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Determining thresholds of traffic volume and skid resistance to reduce pavement's wet accident ratio

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Abstract: Amid at current research on wet pavement accidents primarily focused on the qualitative or simple quantitative effects of skid resistance and traffic volume, however, recommended values of skid resistance and traffic volume have not been explicitly proposed. As a result, the potential safety hazard of vehicles on wet and slippery roads was higher, and threat to traffic safety. To analyze the impact of these two main factors on wet pavement accidents and to reduce the frequency of accidents on rainy days, firstly, the wet accident ratio (WAR) was determined. Then, the influence of the pavement's skid resistance under different traffic grades, using statistical principles and analysis methods, as well as the traffic volume under different skid resistance grades on the WAR, were analyzed by MATLAB. Three regression models for the annual average daily traffic (AADT), skid number (SN), and sideway force coefficient (SFC) on the WAR were established. The effects of the AADT, SN, and SFC on the WAR were analyzed quantitatively with those models. Finally, the coupling effect of skid resistance and traffic volume was considered, and the thresholds of the two factors were determined to ensure highway safety. The results show that the threshold of the AADT ranges from 6 500 to 15 000, and the ranges of the skid resistance number and wet accident ratio are 27 to 53 and 0.529 to 11.930, respectively. To achieve the zero-accident goal, the maintenance value of the skid resistance should be improved to 52 when traffic is heavy, to ensure driving safety in rainy days. The recommended thresholds have an important role in defining the optimum time for the skid resistance maintenance of asphalt pavement, which can also lay a foundation for establishing a more effective preventive maintenance system for highways. 4 tabs, 8 figs, 18 refs.

Key words: road engineering; wet pavement accident ratio; skid number; sideway force coefficient; annual average daily traffic; thresholds values

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面向降低路面湿滑事故率的交通量与抗滑阈值确定

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摘　要:针对目前关于路面抗滑性能与交通量和湿滑事故的相关性主要为定性或简单定量研究,未提出明确的抗滑值与交通量推荐值,导致雨天湿滑路面对道路行车安全造成较大隐患,严重威胁交通安全,为分析抗滑性与交通量 2 个主要影响因素对湿滑路面事故的影响,解决雨天湿滑导致事故频发这一问题,首先,定义路面湿滑事故率(WAR);然后,运用统计学原理及分析方法,借助 MATLAB 分别分析不同交通量等级下路面抗滑性能或不同路面抗滑等级下交通量对路面湿滑事故率的影响,分别建立年均日交通量(AADT)、路面抗滑值(SN)、路面横向力系数(SFC)与路面湿滑事故率的 3 种回归模型,定量分析交通量、路面抗滑值、路面横向力系数对路面湿滑事故率的影响;最后综合分析了抗滑值和交通量的耦合效应,并基于道路行车安全,推荐了两者阈值。研究结果表明:年平均日交通量阈值为 6 500～15 000,抗滑值、湿滑事故率范围分别为 27～53、0.529～11.930;为实现零事故目标,在重交通路段应将抗滑值提高到 52,以保证雨天行车安全。该推荐阈值为控制交通量或路面抗滑性能以减小路面湿滑事故率提供了参考,同时明确了沥青路面抗滑养护最佳时机,为建立更完善的公路预防性养护体系奠定了基础。

关键词:道路工程;路面湿滑事故率;抗滑值;横向力系数;年均日交通量;阈值

0 Introduction

It is widely recognized that wet accident ratio (WAR) is significantly higher than dry accident ratio, because of the rainy days[1]. Except uncontrollable factors such as human behaviours, pavement skid resistance and traffic volume are the main factors affecting pavement wet accidents. However, what grade the pavement skid resistance should be improved and traffic volume should be controlled in different situations, to tackle wet accident and ensure road safety, it is still a controversial issue.

On dry pavement, the contact friction between tire and road surface is highest. However, the contact situation is adverse on wet pavement because of the water film existing between vehicles' tires and road surface, and the worse skid resistance is, the more wet accidents occur. Especially when the drivers hit the brake to stop the vehicle, the poor skid resistance will directly lead to low braking efficiency and long braking distance, which will result in many uncontrollable accidents such as an side slipping accident. There are lots of research conduct skid resistance greater impact on traffic accident, especially in wet pavement[2]. Obviously, the pavement skid resistance provide frictional force to vehicles' tires to avoid sliding, so smaller skid resistance is one of the most important reasons causing the higher WAR[3-6]. There are some models established to quantifying the quantitative relationship between skid resistance and wet accident, and it is no doubt that a higher skid resistance can diminish wet accidents[7-8]. To reduce wet accidents, some critical values are obtained to ensure road safety[9-11], when skid resistance is below the critical value, the accident ratio maybe increases rapidly or considerably high, and in this process, the traffic speed and testing speed are also be considered[12].

