Critical Rut Depth for Pavement Maintenance Based on Vehicle Skidding and Hydroplaning Consideration

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Abstract: Rutting is a major form of pavement distress in asphalt pavements. The main concern with rutting has been related to driving safety. Many highway agencies and researchers suggested that pavement rutting could lead to vehicle hydroplaning and loss of skid resistance in wet weather. However, to date no theoretical basis has been established for an analytical assessment of the severity of rutting for the purpose of pavement maintenance and rehabilitation. Most highway agencies classify rut severity on the basis of engineering judgment or field experience. This paper presents an analytical procedure to assess the severity of rutting based on vehicle skidding and hydroplaning analysis. It considers the worst-case scenario where a rut is filled with water and analyzes (1) if a car will hydroplane at a given speed; and (2) the length of braking distance required for the car traveling at the given speed. A finite-element simulation model is adopted to perform the analysis. For a given rut depth filled with water, the computer model computes the hydroplaning speed for a typical passenger car, and the required braking distance for the car traveling at a known speed. It was found that depending on the rut depth and the surface frictional property of a pavement, the severity classification of a rut may be governed by either hydroplaning risk or safety requirement of braking distance. The traditional method of using the same set of critical rut depths for all pavement sections in a road network is not ideal for effective handling of rutting maintenance. **DOI: 10.1061/(ASCE)TE.1943-5436.0000336.** *© 2012 American Society of Civil Engineers.*

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Introduction

Rutting is a major form of pavement distress in asphalt pavements. It occurs because of plastic deformation of the asphalt layers and the lower layers of the pavement. In theory, it is possible for rutting deformation to continue under traffic loading up to a stage of structural failure. However, this is unlikely the case in practice because before this stage could be reached, functional service requirements of the pavement would have been violated and traffic operations would have been severely affected. In other words, long before reaching structural failure, maintenance treatment or rehabilitation of the rutted pavement would have to be performed to restore pavement surface condition for safe traffic operations.

It is generally accepted that pavement rutting could lead to driving safety problems such as hydroplaning and skidding (AASHTO 1989; Hicks et al. 2000). Unfortunately, there does not exist any quantitative engineering basis for detemining the rut depth threshold for pavement maintenance or rehabilitation. As a result, practically all highway agencies classify rut severity on the basis of engineering judgment or past practical experience for the purpose of pavement maintenance and rehabilitation.

The absence of a sound engineering criterion for determining the critical rut depth threshold for pavement maintenance and rehabilitation is unsatisfactory especially when driving safety is involved. It is also unsatisfactory from pavement management perspective. By relying on engineering judgment, it presents an uncertainty as to whether the scheduled timing for pavement maintenance and rehabilitation treatments of rutting is ideal or appropriate or not for different road designs, road classes, and pavement types. Therefore, it is desirable to establish an analytical engineering basis for assessing the severity of rut depth based on the consideration of driving safety.

This paper presents the findings of a research study that aims to establish quantitative engineering criteria as a basis for determining the critical rut depth threshold for pavement maintenance and rehabilitation. The study proposes an analytical approach, on the basis of solid mechanics and hydrodynamics theories, to evaluate the hydroplaning potential and loss of skid resistance (and the corresponding length of braking distance) of a vehicle traveling along the flooded ruts of road pavement. By performing this evaluation for different rut depths, an assessment of the relative severity levels of different rut depths with respect to hydroplaning and braking distance requirements can be made.

Current Practice for Rut Severity Classification

According to past literature, the main concern with rutting is related to driving safety, although there is no clear and definite relationship between rut depth and traffic accidents (Start et al. 1998; Ihs et al. 2002; Christensen and Ragnoy 2006). One of the primary problems encountered in such statistical correlation studies has been the

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difficulty to separate the effect of rut from those of other factors, pavement or nonpavement related. These studies suggest that statistical analysis on the basis of traffic accident data is not an ideal method to classify rut severity with respect to safety.

Since the early 1970s, pavement engineering researchers have produced experimental evidence that ponding of pavement ruts could lead to hydroplaning and loss of skid resistance. Barksdale (1972) concluded that in pavements with rut depths of approximately 0.5 in. (12.7 mm), ponding is sufficient to cause automobiles traveling at speeds of 50 mi/h (80.5 km/h) or faster to hydroplane. Lister and Addis (1977) also found from their experience in the United Kingdom that pavements with ruts deeper than approximately 0.5 in. (12.7 mm) could result in ponding of water and cause hydroplaning or loss of skid resistance.

