Analysis of Rutting Index for Pavement Maintenance based on Driving Safety on Surface Gathered Water Consideration

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ABSTRACT

A common distress in asphalt pavements, rutting is a primary influencing factor in cases of hydroplaning on rainy days. During hydroplaning events, steering stability performance of vehicles is drastically reduced Based on analysis of the lateral stability and the steering stability of vehicles traveling on the water's surface while hydroplaning, this paper presents a theoretical analysis for rutting length and depth severity classification. Through creation of a vehicle dynamics model and use of CarSim the theoretical variations of lateral offset and lateral acceleration under different speeds were simulated. Through this analysis, it was found that when a vehicle's speed exceeds 80 km/h, the lateral offset and lateral acceleration of the vehicle will increase noticeably and will exceed the safety threshold. In addition, for a given rutting scenario, an interaction effect among rutting depth, rutting length, and vehicle speed is also apparent. Ultimately, a vehicle's lateral offset and lateral acceleration under different rutting depths are recommended for use as factors/indicators of rutting length.

INTRODUCTION

Rutting is a type of distress commonly experienced by asphaltic road surfaces. In general, rutting occurs at locations where vehicles brake and where they accelerate from a stop. Rutting not only affects the smoothness of the road and leads to decreased riding quality, but it also reduces the pavement skid resistance on roads with poor drainage on rainy days. It can even lead to hydroplaning which can in turn create safety issues for drivers (Sha, 2008; TMRI, 2011). *Technical Specifications for Maintenance of Highway Asphalt Pavement*, published by the Ministry of Transport of the People's Republic of China (MOT), defined depth of rutting as: 15 mm for first-class highway and expressway facilities. The specifications also noted that the standard depth for rutting maintenance is greater than 25 mm (MOT, 2001). However, the rutting depth is only one possible evaluation index as it neglects the effect of a rut's height difference and does not reflect the effect of ponding on driving safety. In addition to rutting depth, the water depth in the ruts also should be considered as a main effect factor on driving safety. Ultimately though, rutting length is supposed to be the main evaluation index (Tian, 2011).

By using a computational fluid dynamics (CFD) approach for a three-dimensional finite element simulation of the acting surface between a tire and water, Fwa et al. (2011) found that tire load, tire inflation pressure, and tire tread pattern have apparent effect on the critical hydroplaning speed. Based on these findings, they recommended that the critical hydroplaning speed and vehicular braking distance should be used as evaluation indices of rutting depth (Fwaet al, 2011). When considering the braking performance and handling stability of vehicle, an allowable rutting depth of 10 - 12.5 mm is recommended by Xu (1994) based on the relation of water depth and vehicle handling stability consideration (Xu, 1994). Hou et al. (2006) verified and explored the current rutting index based on driving safety. In addition, they studied the feasibility in using the maximal rutting depth, rutting width, maximum probable water area in rutting, and average curvature radius of ruts to characterize rutting feature (Hou, 2006). According to the simulation results of ADMAS, Xu (2009) pointed out that when only one side of the car was driving on the water surface (i.e., one front tire and one rear tire on the same side of the vehicle traveling on the water surface), the difference between the left and right tires' peripheral velocities in a given time is the main cause of car's sideslip. Additionally, the longer the car drives in the water zone, the larger difference between the left and right tires' peripheral velocities. This in turn leads to increased possibility of sideslip (Xu, 2009). Depending on the analysis, rutting length has been shown to have a noticeable effect on driving safety.

Research has shown that water depth and length of rutting have a significant effect on driving safety. However the studies on water depth and length of rutting are not few in number and lack of comprehensive quantitative analysis. Therefore, using-hydromechanics, this paper quantitatively analysed water depth in rutting under different speed conditions. This information was then used to compute the critical water depth in rutting that can cause hydroplaning to occur. Based on vehicle dynamics, lateral offset from design and lateral acceleration were selected as evaluation indices of rutting length. Considering these metrics, this paper quantitatively researched lateral stability and handling stability with different vehicle speeds and determined the relation between rutting length and water depth.

ANALYSIS OF VEHICLE LONGITUINAL STABILITY IN THE WATER SECTION

A vehicle's longitudinal stability in roadway sections with water on the pavement is an essential factor in driving safety, which includes dynamic performance and driving performance. Additionally, the adhesion between tire and road is the major factor affecting driving performance and braking performance. The more hydrops are in the rut, the less contact area is between tire and road, which leads to a decrease in adhesion. When the road surface is separated from a vehicle's tire by water, the adhesion will be zero and hydroplaning will occur. The Federal Highway Administration (FHWA) notes that: the rutting of which depth exceeds 5.08mm (0.2in) will cause hydroplaning (FHWA, 2013).