As one of the main transportation issues, the growth of vehicles number on the road cause congestion, and congestion can lead to increase accident risks due to the expansion in transportation systems. Hence, traffic volume is also an important influence factor in accident[13-15]. The relationship between wet pavement accident and traffic volume are identified, and they find when vehicle running speed is no more than 80 km/h, wet accident embodies much higher value than when the range of AADT from 5 001 to 10 000 compared to 1 to 5 000, but the quantitative relationship was not used to clarify the influence of traffic volume on wet pavement accident because of the limited data[16]. Other researchers find that the traffic volume is the most vital induction factor of the traffic accidents, and traffic volume increases leads to substantial increasing traffic accidents on highways[17]. So the traffic jam maybe a signal of road safety, and how to control traffic volume or set some thresholds is very necessary.

However, when we want to improve skid resistance or control traffic volume to reduce wet pavement accident and alleviating road safety problem, the coupling effect of the two factors should be considered. Based on above research, the regression curve of traffic volume and WAR or skid resistance and WAR are obtained. According to regression results, thresholds values of skid resistance, traffic volume and WAR are obtained and the recommended values are given for controlling traffic volume and clarifying maintenance standards to reduce WAR.

1 Definition and analysis method

1.1 Wet accident ratio

There are various kinds of definitions about accidents occurring in wet pavement surface in rainy days. The crash ratio ratio (CRR) is defined by the ratio of accumulative percentage of road accidents and the accumulative percentage of road mileage under the same skid resistance[8]. The CRR will be 1 if there is no influence on accidents caused by the poor pavement skid resistance and the formula is shown as following

$$C_{RR}=\frac{P_{CR}^{SN}}{P_{LM}^{SN}} \tag{1}$$

Where C_{RR} is the value of CRR; P_{CR}^{SN} is the cumulative percentage of total crashes at or below skid number (SN); P_{LM}^{SN} is the cumulative percentage of total lane miles at or below skid number.

The ratio of accidents occurred in 1×10^8 miles to the multiplied result involved in the annual average daily traffic (AADT) and 365 d was shown in Eq. (2). However, the definition is not perfect as it can't explore the impact of traffic volume on wet skid accidents[5].

$$W_{AR}=\frac{10^7\ N_W}{365A_{ADT}} \tag{2}$$

Where N_{WA} is the number of wet accidents; A_{ADT} is the value of annual average daily traffic.

Since there is much difference of wet accident ratio in different skid resistance interval, the sideway force coefficient (SFC) is classified into 8 groups and the accidents in each interval are counted. However compared with the above formula, the length of the statistical section corresponding to the SFC level are added into denominator, and it is difficult to analyze correlation between traffic accidents and traffic accidents[1]

$$W_{AR}=\frac{10^8\ N_{SFC}}{365\ L_{SFC}} \tag{3}$$

Where N_{SFC} is the number of wet accidents in SFC interval; L_{SFC} is the length of road section in SFC interval, SFC is classified into 8 groups and the minimum is less than 40 while the uniform growth is 5.

With the comprehensive considerations such as the longer the statistical road length and time are, the more wet accidents will be, so the W_{AR} in this paper is defined as following

$$W_{AR}=\frac{T_{WC}}{LT} \tag{4}$$

Where T_{WC} is total wet accidents at the section; L is statistical length of the road section; T is statistical time of the road section, and the unit is year.

1.2 Regression model

According to investigation, the poorer pavement skid resistance will result in higher accident ratio, and the law is more obvious in rainy days. However, when the pavement skid resistance is improved into a level, the influence of skid resistance on WAR is so minuscule, which can be ignored. As for traffic volume, it will maintain a stable state when the traffic volume is saturated, although pavement accident ratio increases with the increase of traffic volume, when the traffic volume is small. With so many considerations and repeated trial calculation, the best function to quantifying the mathematical relationship between traffic volume and WAR or skid resistance and wet accident ratio is shown as following

$$W_{AR} = e^b x^a \tag{5}$$

Where x is refer to SN in WAR-SN Curve, SFC in WAR-SN Curve or AADT in WAR-AADT Curve; a, b are coefficients.

