Mathematical model for optimizing the repair plan for the international roughness index IRI

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Abstract. The authors analyzed the existing regulatory documents and studies on the road surface evenness impact on the traffic flow speed, the transportation and traffic safety costs. Currently available methods of forming a plan of repair work are focused on the use of the roads diagnostics results according to the evenness level of the carriageway obtained with the help of thrusters. The transition to the international evenness index (IRI) requires a review of the previously obtained mathematical dependencies and existing approaches to optimizing the road network repair program. In this work, the authors established a correlation of the traffic flow average speed, losses from the road traffic accidents (traffic accidents) and the road transport costs from flatness of coverage. Based on the identified statistical patterns of changes in the IRI index, a method for calculating the road section length that requires the restoration of transport and operational indicators (TOI) is proposed. The developed mathematical model for optimizing the repair plan will make it possible to create a list of road objects taking into account their priority within the budget funding of the annual program. The proposed model is based on diagnostics and assessment of the territorial road network technical condition in the Volgograd region.

1. Introduction
The road transport complex modernization in the Russian Federation involves large-scale reconstruction and repair of the existing network of roads, both under the authority of the federal road agency, and in the ownership of regional and municipal entities. One of the main indicators determining the operational condition of the roadway and the volume of road repair work is the evenness of the coating. The introduction of modern diagnostic tools and the transition to the international IRI evenness indicator cause difficulties in using the existing methods of forming the road repair plans based on the use of flatness measurement data with push-taps or strength with deflection meters [1]. The rational use of financial resources is problematic without developing the models for optimizing annual and long-term plans for repairing the road network and creating a new methodology for creating the optimal plan for the flatness level of the roadway IRI.

2. Relevance
The optimization model and the formation of a repair work plan is based on socio-economic losses in transport from a decrease in the roads TOI. The decrease in transport and operational indicators is reflected in the amount of losses caused by an increase in the transportation cost of goods and passengers, losses from the road traffic accidents growth, an increase in the time spent by the...
passengers on the road, additional capital investments in road transport and the need for working capital. In this case, the most tangible are the losses associated with an increase in the transportation costs and road accidents losses.

The development of a mathematical model is based on the diagnosis and assessment of the road network’s technical condition in the Volgograd region conducted in 2019. Analysis of the results of road diagnostics of II – IV technical categories with a total length of more than 3,500 km showed that 64% of regional roads correspond to the normative state of coverage by the longitudinal evenness and 83% - by the presence of unacceptable defects on the carriageway. In general, the state of the regional road network needs to be repaired, and the evenness indicator more objectively reflects the operational condition of the carriageway, as compared to coating defects. The development of a new methodology for the IRI indicator repair plan formation is relevant.

3. Main part
Statistical processing of diagnostic data revealed the priority of the IRI indicator in assessing the roadway operational status. A linear relationship was established between the evenness index and the length of the destroyed sections with a correlation coefficient of 0.93-0.99. According to a statistical sample of roads with wear from 4% to 93%, it was proved that regardless of the carriageway wear degree, the IRI indicator is described by a Gaussian curve (Figure 1) and confirmed by the Pearson and Kolmogorov criteria [2-4].

![Figure 1. Evenness distribution IRI.](image)

The studies of the roadway surface uniformity showed that the coefficient of variation of the IRI evenness index \( C_V \) changes as the roadway wears out. For the new coatings, when the degree of wear is negligible it is: \( C_V = 0.18 – 0.22 \). During the road operation with the coating wear from 20 to 70%, the IRI indicator has the greatest heterogeneity, \( C_V = 0.24 – 0.40 \). As the road surface deteriorates (more than 70%), the coefficient of variation decreases to 0.08 - 0.18, which is explained by the carriageway destruction along the entire road length.

The variation coefficient dependence on the mathematical expectation of IRI has the form:

\[
C_V = -0.0178 \ IRI^2 + 0.173 \ IRI - 0.10
\]  

(1)

The share of roads with evenness exceeding the standard \( (L_D) \), depends on mathematical expectation (\( \mu \)) IRI (Figure 2):

\[
L_D = 0.071 IRI^{3.63} \quad (r = 0.91)
\]

(2)
Figure 2. The dependence of the share of the road with an IRI indicator of more than normative $L_D$, from his mathematical expectation ($\mu$) IRI.

The normality of the IRI indicator distribution makes it possible to calculate the road length that requires repair to restore the normative evenness of the roadway ($L_P$) with a given level of reliability:

$$L_P = L \times L_\mu \times (1 + t \times C_V) \quad (3)$$

where $L$ – is the total length of the road, km.

The mathematical model for optimizing the road network repair plan is based on the regression dependencies of losses from the road traffic accidents ($D_{AT}$) and the transportation cost ($C_{AT}$) from the IRI indicator. The studies have shown that the selected economic indicators are the most significant, in the total cost of transporting passengers and goods on the road network.

