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Influence of pavement frictional properties on braking distance

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Abstract: In order to study the relationship between pavement friction management criteria and braking distance requirements of road geometric design, an approach for determining the braking distance considering pavement frictional properties is proposed. A finite element model (FEM) of a rolling tire under steady state is established based on theoretical hydrodynamics and mechanics principles, in which factors, including tire type, water film thickness, pavement surface properties, and vehicle speed, are considered. With the FEM, braking distances under different operating conditions are calculated. Furthermore, the allowable water film thickness is determined by comparing braking distances calculated with friction management criteria and that required by road geometric design. The results show that the braking distance is affected by the above operating conditions. As a result, it is necessary to maintain consistency between geometric design braking distance requirements and pavement friction management to achieve safe road operations.

Key words: pavement frictional properties; braking distance; operating conditions; finite element simulation

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Providing a safe braking distance is an important requirement in road geometric design. According to Chinese design specifications for highway alignment[1], the determination of the braking distance is based on a selected constant value of the tire-pavement friction coefficient, without clearly stating pavement frictional properties. The tire-pavement skid resistance varies with a vehicle's different operating conditions related to tire, pavement surface, the presence of water on the pavement surface and so on[2-3]. However, these aspects have not been sufficiently reflected in the existing determination of braking distance[4-5].

Pavement frictional properties decrease with the increase in road age. The maintained skid resistance depends on the pavement friction management threshold. As a result, to ensure safe driving conditions, the ability to connect braking distance requirements with pavement friction management is of high practical significance.

This paper proposes an approach to determining the braking distance considering pavement frictional properties via basic mechanics and a finite-element skid resistance model. Furthermore, it examines the relationship between braking distance requirements of design specifications for highway alignment and the skid resistance threshold adopted by technical specifications for the maintenance of highway asphalt pavement[6].

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1 Determination of Braking Distance Considering Pavement Frictional Properties

1.1 Theoretical determination of braking distance

Braking distance D is generally computed as

$$D = \int_0^T v(t)\,\mathrm{d}t = \int_0^T \left[v(t=0) - \int_0^{t_i} a(t)\,\mathrm{d}t \right]\mathrm{d}t = \int_0^T \left[v(t=0) - \int_0^{t_i} \mu(t) g \mathrm{d}t \right]\mathrm{d}t \tag{1}$$

where $v(t)$ is the vehicle speed at time t; $a(t)$ is the deceleration rate at time t; $\mu(t)$ is the coefficient of friction between tire and pavement surface; and g is the acceleration due to gravity.

In this paper, pavement skid resistance is numerically related to the sideway force coefficient (SFC), which is in accordance with the skid resistance factor used in the maintenance specifications.

1.2 Determination of pavement frictional properties by finite element simulation

1.2.1 Simulation model adopted

In the case of the tire rolling on the wet pavement, forces acting on the tire are illustrated in Fig. 1. G is the gravity. Both the force of the pavement acting on the tire (a horizontal force f and a vertical force N) and the force of water film acting on the tire (a horizontal force W_H and a vertical force W_V) are distributed forces, while the force of the pavement can be calculated by the finite element simulation model.

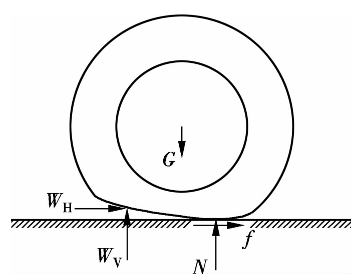

Fig. 1 Schematics of forces in rolling tire with water film

The origin of coordinates O is set to the center of the tire rim as illustrated in Fig. 2. The tire is considered to be in no translational motion, while the pavement moves at a speed of V. The point B of the tire is subjected to water pressure p, which is resolved into a horizontal component p_H and a vertical component p_V. Assume that a tube of flow is moving from point A to B, and its speed slows from V to zero. Its kinetic energy is entirely converted into pressure energy. The pressure of the dynamic head H_V acting on point B is

$$p = \gamma_w H_v = \gamma_w \frac{V^2}{2g} = \frac{\rho_w V^2}{2} \tag{2}$$

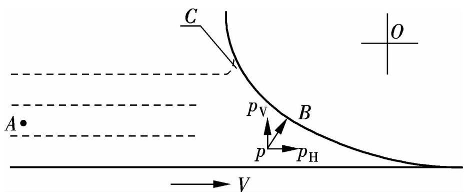

Fig. 2 Schematics of hydrodynamic pressure

where γ_w is the bulk density of water in N/m^3, and ρ_w is the density of water in kg/m^3.

