A QUANTITATIVE MODEL OF ROAD-SURFACE SAFETY

Jiangbi Beijing University of Technology, China

ABSTRACT

Safe operation of vehicles is affected by natural factors, human factors, and traffic loads. A reduction in the quality of the road surface leads to a decrease in the safe following distance and stability on curves and causes accidents such as rear-end collisions and skids. In addition to the surfacing type, road alignment, and operating speed, traffic safety is also related to the pavement roughness, texture, and skid resistance as well as other road surface conditions. Eight road surface skid-resistance evaluation parameters, including the maximum longitudinal and transverse friction coefficients, the allowable longitudinal friction coefficient f_{TA}, the allowable transverse friction coefficient f_{SA}, the expected longitudinal friction coefficient f_{TR}, the expected transverse friction coefficient f_{SR}, and the longitudinal and transverse critical values of road surface safety condition Δf_S and Δf_T, were used to establish a quantitative model of road-surface safety. A case study and road-surface model showed that the critical values of road surface safety condition Δf of test sections of a road in China was 13.2, indicating that the minimum technical standard for the friction coefficient of bituminous penetration-type pavement is lower in China than in other countries and is one of the critical factors in skidding accidents.

Key words: pavement performance; pavement safety; pavement friction; allowable friction coefficient; expected friction coefficient; traffic accident

INTRODUCTION

Traffic safety is strongly related to pavement condition (Ministry of Public Management, 1991). Vehicle handling under various road-alignment conditions is associated with pavement (surface)roughness and pavement skid resistance. In addition, the friction between the tire and surface is the basic parameter that limits vehicle speed and stability, and it plays a very important role in traffic safety and driver comfort. For this reason, many countries regulate the minimum value of the friction coefficient of pavement, setting a standard that must be met when a new road is opened to traffic and as the road is maintained throughout its life cycle. (EDITH BUSS, 2000; Zhang Yu-hua,1980; JH,1991) In Western European countries, the minimum permissible value of the friction coefficient ranges from 0.6 in Belgium to 0.4 in France (Ren Fu-tian et al., 1993). Construction standards in the former Soviet Union specified that the road surface friction coefficient be determined by the expected traffic conditions and type of use (Xie Shang-zhi, 1973). In dangerous sections such as small-radius curves, level intersections, and at crosswalks, the road surface friction coefficient should not be less than 0.6. Under good conditions, the road-surface friction coefficient should not be less than 0.45, and under ordinary conditions, it should not less than 0.3 (Xie Shang-zhi,1973).

Research into pavement skid resistance conditions began in China in the 1980s, but it was only in 1996 that new specifications for highway pavement design were introduced, which included standards for an indicator of pavement skid-resistance conditions. The pavement skid-resistance condition indicator is still based on the SRV (skid-resistance value) tested by a static pendulum skid-resistance tester, and the specifications only state an acceptable range, with no allowance for different pavement conditions. Thus, the specified SRV value of secondary roads is 47–50, with a SMTD of 0.4–0.6 mm. The pavement skid-resistance condition evaluation criterion for maintenance standards (Technical Specifications of Maintenance for Highway, 1996) is also specified as a range: SFC (Side-friction coefficient) of asphalt, concrete pavement, and Bitumen macadam pavement should be greater than 40, whereas the SFC of bituminous penetration-type pavement and penetration-type macadam with coated chips should be greater than 30. These indices were based mainly on foreign research and experience, but have not been verified empirically. This article thus discusses a quantitative safety model for highways in China based on actual conditions of driving safety and pavement condition with a focus on the suitability of the current standards for the pavement friction indicator.

SAFETY FACTORS IN THE INTERACTION BETWEEN VEHICLE AND PAVEMENT

The conditions for safe vehicle travel on a road include the automobile traction balance, dynamic performance, economic characteristics, sliding and braking characteristics, shifting and starting characteristics (JH ,1991), and driver comfort.

