Method of Calculating the Limiting Depth of Ruts on the Pavement of Automobile Roads

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Abstract. Proposed the criterion for design pavement, limiting the rut depth RD by limiting value RDlim, which depends on the required values of transport and exploitation characteristics. The solution to the problem is based on the classical dependence of the dynamic coefficient on speed at the point of impact of bodies. In this fundamental dependence, the collision speed of the tire with coated is determined by the speed of the wheel and the depth of the irregularities. From this fundamental formula, the functional dependence of the irregularities depth on the speed of movement, the deformation characteristics of the pavement, the power parameters of the moving load (dynamic coefficient), the distance of entry and exit of the wheel from the rut when overtaking another car is obtained. The analysis of the work of specialists of the road industry, which allowed to establish the limit values of all the factors under consideration for coatings, the state of which is characterized by different assessments (excellent, good and satisfactory). For different conditions of coverage, the limiting values of the rut depth RDlim are given.

1. Introduction

The rut formed on the road surfaces leads to a number of negative consequences. Therefore, in the process of instrumental assessment of the condition of the pavement, a rut depth measurement and its comparison with limit values are performed. Thus, the criterion for the road’s working capacity along the rut depth can be written as:

\[ RD \leq RD_{lim} \]  

where RD and RDlim – actual and limit rut depth, mm.

In case of precipitation, water accumulates in the rut, and at freezing temperatures snow and ice. These types of slippage lead to a decrease in the coefficient of adhesion of the tire and coating, which reduces driving safety. Therefore, the depth of the rut must be limited so as to maintain traffic safety [1]. This approach encounters a difficulty in that there is no clear dependence between the rut depth and the number of traffic accidents and the severity of their consequences (the number of fatalities and injuries in traffic accidents). The statistics on traffic accidents do not allow to single out the number of accidents that occurred only because of the rut [1-4]. Therefore, it is not possible to determine the limit rut depth at which traffic accidents do not occur. Despite the lack of methods for calculating the limit rut depth, the standards for its limitation are developed and applied by various Highway Agency.
generalization of the results of works on limiting the rut depth was made by the authors of [1] and
given by us in Table 1. In the Table 2 presents the requirements for permissible and limit values of the
rut existing in Russia.

Table 1. Rut Severity Classification by Highway Agencies [1].

| Highway Agency                                      | Low         | Medium     | High        |
|-----------------------------------------------------|-------------|------------|-------------|
| Pavement Condition Index (PCI) [1, 5]                | 0.25–0.5    | 0.5–1      | >1          |
| PASER Manual, Asphalt Roads [1, 6]                  | 0–0.5       | >1         | >25,4       |
| Washington State DOT (WsDOT) [1, 7]                 | 0.25–0.5    | 0.5–1      | >0.75       |
| Ohio DOT (OhDOT) [1, 8]                             | 0.125–0.375 | 0.375–1.5  | >0.75       |
| Massachusetts Highway Dept. (CMMPO) [1]             | 0.25–0.5    | 0.5–1.5    | >1.5        |
| Ministry of Transportation and Infrastructure, British Columbia (MTI BC) [1, 9] | –           | 3–10       | >20         |
| California DOT (Caltrans) [1]                       | Schedule corrections when rut depth >1 in. (>25.4 mm) |

Table 2. Depth rut requirements for Russian roads.

| Estimated speed, km/h | Rut depth, mm |
|-----------------------|---------------|
|                       | permissible   | limit       |
| >120                  | 4             | 20          |
| 120                   | 7             | 20          |
| 100                   | 12            | 20          |
| 80                    | 25            | 30          |
| 60 and less           | 30            | 35          |

According to Russian regulation documents the rut should be eliminated, if the depth exceeds the limit, but this requirement is a recommendation. Depth rut that exceed the limit values are subject to immediate elimination and are considered dangerous by driving conditions.

In the Table 3 shows the classification of states of road by rut depth accepted in Estonia.

