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Application of Fuzzy Synthesis Evaluation to Driving Safety Analysis of Sharp Curves on Mountain Expressways

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Abstract: Facing with widespread dangerous sharp sections on the mountainous expressways, the fuzzy synthesis evaluation for driving safety analysis of sharp curves on mountainous expressways was employed in order to analyze the risk extents in different sections of mountainous expressways and provide a reference for road designers and safety managers. The influences of road alignment, driving speed and proportions of vehicle types were taken into account. Critical adhesion coefficient and load transfer ratio were respectively considered as evaluation index of passenger cars and large trucks, and simulation analysis method was used to get the specific values of the evaluation indexes. The influence factors and their weight vectors were determined with the orthogonal experiment method, then the regression model of evaluation indexes was got. Considering different proportions of passenger cars and trucks and different driving speeds simultaneously, the method of fuzzy synthesis evaluation was used to analyze the data, and finally risk extents in sections were obtained. The results show that driving speed and circular curve radius are the most important factors which endanger the driving safety; when the expressways have the same alignment, the higher the proportion of passenger cars, the greater the possibility of traffic accidents; the method of fuzzy synthesis evaluation can achieve a higher accuracy in the risk extent analysis and ranking of the sharp sections. This method can provide theoretical basis for the designers to modify the road alignment and for road safety managers to improve the efficiency of capital utilization.

Key words: road engineering; risk analysis; fuzzy synthesis evaluation; horizontal curve sections; safety analysis

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山区急弯路段行车安全性模糊综合评判分析方法

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摘要:为了分析山区高速公路不同路段危险性大小,给设计人员和道路安全管理人员提供参考,针

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对普遍存在危险的山区高速公路急弯路段,考虑道路线形、行驶速度、车型占比等因素的影响,进行了急弯路段行车安全性模糊综合评判的研究。分别以临界附着系数和荷载转移比作为小客车、大货车评价指标,采用仿真分析的方法得到评价指标具体数值,运用正交试验的方法确定影响因素及其权重向量,并得到评价指标的回归模型,在考虑小客车、大货车实际行驶速度不同以及车型占比不同的情况下,运用模糊综合评判的方法对数据进行分析,最终得到路段危险性大小。研究结果表明:行驶速度和圆曲线半径大小是影响行车安全的最主要因素;当高速公路线形相同时,小客车车型占比越高,发生交通事故的可能性越大;使用模糊综合评判的方法对急弯路段危险性大小进行分析和排序准确性较高,该方法可为设计人员修改道路线形,以及道路安全管理人员提高资金利用效能提供理论依据。

关键词:道路工程;风险分析;模糊综合评判;平曲线路段;安全性分析

0 Introduction

According to the *Statistics Yearbook of China in 2014*, expressway mileage in China has reached 111 900 km, making it the longest in the world; however, due to bad driving behaviors of drivers and complicated highway configurations, traffic accidents have occurred frequently. Road accident statistics of China in 2010 showed that one of the main causes of traffic accidents was over speeding, accounting for 11.4% of the total number of accidents. Furthermore, driving on curve sections ranked second to over speeding, accounting for 10.5% of accidents. Consequently, much more funds should be invested in expressway safety management. Actually, the funds available are insufficient to support the large number of needed improvements, presenting decision-makers a problem that requires immediate solutions.

The prime and critical steps for improving transportation safety are identifying, grading, and ranking dangerous sharp curves. Effati et al. [1] put highway parameters of potentially dangerous sections and accident data into a geographic information system (GIS) and used point estimate method to establish fuzzy membership functions of evaluation criteria. Agarwal et al. [2] divided potentially dangerous sections into linear segments, curve segments, and intersections and identified the factors that affected the safety of each section. Shu et al. [3] investigated the application of GIS technology in the expressway emergency rescue system and built a GIS-based expressway emergency assistant decision support system to provide a reference and basis for expressway planning, design, and management. Li et al. [4] designed and developed a traffic guidance decision support system that combined GIS with highway traffic conditions by GIS visualization and spatial information processing technology, integrated computer software technology and traffic engineering theory.