Through analysing data computed from hydroplaning simulation, Xu (2011) noted that for a given speed, when the water depth is in the range of zero to five mm, the adhesion will decrease nonlinearly with water depth. However, when water depth exceeds five mm, the adhesion will decrease linearly (Xu, 2011), the linear equation is shown as follows:

$$\varphi - 0.3696 = -0.01155\left(h-5\right) \quad V = 60\text{km/h} \tag{1}$$

$$\varphi - 0.1921 = -0.01106\left(h-5\right) \quad V = 80\text{km/h} \tag{2}$$

$$\varphi - 0.08 = -0.00574\left(h-5\right) \quad V = 100\text{km/h} \tag{3}$$

$$\varphi - 0.0502 = -0.00398\left(h-5\right) \quad V = 120\text{km/h} \tag{4}$$

The critical water depth under different speed and adhesion scenarios can be computed from Equations (1) through (4). A selection of values for varying speed and adhesion pairings is shown in Table 1. The computed results show that the water depth in ruts has an apparent effect on the adhesion; hence the rutting maintenance index should ignore the influence.

Table 1. Critical water depth in rutting under different adhesion and speed (mm)

Speed \ Adhesion	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07
60 km/h	37	36	35	34	34	33	32	31
80 km/h	22	21	21	20	19	18	17	16
100 km/h	19	17	15	14	12	10	8	7
120 km/h	18	15	13	10	8	5	3	2

ANALYSIS OF VEHICLE LATERAL STALIBITY IN THE WATER SECTION

Consider a scenario in which the car's drive type is front-wheel drive (FWD), the left front tire is moving on the water section at a given speed and the right one is moving on the dry pavement. Based on vehicle dynamics, the center of the tire bears the yawing force, F_Y, in the Y direction. Considering that the wheel is rigid and the sliding speed is Δv, the tire would sideslip when F_Y takes the value of the adhesion limit between tire and road. In this case, the car would move in the same direction as the resultant speed (Karl & Werner, 2010).

As F_Y increases, the tire's sideslip angle will increase rapidly and the tire will experience partial sideslip. When F_Y equals the adhesion limit, the tire experiences complete sideslip. The maximal yawing force depends on the adhesive condition between tire and road, i.e., vertical load, tire tread pattern, tires inflation pressure and water depth in rutting.

Supposing that the car is a two degree of freedom (DOF) model, two equilibrium equations can be deduced as presented in Equations (5) and (6): mechanical equilibrium and moment equilibrium, respectively:

$$F_{Y1} + F_{Y2} = ma_y \quad (5)$$

$$F_{Y1}a - F_{Y2}b = I_z\dot{\omega}_r \quad (6)$$

where F_{Y1} and F_{Y2}, are the yawing force of the front wheel and rear wheel, respectively; m is car's mass; a_y is the centroid acceleration; I_z is the centroid rotational inertia of car; and $\dot{\omega}_r$ is the yaw angular acceleration.

According to Equations (5) and (6), the sum of F_{Y1} and F_{Y2} equals ma_y, but the distribution of F_{Y1} and F_{Y2} depends on $I_z\dot{\omega}_r$, with inertia torque's increasing, F_{Y1} will increase and F_{Y2} will conversely decrease. Figure 1 shows the force situation of the car's steady state circular moving state. It can be deduced from Figure 1 that:

$$F_{Y1}a + F_{X2}d_a - F_{Y2}b = 0 \quad (7)$$

According to Equation (7), F_{Y1} will decrease and F_{Y2} will increase. On the contrary, the car's front sideslip angle will decrease and the rear one will increase, which leads to the car's sideslip. If the car still moves at a high speed or accelerates, the car will experience forward acceleration and the corresponding yaw angular acceleration $\dot{\omega}_r$. The front wheel will experience a ground reactive force in the longitudinal and lateral directions, and the car will experience tremendous sideslip with possible loss of control.