1.3 Definition of thresholds values

1.3.1 Thresholds values of skid resistance

As shown in Fig. 1, according to the thresholds of wet accident ratio ($W_{AR1}=1.05$, $W_{AR2}=2.0$, $W_{AR3}=3.0$) and WAR-SN regression curves, the thresholds of skid resistance (S_{N1}, S_{N2} and S_{N3}) are determined[8]. When the skid resistance is less than S_{N3}, the wet pavement accident ratio is seriously beyond the normal acceptable range. Hence, it is urgent to carry out network level maintenance to improve pavement skid resistance. When $S_{N3}<S_N<S_{N2}$, the pavement wet slip accident ratio is beyond the acceptable range. Therefore, the project level maintenance measures should be taken to reduce the wet pavement accident ratio. When $S_{N2}<S_N<S_{N1}$, little maintenance is considered to improve skid resistance, and when the road skid resistance is greater than S_{N1}, there is no need for skid maintenance.

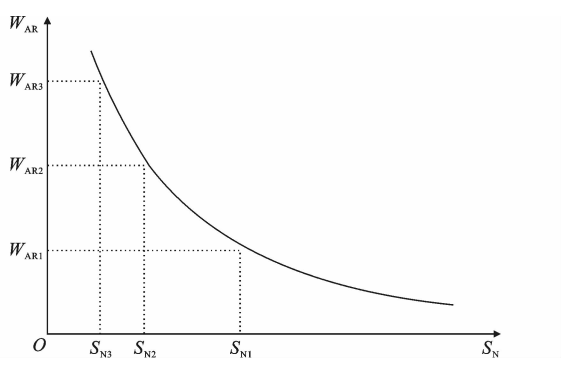

Fig. 1 Thresholds values of S_N determined by thresholds of W_{AR}

图 1 基于 W_{AR} 阈值的 S_N 阈值

1.3.2 Thresholds of annual average daily traffic

As shown in Fig. 2, the thresholds of traffic volume A_{ADT1}, A_{ADT2} and A_{ADT3} are determined according to thresholds of wet accident ratio ($W_{AR1}=1.05$, $W_{AR2}=2.0$, $W_{AR3}=3.0$) and WAR-AADT regression models. When $A_{ADT}<A_{ADT1}$, the wet pavement accident ratio is in the normal acceptable range, so there is no need to take appropriate measures. When $A_{ADT1}<A_{ADT}<A_{ADT2}$, the wet pavement accident ratio is beyond the normal acceptable range, so the small scope measures are considered to reduce the wet pavement accident ratio, when $A_{ADT2}<A_{ADT}<A_{ADT3}$, a large range of measures should be carried out on to reduce the wet pavement accident ratio. When $A_{ADT}>A_{ADT3}$, it is necessary to restrict traffic and take effective measures to make the wet pavement accident ratio less than W_{AR1}.

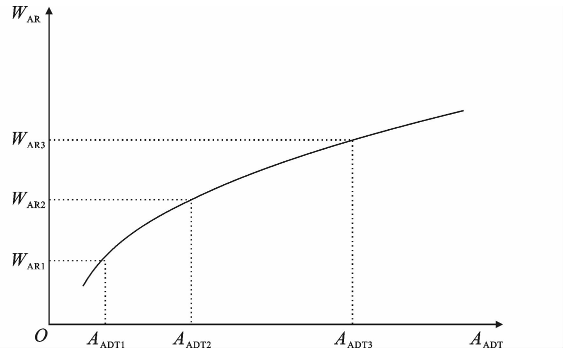

Fig. 2 Thresholds values of A_{ADT} determined by thresholds of W_{AR}

图 2 基于 W_{AR} 阈值的 A_{ADT} 阈值

1.3.3 Thresholds values of wet accident ratio

As shown in Fig. 3, according to *Highway performance assessment standards* (JTG H20—2007), the skid resistance of highway asphalt pavement is classified into five grades. Through the WAR-SFC regression model, the thresholds of wet accident ratio (W_{AR1}, W_{AR2}, W_{AR3}, W_{AR4}) are calculated according to the thresholds of value of the pavement sideway force coefficients (S_{FC1}, S_{FC2}, S_{FC3}, S_{FC4}) corresponding to each grade of the standard. According to *Technical specifications of maintenance for highway* (JTG H10—2009), when $S_{FC}<40$ for highway and the class-I highway, or $S_{FC}<35.5$ for other highways, the corresponding measures should be taken to improve the skid resistance of the road surface.

