flow on each road of the transport network. In this case, the number of cars on each road I_i, is:

$$I_i = x_i \cdot t_i \tag{5}$$

The probability that a particular car on the *i-th* road will take a particular route k between an origin r and a destination s is [7]:

$$\Pi_{i,rs} = \frac{\sum_{k \in \Psi_{rs}} f_k^{rs} \delta_i}{x_i}, \tag{6}$$

where f_k^{rs} is the traffic volume of the *k-th* route between the source point r and the destination point s; Ψ_{rs} is the set of all routes between r and s.

Using equation (6), each car on the *i-th* road is randomly assigned a direction of travel. The probability that an individual car assigned a particular direction of travel *r-s* will travel a particular route *r-t* is [7]:

$$\Pi_{i,rt}^{rs} = \frac{f_{rt}^{rs}\,\delta_{i,rt}}{\sum_{k\in\Psi_{rs}} f_{k}^{rs}\,\delta_{i}} \tag{7}$$

Using equation (7), each vehicle on the *i-th* road is randomly assigned a route. Assuming that the vehicles are uniformly distributed across the roads (links in the transport network), the time it takes for the *j-th* vehicle in the queue to reach the intersection between the links is [7]:

$$t_{j,a} = t_i(x_i)\cdot\frac{j}{I_i} \tag{8}$$

V. Algorithm for assessing the durability of road surfaces

The durability of a road surface is usually understood as the time during which it retains its basic properties at a level that satisfies operational requirements.

Currently, to assess the durability of the road surface of a specific section of the road network, the initial reliability is set (the probability of failure-free operation at standard average values of the strength and rigidity parameters of the road surface).

From the standpoint of reliability theory, a highway is a recoverable system. Since analytical calculation of recoverable network systems reliability as yet has not been developed, the highway during the time between repairs is considered as a non-recoverable system [4].

Elements of non-repairable systems have the following durability indicators [4]:

$P(t)$ is the probability of failure-free operation of an element during time t (lifetime function);

$f(t)$ is the density of distribution of time between failures;

$\lambda(t)$ is the failure rate at time t;

T_0 mean time between failures;

P_0 is the initial reliability of an element (the probability of failure-free operation at standard average values of the strength and rigidity parameters of a road).

The following relationships exist between durability indicators [4]:

$$P(t) = P_0 e^{-\int_0^1 \lambda(t)dt} \tag{9}$$

$$T_0 = \int_0^\infty P(t)dt \tag{10}$$

These expressions show that the initial function in the durability calculation is the failure rate. To determine the durability (mean time between failures) of a road surface, the Weibull distribution law is used:

$$\lambda(t) = \alpha\lambda t^{(\alpha-1)} \rightarrow P(t) = P_0 e^{-\lambda t^{\alpha}} \rightarrow T_0 = P_0 \int_0^\infty e^{-\lambda t^{\alpha}} dt \tag{11}$$

The existing method of determining durability is not objective, since the initial reliability of the road surface is specified from regulatory documents during the calculation. For an objective assessment of durability, it is necessary to calculate the probability of failure-free operation of the road surface on each section of the road network.

The elastic moduli E_{total} and E_{min} are taken as random variables for assessing the durability of the road surface [5].

The reliability of asphalt concrete road surfaces as flexible road surfaces is determined by the permissible elastic deflection:

$$E_t \geq E_{min} \cdot K_{cr} \tag{12}$$

where E_t is the total calculated modulus of elasticity of the road surface structure, MPa,

E_{min} is the minimum required overall modulus of elasticity of the road surface, MPa,

K_{cr} is the required coefficient of road surface strength according to the elastic deflection criterion K_{cr} = 1,17 [2].

The value of the minimum required overall modulus of elasticity of the road surface structure is calculated using the empirical formula [5]:

$$E_{min} = 98{,}65 \cdot [\, lg(\sum N_p) - c], \ \ Mpa, \tag{13}$$

Where $\sum N_p$ is the total estimated number of load applications over the service life of the road surface;

c - empirical parameter adopted for different axle loads of a vehicle. For the maximum calculated axle load of 100 kN (with a lightweight type of road surface) c = 3.55.