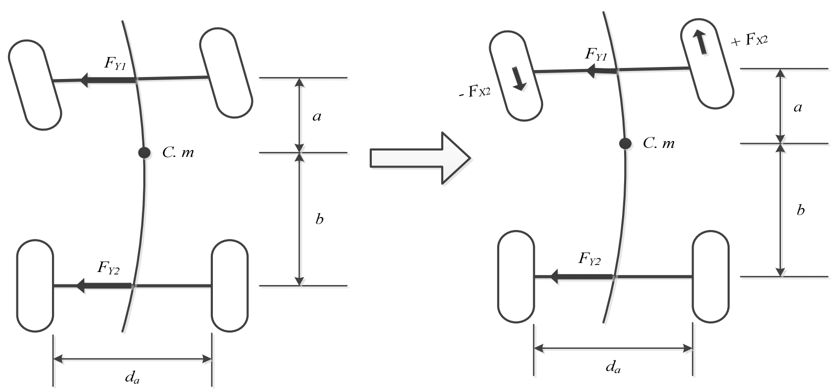


Figure 1. Condition of stabilized steering.

For a given speed, the rutting length has an apparent effect on the time car travels through a roadway section with water. The travel time is directly proportional to the yaw moment of couple $F_{X2}d_a$. The larger $F_{X2}d_a$ is, the greater the chances of sideslip. Ultimately, the car's stability control is plagued by two problems, one of which is the path-keeping problem and is signified by lateral offset. The other is a handling stability problem which is signified by lateral acceleration.

ANALYSIS OF IMAPCT OF RUTTING LENGTH ON THE DRIVING SAFETY

Vehicle Dynamics Model

Vehicle Model

In this paper, CarSim is used to establish the vehicle model. (Xiao, 2007). The vehicle structure includes two-way cartridge front and rear independent suspension, rack and pinion steering gear, pendular strut IFDA (with QS), caliper disc brake (front wheels), self-adjusting drum brake (rear wheels) and FWD. The essential parameters in CarSim are shown in Table 2.

Table 2. Parameters of the vehicle dynamics model

Dynamical Parameter	Symbol	Value	Unit
Weight of Full Equipment	M	1210 (Empty car) + 70 (driver)	kg
Size of Full Equipment	$L \times W \times H$	4680×1700×1423	mm
Roll Inertia	I_{xx}	524.26	kg·m^2
Pitch Inertia	I_{yy}	2552.25	kg·m^2
Yaw Inertia	I_{zz}	2644.52	kg·m^2
Front Wheelbase	a	1300	mm
Rear Wheelbase	b	1356	mm
Front Tread	d_a	1414	mm
Rear Tread	d_b	1422	mm
Height of Mass Center	h_0	500	mm

Model of Rutting Gathered with Water

The length of road section used in the model is 1000 m. The car in the model begins to travel into the water section after travelling 350 m along the central line at a given speed. The length of the water section is 650 m; the width of pavement in the model is 3.75m. The adhesion of dry pavement is 0.8. In order to avoid the impact of the width of water section, this paper set the width of the water section to be 1.875 m on each side of the car as shown in the Figure 2.

In the model, the car's width is 1.7 m so when the lateral offset of car exceeds 1.025 m (shown in Figure 2), the car will run into the adjacent lane and collide with the other cars in the adjacent lane. Meanwhile, when the car's lateral acceleration exceeds 0.4g, the wheels will operate in the nonlinear portion and average drivers will have difficulty handling the car (*MOT, China, 1980*).

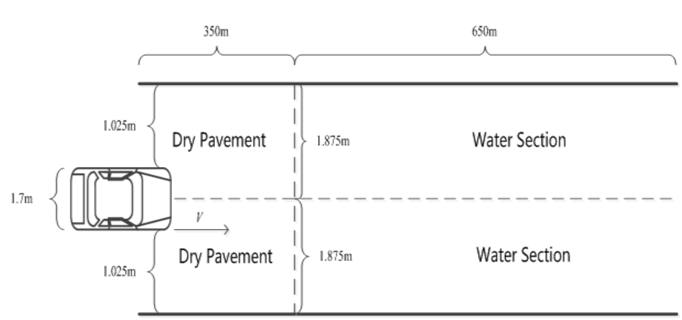
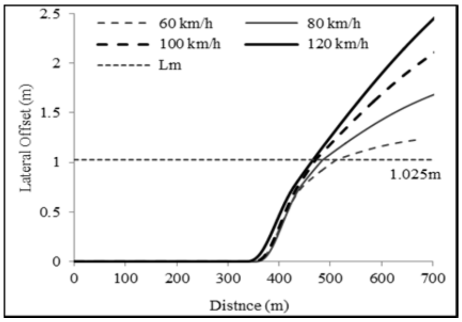


Figure 2. Schematic of rutting section with trapped water.