There are also considerable researches provided by Chinese scholars in identifying dangerous sections, thereby assisting decision-making. However, results generated by the methods from these previous studies relied heavily on actual accident data. For instance, on the basis of traffic investigation and rear-ended data collection, Meng et al. [5] identified rear-end collision risk on expressway work zone and its prominent influencing factors. Zhao et al. [6] used driving violation type and accident statistics in 2006 to investigate risk sources classification and assessment relating to regional highway traffic accident casualty. However, accident database in China is not perfect; in addition, due to the limited funds available for security management, the government can only invest in urgently needed improvements in dangerous sections. Therefore, classifying dangerous sections by risk without depending on accident statistics avoids the error resulting from inaccuracy of traffic accident data. Moreover, decision-makers can use the outcome to find dangerous sections that need urgent improvements so as to facilitate safety management and efficiency of capital utilization.

1 Fuzzy Comprehensive Evaluation Method

The essence of fuzzy comprehensive evaluation model is divided into the objects of study according to some certain basis and these objects are sorted according to their merits.

Supposing fuzzy vector A can be expressed as

$$A=(a_{11},a_{12},\cdots,a_{1k})^{\mathrm{T}} \tag{1}$$

where a_{1k} ($k=1,2,\cdots,p$) corresponds to the weights of different influence factors u_k and $a_{11}+a_{12}+\cdots+a_{1k}=1$.

Considering the values of different factors in the evaluation sets, $\boldsymbol{R}_i$ is the single factor i evaluation matrix, which has p rows and m columns. Therefore the following matrix can be obtained

$$\boldsymbol{R}_i=\begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & & \vdots \\ r_{p1} & r_{p2} & \cdots & r_{pm} \end{bmatrix}_{p\times m} \tag{2}$$

where arbitrary value r_{kj} represents the proportion of kth factor in item j of the evaluation sets.

In summary, the comprehensive evaluation of the ith object of study is

$$J_i=A\circ\boldsymbol{R}_i=(c_{1j})_{1\times m}=[\bigvee_{k=1}^{p}(a_{1k}\wedge r_{kj})]_{1\times m} \tag{3}$$

where $j=1,2,\cdots,m$; $A\circ\boldsymbol{R}_i$ represents that A compounds $\boldsymbol{R}_i$; $\vee$ and $\wedge$ are Zadeh operators, for any of a and b value lies between 0 to 1, "$a\vee b$" is defined as a larger value of a and b, and "$a\wedge b$" is defined as a smaller value of a and b.

In the above formula, the comprehensive evaluation G_i is obtained by normalizing J_i, and the coefficient matrix of the normalized comprehensive evaluation is defined as Y[7].

It is noticed that the results generated by the above calculation methods are a set of comprehensive evaluation coefficients. In accordance with the sizes of the coefficients, the objects can be sorted.

2 Determination of Influencing Factors and Weights

On a flat road, the centripetal force is purely caused by the lateral friction acting on the wheels. If the limit of adhesion between the road surface and wheels is not exceeded, a slip angle is presented between the path of the vehicle and the direction in which the tires are pointing[8]. For slip angles exceeding 5°, maximum cornering forces for most street tires are induced, and controlling the vehicle is difficult at high speed[9]. By making curves higher on the outer edge-known as superelevation-vehicles can maintain control when getting through sharper curves at high speeds because of the extra centripetal force induced by the slant. The addition of precipitation also influences driving control as the thin layer of moisture reduces friction and thereby the limit of adhesion[10]. Finally, vehicles which have a high center of gravity are subject to the effects of crosswind, which increases lift and applies a lateral force to these vehicles; at high speeds, sideslip occurs, leading to accidents[11].

2.1 Determination of Influencing Factors

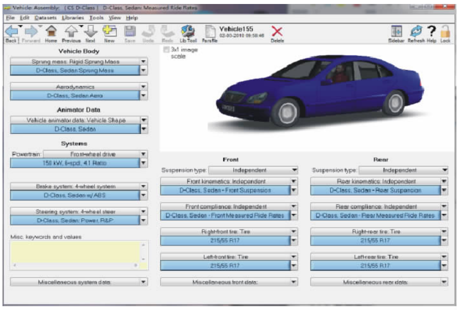
2.1.1 Determination of Influencing Factors for Passenger Cars

Zhang et al.[12] considered driving speed and highway conditions by taking the critical adhesion coefficient μ (the absolute value of the maximum ratio of the lateral force experienced by each wheel of vehicle to the vertical force) as the evaluation index. CarSim software was used to build the driver, vehicle and road models, as shown in Tab. 1 and Fig. 1.

