Establishing the requirements for the minimum values of stopping sight distance on the road surface from the condition of vehicle braking safely

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Abstract. The article is devoted to determine the stopping sight distance from the condition of the possibility stopping a car that moving at design speed. Determination is based on experimental studies of the dependences the coefficient of friction on the vehicle’s speed, when braking happens on the road surfaces that have the minimum permissible coefficient of friction value, established by the current regulatory literature. Braking of vehicles was studied on two surfaces with a minimum value of the coefficient of friction, but they were differing in surface roughness. Based on theoretically calculated braking distances, requirements for stopping sight distance with different design speeds have been developed. The obtained values of stopping sight distances are compared with the values contained in the normative documents of Russia and foreign countries.

1. Introduction

When calculating the required distance of visibility of the road surface, providing the possibility of stopping, two terms are usually considered - the distance traveled by the car in the time required for the driver to perceive an unexpected obstacle and the start of braking (the estimated driver’s reaction time) and the braking distance - the distance traveled by the car from the start of braking until it stops completely [1,2,3,4]. The calculated visibility distance $S$ is calculated by the formula:

$$S = \left( \frac{t_r \cdot V}{3,6} \right) + \left( \frac{K \cdot V^2}{2g \cdot (\Phi \pm i)} \right)$$

where $V$ is the speed before braking,
$t_r$ is driver reaction time,
$K$ is the coefficient of the operational state of the brakes,
$\Phi$ is coefficient of friction,
$i$ is longitudinal slope

The analysis of formula (1) shows that the coefficient of friction of the wheel to the road surface and the estimated speed of movement have the greatest influence on the visibility distance from the stopping condition.

2. Background

Since the braking distance of a vehicle largely determines the magnitude of the visibility distance, the justification of this length for various values of the design speeds should be given primary attention. The main parameter that determines the length of the braking distance, all other things being equal, is...
the coefficient of friction, which largely depends on the condition of the road surface. The road surface can be in various states - dry, wet, dirty, snowy, icy. Obviously, in snowy, icy and dirty conditions, the vehicle cannot move at the design speeds due to a decrease in the friction coefficient. Moreover, the driver has the ability to visually determine these conditions and to reduce the speed in a timely manner. Therefore, such pavement conditions should not be considered when justifying the visibility of the road surface. With a dry and clean surface, the grip qualities of the road surface enable the driver to drive at speeds permitted by the traffic regulations. As studies show [5, 6, 7, 8], the coefficient of friction of dry surfaces to a small extent depends on the speed of movement, its values are very high on both rough and smooth surfaces, which allows, when justifying a safe distance, the visibility of the road surface do not consider driving the vehicle on a dry surface at the design speed.

Traffic rules do not limit driving speeds when the roadway is wet. And in the rain, the driver has the right to move along the road at the same speeds as in the dry state of the roadway. At the same time, the adhesion qualities of the road surface during wetting can sharply decrease to an unacceptable level for safe driving. Studies show that wet adhesion coefficients are largely determined by the macro- and micro-roughness of the road surface. The driver in the rain under a layer of water does not have the technical ability to assess the state of roughness, and the traffic rules do not require this from him. Therefore, in the rain, the driver is able to drive at the same speeds as in dry conditions. To get an answer to the question - does the wetting of the pavement affect the speed of movement, we analyzed the data of the speed of movement recorded by video surveillance cameras on the toll road "Northern Bypass of Odintsovo". In the summer of 2018, two days were selected, one of which was clear, sunny, and the other rainy, and the rain was characterized by a low intensity. The results showed that neither the average speeds, nor the 95 percent rainfall rates significantly changed. Similar results were obtained by Ph.D. N.A. Lushnikov [9] in the course of observing the speed of movement on wet slippery and non-slip sections of the road surface. Observations show that the speed of movement does not depend on the state of the roughness of the road surface, including when it is wet.