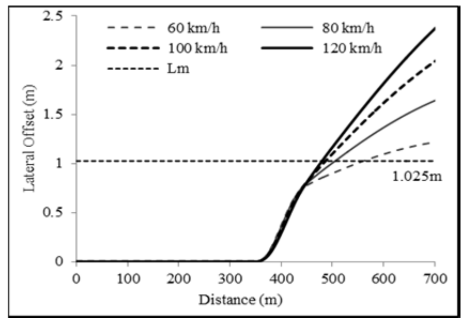
Analysis of Simulation Result

The Impact of Rutting Length on Lateral Stability

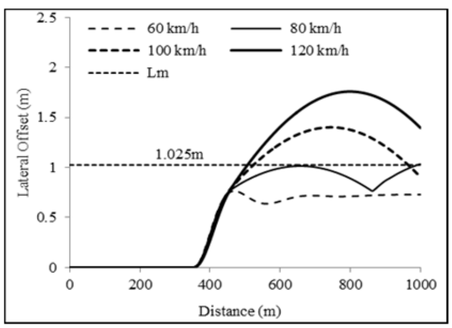
This model applies CarSim to simulate scenarios in which the the car is driving in the water section under different speeds (60 km/h, 80 km/h, 100 km/h, and 120 km/h). The adhesion of the water section in ruts ranges from 0.0 to 0.2 and Figure 3 shows the simulation results for a variety of adhesion values including 0.00, 0.02, 0.04, 0.06, 0.08, and 0.10.



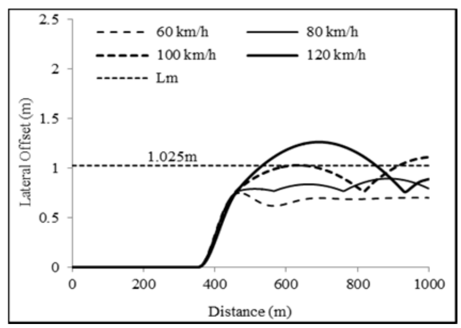
$\mu = 0.00$



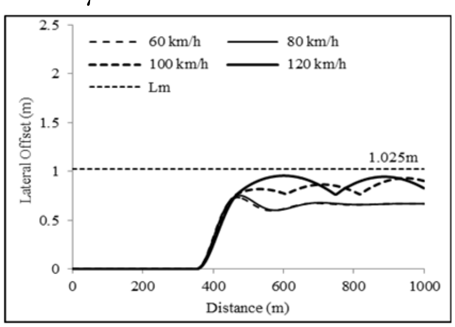
$\mu = 0.02$



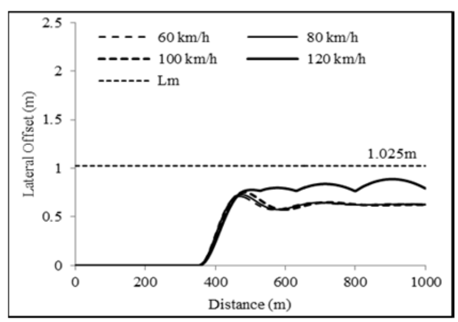
$\mu = 0.04$



$\mu = 0.06$



$\mu = 0.08$



$\mu = 0.10$

Figure 3. Lateral offset from design path of vehicle with different adhesion and speed values (L_m = 1.025m).

The simulation results show that, for a given speed, the car's lateral offset will noticeably decrease as adhesion decreases. When the adhesion exceeds 0.08, the car will not experience sideslip into the adjacent lane even if the speed is 120 km/h. As the adhesion exceeds 0.2, the water in the rut has a minimal effect on the car's lateral stability.

Table 3. Safety distance of lateral stability with adhesion and speed (m)

Speed \ Adhesion	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07
60 km/h	161	161	211	—	—	—	—	—
80 km/h	135	135	156	195	291	—	—	—
100 km/h	121	121	137	156	173	195	265	—
120 km/h	116	116	129	145	157	168	183	212

Table 3 lists the safety distances at which the car will first run into the adjacent lane in the water section under different adhesion values (0.00 - 0.07). The results show that:

(1) When the car's speed is below 80 km/h, with increasing values of adhesion, the safety distance will increase nonlinearly and the rate of change will gradually increase too. When the car's speed exceeds 80 km/h and adhesion ranges from 0.00 to 0.05, the safety distance will increase linearly as adhesion increases. When adhesion exceeds 0.05, the safety distance will increase nonlinearly.