In 1989, the AASHTO Joint Task Force on Rutting stated in their report that wheel path ruts greater than a third to a half an inch (8.5 to 12.7 mm) in depth are considered by many highway agencies to pose a safety hazard because of the potential for hydroplaning, wheel spray, and vehicle handling difficulties (AASHTO 1989). Conversely, Sousa et al. (1991) stated in a Strategic Highway Research Program (SHRP) study report that for rut depths that exceed 0.2 in. (5.1 mm), hydroplaning is a definite threat particularly to cars.

In a study on preventive maintenance treatments for flexible pavements, Hicks et al. (2000) adopted the following three severity levels for ruts on the basis of the potential for hydroplaning and wet-weather accidents:

- Low severity—Rut depth is less than 6 mm. Problems with hydroplaning and wet-weather accidents are unlikely;
- Moderate severity—Rut depth is in the range of 7 to 12 mm. Inadequate cross slope can lead to hydroplaning and wet-weather accidents; and
- High severity—Rut depth is greater than 13 mm. The potential for hydroplaning and wet-weather accidents is significantly increased.

Despite the common understanding by researchers that hydroplaning and loss of skid resistance during wet weather should form the basis for classifying rut severity for pavement maintenance management, no quantitative engineering-based guidelines are currently available to assist pavement agencies to establish thresholds for assigning severity levels of ruts.

Table 1 shows examples of rut depth thresholds used by different highway agencies in severity level classification of ruts for pavement maintenance management. The rut depth thresholds for the "high severity" classification can be considered to be a severity level that warrants maintenance treatment. It is seen from Table 1 that three agencies consider rut depths exceeding 19.1 or 20 mm to be severe enough to justify a "high severity" classification; two agencies assign "high severity" to rut depths exceeding 25.4 mm; one agency assigns "high severity" to rut depths exceeding 38.1 mm; and one agency assigns "high severity" to rut depths exceeding 50.8 mm. These examples clearly suggest that there exist differences in engineering judgment among different agencies regarding severity classification of ruts. Therefore, the establishment of a quantitative engineering basis for severity classification of ruts will be useful in offering a rational explanation and reconciling some of these differences.

Proposed Approach for Rutting Severity Determination

Basis for Proposed Approach

Following major experimental research efforts by pavement engineering researchers starting from the 1950s, it is now common knowledge that the skid resistance and hydroplaning speed (i.e., the vehicle speed at which hydroplaning occurs) on a pavement are dependent on the following primary factors (Horne and Dreher 1963; Horne 1969; Huebner et al. 1986):

1. Pavement factors: Pavement properties such as mix design and aggregate type, and pavement surface microtexture and macrotexture;
2. Vehicle factors: Vehicle speed, tire inflation pressure, tire slip ratio, tire tread pattern and depth; and
3. Environmental factors: Water-film thickness on pavement surface, temperature.

Thus, on a given pavement with a known rut depth filled with water, the skid resistance characteristics and hydroplaning potentials of the pavement are dependent on the operating vehicle speed and pavement surface characteristics. This means that for a given rut depth, pavement sections belonging to different highway classes (hence different prevailing operating speeds) or having different pavement microtexture and macrotexture will have different skid resistance characteristics and hydroplaning potentials. In other words, based on the considerations of skid resistance (i.e., braking distance) and hydroplaning risk, the critical rut depth for different pavement sections may not be the same. That is to say, different road sections of a highway with either different pavement mix designs, or different design speeds or posted speeds, will have different critical rut depths. Thus, the traditional method of using the same set of critical rut depths for all pavement sections in a road network is not ideal for effective handling of rutting maintenance.

To overcome the previously mentioned limitation, an analytical procedure for evaluating the skid resistance (i.e., braking distance)