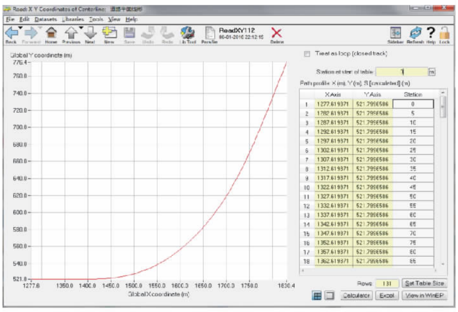
Tab. 1 Main Parameters of Test Passenger Car

表 1 试验所用小客车车型的主要参数

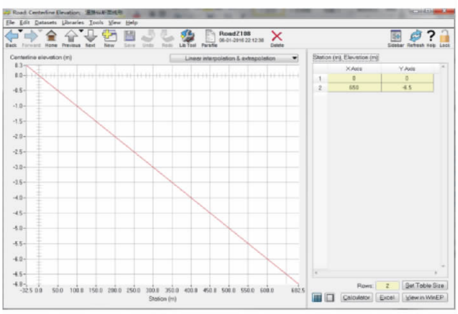
Models	Parameters	Value
Appearance	Total Mass/kg	1 530
	Mass Center Height/mm	540
	Length×Width×Height/mm	4 350×1 795×1 550
Engine	Maximum Power/W	125
	Gear	6
	Gear Ratio	4∶1
Braking	Front/Rear Wheel Maximum Braking Force/(N·m·MPa^{-1})	600/400
	Sliding Rate when Launching ABS	0.2
Steering	Kingpin Inclination Angle/(°)	10
	Kingpin Caster Angle/(°)	3
	Castor Trail/mm	8
Suspension	Un-sprung Mass/kg	100
	Tread/mm	1 475
Tire	Tire Size	215/55R17
	Maximum Load/N	6 500



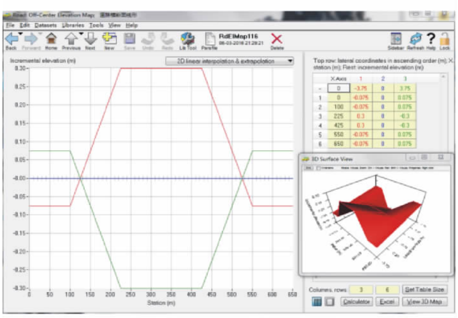
(a) Interface of Vehicle Model



(b) Interface of Horizontal Alignment Settings



(c) Interface of Longitudinal Alignment Settings



(d) Interface of Cross Alignment Settings

Fig. 1　Interface of CarSim

图 1　CarSim 界面

Then, the output data will be analyzed with the method of orthogonal design to obtain the results of deviation and variances. The F-values of driving speed v, curve radius R, cross slope α are 0.241 805, 0.269 906, 0.025 730 respectively. It shows that the F-values of v and R are similar, where the F-value of v is over 20 times larger than that of α, clearly indicating that v and R more significantly affect the critical adhesion coefficient μ than α. The regression equation of critical adhesion with speed and highway parameters was obtained

$$\mu=\frac{0.014\,4v^2}{R}-0.031\,2\cos(\alpha)+0.093\,6,$$
$$r^2=0.96 \tag{4}$$

where r^2 represents correlation index.

Ji[10] used regression analysis based on measured data to obtain regression equations between water film thickness and rainfall intensity. The regression equations between highway adhesion coefficient and water film thickness are merged into one equation between rainfall intensity and highway adhesion coefficient

$$\psi=0.945\,8-0.005\,7v-$$
$$0.000\,7l^{0.613\,4}\alpha^{-0.313\,3}q^{1.448\,3},r^2=0.88 \tag{5}$$

where ψ represents highway adhesion coefficient; l represents slope length; q represents rainfall intensity.