The dynamic performance of the automobile and a variety of external forces acting on it (i.e., driving force and driving resistance) determine the automobile's laws of motion. The dynamic performance of an automobile does not take place without a human at the wheel, so the laws of motion affecting the vehicle's performance on the road are called the "driving dynamics" (JH, 1991). The range of possible vehicle behaviors for various road alignment conditions and thus overall driving safety are related to the roughness of the pavement and its skid-resistance condition.

Equations (1) and (2) must be satisfied for safe operation of a vehicle traveling on any road. Automobile traction balance equation:

$$P = Z_{\omega} + Z_{\psi} + Z_{j}, \qquad (1)$$

where$P$ is the automobile traction force (kg), and Z_{ω}、Z_{ψ}、Z_{j}、、are the air resistance, road resistance, and inertia resistance (kg), respectively.

The automobile traction force is limited to the friction between the driving wheels and the pavement:

$$P \leq \psi \cdot G_{K}, \qquad (2)$$

Where G_K is the diving wheel load, and Ψ is the adhesion coefficient between the tire and pavement.

When the vehicle is moving, the force is transferred between the tire and the pavement by friction. The maximum transmission friction is a function of the friction performance and the area of contact between the tire and pavement. Factors affecting the automobile's friction include:

- Pavement factors: type (material, texture), road-design performance (curvature, cross slope, longitudinal slope, etc.), and condition (e.g., dry, wet, winter, smooth, muddy).
- Vehicle factors: automobile design (e.g., front-, rear-, or four-wheel drive), wheel load, slide angle, center of gravity, brake angle, tire conditions (e.g., width, diameter, cross section, expansion pressure, etc.), tire characteristics (e.g., type, material, tread pattern, etc.), and operating characteristics (e.g., speed, acceleration, and deceleration).

Therefore, the friction caused by interaction between the tire and pavement is not constant, but depends on the interaction between the pavement and changes in the tire parameters. The friction caused by the interaction between the tire and the pavement is the basic parameter of driving direction and driving speed. It plays a very important role in driving safety and comfort.

There are two main components in the friction caused by contact between the tire and pavement: longitudinal friction and transverse friction. When the vehicle is traveling in a straight line or the braking resistance is parallel to the driving direction, only longitudinal friction is involved. When the front wheels are turned at an angle to the direction of travel, a transverse force occurs, which produces transverse friction. When longitudinal and transverse friction occur simultaneously, the integrated force should not exceed the maximum friction force F, as shown in Fig. 1; this is calculated using

$$F^2 = F_R^2 + F_T^2 , \qquad (3)$$

where F is the friction force, F_R is the transverse friction force, and F_T is the longitudinal friction force.

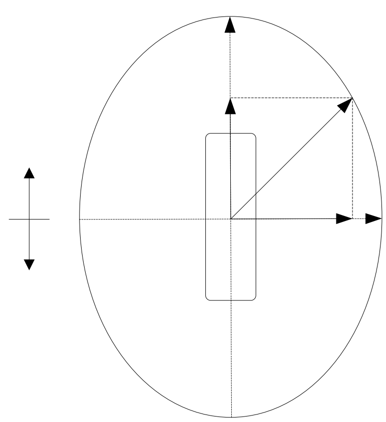

Figure 1: Friction between tire and pavement.

When Fmax is exceeded the vehicle will slide, not roll. It may roll after leaving the road. For example, braking suddenly on a curve may cause the vehicle to exceed the maximum friction and roll.

Excessive speed is the major cause of accidents on curved sections of highways, and the low friction coefficient, lack of superelevation on the curves of one national highway in China causes six sliding per year. Figure 2 shows the relationship between the number of traffic accidents in 1999 and the SFC values for kilometers 101–268 of a freeway (Technical Specifications of Maintenance for Highway, 1996). The number of accidents is slightly higher for low values of SFC.