The cost of transportation depends on traffic intensity, the composition of the traffic flow and its average speed. Statistical processing of diagnostic results and research data of scientists [5-14] showed that with an increase in the IRI evenness index from 1.73 to 11.73, the average speed of the traffic flow decreases to 30%, from 71.65 to 52.37 km/h (Figure 3):

$$V_{AV} = -0.066 \text{IRI}^2 - 1.04 \text{IRI} + 73.65 \quad (km/h) \quad (4)$$

Figure 3. The dependence of the traffic flow average speed on the coating evenness.

During the regression analysis, it was found that the annual transportation cost is directly proportional to traffic intensity ($N$), IRI flatness, road length ($L$) and inversely proportional to the cars share in the stream ($\alpha$):
where $IRI$ – is the evenness indicator m / km; $N$ – is the traffic intensity cars per day.; $\alpha$ – is the cars share in the stream.

The calculations showed that the road transport cost mostly depends on traffic intensity (Figure 4).

\[
C_{AT} = \frac{0.003 \times IRI^{0.074} \times N^{1.006} \cdot L}{\alpha^{0.8399}} \quad \text{(million rubles / year)} \quad (5)
\]

Figure 4. The transportation cost dependence on the average speed of the traffic flow and traffic intensity: 1 - 4000 cars / day; 2 - 3000 cars / day; 3 - 2000 cars / day; 4 - 1500 cars / day; 5 - 1000 cars / day; 6 - cars / day; 7 - 200 cars / day.

The studies [8] show that with the roadway evenness deterioration in the initial period, an increase in accident rate is observed, and with a further accumulation of the coating unevenness, its decrease. This phenomenon is explained by the psychological characteristics of the drivers’ behavior. With an IRI of up to 5 - 7 m / km, a high speed of cars is observed, which leads to an increase in the accidents risk [9]. With an increase in traffic intensity up to 4000 cars / day, losses from traffic accidents ($D_{AT}$) increase by 7 times, reaching a maximum with an IRI of 6 m / km. With further accumulation of irregularities (more than 55% of coverage), the drivers start reducing the movement speed, reducing the likelihood of an accident (Figure 5).

Figure 5. Dependence of losses in traffic accidents on the evenness of the roadway and traffic intensity: 1 - 4000 cars / day; 2 - 3000 cars / day; 3 - 2000 cars / day; 4 - 1500 cars / day; 5 - 1000 cars / day; 6 - 500 bus / day; 7 - 200 cars / day.
The complex effect of traffic intensity and evenness on road accident losses can be represented as a relationship:

\[ D_{AT} = \frac{0.093 \times N \times L}{1000 \times IRI^{0.094}} \]  

(million rubles / year)  

(6)

The total costs associated with transportation and losses from accidents can be represented by the expression:

\[ S_F = C_{AT} + D_{AT} \]  

(million rubles / year)  

(7)

The performed studies are the basis of the optimization methodology for the annual regional road network repair program based on the IRI coverage evenness diagnostics results, the analysis of traffic intensity and composition. The priority of the regional road network repairing sections is determined by the condition for the maximum reduction in the cost of transportation and losses from the accidents caused by exceeding the normality of the road evenness (\( \Delta \)):

\[ \Delta = S_F - S_N \rightarrow \text{max} \]  

(8)

The condition for optimizing the network repair plan, consisting of \( N \) highways has the form:

\[
\begin{align*}
\sum_{i=1}^{N} S_{F}^{i} - S_{N}^{i} & \rightarrow \text{max} \\
\sum_{i=1}^{N} L_{i} \times K & \leq K_{F}
\end{align*}
\]  

(9)

where \( K \) – is the specific standard for the carriageway repair, million rubles / km, \( K_{F} \) – is the annual amount of financing allocated from the budget for the repair of the road network, million rubles.

The optimal distribution of funds over the regional road network’s sections in time is carried out on the basis of a computer search of financing options within the allocated budget funds. The proposed mathematical model (9) gives an opportunity to simplify the process of optimization and the formation of a road repair plan aimed at restoring the transport and operational performance of the road network.

4. Summary

Diagnostic results of more than 3,500 km of roads have shown that the regional road network state needs repair, and the evenness indicator more objectively reflects the operational condition of the roadway, as compared to the coating defects.

Based on the established statistical laws of the IRI indicator change, the dependence of calculating the road section length, requiring the restoration of the pavement evenness, is proposed.

The dependences of the transportation costs and the losses from the traffic accidents on the carriageway evenness, the intensity and composition of traffic flows, the length of the road section have been established.

A mathematical model for optimizing the repair plan has been developed, which allows forming a list of road objects taking into account their priority within the budget financing of the annual program.

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