1.4 Analysis procedure

There are many factors that have influence on wet pavement accident ratio such as traffic volume, skid resistance, alignment, vehicle tire and pavement pollutants. According to many studies, annual average daily traffic (AADT) and skid resistance (SN and SFC) are chosen to analyze their influence on wet accidents, and the analysis includes 3 main steps:

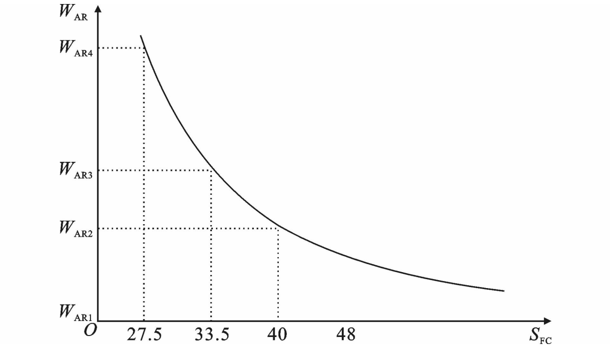

Fig. 3 Thresholds values of W_{AR} determined by thresholds of S_{FC}

图 3 基于 S_{FC} 阈值的 W_{AR} 阈值

(1) Step 1, Data classification

For the purpose to minimize the influence on WAR caused by traffic volume, the traffic volume is divided into different groups to discuss the relationship between skid resistance and WAR in each traffic volume intervals. When quantitative relationships between traffic volume and WAR are determined, the classification of different skid resistance groups is also necessary.

(2) Step 2, Data cluster and regression model

Before quantitative relationships between skid resistance and WAR in different traffic volume, groups are analyzed, the clustering results should be determined according to the within groups sum of squares method in the group and the bootstrap method. Before quantitative relationships between traffic volume and wet accident ratio in different skid resistance groups are analyzed, the clustering results should be determined by the same method.

(3) Step 3, Threshold determination

According thresholds values of WAR, thresholds of SN and AADT are determined by WAR-SN curve and WAR-AADT curve, respectively, and thresholds of SFC are determined by WAR-SFC curve and *Highway performance assessment standards* (JTG H20—2007).

2 America wet accident data analysis

2.1 Data pre-processing

For America data, we choose the Virginia data to clarify the analysis process[5]. And the scatter diagrams between AADT, SN and WAR are plotted as Fig. 4 shows.

Fig. 4 shows that almost all sites with better skid resistance have lower traffic volume. When AADT is more than 6.0×10^4 veh, the SN is less than 40. The reason for this lower skid resistance may be tire polishing effect because of the higher traffic volume. The WAR decrease when SN increase, but the WAR increase with AADT increase.

However, the scatter diagrams could not show quantitative relationship between SN, AADT and WAR. This section will do some research on quantifying the relationship between AADT and WAR based on specific SN groups or the relationship between SN and WAR based on specific AADT groups, for the purpose to reduce wet accident by control traffic volume or increase pavement skid resistance.

2.2 WAR-AADT regression model

2.2.1 SN classification and WAR-AADT curve in Virginia

Before analyzing the influence of AADT on WAR, SN should be classified into several groups. And then the WAR-AADT curve can be got for each SN group. It's worth to say that the skid re-