Table 3. The limit values of rut depth are described as follows (Department of Tallinn).

| Pavement condition | Characteristics (traffic safety and impact on the road user) | Rut depth limits (mm) |
|--------------------|-------------------------------------------------------------|-----------------------|
| Very good          | Pavement has no ruts.                                       | < 5                   |
| Good               | No ruts can be observed in the pavement and there is no impact on road users. | 5 – 10                |
| Fair               | Ruts in the pavement can be observed. When it rains water accumulates in the ruts. Road users start to search for best trajectory. Ruts should be eliminated within 1 to 3 years. | 10 – 20               |
| Poor               | Ruts can clearly be seen in the pavement, driving speed as well as trajectory are influenced. When it rains, a lot of water accumulates in ruts and aquaplaning may occur. Ruts should be eliminated. | 20 – 30               |
| Very poor          | Ruts can clearly be seen in the pavement, driving speed as well as trajectory and traffic safety are influenced. Ruts affect traffic safety both in rain and in dry conditions. Ruts should be eliminated immediately. | > 30                  |

The authors of [1] obtained a dependence between the rut depth and speed, such data are given in Table 4.
Table 4. Hydroplaning Speeds for Rut Depth Levels.

| Rut depth (mm) | 5   | 10  | 15  | 20  | 25  |
|---------------|-----|-----|-----|-----|-----|
| Hydroplaning Speed (km/h) | 91  | 87  | 83  | 76  | 72  |

In [10], the authors obtained a mathematical solution to the problem of the limit rut depth from the condition of providing the required coefficient of adhesion of the tire with a wet rough coating at different speeds. This solution takes into account the variability of water depth and coating roughness parameters. According to this decision, the maximum rut depth is in the range of 1.5–20 mm.

Such limit rut depths are characteristic to reduce driving safety. Therefore, they are the largest of all possible limit values.

In the absence of precipitation, the rut negatively affects the transport and exploitation characteristics of the road. For example, when overtaking, the driver is forced to first leave the rut, and at the end of the maneuver, on the contrary, drive into the rut. In this case, the suspension elements experience vibrations leading to a change in the load on the wheel. The dynamic character of the load application is taken into account by introducing a dynamic coefficient into the calculation formulas used in the design of pavements. The value of this coefficient is accepted 1.3. In fact, the value of the dynamic coefficient depends on the speed of the car and the depth or height of the irregularities. If the actual dynamic coefficient exceeds 1.3, then the value of stresses and deformations arising in the layers of road structures will increase. This circumstance reduces the service life. Another negative factor is the emotional state of the driver. When hitting an irregularities, the driver experiences emotional stress, and instinctively reduces the speed of movement [12].

At present, a large number of works have been completed in which models for calculating the rut depth were developed. The use of such models allows the criterion (1) to be applied in the practice of designing pavements.

Methods for predicting changes in depth rut during the operation of the road can be divided into two groups. The first group includes mechanic-empirical methods for calculating the depth of the rut. Among these methods, one can distinguish empirical formulas that relate the rut depth to the number passes of axles of vehicles with a certain load [12], and formulas that determine the rut depth from the amount of deformation of asphalt concrete in the pavement, soil in the subgrade or granular material of the base of the pavement [13–16]. The second group includes methods that relate the rut depth to the value of uneven residual deformation of the coating in the transverse direction. The rut depth at each point is determined by the difference between the irreversible displacements of the coating surface at the considered cross-sectional point and at the section point with the least accumulated residual deformation. In such calculations, the residual deformation at each point of the transverse profile is determined by the sum of the plastic displacements of the subgrade surfaces, base layers and pavement coatings. The displacement of the surface of the layer depends on the deformations that occur at the points of this layer. To calculate the deformations of materials and soils, models can be used that are summarized in [17–25].

2. Materials and methods

Having set of publication goal the conclusion of the mathematical dependence of the limiting rut depth on the characteristics of a moving car and pavement, we will use the classical formula for calculating the dynamic coefficient as a starting idea. This formula allows you to calculate the value of the dynamic coefficient depending on the speed at the point of impact of the bodies and deformation of the body under the static action of the load. The formula has the form:

\[ K_d = 1 + \sqrt{\frac{\vartheta_0^2}{g \cdot U}}, \]  

where \( \vartheta_0 \) – velocity at the point of impact of bodies, m/s; \( g \) – acceleration of gravity, m/s\(^2\); \( U \) – body
deformation under the static action of the load, m.