The sharp curves studied in this paper commonly exist in mountainous regions, hence the design speed is set as 80 km • h^{-1}, and the standard value of the corresponding half of highway surface width is set as 12.25 m. The value of highway surface width is related to α, so they can be treated as one factor. Referencing the data processing method developed by Zhang et al. [12], 3 groups of data are selected for driving speed v, composed slope α, and rainfall intensity q, which are presented in Tab. 2. The regression analysis results are presented in Tab. 3. The minimum limited radius is 250 m and the common minimum radius is 400 m, so sections whose radii are 250 m and 400 m can be seen as sharp curves. Although the curve whose radius is 600 m is not a representative sharp curve, it had a relationship with the curves whose radii are 250 m and 400 m, which is listed in Tab. 2.

In the light of Tab. 3, the influence of driving speed v is 100 times more than that of rainfall intensity q, and approximately 170 times more than that of the composed slope α. The effect of q and α on the highway adhesion coefficient ψ is insignificant. Therefore, only driving speed and circular

Tab. 2 Factors and Levels Table for Passenger Car

表 2 小客车因素及水平表

Levels	1	2	3
Driving Speed $v/(\text{km}\cdot\text{h}^{-1})$	60	80	100
Curve Radius R/m	250	400	600
Composed Slope α/%	4.12	6.71	9.43

Tab. 3 Analysis Results of Deviation and Variance Based on Road Adhesion Coefficient ψ

表 3 基于路面附着系数ψ的离差及方差分析结果

Factors	v	q	α
Sum of Squares S	0.078 452	0.000 259	0.000 005
Freedom	2	2	2
F-value	30 368	303	2

curve radius have a significant impact in theory.

Vehicles can easily experience sideslip when moving on sharp curves. The sideslip occurs when the critical adhesion coefficient μ is larger than the highway adhesion coefficient ψ. According to the analysis results in Tab. 2 and Tab. 3, the main factors that affect the critical adhesion coefficient μ are driving speed v and curve radius R. Meanwhile, the main factor that affects the highway adhesion coefficient ψ is driving speed v. Therefore, both driving speed v and curve radius R are selected as influence factors.

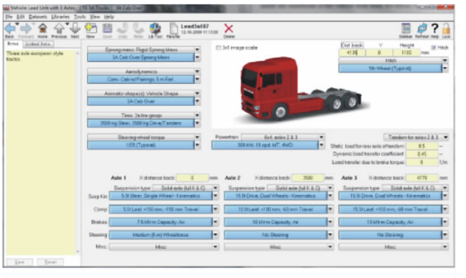
2.1.2 Determination of Influencing Factors for Trucks

When trucks move on curve sections, higher driving speeds lead to the reduction of inside load in vertical direction, and the medial load transfers to the outside. When the inside vertical force of the load drops below 0, trucks can't maintain balance in the roll plane, causing it to rotate around the axis of the lateral tire contact point, which leads to rollover accidents[13]. The ratio of load transfer L_{TR}, which can be used as an evaluation index, is given as follows

$$L_{TR}=\left|\frac{F_1-F_w}{F_1+F_w}\right| \tag{6}$$

where F_1 and F_w represent the sums of vertical forces of the inside and outside wheels at the moment of rotation respectively. When trucks move on straight sections, the forces on the inside and outside wheels are equivalent obviously. So the L_{TR} is 0. However, when trucks move on curved sections, the force on their inside wheels decreases while the force on the outside wheels increases. If the force on the inside wheels is 0, the L_{TR} is 1 and the truck is unstable.

Mirroring the analysis method used earlier for passenger cars, trucks dynamics simulation software TruckSim was utilized to build the vehicle (shown in Fig. 2), driver and road models (same as CarSim). In recent years, linear monomer trucks have not been able to meet the requirements of heavy loads under high speeds. In the year of 2011, the 6-axle semi-trailer freight turnover ratio has reached 58.22%[14]. Therefore, Liberation CA4250P66K2T1E type tractor and Huajun ZCZ9402HJD type semi-trailer were chosen as test vehicle models, packed with a total weight of 49 t and a rated load of 34.5 t. By testing the vehicle total loads under different conditions, the major parameters were obtained, as shown in Tab. 4.