To determine the durability for each section of the road network, it is necessary to determine the value of the minimum required overall modulus of elasticity of the structure E_{min}. To do this, it is necessary to calculate the total estimated number of load applications over the service life of the road surface on each section of the network according to [3], in the following sequence:

First, the prospective traffic intensity at the end of the inter-repair period N_{ps} is determined using the formula [3]:

$$N_{ps} = N_{in}(1+\frac{p}{100})^t, \tag{14}$$

Where N_{in} is the initial traffic intensity, vehicles/day;

p is the annual increase in traffic intensity, %;

t is the prospective period, years.

Then the traffic intensity N_p [3] reduced to the calculated two-axle vehicle is determined:

$$N_p = f_{st} \sum_{m=1}^{n} N_m \cdot S_{mt}, \ cargo\ units/day, \tag{15}$$

where f_{st} is a coefficient that takes into account the number of traffic lanes and the distribution of traffic across them;

n is the total number of different brands of vehicles in the traffic flow;

N_m is the traffic intensity of vehicles of the m-th brand (number of trips per day in both directions of vehicles of the m-th brand);

S_{mt}, is the total coefficient of reduction of the impact of the m-th brand vehicle on the road surface [3].

The multi-lane coefficient f_{st} is assigned according to Table 3.2 [3]. The roadway lane number is counted from the right in each direction of vehicle traffic. For two-lane roads f_{st} = 0.55.

Next, the total calculated number of applications of the calculated load to a point on the road surface during the service life is found using the formula [3]:

$$\sum N_p = 0{,}7 \cdot N_p \frac{K_c}{q^{(T_{lt}-1)}} \cdot T_d \cdot K_n\ , \tag{16}$$

Where q is the indicator of change in traffic intensity over the years;

T_{lt} is the estimated service life;

K_c is the summation coefficient;

T_d is the estimated number of days per year corresponding to a certain state of deformability of the road surface;

K_n is a coefficient that takes into account the probability of deviation of the total movement from the expected average.

The estimated service life T_{lt} is set according to table P6.2 [3].

The summation coefficient K_c is determined by the formula [3]:

$$K_c = \frac{q^{T_{lt}-1}}{q-1} \tag{17}$$

For Eastern and Western Siberia, the calculated number of days per year corresponding to a certain state of deformability of the road surface is taken as T_d = 130 days [3].

The coefficient K_n, which takes into account the probability of deviation of the total movement from the expected average, is found from Table 3.3 [3].

Having data on the minimum and total calculated modulus of elasticity of the road surface of each section of the road, it is possible to determine [4,5]:

The average value of the bearing capacity reserve:

$$[g] = [E_t] - [E_{min}]\ , \tag{18}$$

where $[E_t]$ – average value of the total calculated modulus of elasticity of the road surface structure;

$[E_{min}]$ - average value of the minimum required overall modulus of elasticity of the road surface structure.

The dispersion of the reserve of bearing capacity:

$$S_g^2 = S_{E_t}^2 + S_{E_{min}}^2\ , \tag{19}$$

Where $S_{E_t}^2$ is the dispersion of the total calculated modulus of elasticity of the road surface structure;

$S_{E_{min}}^2$ is the dispersion of the minimum required overall modulus of elasticity of the road surface structure.

Standard deviation of the bearing capacity reserve:

$$S_g = \sqrt{S_g^2} \tag{20}$$

Where S_g^2 is the dispersion of the reserve capacity.

Reliability index:

$$\beta = \frac{\bar{g}}{S_g}, \tag{21}$$

Where $\bar{g}$ is the average value of the bearing capacity reserve;

S_g is the standard deviation of the bearing capacity reserve.

And finally, the probability of failure-free operation, i.e. the reliability indicator of the road surface structure:

$$P(\bar{g} \geq 0) = 0{,}5 + F(\beta), \tag{22}$$

Where $F(\beta)$ is the value of the Laplace function.