Table 1. Rut Severity Classification by Highway Agencies

Highway agency	Low	Medium	High
Pavement Condition Index (Shahin 1994)	0.25–0.5 in. (6.3–12.7 mm)	0.5–1 in. (12.7–25.4 mm)	> 1 in. (> 25.4 mm)
Pavement surface evaluation and rating manual, asphalt roads (Walker 2002)	0–0.5 in. (0 12.7 mm)	> 1 in. (> 25.4 mm)	> 2 in. (> 50.8 mm)
Washington State Department of Transportation (WSDOT 1999)	0.25–0.5 in. (6.3–12.7 mm)	0.5–0.75 in. (12.7–19.1 mm)	> 0.75 in. (> 19.1 mm)
Ohio Department of Transportation (ODOT 2006)	0.125–0.375 in. (3.2–9.5 mm)	0.375–0.75 in. (9.5–19.1 mm)	> 0.75 in. (> 19.1 mm)
Massachusetts Highway Department (CMRPC 2006)	0.25–0.5 in. (6.3–12.7 mm)	0.5–1.5 in. (12.7–38.1 mm)	> 1.5 in. (> 38.1 mm)
Ministry of Transportation and Infrastructure, British Columbia (BC MTI 2009)	3–10 mm	10–20 mm	> 20 mm
California Department of Transportation (Caltrans 2006)	Schedule corrections when rut depth > 1 in. (> 25.4 mm)		

Note: 1 in. = 25.4 mm.

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and hydroplaning risk must be developed to take into consideration the various pavement, vehicle, and environmental factors identified previously. This will enable the highway maintenance agency to determine the critical rut depth threshold for each pavement section. This is the primary aim of the proposed procedure presented in this paper. The following subsections present the proposed analytical model for skid resistance and hydroplaning speed evaluation, and the procedure for determining the critical rut depth for a given pavement section.

Analytical Model for Skid Resistance and Hydroplaning Evaluation

An analytical model developed by the writers for skid resistance and hydroplaning speed determination (Fwa and Ong 2007; Ong and Fwa 2007a) is adopted for the present study. It is a three-dimensional (3D) finite-element simulation program based on the theories of solid mechanics and hydrodynamics. The model consists of three primary components, namely the pneumatic tire submodel, the pavement surface submodel, and the fluid submodel. The simulation considers interactions between these submodels, i.e., tire-pavement contact modeling, tire-fluid interaction, and fluid-pavement interactions. Fig. 1 shows the finite-element mesh of the tire and the pavement surface.

The theoretical skid resistance and hydroplaning model used in this study has been validated for car and truck tires respectively by the authors (Ong and Fwa 2007b; Fwa et al. 2008; Fwa et al. 2009; Ong and Fwa 2010) using field measured data. On the basis of the validation studies conducted in these works, most of the cases analyzed produced "critical speed" within 5% of measured values, and all cases within 15% of measured values. The input parameters include the following:

1. Pavement parameters: The pavement structure is represented by elastic modulus, Poisson ratio and density. The effect of pavement surface properties is represented by μ_0 which is the skid resistance at zero sliding speed; μ_0 can be measured by static friction test in the laboratory, or approximated using the measurement of the British Pendulum test;
2. Vehicle parameters: The required parameters are vehicle sliding speed, wheel load, and tire inflation pressure, tire diameter and width, and tire tread pattern and depth. The load deformation properties of the tire are represented by the elastic modulus and Poisson's ratio of tire rim, tire sidewalls, and tire tread; and
3. Environmental factors: Water-film thickness on pavement surface, temperature, and properties of water including density, dynamic viscosity, and kinematic viscosity.

For a given rut depth filled with water, the output of the analysis gives the available tire-pavement skid resistance at different sliding speeds up to the hydroplaning speed.

Determination of Critical Rut Depth Threshold

For a car traveling at a given speed of the road section analyzed, the critical rut depth is considered to be reached when one of the following two events takes place: (1) hydroplaning of any of the tires of the vehicle; and (2) the length of braking distance exceeds the design braking distance.

Critical Rut Depth Threshold based on Hydroplaning Consideration

As explained in the preceding section, the simulation analysis produces hydroplaning speed as one of its outputs. Using the simulation model, the rut depth can be varied to obtain the hydroplaning speeds for different rut depths. The rut depth that gives a hydroplaning speed equal to the maximum allowed travel speed on the road section is the critical rut depth for that road section based on the consideration of hydroplaning.

Critical Rut Depth Threshold based on Braking Distance Consideration

In accordance with the law of motion, for a vehicle traveling at a speed of V_0, the braking distance (D) required on a road with a constant friction coefficient and a highway grade is given by Eq. (1)

$$D = \frac{(V_0)^2}{a} = \frac{(V_0)^2}{(\mu \pm G)g} \tag{1}$$

where V_0 = initial vehicle speed when the brake is applied; a = rate of deceleration; μ = friction coefficient; G = highway grade; and g = acceleration attributed to gravity.