The speed of collision tire with coating is determined by the formula prof. A. Berulay, which relates the speed of impact with the horizontal speed of the wheel, the size of irregularities and the length of irregularities or the distance between irregularities. The formula has the form:

$$\vartheta_0 = \frac{2 \cdot h \cdot g}{S},$$  \hspace{1cm} (3)

where \( h \) – irregularities value, m; \( \vartheta \) – horizontal vehicle speed, m/s; \( S \) – length or distance between irregularities, m.

Certainly, dependence (3) can be substituted into formula (2), after which we obtain a formula for determining the dynamic coefficient of the transport load moving along the pavement with various irregularities. This formula has the form:

$$K_d = 1 + \sqrt{\frac{1}{g \cdot U} \left( \frac{2 \cdot h \cdot g}{S} \right)^2}.$$ \hspace{1cm} (4)

An analysis of the functional dependence (4) shows that for known (given) values of \( S, U \) and \( \vartheta \) the value of irregularities strictly corresponds to the dynamic coefficient. If the pavement is designed with a certain dynamic coefficient, for example, \( K_d=1.3 \), then it should not receive damage from the loads acting with this dynamic coefficient. We introduce the concept of the limiting dynamic coefficient \( K_{d\text{lim}} \), which characterizes the level of the dynamic stress-strain state in which the pavement does not receive damage and unacceptable deformations. Therefore we accept \( K_{d\text{lim}}=1.3 \).

As the length of the irregularities, you can take the length of the trajectory of the wheel leaving the track or, conversely, the wheel entering the track when the driver overtakes. In this case, it is necessary to have data about rut width \( b_{\text{rut}} \) and the angle of exit of the wheel to the oncoming lane \( \alpha \). Then the length of the trajectory of the wheel can be determined using the trigonometric ratio of right triangles. In this case we get:

$$s_{\text{rut}} = \frac{b_{\text{rut}} \sin \alpha}{\sin \alpha}.$$ \hspace{1cm} (5)

When solving the problem of determining the rut width, it is necessary to take into account that with a small limit rut depth, there should be no shear deformation in asphalt concrete. Therefore, the rut we are considering should not have lateral bulging. The reason for the formation of ruts without lateral bulging is the wear of the coating and deformation of base layers of granular material and subgrade. It is known that the rut width without side bulging can be taken equal to the width of the track, which is understood as the width of the strips, within which 80% or more of the passes of the tires of the left and right sides of the cars are distributed. The width of the track is 0.9–1.2 m. It follows that \( b_{\text{rut}} \approx 1.05 \) m.

The angle \( \alpha \) can be calculated by considering the most safe conditions of overtaking a truck. On Fig. 1 shows a scheme for overtaking a truck.

**Figure 1.** Scheme of overtaking a truck with a length of \( l_{\text{car}} = 16.5 \) m.

On Fig. 1 shows that an overtaking car must pass a path equal to \( \Sigma L = L_1 + L_2 + L_3 \) when performing a maneuver. It is assumed that the lengths of the vehicle exit paths to the oncoming lane \( L_1 \) and return after overtaking to its lane \( L_1 \) are the same, that is, \( L_1 = L_3 \). The path traveled by the car in the oncoming lane is assumed to be 1.5 of the full length of the vehicle being overtaken, that is \( L_2 = 1.5 \times \)
l_{car}. To calculate the angle $\alpha$, it is necessary to determine the lengths $L_1$ or $L_3$, as well as the lengths of the segments $b_1$ or $b_2$. The values of the distances $b_1$ and $b_2$ can be taken equal to the width of the lane. Therefore, for roads I and II of technical categories $b_1 = b_3 = 3.75$ m, on roads of category III $b_1 = b_2 = 3.5$ m, and for roads of category IV $b_1 = b_3 = 3.0$ m. The total length of the maneuver trajectory $\Sigma L$ is determined by the product of the difference of the speeds of movement $\Delta \delta$ of the overtaking car $\delta_1$ and the overtaken car $\delta_2$ to the time of the maneuver $t_m$. Then we get the formula:

$$\alpha = \arcsin \frac{h}{L_1} = \arcsin \frac{h}{0.5 \cdot (\Sigma L - L_3)} = \arcsin \frac{2 \cdot h}{(\Delta \delta \cdot t_m - 1.5 \cdot l_{car})},$$  \hspace{1cm} (6)$$