(2) When the adhesion is below 0.01, the speed is the only influencing factor on safety distance. As speed increases, the impact of adhesion on the car's lateral stability increases. When the car's speed is 60 km/s, as the adhesion exceeds 0.02, the lateral stability will stay within the safety margin. When the car's speed is 120 km/h, the lateral stability will stay within the safety margin as long as the adhesion exceeds 0.07.

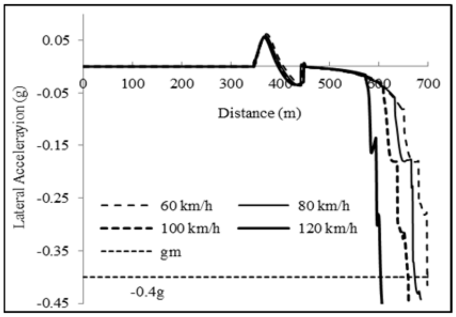
The Impact of Rutting Length on Handling Stability

This model applies CarSim to simulate the car's lateral acceleration in the water section under different speed scenarios (60 km/h, 80 km/h, 100 km/h, and 120 km/h). The adhesion of the water section in rutting ranges from 0.0 to 0.1 and Figure 4 shows the simulation results for adhesion values of 0.00, 0.01, 0.02, and 0.03.

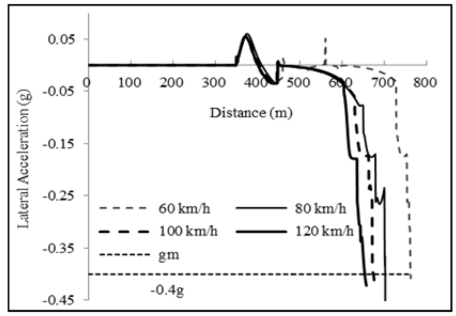
According to Figure 4, when the car travels into the water section with a given length, when the adhesion value is below 0.02, the speed and adhesion will have a noticeable effect on the car's lateral acceleration. For a water section in which adhesion exceeds 0.02, the impact of speed and adhesion on the car's lateral acceleration will tend to decrease. Additionally, for a water section in which adhesion is below 0.02, as speed of the vehicle increases, the safety distance at which the car begins to lose its stability will decrease. For a given speed, as adhesion decreases, the car's lateral acceleration also will decrease.

Table 4. Safety distance of lateral stability with adhesion and speed

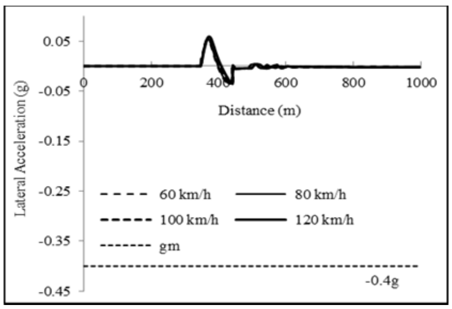
Speed \ Adhesion	0.00	0.01
60 km/h	354 m	413 m
80 km/h	323 m	352 m
100 km/h	310 m	323 m
120 km/h	254 m	301 m



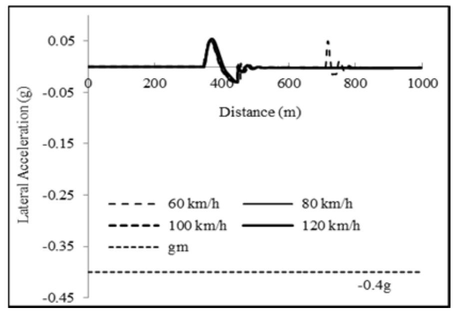
$\mu = 0.00$



$\mu = 0.01$



$\mu = 0.02$



$\mu = 0.03$

Figure 4. Lateral acceleration of vehicle with different rutting length and speed (g_m = -0.4g).

Table 4 lists the safety distances at which the car will first lose its stability (i.e., the car's lateral acceleration exceeds 0.4g) in the water section with two different adhesion values (0.00 and 0.01). The results show that:

(1) When the car drives on the water section with a given adhesion, as speed increases, the safety distance that the car's lateral acceleration will first exceeds 0.4g will decrease nonlinearly. Based on the data, the safety distance increases 35 m on average for each 10km/h increment in speed. Thus, the speed has a more noticeable effect on the lateral acceleration than lateral offset.