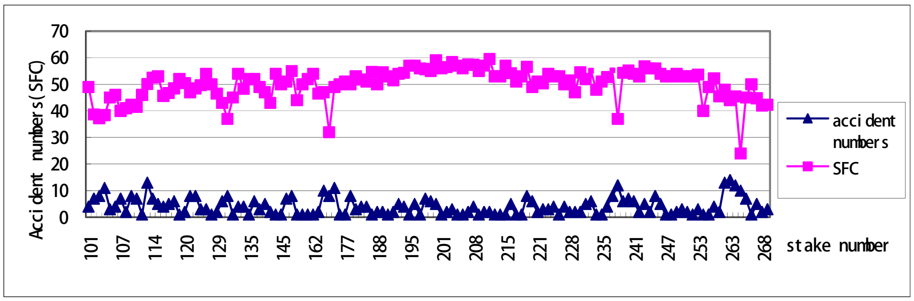

Figure 2: Relationship between number of accidents and SFC.

PAVEMENT PERFORMANCE AND TRAFFIC SAFETY

The pavement is the material carrier of vehicle travel, and the pavement skid resistance is fundamental to the mechanics of rolling wheels. Many highway skid accidents are attributed to overspeed when in fact, the pavement should provide a safe level of skid resistance to meet drivers' expectations for braking. Although under many circumstances, dry pavement provides sufficient skid resistance, this is generally not the case under wet conditions. This may be due to water in ruts that forms a water film, accumulated oil on the pavement, or heavy rain and other factors that reduce skid resistance to the point where accidents occur.

For a moving vehicle, it is not only the state of motion that changes, but also the normal reaction forces on the front and rear wheels. If the vehicle is in a certain state of movement and the normal reaction forces of the front wheels drop to zero, the wheels of the front axle may raise off the ground, resulting the car's overturning. When the normal reaction forces of the rear wheels are at zero the traction force is lost base on the adhesion condition, and if the automobile is unable recover, it may slide.

SFC is divided into eight Levels of skid resistance without considering influence of traffic volume and rainfall on traffic accidents, as shown in table 1. According to the crash data and SFC value of each traffic accident location, statistics crash number of SFC interval on each road section, then all the crash number of SFC interval, rainy day accident rate and rainless day accident rate are calculated according to equation(4).

Table 1: Levels of SFC.

Levels of SFC	1	2	3	4	5	6	7	8
corresponding Interval-Valued	<40	40~45	45~50	50~55	55~60	60~65	65~70	>70

$$\text{Rainless or Rainy day accident rate} = \frac{\text{Rainless or Rainy day accident number under a certain levels of SFC} \cdot 10^{8}}{\text{Statistical road length corresponding levels of SFC} \cdot \text{AADT} \cdot 365} \quad (4)$$

Table 2 shows the correlation between pavement skid resistance and frequency of traffic accidents under different climatic conditions on a certain expressway. Figure 3 shows the relationship between accident rates for different weather conditions and SFC (Technical Specifications of Maintenance for Highway, 1996).

Table 2: Statistical results of accidents on a certain expressway.

Grades of SFC	**SFC statistical frequency (No.)**	**Rainless day accidents (No.)**	**Rainy day accidents (No.)**	**Length of road section (km)**	**Rainless day accident rate (%)**	**Rainy day accident rate (%)**	**average value of SFC**
1	245	18	19	4.97	110.3	116.5	38.82
3	1775	104	40	36.02	88.0	33.8	48.44
4	1887	74	16	38.29	58.9	12.7	52.39
5	109	4	0	2.21	55.1	0	58.39
summary	4016	200	75	81.5	74.8	28	49.98

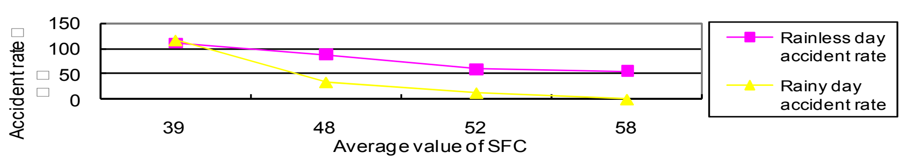

Figure 3: Accident rate versus SFC for rainless & rainy days

So accident rates thus increase as SFC decreases due to rainwater on the road. A case study of a secondary highway showed that four accidents of six occurred at curves under wet road conditions.