(a) Interface of Vehicle Model

(b) Interface of Semitrailer Model

Fig. 2 Interface of Vehicle Model

图 2 车辆模型界面

After that, the influence of driving speed as well as those curve radius, crosswind and super-elevation relating to driving risks of trucks moving on sharp curves of mountain expressways is needed to be analyzed. According to the Design Specification for Highway Alignment[9] and the Dictionary

Tab. 4　Main Parameters of Test Truck

表 4　研究所用大货车车型的主要参数

Models	Parameters	Value
Appearance	Number of Axles	6
	Wheel Base (distance of front axle)/m	0/3.50/1.27/1.93/2.20/1.20
	Vehicle Length/mm	13 768
	Un-sprung Mass (front/rear)/kg	570/690
Steering System	Kingpin Inclination Angle	7.2
	Kingpin Caster Angle	5.2
Suspension	Front Axle Plate Spring Stiffness/($N \cdot mm^{-1}$)	250
	After 2 Coupling Plate Spring Stiffness/($N \cdot mm^{-1}$)	700
	After Joint Shaft Plate Spring Stiffness/($N \cdot mm^{-1}$)	2 500
	Front Axle Damping Coefficient/($N \cdot s \cdot mm^{-1}$)	15
	After 2 Coupling Damping Coefficient/($N \cdot s \cdot mm^{-1}$)	30
	After Joint Axis Damping Coefficient/($N \cdot s \cdot mm^{-1}$)	30
Tire	Tire Size	11.00R20
	Maximum Load/N	1 000 000

of Atmospheric Science[14], 3 sets of data were selected for each aspect, as shown in Tab. 5. In this table, at crosswind speeds of 0.36, 15.84, 44.28 $km \cdot h^{-1}$, the wind scales are 0, 3, 6 respectively.

Tab. 5　Factors and Levels Table for Trucks

表 5　大货车因素及水平表

Levels	1	2	3
Driving Speed v/($km \cdot h^{-1}$)	60	80	100
Curve Radius R/m	250	400	600
Crosswind Speed v_K/($km \cdot h^{-1}$)	0.36	15.84	44.28
Super-elevation e/%	6	8	10

This test simultaneously considers four unique factors. In addition, the interaction of driving speed and circular curve radius should be taken into account since there is a linear relationship between centripetal forces and the square of driving speed divided by the curve radius. Therefore, there are five influencing factors in total. If the 3 groups of data as shown in Tab. 2 were used, a significant amount of data would be produced when analyzing the five effect factors. Therefore, a $L_{27}(3^{13})$ orthogonal table was selected and orthogonal design was used to reduce the amount of necessary data. Taking the 27 groups of data into the TruckSim simulation, the output data was processed to retrieve the maximum L_{TR} values under each data set which were used as the orthogonal design values. The analysis results are shown in Tab. 6.

Tab. 6　Analysis Results of Deviation and Variance Based on L_{TR}

表 6　基于 L_{TR} 的离差及方差分析结果

Factors	v	R	v_K	e	Rv	Error
Sum of Squared Residuals S	0.320 696	0.290 626	0.000 217	0.006 594	0.051 031	0.000 568
Degree-of-freedom	2	2	2	2	4	14
F-value	131	119	0.1	5	46	
Significance	Significant	Significant	Non-significant	Non-significant	Significant	
Critical Value	$F_{0.01}(2,10)\approx 10$	$F_{0.01}(2,10)\approx 10$	$F_{0.01}(2,10)\approx 10$	$F_{0.01}(2,10)\approx 10$	$F_{0.01}(2,10)\approx 10$	

In the Tab. 6, as for importance, according to value of residuals, the factors that affected L_{TR} (from strong to weak) are driving speed, circular curve radius, the interaction between driving speed and circular curve radius, super-elevation, and crosswind speed. Furthermore, the F-values of driving speed v_K, circular curve radius, the interaction of driving speed and circular curve radius are bigger than the critical values, but those of crosswind speed and super-elevation are smaller than the critical value. Therefore, only driving speed and circular curve radius have a significant impact in theory, which means that cross wind speed and super-elevation effects are not significant.