To determine the average values of elastic moduli, the variation coefficients are used:

$$[E_t] = \frac{E_t}{(1\text{-}C_{E_t})};\ [E_{min}] = \frac{E_{min}}{(1+C_{E_{min}})} \tag{23}$$

Where C_{E_t} is the coefficient of variation of the total calculated modulus of elasticity of the road surface structure, $C_{E_t} \leq 0{,}2$;

$C_{E_{min}}$ is the coefficient of variation of the minimum required modulus of elasticity of the road surface structure, $C_{E_{min}} \leq 0{,}2$.

The dispersions of elastic moduli are also determined using the coefficients of variation [5]:

$$S^2_{E_t} = (C_{E_t} \cdot [E_t])^2;\ S^2_{E_{min}} = (C_{E_{min}} \cdot [E_{min}])^2 \tag{24}$$

VI. Example of application of the methodology to the Ural Federal District road networks

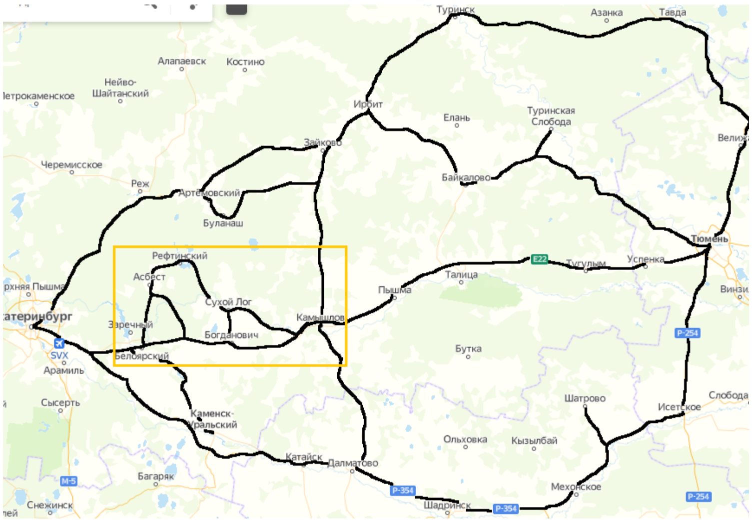

Figure 1: *The main road network with a highlighted area of the secondary road network in the Urals Federal District*

To assess the road surface reliability and durability, a network of highways (Figure 1) was selected, located in the Sverdlovsk, Tyumen and Kurgan regions of the Ural Federal District, which provides ground communication to two regional capitals: Yekaterinburg (with a population of over 1,5 million) and Tyumen.

According to the road-climatic zoning, the entire selected automobile network is located in the second road-climatic zone, II subzone, and is divided into following sections:

1) The main highway R-351 in the direction of Yekaterinburg-Tyumen through the intermediate settlements: Beloyarsky - Bogdanovich - Kamyshlov - Pyshma - Talitsa - Tugulym - Uspenka (length 330 km). Traffic intensity - 7980 vehicles/day.

2) Northern secondary direction Yekaterinburg-Tyumen through intermediate settlements: Artemovsky - Zaikovo - Irbit - Turinsk - Tavda - Velizhany (length 500 km). Traffic intensity - 5100 vehicles/day.

3) The southern secondary direction Yekaterinburg-Tyumen through the intermediate settlements: Kamensk-Uralsky - Kataysk - Dalmatovo - Mekhonskoye - Isetskoye (length 432 km). Traffic intensity - 6520 vehicles/day.

4) Direction Reftinsky – Asbest – Beloyarsky (length 57 km). Traffic intensity - 450

vehicles/day.

5) Direction Reftinsky – Sukhoi Log – Bogdanovich (length 61 km). Traffic intensity – 690 vehicles/day.

6) Direction Zaikovo - Kamyshlov (length 81 km). Traffic intensity - 750 vehicles/day.

7) Direction Irbit – Baikalovo – Talitsa (length 110 km). Traffic intensity – 800 vehicles/day.

8) Direction Turinskaya Sloboda – Tyumen (length 110 km). Traffic intensity – 2100 vehicles/day.

9) Direction Baikalovo – Turinskaya Sloboda (length 49 km). Traffic intensity - 1000 vehicles/day.