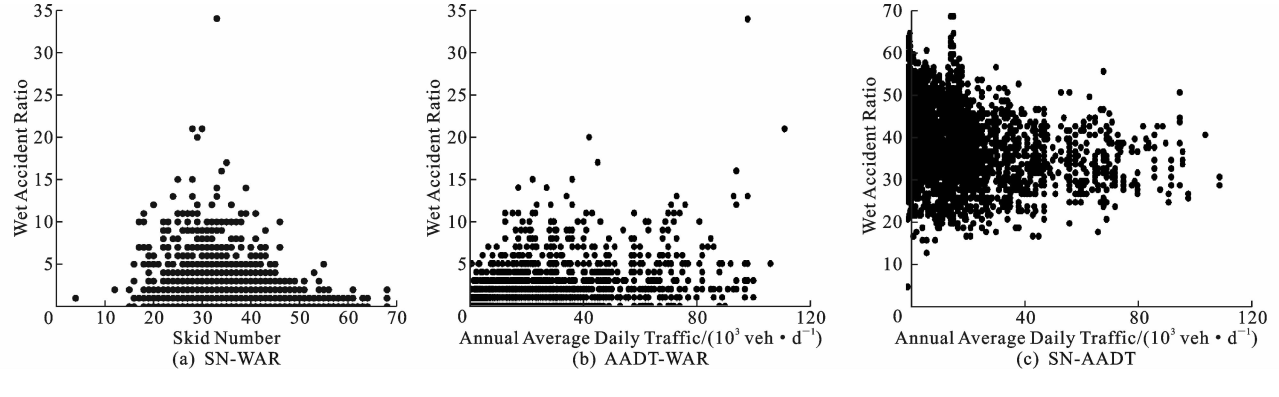

Fig. 4 Scatter diagrams between AADT, SN and WAR

图 4 AADT、SN 与 WAR 散点图

sistance in Virginia is expressed by skid number (SN), and the measuring method is lock wheel trailer method at a speed of 64 km/h with smooth tire. Quantifying the relationship between AADT and WAR in the 6 SN groups and getting WAR-AADT curve shown in Fig. 5 as following.

Fig. 5 shows that the WAR will increase when AADT increase in all SN groups. Compared with the WAR-AADT regression curves in different SN groups, the higher the pavement skid resistance, the smaller the slope of the curve. It means that the increase ratio will be smaller with the AADT increase, when the pavement skid resistance is good.