Overtaking is a dangerous maneuver, so it should take as little time as possible. The rational overtaking time is 3 s, but overtaking trucks requires a slightly longer time. In any case, it is recommended to overtake in no more than 5 s. Then, having accepted in formula (6) $t_m$, we can calculate the angle $\alpha$ for the road of any category.

From the analysis of formula (4), it follows that for its application in calculating the limit values of irregularities, in particular the limit depth of rut, it is necessary to determine the speed of the wheel $\delta$ and the deformation of the coating under the static action of the load. Under the deformation of the pavement from the action of the fixed wheel, we can understand the deflection of the coating, for the calculation of which you can use the model of layered elastic half-space. As parameters characterizing the elastic properties of the material of the half-space, we can take the equivalent modulus of elasticity of the pavement $E_{eq}$ (MPa), determined by known solutions, and the Poisson coefficient $\mu_{av}$ averaged over the thickness of the structure. Then the deformation of the pavement under static load is calculated by the formula:

$$U = \frac{p \cdot (1 - \mu_{av}^2)}{E_{eq}} D,$$  \hspace{1cm} (7)

where $p$ – wheel pressure, MPa; $D$ – wheel imprint diameter, m.

When calculating pavements, due to the small influence of the average value of the Poisson's ratio $\mu_{av}$ on the results, it is recommended to take $\mu_{av} = 0.3$. The pressure transmitted by the wheel to the coating is taken equal to the air pressure in the tire. The value of this pressure, as well as the values of the diameters of the imprint of the wheels of a moving and stationary settlement car are given in regulatory documents and state standards.

For the practical application of formula (4), we classify the state of the coating by the speed of movement. For these purposes, we will use the requirements of regulatory documents and the data of prof. I.A. Zolotar. After analyzing these values, the state of the coating is characterized by the values of the speed of a single passenger car and the average flow rate, presented in Table 5.

**Table 5.** The required speed at different conditions of the coating.

| Road category | Allowed speed at the state of coverage, km / h |
|---------------|----------------------------------------------|
|               | excellent | good | satisfactory |
| I-a           | 150/90    | 120/70 | 110/65 |
| I-b, II       | 120/70    | 100/60 | 90/50  |
| III           | 100/55    | 90/50  | 75/40  |
| IV            | 80/50     | 70/40  | 60/35  |

Note: Above the line is the speed of a single passenger car, below the line is the average flow rate.

Considering the analysis performed, equation (4) is solved with respect to the value of $h$, but first accept in dependence (4), $h = h_{lim} = RD_{lim}$, $S = S_{req}$, $K_s = K_{d(lim)}$ and $\delta = \delta_{req}$. Then we get:

$$h_{lim} = RD_{lim} = \frac{S_{req} \cdot (K_{d(lim)} - 1)}{2 \cdot \delta_{req}} \sqrt{g \cdot U}.$$  \hspace{1cm} (8)

We bring formula (8) to its final form, substituting dependence (7) and formula (5) into it, taking into account equation (6). In doing so, we observe the rule that:
The angles of departure (degree) of the car in the oncoming lane on the road category

| Maneuver time, s | Speed difference Δθ | km/h | 20 | 25 | 30 | 35 | 40 |
|-----------------|----------------------|------|----|----|----|----|----|
|                 |                      | m/s  | 5.6| 6.9| 8.3| 9.7| 11.1|
| The length of the trajectory when overtaking ΣL, m | 27.8 | 34.7 | 41.7 | 48.6 | 55.6 |
| Length of departure trajectory to the oncoming lane ΣL-L2, m. | 3.0 | 10.0 | 16.9 | 23.9 | 30.8 |
| Lane width (m) for a road category | I and II | 3.75 | 3.75 | 3.75 | 3.75 | 3.75 |
| Lane width (m) for a road category | III | 3.50 | 3.50 | 3.50 | 3.50 | 3.50 |
| Lane width (m) for a road category | IV | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 |
| The angles of departure (degree) of the car in the oncoming lane on the road category | I and II | Maneuver | 49 | 26 | 18 | 14 |
| The angles of departure (degree) of the car in the oncoming lane on the road category | III | time more | 45 | 24 | 17 | 13 |
| The angles of departure (degree) of the car in the oncoming lane on the road category | IV | than 5 s | 37 | 21 | 15 | 11 |