10) Direction Artemovsky - Bulanash - Zaikovo-Kamyshlov highway (length 73 km). Traffic intensity - 400 vehicles/day.

11) Direction Beloyarsky – Kamensk-Uralsky (length 72 km). Traffic intensity - 600 vehicles/day.

12) Direction Kamyshlov – Dalmatovo (length 80 km). Traffic intensity – 550 vehicles/day.

13) Direction Shatrovo – southern highway Yekaterinburg – Tyumen (length 22 km). Traffic intensity – 300 vehicles/day.

Using the above methodology, all necessary parameters of road surface wear for each section of the road network were calculated, the results of which are shown in [13].

Based on the obtained results, the initial reliability P (the probability of failure-free operation of the road surface structure at the beginning of road operation after the next repair) of each section of the road network was calculated, which is necessary for calculating the durability of the road surface.

A 100x50 km rectangle is selected from the main road network, in which all secondary roads adjacent to the main network are displayed (Fig. 1). The secondary road network has 30 nodes and 37 links.

To assess the maximum possible impact of a traffic accident on the capacity of the main route of the road network under study, a traffic accident was simulated. The accident was set at 9:00 (when the entire transport network is maximally loaded with vehicles) on the main highway R-351 in the direction of Yekaterinburg-Tyumen in the settlement of Gryaznovskoye, involving a fuel tanker, which led to a fire and explosion, with the subsequent destruction of a bridge structure. This made it impossible for vehicles to continue moving along this road until the bridge was completely restored [13].

The use of an agent-based model to analyze the consequences of the accident showed that the road accident led to a significant decrease in the speed of movement of vehicles and their accumulation, which directly depends on the speed of movement of cars. The average speed of the flow during normal functioning of the transport network is 57.5 km/h [11].

The destruction of the bridge as a result of the accident and the impossibility of driving along this section of the road led to the extension of the route along the main highway R-351 by 85 km (taking into account detours). The maximum time to bypass the destroyed section of the road using detours is $t_1=S/V=85/30=2{,}8$ hours, where S is the length of the detour, km; V is the average speed of movement along the detour, km / h.

The length of the bypass section of the road is 39 km. Provided that this section of the road is fully operational, the travel time along it t_2 at an average speed of 57.5 km/h is 0.7 hours. Time loss when bypassing the destroyed section of the road $\Delta t = t_1 - t_2 = 2{,}8 - 0{,}7 = 2{,}1$ hours. Thus, the travel time along the R-351 highway in the direction of Yekaterinburg-Tyumen in the event of the destruction of the bridge in the Gryaznovskoye settlement increases by 2.1 hours.

For a more accurate calculation of the probability of road pavement failure and the time tothe next repair, it is necessary to take into account all factors affecting the wear of the road pavement. In this regard, it is necessary to analyze the impact of each event on the probability of failure (POF) of the road pavement structure. One promising method for assessing and predicting the failure of any system with a large number of cause--effect relationships between events is Bayesian networks. BNs are graphical models that describe probabilistic relationships between a set of variables. Formally, they are directed acyclic graphs (DAGs), the nodes of which represent variables related to the system, and the arcs of directed action represent probabilistic dependencies between the variables [12]. Modeling a system with cause--effect relationships allows for a deeper understanding of the main mechanisms of its degradation and allowing studying how external interventions affect the system. The GeNIeModeler software package (hereinafter referred to as GeNIe) is used for this purpose. In this work, impacts, external influences, mechanical damage and the human factor are taken as factors influencing the probability of road surface failure.

When constructing a Bayesian network model to determine the probability of road surface structure failure, it is necessary to understand the circumstances leading to the object's failure. Due to the poorly developed system of monitoring road networks, the necessary statistics on road surface destruction are absent, therefore the conditional probabilities of failure of the road surface structure are specified by experts.

The probabilities of failure of the road surface structure on each section of the road network before the next major repair using the "GeNIe" software package are presented in [13].

According to the obtained results, the highest POF of the road surface structure is found in section № 9 (Q = 0.3176) in the direction of Baikalovo - Turinskaya Sloboda of the road network.