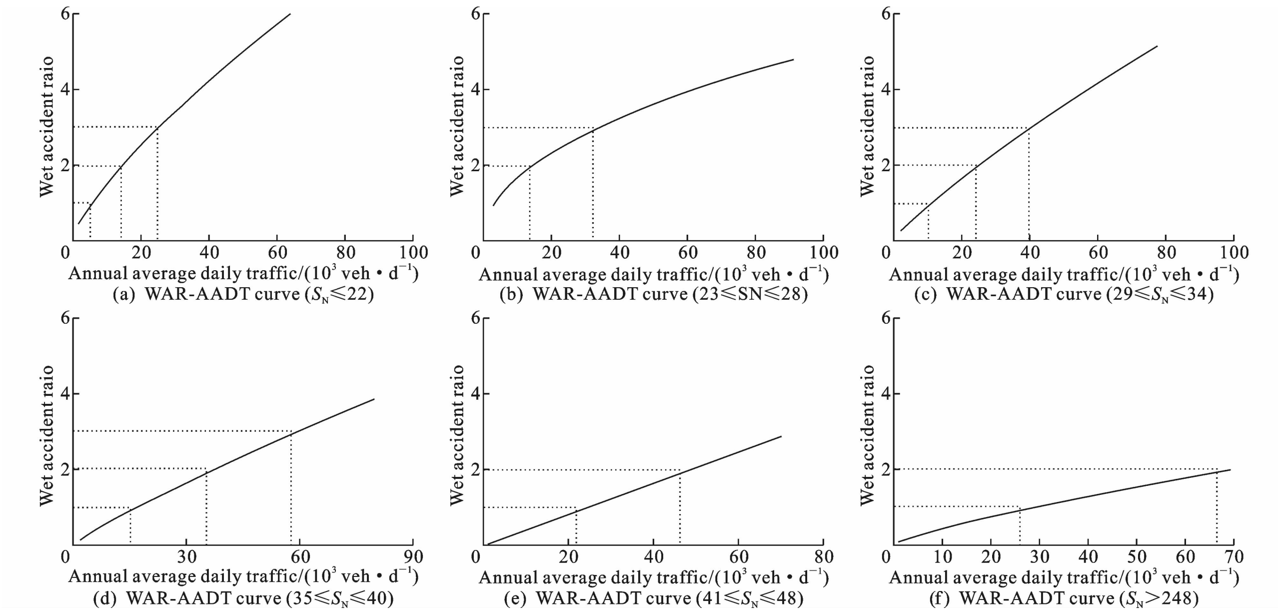

Fig. 5 WAR-AADT Curves

图 5 WAR-AADT 曲线

2.2.2 Thresholds of annual average daily traffic

According to the three thresholds values of WAR ($W_{AR1}=1.05$, $W_{AR2}=2.0$ and $W_{AR3}=3.0$), the threshold of A_{ADT} (A_{ADT1}、A_{ADT2} and A_{ADT3}) could be got easily by WAR-AADT curves. The A_{ADT1}、A_{ADT2} and A_{ADT3} in 6 SN groups are shown in Tab. 1. As Tab. 1 shows that the A_{ADT1}, A_{ADT2} and A_{ADT3} are ranging from 6 500 to 33 000, 15 000 to 85 000, 26 000 to 150 000 in different SN groups Ⅰ to Ⅵ, respectively.

Tab. 1 Thresholds values of AADT in different SN groups

表 1 不同 SN 等级 AADT 阈值 veh • d^{-1}

SN group	$AADT_1$	$AADT_2$	$AADT_3$
Ⅰ	6 500	15 000	26 000
Ⅱ	8 200	17 000	36 000
Ⅲ	10 000	25 000	42 000
Ⅳ	16 000	38 000	65 000
Ⅴ	22 000	52 000	89 000
Ⅵ	33 000	85 000	150 000

2.3 WAR-SN regression model

2.3.1 AADT classification and WAR-SN regression model

Firstly, AADT are classified into several groups for minimizing the influence caused by traffic volume, and then WAR-SN curve in different AADT groups will be obtained for research on relationship between SN and WAR.

According to within group sum of squares method and K-means clustering algorithm, the AADT is divided into 4 groups. The WAR-SN curves are obtained as Fig. 6. The Fig. 6 shows that WAR decrease sharply when SN increase at the beginning, and the decrease ratio decrease until WAR become stable value finally. For different AADT groups, the change trends of WAR and SN in different traffic volume groups are coincident, but for same SN, if traffic is heavy, the WAR is greater than light traffic, which means there is requirement for higher skid resistance to reduce wet pavement accident ratio when traffic is heavy.