The braking distance of a car is largely determined by the grip of the road surface. Today in Russian Federation the value 0.3 (GOST 50597 p. 3.1.4.) is taken as the minimum admissible coefficient of friction in the wet state of the pavement [10]. In this case, the coefficient of friction should be measured at a speed of 60 km/h using a full-size automobile tire with a smooth tread with a landing size of 13 inches on a dynamometer trailer. As the results of studies carried out by MADI (STU) for many decades show, road surfaces characterized by values of the coefficient of friction is close to the minimum permissible can differ significantly in surface roughness. Studies show that macro-roughness - the roughness created by particles protruding on the surface of the pavement, determines the ability of the pavement to quickly drain water from the contact zone of a tire sliding on a wet road. Micro-roughness - the intrinsic roughness of protruding particles - contributes to the rapid destruction of liquid films present on the protrusion after removing its layer. The road surface can be characterized by a coefficient of 0.3 with a satisfactory macro-roughness, but minimal micro-roughness. The same coefficient can be characterized by a coating with a minimum macro-roughness in the presence of a satisfactory micro-roughness. Studies show that the graphs of the dependence of the coefficient of friction on the speed of movement on these surfaces differ from each other. On a macro-rough surface, at speeds up to 60 km / h, the curve is lower than a similar curve obtained on a surface with less macro-roughness, but at higher speeds the curves change places. This is due to the fact that at low speeds in contact between the tire and the road, the dry interaction zone has a large area of direct contact. At the same time, the frictional qualities created by the microroughness play a decisive role. At higher speeds with insufficient microroughness, the area of wet interaction in the contact of the tire decreases due to a decrease in drainage capacity, which leads to a more rapid decrease in the coefficient of friction on such surfaces.

3. Experiments and results
Studies carried out at MADI (STU) have established that macrorough coatings characterized by coefficient values close to the minimum allowable are, for example, coatings made of rubbed-mastic
asphalt concrete (RAC) with an excess of binder immediately after their construction. As the binder wears out during intensive traffic in the first months of operation, the adhesion qualities of such coatings rapidly increase to values of 0.55 - 0.6. Rough coatings with the minimum allowable coefficient values were recorded by the MADI laboratories in the 70s - 80s on the Rostov-Baku road, where surface treatments were performed using river pebbles, which did not have good microroughness. Macro-rough surfaces with a long service life on roads with heavy traffic also have coefficients close to the minimum permissible value.

Coatings with low macro-roughness, which have the minimum admissible value of the friction coefficient, are much more common than macro-rough ones. As a rule, these are freshly laid asphalt concrete pavements made of mixture B, but sometimes also A, as well as pavements with a significant service life, made of asphalt concrete on crushed stone of low wear resistance.

Since pavements characterized by the minimum admissible values of the coefficient of friction have a right to exist, it is obvious that the calculated visibility distances should be determined considering the stopping distance on these pavements. In order to determine the length of the braking distance on such surfaces, experimental curves of the dependence of the coefficient of friction on the speed of movement were obtained (Fig. 1), one of which was recorded on the lower layer of the M-11 road during its construction, and the other - on rubbed asphalt concrete, made with excess bitumen on the surface.

![Figure 1. Dependence of the coefficient of friction on the speed of movement for a tire with a smooth tread (row 1 - micro-rough, row 2 - macro-rough).](image)

The dependencies (Fig. 1) were obtained using a modified PKRS-2 device, the irrigation system of which was made with water supply under the action of excess air pressure in the water tanks, which made it possible to provide the flow rate required to create a water film of 1 mm at a speed of up to 90 km/h. Dependences similar in configuration were once obtained during mass tests of tires carried out by MADI (STU) in the 70s - 90s using the MADI-8 dynamometric laboratory. The watering system of the laboratory made it possible to carry out measurements at speeds up to 120 km/h.

Due to the fact that the Road Traffic Regulations allow the operation of tires with a residual tread depth of up to 1.6 mm, it becomes necessary to recalculate the dependences shown in Fig. (1) for the case of using tires with the maximum permissible tread wear on a car. Obviously, due to the presence of a pattern, the graphs of the ratio of the coefficient on the speed of movement for tires with a pattern will be located above the given ones. However, as shown by the studies carried out during tire tests, carried out in the 70s - 90s by order of the Research Institute of the Tire Industry, the ratio of the coefficients for tires with permissible wear and smooth depends on both the surface roughness and the speed of movement. So, on fine-rough surfaces at low speed, the ratio of the coefficients can be taken equal to 1.07, while at a speed of 90 km/h this ratio increases to 1.24. The ratios of the coefficients show that on fine-rough surfaces, the role of the tread pattern with an increase in the speed of movement increases significantly, since on such surfaces the drainage capacity of the coating is low and the pattern begins to play a significant role in reducing the area of wet interaction in the contact of
the tire. On a macro-rough surface, the drainage of the contact zone is mainly carried out due to roughness, while the role of the pattern in water drainage is significantly reduced. Experiments show that on such surfaces, for all speeds, the same coefficient of 1.07 can be applied to recalculate the coefficients.