Communication between Yekaterinburg and Tyumen is provided by six routes with corresponding failure probabilities Q:

1) The main highway R-351 (Q = 0.2818);
2) The northern direction Yekaterinburg-Tyumen (Q = 0.2875);
3) The southern direction Yekaterinburg-Tyumen (Q = 0.2943);
4) The northern direction through the settlements of Baikalovo and Turinskaya Sloboda (Q = 0.4813);
5) The northern direction through the settlements of Zaykovo and Kamyshlov with an exit to the main highway R-351 (Q = 0.6397);
6) The main highway R-351 through the settlements of Kamyshlov and Dalmatovo with an exit to the southern road (Q = 0.613).

The reliability of the transport network under consideration in this case is equal to:

$$R_n = 1- 0{,}2818 \cdot 0{,}2875 \cdot 0{,}2943 \cdot 0{,}4813 \cdot 0{,}6397 \cdot 0{,}613 = 0{,}9955 \tag{25}$$

It should be noted that not all six routes could ensure the smooth movement of heavy-duty vehicles with a carrying capacity of over 20 tons. This is due to the fact that some routes have insufficient roadway width and weak points (bridges with reduced carrying capacity), which don't allow passing heavy-duty vehicles. For these reasons, routes No. 4 and 6 cannot ensure the movement of vehicles with a carrying capacity of over 20 tons. Hence, the reliability of the transport network along the Yekaterinburg-Tyumen route in this case will be determined only by: Main highway R-351 (Q = 0.2818); **N**orthern direction Yekaterinburg-Tyumen (Q = 0.2875); **S**outhern direction Yekaterinburg-Tyumen (Q = 0.2943); Northern direction through the settlements of Zaikovo and Kamyshlov with an exit to the main highway R-351 (Q = 0.6397).

So,the reliability of the network with respect to heavy-duty vehicles is:

$$R_n = 1- 0{,}2818 \cdot 0{,}2875 \cdot 0{,}2943 \cdot 0{,}6397 = 0{,}9847 \tag{26}$$

Calculation of network reliability shows that the more paths the selected route has, the higher its reliability, and, accordingly, the higher is the reliability of the entire transportation network. The results of calculating the residual resource (in years) of each section of the road network under consideration based on the elastic modulus of the road surface structure reduction criterion (formation of potholes on the roadway) are presented in [13]. The maximum permissible (critical) dimensions of a pothole are: length - 60 cm, width - 15 cm, depth - 5 cm.

One of the types of failure of the road surface structure is the formation of a rut on the roadway, as a consequence of decrease in the elastic modulus of the road surface structure during operation. The work [13] presents a calculation of the residual life of each section of the transport network based on the criterion of the formation of a longitudinal rut, the depth of which exceeds the maximum permissible value of 35 mm.

VII. Conclusion

The paper proposes a method for calculating durability and residual lifetime based on: the criteria of pothole and longitudinal rut formation, and the regional road network reliability based on the permissible residual deflection caused by multiple elastic-plastic deformation of the road surface under the influence of traffic.es

To determine the POF of each section of the road network, a method for assessing the initial reliability has been developed taking into account traffic and atmospheric) impacts and the human factor (violation of the asphalt concrete laying method), using Bayesian networks in the format of the GeNie software package.

The application of the developed methodology to the assessment of the FR of the Yekaterinburg-Tyumen route, showed that its reliability for conventional transport is 0.9955, and for vehicles with a carrying capacity of over 20 tons is 0.9847.

The use of an agent-based model of driver behavior for assessing and analyzing the vulnerability of the Yekaterinburg-Tyumen UFD transport network in the event of a main road failure due to a bridge collapse showed that the more developed the transport network is, the more robust it is.

The most vulnerable sections of the Yekaterinburg-Tyumen transport network in terms of road surface wear are**:** section No. 9 of the Baikalovo-Turinskaya Sloboda direction (with POF= 0.6824 and minimum failure-free service life of 4.5 years according to the pothole formation criterion), and section No. 10 of the Artemovsky-Bulanash direction (failure-free service life 4.39 years, with POF= 0.6842).

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