During the finite element analysis, hydrodynamic pressure is added to the tread elements within the scope of tire-fluid interaction. According to technical specifications, pavement skid resistance is tested by SCRIM using a smooth tire of 3.00-20[7]. The pavement is assumed to be rigid with an elastic modulus of 30 GPa (see Fig. 3).

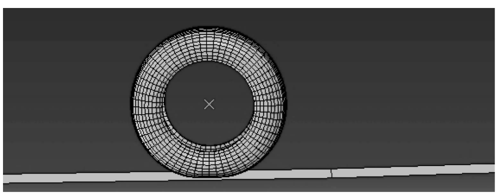

Fig. 3 Finite element simulation model

1.2.2 Input parameters

The finite element software package ABAQUS is used to simulate the tire-fluid-pavement interaction process. The key input parameters to the simulation model are listed below:

- Tire dimensions and inflation pressure;
- Physical properties of water (bulk density and density);
- Water film thickness on pavement surface;
- Sliding speed of tire;
- Static frictional coefficient of tire-pavement contact.

1.2.3 Determination of wet pavement skid resistance at a given speed

The skid resistance of the whole tire is

$$\mu' = \frac{F_x}{F_z} = \frac{f + W_H}{G} \tag{3}$$

where f is the traction force developed on the tire-pavement contact; F_z is an input parameter and it remains constant throughout the simulation.

2 Braking Distance Requirement and Pavement Friction Management

The following two main steps are involved in the analysis:

Step 1 The SCRIM smooth tire skid resistance test uses a water film thickness of 0.5 mm. For a given friction maintenance threshold value SFC, we determine the corresponding tire-pavement coefficient of friction μ_{dw} at any given water film thickness d_w using the finite element simulation model.

Step 2 For each computed μ_{dw}, we calculate the braking distances for different vehicle speeds, using the braking distance computation procedure described in the previous section of this paper.

The results in Tab. 1 list the friction maintenance thresholds and the corresponding μ_{dw} values for the test tire at a speed of 50 km/h with the specified water film thickness d_w (i.e., analysis performed in step 1).

Tab. 1 Frictional coefficients μ_{dw} under different maintenance thresholds and water film thicknesses

$SFC_{threshold}$	d_w/mm					
	0.5	1	2	5	8	10
25	0.25	0.22	0.20	0.18	0.17	0.17
30	0.30	0.26	0.24	0.23	0.21	0.21
35	0.35	0.31	0.28	0.26	0.24	0.24
40	0.40	0.35	0.32	0.29	0.27	0.27
45	0.45	0.39	0.36	0.34	0.31	0.31

As an illustration, the results for the case where the pavement has a skid resistance value of SFC = 30 are plotted in Fig. 4 (i.e., analysis performed in step 2).

Fig. 4(a) shows that braking distance on wet pavement increases at a decreasing rate with the increase in water film thickness. The highest rate of increase in braking distance occurs initially up to a water film thickness of about 2 mm. Thereafter, the rate of increase tends to level off.

Fig. 4(b) shows that braking distance on wet pavements increases with the increase in vehicle speed. The rate of increase of braking distance rises considerably when vehicle speed goes beyond about 40 km/h.