Considering the indicated coefficients, we calculate the dependence of the friction coefficients on the speed of movement and extrapolate them to a speed of 150 km/h (Fig. 2).

**Figure 2.** Dependence of the coefficient of friction on the speed of movement, calculated for tires with a tread pattern of 1.6 mm (row 1 - micro-rough surface, row 2 - macro-rough surface).

The obtained dependences clearly show that on roads with design speeds below 80 km/h, it makes no sense to arrange macrorough surfaces. On surfaces with less macro-roughness on such roads, the braking distance will be much shorter. Experiments on measuring braking distances during tire tests in braking mode, carried out in the past years, showed that on rough surface treatments at a braking speed of 60 km/h, there was always more braking distance recorded on rough surface treatments.

When comparing the obtained graphs, it should be borne in mind that the braking distance when the speed decreases, for example, by 10 km/h, is proportional to the square of the speed differences. Therefore, to reduce the speed of movement from 110 km/h to 100 km/h, it is necessary to spend 8 times more work than when reducing the speed from 20 km/h to 10 km/h. Therefore, a visual examination of the curves creates an erroneous impression of their identity. Calculations based on the dependences obtained, given in (Table 1.) and shown in (Fig. 3), indicate that due to the seemingly insignificant difference in friction coefficients at speeds of more than 80 km/h at high speeds, a large difference in braking distances is obtained.

**Figure 3.** Dependence of the stopping distance on the speed of movement (row 1 - micro-rough surface, row 2 - macro-rough surface).
Table 1. Sliding condition of the locked wheels of cars

| Braking start speed, km/h | Braking distance, m |
|--------------------------|---------------------|
|                          | micro-rough coating | macrorough coating |
| 60                       | 31.8                | 35                 |
| 90                       | 104.4               | 105                |
| 110                      | 197.2               | 183.8              |
| 120                      | 261.1               | 239.6              |
| 140                      | 427.8               | 358.6              |
| 150                      | 532.3               | 434.6              |

Table (1) is calculated based on the sliding condition of the locked wheels of cars. However, today almost all cars, including light trucks, are equipped with anti-lock braking systems that allow emergency braking without locking the wheels, with their partial slipping. As shown by studies carried out in MADI on passenger cars (Nissan, Peugeot) and light trucks (Volkswagen Crafter, Mercedes Sprinter), on snowy, icy and wet surfaces, braking distances during braking with full blocking and using anti-lock braking systems are characterized by similar values. However, braking with full blocking at speeds above 60 km/h always ends in a skid, while when the systems are on, emergency braking is possible at significantly higher speeds.

4. Conclusion

The study showed that even without considering the distance traveled by the car during the driver's reaction time, the values of the visibility distances adopted today at the minimum admissible value of the coefficient of friction cannot guarantee driving safety at speeds above 110 km/h. At a speed of 150 km/h, the braking distance on surfaces with the minimum admissible coefficient of friction becomes commensurate with the braking distance of a steam locomotive! To solve the problem, it seems advisable to increase the minimum admissible value of the friction coefficient for roads with an estimated speed of 120 km/h to 0.35, and for roads with an estimated speed of 150 km/h to 0.40.

The given values of the coefficients are technically achievable today without the transition to a ubiquitous surface treatment device. The experience of their widespread use in the 70s and 80s showed that due to the low quality of their device in those years, the coverage was slippery for 30% of the network length - it was characterized by friction coefficients below 0.3. The main defect of such coatings is bitumen on the rolling strips. Today, surfaces with adhesion values below 0.3 are rare. Another measure aimed at reducing the braking distance may be to increase the minimum permissible tread depth of the tires. However, special research is required to justify this value.

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