Pavement texture is related to aggregate (especially coarse aggregate) quality and its ability to resist vehicle polishing. Its function is to enhance the contact between the pavement and tire despite water film on a wet road. The aggregate texture has a significant effect on the adhesion of the tire to the pavement; when the microstructure of the aggregate is large, then the skid resistance capability is good (Rioh et al., 2003).

Figure 4 shows experimental measurements of the relationship between slip speed and maximum skidresistance value SN□Skid Number□for different types of pavement (Rioh et al., 2003).

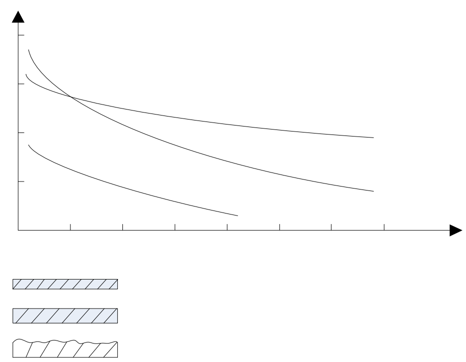

Figure 4: Effect of pavement conditions on skid resistance.

For a vehicle speed greater than a certain value (≥20 km/h in this experiment), pavement with a coarse microstructure and fine macrostructure has a lower skid resistance value than pavement with coarse microstructure and macrostructure. Pavement with a coarse microstructure and fine macrostructure has the best SN value for a vehicle speed less than a certain value (<20 km/h in this experiment).

Experimental results related to pavement structure show that the skid-resistance coefficient of wet pavement is lower than that on dry pavement, stopping sight distance and design of curve radius are influenced by the degree of wetness. Therefore, the road skid-resistance coefficient should be affected by the degree of wetness and the safety models of Eqs. (5) and (6).

$$S_{stop} = V \cdot \frac{t}{3.6} + \frac{V^2}{254\Psi}, \qquad (5)$$

where S_{stop} is the stopping sight distance, t is the sum of the perception and braking reaction times, V is the vehicle speed, and Ψ is the lengthways coefficient of friction between the tires and pavement (skid-resistance coefficient).

$$R_{\min} = \frac{V^2}{127(\mu_{\max} + e_{\max})}, \qquad (6)$$

where R_{min} is the minimum curve radius, V is the vehicle speed, μ_{max} is the allowed maximum SFC, and e_{max} is the maximum superelevation.

SMTD gradually decrease over the time that the road is open to traffic. Although stone is abrasion resistant, the SMTD decreases to half its initial value without obvious flushing and soil contamination. Figure 5 shows changes in SFC of kilometers 0–48 of a certain highway in 1994, 1995, and 1997; the highway was opened to traffic in September 1993.

Figure 5 shows that the SFC was in the range 0.37–0.57, 6 months after starting operation, and the pavement's skid resistance ability was good. After 18 months, the SFC had decreased to 0.23–0.38; the decrease in the skid-resistance value was greater for kilometers 0–22. For kilometers 22–42, the decrease in skid resistance was smaller, although the SFC decreased to 0.32–0.48. Because of pavement flushing in the summer of 1995, the SMTD decreased significantly to only about 0.3 mm (the hard shoulder SMTD was 0.6–0.7 mm in 1996), and the SFC decreased significantly (Rioh et al., 2003).