From the analysis of the data from Table 6 follows that at Δθ=20 km/h the driver does not have time to overtake within the recommended 5 seconds. At Δθ=25 km/h on roads of all categories, the angle α has higher values compared to 25 degrees. For the first and second technical categories, the angle α is greater than 25 degrees and at a speed difference Δθ=30 km/h. Therefore, for category I and II roads, the speed difference between the overtaking car and the overtaken car should be more than 30 km/h, that is, Δθ>30 km/h. Note that the values of the required speed of the traffic flow, presented in table 5 correspond to the speed of the overtaken car θ₁. Knowing this speed and the speed difference Δθ it is easy to find the speed of the overtaking car θ₂. This speed should not be unrealistically high. We will accept that for roads of category Ia Δθ=35 km/h, then the speed of an overtaking car with an excellent state of coverage will be 125 km / h. It follows that for roads of categories I and II, the speed difference Δθ can be taken 35 km / h, and for roads of other categories Δθ=40 km/h.

Having performed this analysis, it is possible to calculate the limit rut depth for roads of any technical category with different equivalent elastic modulus. The results of calculating the limit rut depth for roads of categories Ib and II are shown in Fig. 2a, and in Fig. 2b shows the limit rut depth for roads of category III.
Figure 2. Rut depth limit: a – road categories Ib and II; b – road categories III.

The numbers on the curves in Fig. 2 indicates the condition of the coating. The number 1 corresponds to excellent condition, 2 - good and 3 satisfactory.

We point out that the limit values of the rut depth calculated by us allow us to prevent the occurrence of excessive dynamic loads when the wheel leaves the track and the wheel enters the track. When rainwater enters the rut, with the limit values of its depth set by us, the aquaplaning effect does not occur. Thus, the proposed limitation of the depth rut allows to ensure traffic safety and prevent the occurrence of excessive dynamic loads that accelerate the fatigue failure of asphalt concrete pavement and layers of pavement.

4. Discussion
The developed calculation method allows to limit the rut depth by a limiting value at which the dynamic load from the wheel leaving the rut or, conversely, entering the rut corresponds to the value of limit dynamic coefficient. This allows us to ensure compliance with the operating conditions of road pavements and their asphalt concrete pavements with the calculated schemes used in the design.

The limit depth of the rut has smaller values in comparison with their counterparts proposed by other authors and used by various road agencies. Therefore, the rut, the depth of which is limited by the proposed values, does not affect traffic safety. In conditions of stagnation in such rut the water, the effect of aquaplaning does not occur.

The methodology for calculating the limit rut depth in conjunction with models for predicting the growth of the rut under repeated loads allows to use condition (1) as a separate, independent criterion for the design of pavement. The dependence of the limit rut depth on the equivalent modulus of elasticity of the pavement allows to limit rut depth for pavement with any value of this module. The importance of this conclusion is due to the fact that with an increase in the equivalent modulus of elasticity, the maximum depth of the rut decreases. This functional dependence is due to the fact that, ceteris paribus, the force of the wheel rebound from the road surface is higher, the higher the stiffness of the pavement. Consequently, after the suspension elements react to an blow on irregularities, the
wheel on a more rigid road surface will exert a force effect with a higher dynamic coefficient. In order for the dynamic coefficient not to exceed the limit value, the rut depth should be reduced. It is this dependence that is inherent in our method of calculating the limit rut depth.

The limit values proposed by us can be used in the diagnostics of roads and in the assessment of their technical condition. In this case, using instruments that measure the depth of the ruts with an accuracy of 1 mm, our limit values can be rounded. When using instruments with a higher resolution of up to 1 mkm, such rounding is not required.

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