It is known that when a vehicle slides on wet pavement, the skid resistance increases as the sliding speed reduces (Hayes et al. 1983; Horne and Joyner 1965). This relationship between vehicle speed (v) and friction coefficient (μ) can be obtained from the

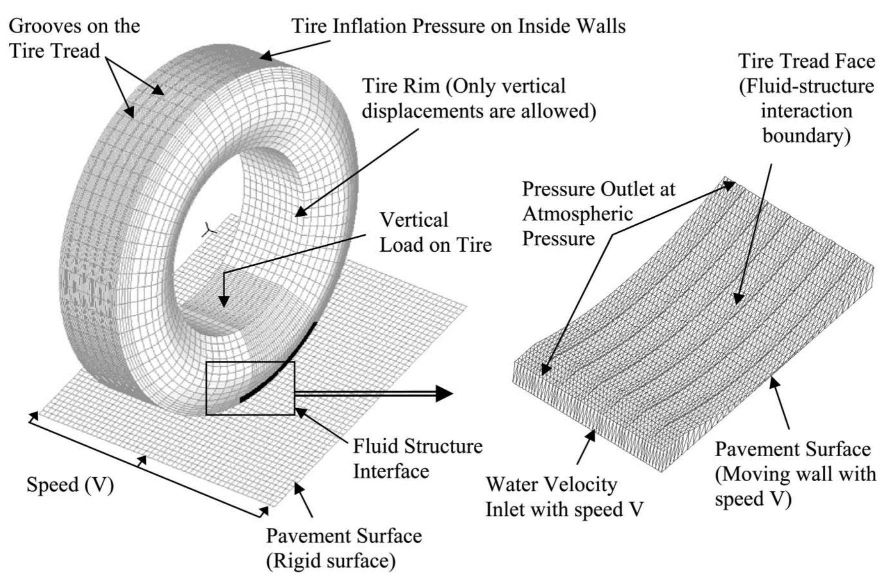

Fig. 1. Three dimensional finite-element model used for simulation

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simulation analysis described in the preceding section. Hence, as shown in Eqs. (2–4)

$$\mu = h(v) \tag{2}$$

and

$$a = (\mu \pm G)g = f(v) \tag{3}$$

The braking distance can then be calculated as

$$D = \int_{v=V_0}^{v=0} \frac{v}{a} dv = \int_{v=V_0}^{v=0} \frac{v}{f(v)} dv \tag{4}$$

In this study, the braking distance as defined in Eq. (4) is computed by means of numerical integration.

For a given rut depth, the simulation program described previously in this paper can generate the skid resistance for all speeds up to the hydroplaning speed. Setting V_0 in Eq. (4) as the maximum allowed travel speed of a road section, the braking distance corresponding to a given rut depth can be calculated. By varying the rut depth, the required braking distances for different rut depths can be calculated. The rut depth that gives a braking distance equal to the design braking distance is the critical rut depth for the road section based on the consideration of braking distance.

Numerical Illustration

To illustrate the application of the proposed approach to determine the critical rut depths for pavement maintenance management, a numerical illustration is presented in this section for the basic case involving the ASTM standard ASTM E501 rib tire (ASTM 2008) with 1/16 in. (1.6 mm) tread depth. This tread depth corresponds to the legal minimum allowed for passenger car tires in most states in the United States and in most countries in Europe (Blythe and Seguin 2006; Bullas 2004). The critical rut depths thus obtained serve as a conservative reference of threshold rut depths for maintenance planning. The results of this basic case, in comparison with the common rut depth severity classifications currently adopted in practice, will also serve to demonstrate the applicability of the proposed approach for critical rut depth determination.

Problem Parameters

For illustration purposes, the analysis was performed for the following five cases of rut depths: 5 mm, 10 mm, 15 mm, 20 mm, and 25 mm. This range is sufficient to cover the rut depths classified as "high severity" by practically all highway agencies. The pavement surface types considered are characterized by the following static wet-pavement friction values represented as skid number SN_0 (which is equal to 100 μ_0, where μ_0 is the static friction coefficient): 47.5, 55, 60, 72.5, and 80. This range of pavement skid resistance values represent the surface frictional property of most in-service asphalt and concrete pavements found in practice. The values of other input parameters for the simulation analysis are as follows:

1. Tire submodel: Consider ASTM standard E501 rib tire (ASTM 2008) with a tread depth of 1.6 mm, wheel load of 4,800 N, and tire inflation pressure of 165.5 kPa; the elastic moduli and Poisson's ratios for the tire rim, tire sidewalls, and tire tread are 100 GPa and 0.3, 20 MPa and 0.45, and 100 MPa and 0.45, respectively. The density of the rim material is 2,700 kg/m^3, and that of the rubber material of the tire sidewalls and tire tread is 1,200 kg/m^3;
2. Pavement submodel: The pavement elastic modulus is 30 GPa, Poisson's ratio is 0.15, and its density is 2,200 kg/m^3; and
3. Fluid submodel: The properties of water at 25°C are considered. The density, dynamic viscosity, and kinematic viscosity of water at 25°C are 997.1 kg/m^3, 0.894×10^{-3} N-s/m^3, and 0.897×10^{-6} m^2/s, respectively.

Table 2. Hydroplaning Speeds for Rut Depth Levels

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

Results of Analysis

The computed hydroplaning speeds for different rut depth levels are presented in Table 2. These values are valid for different pavement surfaces since the influence of pavement surface type (characterized by μ_0) on hydroplaning speed is practically negligible.

Table 3. Braking Distance for Different Rut Depth Levels and Static Pavement Friction Values (SN_0)

Speed (km/h)		40	50	60	70	80
Design braking distance (m) (AASHTO 2004)		18	29	41	56	73
Skid number						
SN_0	$SN_{64,\mathrm{ASTM}}$	Rut depth = 5 mm				
47.5	27	13	22	34	53	85
55	30	12	19	30	47	76
60	33	11	17	27	43	72
72.5	39	9	14	23	36	62
80	45	8	13	21	33	57
SN_0	$SN_{64,\mathrm{ASTM}}$	Rut depth = 10 mm				
47.5	27	14	23	36	58	98
55	30	12	20	31	51	87
60	33	11	18	29	47	81
72.5	39	9	15	23	37	73
80	45	8	14	22	36	63
SN_0	$SN_{64,\mathrm{ASTM}}$	Rut depth = 15 mm				
47.5	27	14	24	38	60	99
55	30	12	20	33	54	90
60	33	11	19	30	50	85
72.5	39	9	16	25	42	74
80	45	8	14	23	39	70
SN_0	$SN_{64,\mathrm{ASTM}}$	Rut depth = 20 mm				
47.5	27	15	26	42	67	110
55	30	13	22	37	60	101
60	33	12	21	34	57	96
72.5	39	10	17	29	50	86
80	45	9	16	27	47	81
SN_0	$SN_{64,\mathrm{ASTM}}$	Rut depth = 25 mm				
47.5	27	15	27	45	72	108
55	30	13	23	41	66	100
60	33	12	22	38	62	95
72.5	39	10	18	32	56	85
80	45	9	17	30	51	80

Note: $SN_{64,\mathrm{ASTM}}$ = Skid number at 64 km/h under ASTM testing conditions (water film thickness = 0.5 mm, wheel load = 4800 N, pressure = 165.5 kPa, ASTM standard smooth tire).