2.3.2 Threshold values of skid number

According to $W_{AR1}=1.05$、$W_{AR2}=2.0$、$W_{AR3}=$

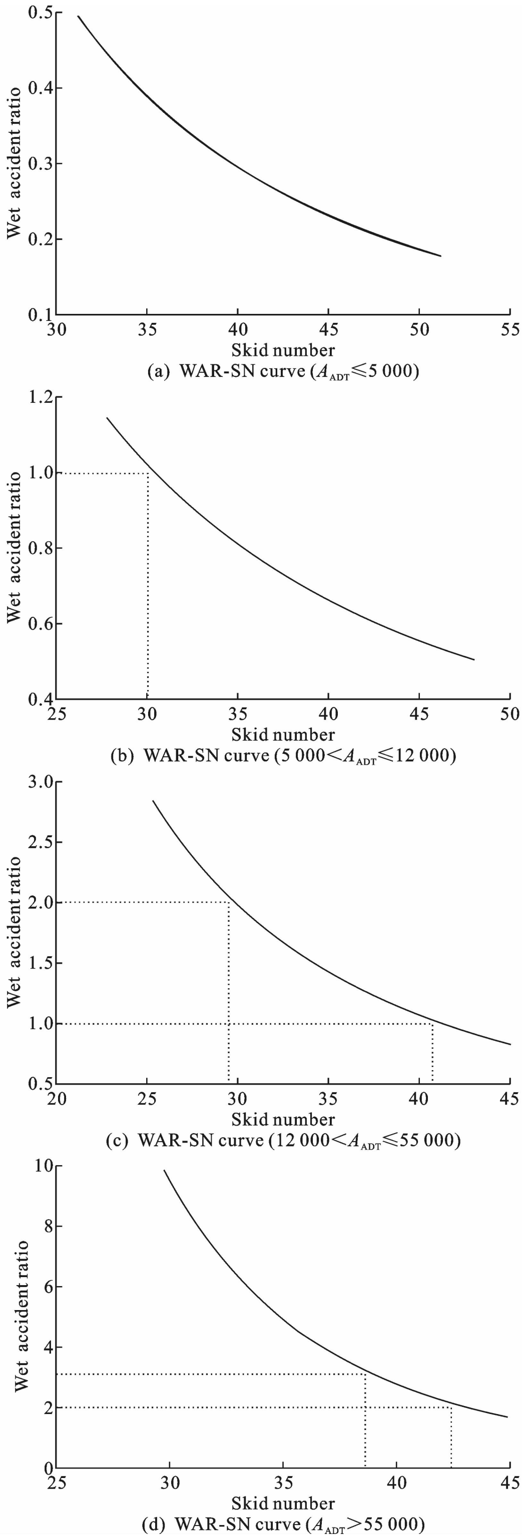

Fig. 6 WAR-SN Curves

图 6 WAR-SN 曲线

3.0 and WAR-SN curves, we can get S_{N1}、S_{N2} and S_{N3} and the results are shown in Tab. 2. It shows that the ranges of S_{N1}、S_{N2} and S_{N3} are 33 to 53, 29 to 45 and 27 to 41 in 4 AADT groups(Ⅰ～Ⅳ), respectively.

Tab. 2 Thresholds values of SN in different AADT groups

表 2 不同 AADT 等级 SN 阈值

AADT groups	SN_1	SN_2	SN_3
Ⅰ	33	29	27
Ⅱ	35	31	28
Ⅲ	38	35	33
Ⅳ	53	45	41

3 China wet accident data analysis

3.1 Data pre-processing

The investigation data include WAR, SFC and AADT. As the SFC is recorded in different section of the road and the AADT is for the road, so we just to find the quantitative relation between SFC and WAR. The scatter diagram is shown in Fig. 7. From Fig. 7 we just know that as SFC increases, WAR will decrease, but the mathematical relationship between SFC and WAR can't be got. Therefore, a cluster method will be applied to get the regression model.

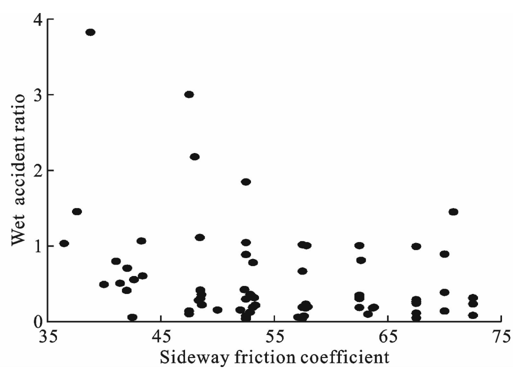

Fig. 7 Scatter diagrams between SFC and WAR

图 7 SFC 与 WAR 散点图

3.2 WAR-SFC curve

Firstly, AADT is classified into 2 groups and then WAR-SFC curve will be obtained. According to Fig. 8, WAR decrease gradually as SFC increase, and at the beginning, when pavement skid resistance is poor, the decrease ratio reduce sharply and the ratio gradually become slow until WAR is stable.

According to *Highway performance assessment standards*(JTG H20—2007), the threshold of sideway force coefficient are 27.5, 33.5, 40 and 48 to classify the highway skid resistance into 5 grades. We can get thresholds values of WAR (W_{AR1}、W_{AR2}、W_{AR3}、W_{AR4}) in different pavement