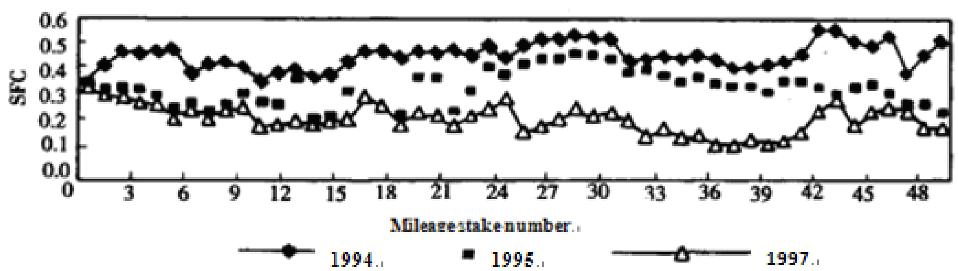

Figure 5: ***SFC as a function of time and location for a certain expressway.***

PAVEMENT SAFETY MODEL

Adequate pavement friction is a necessary condition for vehicles to travel safety. Pavement friction coefficients can be divided into longitudinal friction coefficients and transverse friction coefficients according to conditions of the vehicle running force, i.e., the pavement must maintain longitudinal and transverse balance while the vehicle is running to make the longitudinal friction coefficient and transverse friction coefficient meet the needs of expected longitudinal and transverse force under the most unfavorable driving conditions, as shown in Fig. 1. To satisfy the balance between the actual and expected values, we introduce several basic concepts: maximum longitudinal friction coefficient, allowable longitudinal friction coefficient f_{TA} (allowed transit friction), allowable transverse friction coefficient f_{SA} (allowed side friction), expected longitudinal friction coefficient f_{TR} (required transit friction), and expected transverse friction coefficient f_{SR} (required side friction).

Quantitative safety model for the longitudinal friction coefficient

The longitudinal friction coefficient can be calculated by

$$f_T = F_T / Q \quad , \qquad (7)$$

where f_T is the longitudinal friction coefficient, F_T is the longitudinal friction, and Q is gravity.

For a road that has already been constructed,the allowable longitudinal friction coefficient value f_{TA} is a reliably safe longitudinal friction coefficient that is part of the design and is based on the design speed and the pavement design code, which are part of the highway design, and the pavement completion of construction value. The maximum longitudinal friction coefficient is the maximum value of all the longitudinal friction coefficients under special limiting conditions (Fig. 1). The expected longitudinal friction coefficient is the longitudinal friction coefficient while the vehicle is running at the expected operating speed, i.e., the longitudinal friction coefficient required to maintain stability when turning a corner. The allowable longitudinal friction coefficient f_{TA} is a friction coefficient f_{TR} expected due to a specific expected longitudinal friction produced by the vehicle running at the expected speed over a specific pavement structure with specific vehicle parameters, tire type, tire characteristics, and weather condition. In practice, there is probably a certain standard deviation Δf_T between f_{TA} and f_{TR}, which is calculated by

$$\Delta f_T = f_{TA} - f_{TR} \quad (8)$$

WhereΔf_T is the standard deviation, f_{TA} is the allowable longitudinal friction coefficient, f_{TR} is the expected longitudinal friction coefficient.

When $f_{TA} \leq f_{TR}$, i.e., while $\Delta f_T \leq 0$, the pavement can completely guarantee safe driving at the design speed. This means that the pavement safety performance is "good."

When $\Delta f_T > 0$ but less than a certain "critical value," i.e., for $f_{TA}>f_{TR}$, safe driving is still possible. This means that the pavement safety performance can be considered to be "relatively good."

When $\Delta f_T > 0$ and also more than a "critical value," the pavement is considered "dangerous."

The value of f_{TA} is determined by the relevant pavement friction-coefficient standard, and f_{TR} is the expected friction coefficient at the expected speed, measured by a dynamic friction-coefficient vehicle. In this case, we use the measured value of f_{TR} because the static pendulum skid-resistance tester is still currently used to test the friction coefficient. The "critical value" is such that the longitudinal friction-coefficient value is decreased as the vehicle operating speed and pavement service time increase; when the skid-resistance coefficient decreases beyond the range of the "critical value," it may lead to hidden danger. This range could be tested at locations where accidents frequently occur due to pavement conditions; the critical value depends on the road grade and road condition.

Quantitative safety model for the transverse friction coefficient

The transverse friction coefficient can be calculated by

$$f_s = F_s / Q \quad (9)$$

where f_S is the side friction coefficient, F_S is the side friction force, and Q is the normal force. For a vehicle on a horizontal surface Q would be the gravity force or the weight of the vehicle.