(2) For a given speed, when the adhesion is below 0.02, the safety distance will increase as adhesion increases. The safety distance increases 37 m on average for an increases in adhesion of 0.01. Therefore, the adhesion has a more noticeable effect on the lateral acceleration than lateral offset, as was the case previously.

CONCLUSIONS

Based on the vehicle dynamics theory, this paper simulates the impact of rutting length and water depth in ruts on driving safety under different speed scenarios. The analysis results show:

(1) When the car's speed is below 60 km/h, the adhesion between tire and road varies much less with water depth and the influence can be neglected. Therefore, for a typical road whose design speed is below 60 km/h, the impact of water in rutting on driving safety can be neglected.

(2) When the car's speed exceeds 80 km/h, the rutting length and water depth in the rut begins to have a noticeable effect on driving safety, as shown in the Table 5. Since the design speed of highways in China ranges from 80 km/h to 120 km/h, the

impact of water in ruts on driving safety should be taken into consideration by the highway maintenance departments. When the rutting length exceeds the threshold of lateral stability, as shown in the Table 5, the car may experience sideslip into the adjacent lane and collide with other cars. In this situation, the road section is defined as a low-risk section that needs some primary maintenance measures. When the rutting length exceeds the threshold of handling stability, the car will lose control and the driver will experience difficulty in handling the car. In this situation, the road section is defined to as a high-risk section that will require more extensive maintenance measures over time.

Table 5. Critical rutting length and water depth with speed (m)

Speed \ Adhesion		0	0.01	0.02	0.03	0.04	0.05	0.06	0.07
80 km/h	RD_{cw}	22	21	21	20	19	18	17	16
	L_H	135	135	156	195	291	—	—	—
	L_C	323	352	—	—	—	—	—	—
100 km/h	RD_{cw}	19	17	15	14	12	10	8	7
	L_H	121	121	137	156	173	195	265	—
	L_C	310	323	—	—	—	—	—	—
120 km/h	RD_{cw}	18	15	13	10	8	5	3	2
	L_H	116	116	129	145	157	168	183	212
	L_C	254	301	—	—	—	—	—	—

Note：RD_{cw} is critical water depth in rutting, mm; L_H, L_C are critical rutting length of lateral stability and handling stability, m, respectively.

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REFERENCES

Department of Transportation Federal Highway Administration. (2013) *Practical Guide for Quality Management of Pavement Condition Data Collection*, Washington, D.C., USA.

Fwa, T. F., Pasindu, H. R., and Ong G.P. (2011). "Critical rut depth for pavement maintenance based on vehicle skidding and hydroplaning consideration." *Journal of Transportation Engineering*, 01-21.

Hou, X.S., Ma, S.L., Wang, C.X. (2006). "Research on measurement and evaluation of asphalt pavement rutting based on traffic safety." *Journal of Highway and Transportation Research and Development*, 23(8), 14-17.

Karl, P., and Werner, S. (2010). *Ground vehicle dynamics*, Scientific Publishing Services Pvt. Ltd., Chennai, India

Ministry of Transport of the People's Republic of China. (1980). *Motor vehicle brake test standard of the People's Republic of China (trial)*, Beijing, China.

Ministry of Transport of the People's Republic of China. (2001) *Technical specifications for maintenance of highway asphalt pavement (JTJ 073.2 - 2001)*, Beijing, China.

SHA, Q.L. (2008). *Premature damage and its preservative measures of bituminous pavement on expressway*. Beijing: China Communications Press.

Tian, W.Z. (2011). “Study on the rutting evaluation standard based on multi-index.” *Transportation Science & Technology*, (4), 77 - 78.

Traffic Management Research Institute of the Ministry of Public Security. (2011). *Road Traffic Accident Statistics Annual Report of the People's Republic of China (2010)*, Wuxi, China.

Xiao, C. (2007). *Simulation study on method of vehicle stability control*. Hunan University, Changsha, China.

Xu, J., Peng, Q.Y., Shao, Y.M. (2009). “Mechanism analysis of vehicle accident on surface gathered water in straight sections.” *China Journal of Highway and Transpor*t, 22(1), 97 - 103.

Xu, S.F. (1994). “Pavement rutting depth related to vehicle travel safety.” *Journal of Beijing Institute of Civil Engineering and Architecture*, 10(1), 47-51.

Xu, Y. (2011). *Study on the rutting in asphalt pavement based on driving safety*, Central South University, Changsha, China.