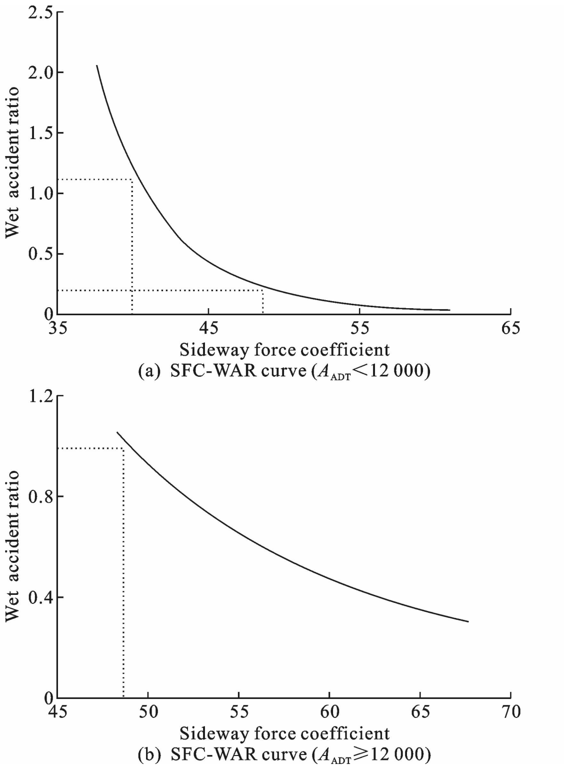

Fig. 8 SFC-WAR curves

图 8 SFC-WAR 曲线

skid resistance as Tab. 3 shows. According to *Technical specification of maintenance for highway* (JTG H10—2009), the SFC threshold for skid resistance maintenance involved in highway or class-I highway is 40. Combining with the regression results and the requirements of skid resistance maintenance, the wet accident ratio is 0.905 when traffic is light, while the ratio is 2.814 when the traffic is heavy. The values mean that there should be an improvement on the threshold of skid resistance maintenance to ensure the safety of the road if the traffic is heavy.

Tab. 3 WAR for different skid resistance groups

表 3 不同防滑等级 WAR 值

Class(SFC values)	W_{AR}	
	A_{ADT}<12 000	A_{ADT}≥12 000
Excellent(≥48)	(0, 0.529]	(0, 1.394]
Good(40～48)	(0.529, 0.905]	(1.394, 2.814]
Medium(33.5～40)	(0.905, 1.524]	(2.814, 5.575]
Bad(27.5～33.5)	(1.524, 2.722]	(5.575, 11.930]
Poor(<27.5)	(2.722, +∞)	(11.930, +∞)

4 Discussion

In section 2, we give the WAR-AADT regression model in different SN groups and WAR-SN regression model in different AADT groups. According to different WAR, the thresholds of AADT and SN are obtained. In section 3, according to WAR-SN regression model, the thresholds of WAR are got.

The optimal state is that there is no wet traffic accident per kilometer, which means WAR should be no more than 1. For the purpose to compare the recommended maintenance value of skid resistance between China and America, the skid resistance of $W_{AR}=1$ is calculated and analyzed. The calculated value is defined as the recommended value of pavement skid resistance maintenance. If there is timely skid resistance on the pavement when the pavement skid resistance is below the recommended value, the pavement will be safety for driving. In order to make the recommended maintenance values of skid resistance between China and America comparable as the skid resistance indexes are different, we use conversion formula between SFC and SN to convert SN into SFC[18]. The conversion results are shown in Tab. 4.

Tab. 4 Comparisons of recommended maintenance values of skid resistance between China and America

表 4 中美防滑养护推荐值对比

Traffic	SFC for America	SFC for China
Light traffic	52 to 53	40
Heavy traffic	55 to 64	52

Tab. 4 shows that, the China recommended maintenance value of SFC is 40 when the traffic volume is light, while the value is 52 for heavy traffic. For America data, the recommended maintenance value of SFC is 52 to 53 and 55 to 64 for light and heavy traffic, respectively. It is obvious that the America recommend maintenance values are much higher than China, which will provide adequate safety to reduce wet accident. However, it isn't necessary to improve the skid resistance when WAR is stable, whether the America recommended value exceed the value or not, there should be deeper research on this problem.

5 Conclusion

(1) As for the influence of AADT on WAR involved in America data, WAR increase and the

increase ratio reduce gradually when AADT increase. And thresholds values of AADT are from 6 500 to 150 000 for different SN groups.

(2) SN is used to measure pavement skid resistance in Virginia. WAR decreases sharply firstly with SN increase and then the decrease ratio become slow gradually until WAR is stable. And thresholds values of AADT are from 27 to 53.

(3) Sideway force coefficient (SFC) is chosen to indicate the pavement skid resistance in China. As SFC increase, the WAR decrease, but the decrease ratio become slow gradually and finally come to stable level. WAR is 0.905 and 2.814 for light traffic (A_{ADT}<16 000) and heavy traffic (A_{ADT}≥16 000) respectively and the suggestion SFC is 52.

(4) When traffic is light, China recommended maintenance value of SFC is 40 and America recommended maintenance value of SFC is 52 to 53. The ranges of recommended maintenance value for China and America are 52 and 55 to 64, respectively. It is obvious that America recommend maintenance value is much higher than China, which will provide adequate safety to reduce wet accident.

(5) However, time and intensity of rainfall are not considered because of the limited conditions in this paper. In the future research, rainfall factors(such as time, intensity, water film and so on) will be fully considered, the results will have better regional applicability.

Acknowledgments

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