Equations (10) and (11) can be obtained from the vehicle travelling-stability equation:

$$f_{SA} = V_d^2 / 127R - e \qquad (10)$$

$$f_{SR} = V_{85}^2 / 127R - e\ , \qquad (11)$$

where f_{SA} is the allowable transverse friction coefficient ,f_{SR} is the transverse friction coefficient, R is the curve radius, V_d is the design speed of the vehicle, V_{85} is the actual velocity of the vehicle, and e is the superelevation rate.

For a road that has already been constructed, f_{SA} is a reliable safety value that is part of the design based on the design speed and the surfacing character. The f_{SA} is both a design value and the pavement completion of construction value.

The maximum transverse friction coefficient is defined as the maximum value of effective transverse friction under extreme conditions; it cannot be measured, but is calculated according to the maximum longitudinal frictional coefficient.

The transverse friction needs is the pavement transverse friction while the vehicle is running at the expected operating speed.

The allowable transverse friction coefficient value f_{SA} is a friction coefficient f_{SR} expected due to a specific expected transverse friction produced by a vehicle running at the expected speed over a specific pavement structure, with specific vehicle parameters, tire type, tire characteristics, and weather condition. In practice, there is a certain standard deviation Δf_S between f_{SA} and f_{SR}, which can be calculated as

$$\Delta f_S = f_{SA} - f_{SR}\ , \qquad (12)$$

where f_{SA} is the allowable transverse friction coefficient, f_{SR} is the expected transverse friction coefficient, Δf_S is standard deviation.

When $\Delta f_S \leq 0$, the pavement can guarantee driving safety, i.e., the pavement safety performance is “good.”

When $\Delta f_S > 0$ but less than a certain “critical value,” the safety performance can be considered “relatively good.”

When $\Delta f_S > 0$ and greater than a “critical value,” the pavement is considered “dangerous.”

The value of f_{SA} can be obtained from the relevant standards and codes. The f_{SR} is the expected friction coefficient required for the expected speed in theory and can be obtained from the test using the movement apparatus. The “critical value” means that the transverse friction value decreases as the vehicle operating speed increases; a dangerous condition may appear if the transverse skid resistance value decreases to a certain range. This range can be tested at locations where accidents frequently occur due to pavement conditions; the critical value is dependent on the road grade and road condition.

Model validation

A certain road in China was divided into three sections according to pavement age: 16 years, 4 years, and new reconstruction completed in September 2003. In the three sections, we chose the accident-prone portions and those with skidding accidents, as shown in Table 3.

Table 3: Accident-prone test locations.

serial number	kilometre number	pavement age	Number of skidding accidents 1999–2002
1*	1205.800–1206.800	16 years	6
2	1210.000–1421.000	16 years	8
3*	1223.448–1224.448	16 years	8
4*	1364.300–1365.300	4 years	0
5*	1361.000–1362.000	1 month	7

Note：The section numbers marked with an asterisk are commonly accident-prone areas and have been treated.

In each test section, we chose five representative points about 5–10 m apart along the path of the left wheel in the driving direction and tested them using the pendulum apparatus. Table 4 shows the test results.

Pavement structure type: 3-cm asphalt concrete, 10-cm bituminous penetration, 20-cm gradation of sand–gravel-doped lime soil.