Simultaneously, quantitative data is needed to be analyzed. However, only 27 groups of discrete data were used, making it difficult to get quantitative analysis results. So a regression model is needed to be formulated. The regression equation between the L_{TR} and influencing factors can be expressed as

$$L_{TR}=f(v,R,e,v_K) \tag{7}$$

L_{TR} is obtained from multi-factor analysis in MATLAB for regression analysis using the 27 groups of data

$$L_{TR}=-15.2174+0.0168\frac{v^2}{R}+15.2291\cos(e)+0.0002v_K, r^2=0.88 \tag{8}$$

2.2 Determination of Weight

Weight represents an index of overall relative importance. To research the importance of driving speed v and curve radius R on driving safety, F-value was used as an index to judge the significance of the factors.

2.2.1 Weights for Under Passenger Cars

The ratio of F-values for driving speed v to curve radius R is 1.116 2 : 1. By using this as the ratio of weights with the fact that the sum of the weights must be 1, the weight vector $A_C=(0.5275, 0.4725)^T$ is obtained.

2.2.2 Weights for Under Trucks

In Tab. 6, the ratio of F-value for driving speed v to curve radius R is 1.103 5 : 1. Similarly to that for passenger cars, the weight vector $A_T=(0.5246, 0.4754)$ is obtained.

3 Determination of Judgment Set

A judgment set is a collection of the total evaluation results that are made by judgers for the objects to be evaluated. Thus, driving risks in sharp curves could be ranked using a judgment set, which could then be applied to fuzzy synthesis evaluation. Therefore, the judgment set for driving speed v and circular curve radius R must be determined.

3.1 Judgment Set for Passenger Cars

The risks for passenger cars moving on sharp curves can be graded according to critical adhesion coefficient μ and road adhesion coefficient ψ, as follow

$$z_C=\frac{\psi-\mu}{\psi} \tag{9}$$

where z_C is the danger classification of passenger car, the danger level is divided into 8 categories with 0.2 as the gradient. Fewer categories would prevent successful determination of influence, while more categories would make the single factor evaluation matrix analysis difficult to be used. Taking 0.2 as the gradient for the reason that it can equally divide the interval $[-0.8, 0.8]$ into 8 portions, most possible situations can be included. The final dangerous classification is as follows: Grade 1, $z_C\in(0.6, 0.8]$; Grade 2, $z_C\in(0.4, 0.6]$; Grade 3, $z_C\in(0.2, 0.4]$; Grade 4, $z_C\in(0, 0.2]$; Grade 5, $z_C\in(-0.2, 0]$; Grade 6, $z_C\in(-0.4, -0.2]$; Grade 7, $z_C\in(-0.6, -0.4]$; Grade 8, $z_C\in(-0.8, -0.6]$;

Grade 1, 2, 3, 4 show dangerous situations and Grade 5, 6, 7, 8 show security situations.

3.2 Judgment Set for Trucks

The risk for trucks moving on sharp curves can be graded according to the load transfer ratio L_{TR}

$$z_T=0.5-L_{TR} \tag{10}$$

where z_T is the danger classification of truck with a threshold value of 0.5—the danger level is divided into 8 levels with 0.1 as the gradient. The threshold value is based on the fact that when the value of L_{TR} is 1, truck slip is likely to risking driving safety. Trucks driving safety can be ensured by selecting a threshold value with a safety factor of 0.5. Therefore, the final danger classification is as follows: Grade 1, $z_T\in(0.3, 0.4]$; Grade 2, $z_T\in(0.2, 0.3]$; Grade 3, $z_T\in(0.1, 0.2]$; Grade 4, $z_T\in(0, 0.1]$; Grade 5, $z_T\in(-0.1, 0]$; Grade 6, $z_T\in(-0.2, -0.1]$; Grade 7, $z_T\in(-0.3, -0.2]$; Grade 8, $z_T\in(-0.4, -0.3]$.