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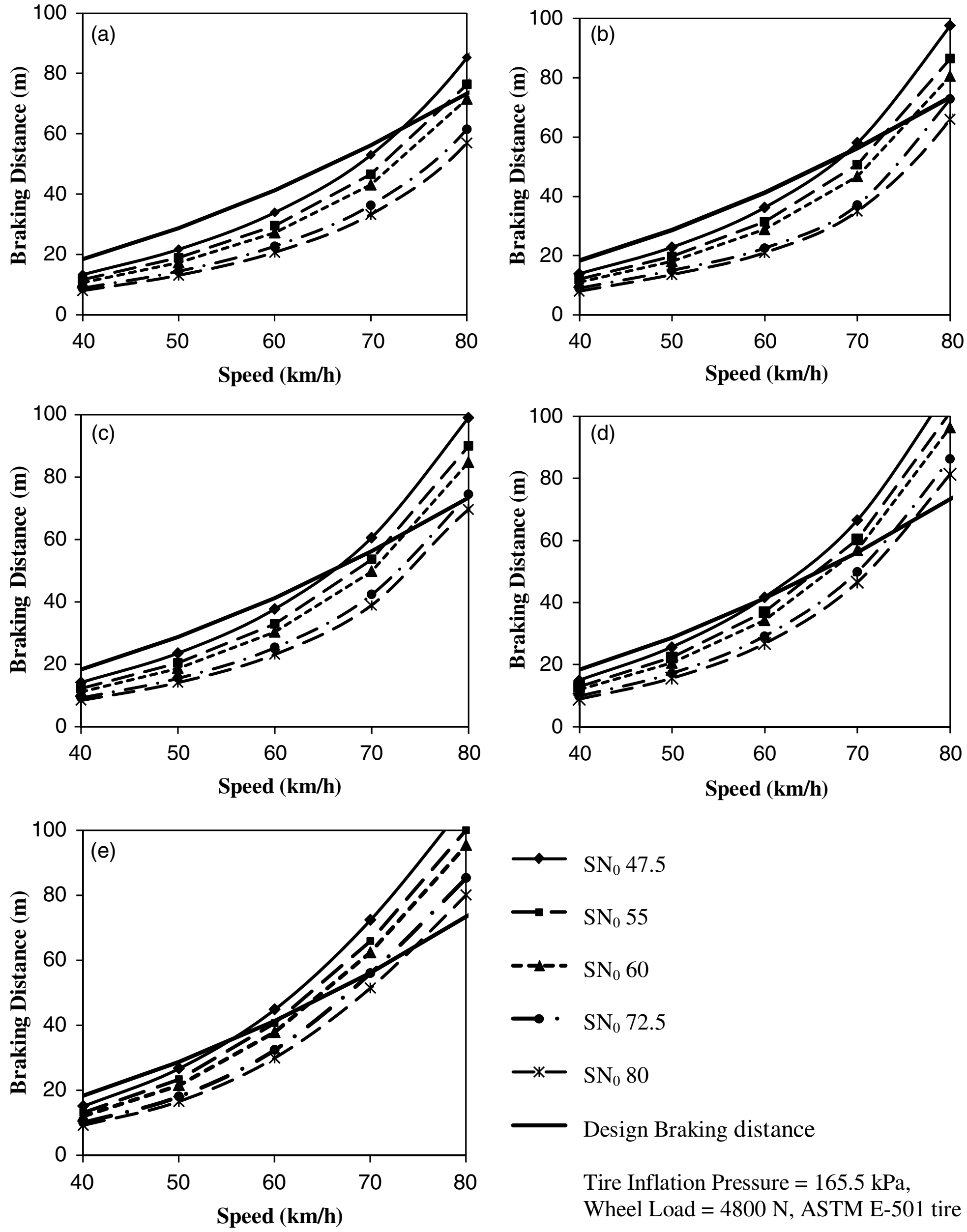

Fig. 2. Braking distance variation with speed at different skid numbers for rut depths: (a) 5 mm; (b) 10 mm; (c) 15 mm; (d) 20 mm; and (e) 25 mm

Conversely, the influence of μ_0 on skid resistance, and hence braking distance as given in Table 3, is significant. Fig. 2 plots the computed braking distances for various rut depth—pavement friction combinations at different initial vehicles speeds. A level pavement section ($G = 0$) is considered in the analysis. Also shown in Fig. 2 are the AASHTO design braking distances (AASHTO 2004). In general, all variables being equal, the results show that as rut depth increases, the hydroplaning speed reduces (i.e., hydroplaning potential increases) and the braking distance increases.

Determination of Critical Rut Depth Threshold for Severity Classification

As explained previously, the critical rut depth of a road section is considered to be reached when either hydroplaning occurs or the required braking distance exceeds the design braking distance, whichever occurring earlier. Fig. 3 presents these two criteria. The hatched area represents the range of speeds within which hydroplaning will occur, whereas the blackened area represents the range of speeds within which the required braking distance exceeds the design braking distance calculated on the basis of the guidelines of AASHTO (2004).

Fig. 3 shows that for the range of rut depths considered, the critical rut depth is basically governed by the braking distance criterion. The hydroplaning criterion only governs when the rut depth exceeds approximately 20 mm and the tire-pavement static friction (μ_0) is higher than approximately 0.72 (i.e., SN_0 exceeds 72). For instance, for a pavement section with μ_0 equal to 0.60 and has rut depth of 10 mm, hydroplaning will occur at 87 km/h, whereas the required braking distance exceeds the design braking distance when the speed exceeds 77 km/h. That is, the skid resistance criterion governs the critical rut depth determination for this pavement section.