Table 4: Measured pavement friction coefficients.

serial number	kilometre number	route characteristic	surface	age of pavement	F_{B20}
1	1205.800–1206.800	curve	smooth, intact, and level with ruts in pavement	16 years	32.8
2	1210.000–1421.000	straight-line segment	smooth, intact, and level with ruts in the pavement	16 years	33.8
3	1223.448–1224.448	curve	cracks and ruts in the pavement	16 years	31.5
4	1364.300–1365.300	straight-line segment	pavement intact	4 years	42.28
5	1361.000–1362.000	straight-line segment	pavement intact	3 months	57.2

According to our current pavement design code, the SRV of second-class highways is 47–50 and requires a minimum value (worst condition) of f_{TA} = 47. Five representative test point f_{TR} values were 32.8, 33.8, 31.52, 42.28, and 57.2. Equation (8) for the quantitative model gave Δf_T values of 14.2, 13.2, 15.48, 4.72, and -10.2 for the road sections tested here. Taking the (Δf_T)=Min(14.2,13.2,15.48)=13.2 as the critical value, we obtain $F_{B20} \geq 47$ ($\Delta f_S \leq 0$); the pavement condition is "good." Section 5 (kilometer 1361.000–1362.000) is such a section; it is newly overlaid, has had no skidding accidents, and can be considered safe. The value of Δf_T is in the range 0–13.2, and although the pavement coefficient is less than the specified value of 47, we consider the pavement conditions to be "relatively good" because no skidding accidents have occurred. The fourth section, with F_{B20} = 42.28, 0 < (Δf_T = 4.72) < 13.2, and no skidding accidents, is a "good" section. Sections 1, 2, and 3, however, with Δf_T > 13.2 and many skidding accidents, can be classified as "dangerous."

According to these calculations, when the friction coefficient decreases to 33.8, transverse sliding and sideways skidding accidents have already occurred, so the delimitation value of SFC = 30 in our current maintenance standard is low. A vehicle traveling on curved sections of the road is subject to transverse rollover and sideways skidding because of centrifugal force. Superelevation is required to ensure driving safety. Current design standards in China require a maximum superelevation value is 6% and the specified value is 5% for second-class highways; in snowy plains, hills, and frozen areas. The superelevation of the kilometer 1205.800–1206.800 section is 3.94%, and the transverse curve radius is R = 400 m. Otherwise, here V85 = 80 km/h; the operating speed is much faster than the design speed (60 km/h) of second-class highways because e is smaller than the specified value of the standard, and f_{SR} is greater than the value specified by the standard. This condition is safe; otherwise, transverse rollover and sideways skidding accidents would occur.

CONCLUSIONS

Field tests of actual road sections and theoretical analysis of the kinetics of safe driving conditions and pavement use characteristics have shown that vehicles should remain in good contact with the pavement, and the road system must establish allowable longitudinal and transverse friction coefficients and follow the pavement-safety quantitative model:

1. Good: $\Delta f_T \leq 0$, $\Delta f_S \leq 0$,($\Delta fT = f_{TA} - f_{TR}$, $\Delta f_S = f_{SA} - f_{SR}$)
2. Relatively good: $0 < \Delta f_S \leq \min(\Delta f_{Si})$, $0 < \Delta f_T \leq \min(\Delta f_{Ti})$,
3. Dangerous: $\Delta f_S > \min(\Delta f_{Si})$, $\Delta f_T > \min(\Delta f_{Ti})$

An analysis of accident-prone section of a certain second-class national highway showed that the critical value Δf of this section was 13.2. This result is preliminary proof that the minimum friction coefficient for penetration-type asphalt pavement allowable in the Chinese highway maintenance standards is too low and can easily contribute to skidding accidents.

Because of restrictions on data acquisition for research, we only used static friction-coefficient detectors to test longitudinal friction coefficients. In addition, the collection of data on traffic accidents is difficult in China, so this is just a preliminary quantitative pavement safety model.

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AUTHOR BIOGRAPHIES

Prof. Hu graduated from Department of Engineering Management of Xi'an Highway Institute in 1987 and then acted as a teacher at that college. She was granted Master's Degree in Road Engineering Management in 1992 and Ph. D in Transportation Planning and Management in 2005 respectively from Xi'an Highway Institute and Beijing University of Technology. After graduation from Beijing University of Technology, she began to engage in Transportation Research Center of Beijing University of Technology. She mainly engages in research on the relationship between driver behavior and road safety, management of road engineering, road engineering management, road safety engineering and so on. She has published more than 60 academic papers both at home and abroad.