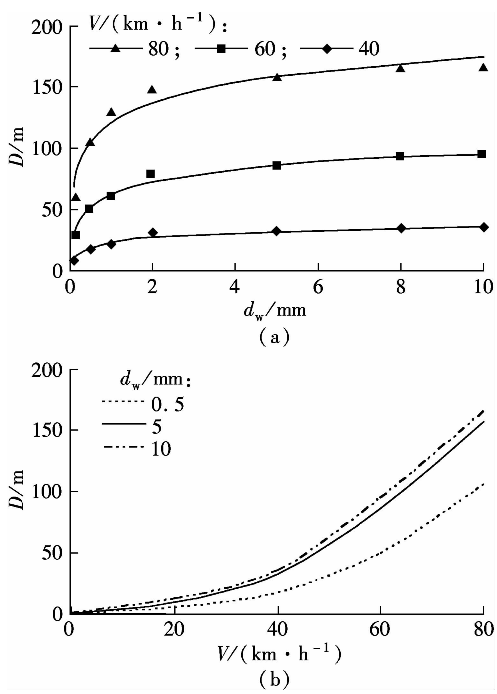

Fig. 4 Effects of different factors affecting braking distance. (a) d_w vs. D; (b) V vs. D

Depending on the design speed, there is a range of water film thicknesses where both braking requirements and pavement friction management thresholds are satisfied. Fig. 5 plots the speed-braking distance relationships of different water film thicknesses for SFC threshold values of 30 and 40, respectively. It can be observed graphically that the allowable water film thickness should be a major consideration in pavement friction management to meet braking distance requirements.

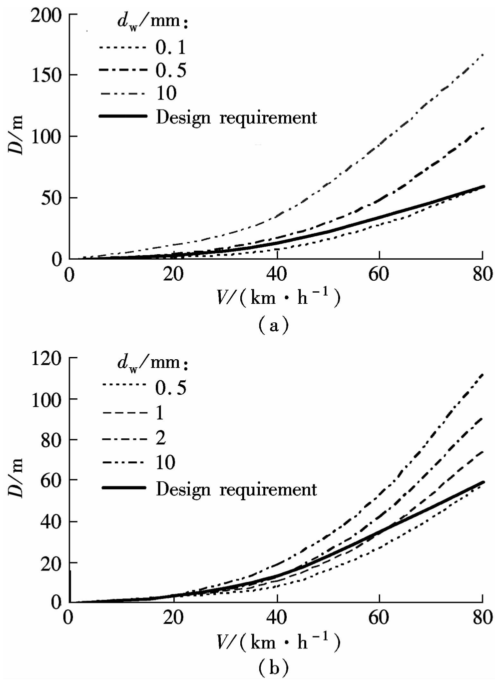

Fig. 5 Comparison of water film thickness satisfying both braking distance and friction requirements. (a) $SFC_{threshold}=30$; (b) $SFC_{threshold}=40$

It must be emphasized that the tread pattern and pavement surface texture are not considered in the presented analysis. They both have major impacts on the skid resistance, leading to a greater breaking distance.

3 Conclusion

This paper presents a rational approach to determining braking distances of in-service pavements considering pavement frictional properties. Braking distance is calculated by the mathematical model, while pavement frictional properties are simulated via the finite element model. The results show that braking distance is significantly influenced by pavement frictional properties. In the actual road operation, a vehicle's braking distance may exceed its requirements specified by geometric design as a result of moisture or high running speed. Therefore, it is recommended to connect the braking distance determination with pavement maintenance on frictional properties.

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路面摩擦特性对车辆制动距离的影响

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摘要:为了深入研究路面养护中抗滑界限与公路设计中制动距离限值间的关系,提出了考虑路面摩擦特性时确定制动距离的方法.基于理论流体动力学和基本力学原理,考虑轮胎类型、水膜厚度、路表特性、行车速度等因素,建立了稳态滚动轮胎的有限元模型;运用该模型计算了不同运行条件下的制动距离;通过比较分别满足养护和设计界限的制动距离,确定了路表允许的水膜厚度.研究结果表明:行车速度、水膜厚度等运行条件对路面抗滑性能有显著影响,进而影响车辆的制动距离.因此,在路面抗滑养护中应确保安全的运行条件,以与公路设计中制动距离的要求相一致.

关键词:路面摩擦特性;制动距离;运行条件;有限元模拟

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