Since most highway pavements will have μ_0 values exceeding 0.60, and assuming that most vehicles will be traveling at speeds

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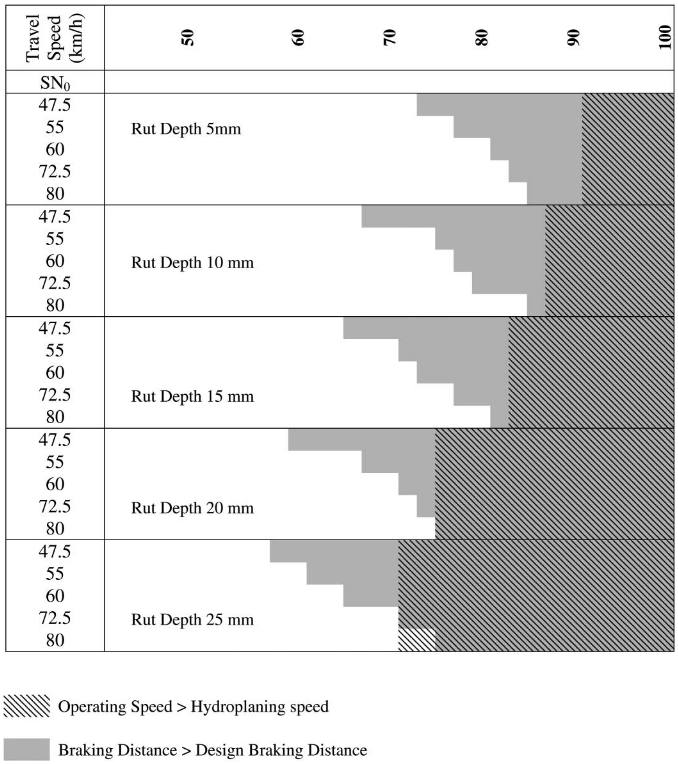

Fig. 3. Governing criterion for safety assessment at different rut depths

not more than 70 km/h on rainy days, the results of Fig. 3 suggest that the critical rut depth threshold would be slightly higher than 20 mm. This magnitude of the critical rut depth is similar to the "high severity" classifications currently being employed by many highway agencies. For example, for a road section with μ_0 equal to 0.725 and a maximum allowed travel speed of 70 km/h, the critical rut depth threshold is 25 mm. This critical rut depth happens to be governed by both the hydroplaning and skid resistance criteria concurrently.

Remark on Critical Rut Depth and Rut Depth Severity Classification

The critical rut depth threshold determined in the preceding section can be taken to be a rut depth of the "high severity" classification for pavement maintenance management. Alternatively, a highway agency can set the "high severity" classification at a rut depth slightly below the critical rut depth so as to allow some lead time for maintenance planning before the rut depth reaches the critical level. Having established the rut depth of "high severity" classification, the corresponding rut depths for "medium severity" and "low severity" can be set by the highway agency concerned on the basis of its own operational consideration.

The critical rut depth analysis requires the knowledge of the maximum allowed vehicle speed for the road section considered. The maximum speed logically refers to wet-weather vehicle operating conditions, and therefore is not equal to the roadway design speed or posted speed for fair-weather conditions. Under wet-weather conditions, vehicles are known to be traveling somewhat slower than the design or posted speed (Kyte et al. 2001; Brilon and Ponzlet 1996; Ibrahim and Hall 1994). This information can be obtained from field surveys or past records of travel speed data.

For efficient practical application of the proposed approach, analyses can be made to compute the stopping distances for the full applicable range of SN_0 values and speeds, for the various types of pavement surfaces in the road network. A database of the stopping distances can be established. This numerical computer database may then be used to quickly obtain the critical threshold vehicle speeds corresponding to the point measurements of rut depth along the length of any given pavement section. By comparing this computed profile of critical threshold vehicle speeds with the corresponding design or posted speed of each section, locations of rutted pavement sections with design or posted speed exceeding the critical threshold vehicle speeds can be identified.

Conclusion

This paper has presented an approach to determine the critical rut depth threshold for pavement maintenance based on the consideration of hydroplaning risk and safety requirement of braking distance. It offers a logical theoretical basis for setting the severity classification of rut depths. This is an improvement over the traditional approach of assigning rut severity classification based on engineering judgment and past experience. The critical rut depth analysis clearly illustrates that if the frictional properties and maximum allowed vehicle speed along different pavement sections of a highway are not the same, their critical rut depths would also be different. This represents a refinement of the severity classification procedure with important road safety and pavement management implications.

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