Grade1, 2, 3, 4 show dangerous situations, Grade 5, 6, 7, 8 show security situations.

4 Determination of Evaluation Matrix and Dangerous Sections Risk Ranking

4.1 Single Factor Evaluation Matrix

The single factor evaluation matrix refers to the grade standards following a judgment set in accordance with a particular method of determining the probability of each classification zone of influence caused by the single factor. Although the probability is random, there are still laws to follow; thus, a large number of sample points need to be analyzed. When the samples are more than 50 points, they can be considered to be large-samples. For passenger cars, the influences of rainfall intensity and composed slope are negligible, so the constant values of 0.05 mm • $\min^{-1}$ (drizzle) and 4.12% (4% superelevation and 1% longitudinal slope) are taken, respectively; for trucks, the influences of crosswind speed and superelevation are negligible, so the constant values of 0.36 km • h^{-1} and 6% are taken, respectively. Tab. 7 indicates the range of factors for the cases of passenger cars and trucks.

Tab. 7 Factor Value-taken Strategies for Passenger Cars and Trucks

表 7 小客车、大货车因素取值策略

No.	Driving Speed $v/(\mathrm{km \cdot h^{-1}})$	Curve Radius R/m
1-1	60	250,255,…,495
1-2	80	250,255,…,495
1-3	100	250,255,…,495
2-1	56,57,…,105	250
2-2	56,57,…,105	350
2-3	56,57,…,105	450

Tab. 8 and Tab. 9 contain the final probabilities. Those statistical values describe the frequencies with which z_C falls within each grade interval. In the light of Tab. 8 and Tab. 9, 9 sets of probabilities are selected to constitute a single factor evaluation matrix for passenger cars.

Tab. 8 Probability of Each Risk Level with Various Driving Speeds for Passenger Cars

表 8 小客车车型下不同行驶速度时每种风险等级发生概率

Driving Speed $v/(\mathrm{km \cdot h^{-1}})$	Probability of Risk at Grade 1 to 8
60	0.82,0.18,0,0,0,0,0,0
80	0,0.40,0.46,0.14,0,0,0,0
100	0,0,0,0.14,0.36,0.24,0.18,0.08

The final probabilities for trucks are contained in Tab. 10 and Tab. 11. From Tab. 10 and Tab. 11, 9 sets of probabilities of data are selected to constitute a single factor evaluation matrix for trucks.

Tab. 9 Probability of Each Risk Level with Various Curve Radii for Passenger Cars

表 9 小客车车型下不同圆曲线半径时每种风险等级发生概率

Curve Radius R/m	Probability of Risk at Grade 1 to 8
250	0.02,0.24,0.18,0.12,0.12,0.10,0.08,0.14
350	0.18,0.24,0.18,0.14,0.12,0.10,0.04,0
450	0.28,0.26,0.20,0.14,0.12,0,0,0

Tab. 10 Probability of Each Risk Level with Various Driving Speeds for Trucks

表 10 大货车车型下不同行驶速度时每种风险等级发生概率

Driving Speed $v/(\mathrm{km \cdot h^{-1}})$	Probability of Risk at Grade 1 to 8
60	0.86,0.14,0,0,0,0,0,0
80	0,0.62,0.34,0.04,0,0,0,0
100	0,0,0.38,0.30,0.22,0.10,0,0

Tab. 11 Probability of Each Risk Level with Various Curve Radii for Trucks

表 11 大货车车型下不同圆曲线半径时每种风险等级发生概率

Curve Radius R/m	Probability of Risk at Grade 1 to 8
250	0.02,0.24,0.20,0.18,0.16,0.16,0.04,0
350	0.24,0.28,0.24,0.20,0.04,0,0,0
450	0.40,0.32,0.28,0,0,0,0,0

4.2 Comprehensive Evaluation and Normalization

9 sets of single factor evaluation in comprehensive evaluation matrices are considered for passenger cars and trucks. Then the comprehensive evaluation values are normalized to guarantee that the sum of comprehensive evaluation is 1. The final normalized results for passenger cars and trucks are shown in Tab. 12 and Tab. 13, respectively.

4.3 Risk Ranking in Dangerous Sections

As shown in Tab. 12 and Tab. 13, the probability of risk varies with driving speed v and circular curve radius R, by which the dangerous highway conditions can be analyzed. However, it is difficult to visually analyze dangerous highway conditions merely using normalized comprehensive evaluation. Hence, it is necessary to quantify the judgment set, which determines the normalized coefficients of comprehensive evaluation matrix.

Tab. 12 Normalized Synthesis Evaluation Results for Passenger Cars

表 12 小客车车型下归一化的综合评判结果

Test Sections	$v/(\mathrm{km \cdot h^{-1}})$, R/m	Comprehensive Evaluation by Grade 1 to 8
1	60,250	0.35,0.16,0.12,0.08,0.08,0.07,0.05,0.09
2	60,350	0.39,0.18,0.13,0.10,0.09,0.07,0.03,0
3	60,450	0.42,0.21,0.16,0.11,0.10,0,0,0
4	80,250	0.01,0.27,0.32,0.10,0.08,0.07,0.05,0.10
5	80,350	0.13,0.28,0.32,0.10,0.08,0.07,0.03,0
6	80,450	0.20,0.28,0.33,0.10,0.09,0,0,0
7	100,250	0.01,0.17,0.12,0.09,0.24,0.16,0.12,0.09
8	100,350	0.11,0.15,0.11,0.09,0.23,0.15,0.11,0.05
9	100,450	0.16,0.15,0.11,0.08,0.21,0.14,0.10,0.05

Tab. 13 Normalized Synthesis Evaluation Results for Trucks

表 13 大货车车型下归一化的综合评判结果

Test Sections	$v/(\mathrm{km \cdot h^{-1}})$, R/m	Comprehensive Evaluation by Grade 1 to 8
1	60,250	0.35,0.16,0.13,0.12,0.11,0.10,0.03,0
2	60,350	0.41,0.22,0.19,0.15,0.03,0,0,0
3	60,450	0.47,0.28,0.25,0,0,0,0,0
4	80,250	0.01,0.37,0.24,0.13,0.11,0.11,0.03,0
5	80,350	0.18,0.39,0.25,0.15,0.03,0,0,0
6	80,450	0.31,0.40,0.26,0.03,0,0,0,0
7	100,250	0.01,0.18,0.28,0.22,0.16,0.12,0.03,0
8	100,350	0.16,0.18,0.25,0.20,0.14,0.07,0,0
9	100,450	0.23,0.19,0.22,0.17,0.13,0.06,0,0

Then, the weighted average of the evaluation results is needed. Although the purpose of determining the coefficient matrix is to rank dangerous highways, the coefficient matrix may vary as long as it can be ensured that the differences between the different risk ratings are equal to the corresponding values. 9 comprehensive evaluation values are obtained for passenger cars and trucks by taking the 9 respective groups of comprehensive evaluation values for the coefficient matrices $\boldsymbol{Y}_{\mathrm{C}}$ and $\boldsymbol{Y}_{\mathrm{T}}$ of passenger cars and trucks, which are selected as $(0.03, 0.06, 0.08, 0.11, 0.14, 0.17, 0.19, 0.22)^{\mathrm{T}}$ according to size. The results of this process for passenger cars and trucks are shown in Tab. 14 and Tab. 15, respectively.

As shown in Tab. 14 and Tab. 15, the comprehensive evaluation coefficients of each group in 1 to 3, 4 to 6, and 7 to 9 have a downward trend, while

Tab. 14 Ranking of Dangerous Sections for Passenger Cars

表 14 小客车车型下危险路段排序

Test Sections	Comprehensive Evaluation Value
1	0.091 3
2	0.075 3
3	0.063 8
4	0.107 3
5	0.085 4
6	0.072 4
7	0.134 0
8	0.120 4
9	0.114 0
Risk Ranking	7,8,9,4,1,5,2,6,3

Tab. 15 Ranking of Dangerous Sections for Trucks

表 15 大货车车型下危险路段排序

Test Sections	Comprehensive Evaluation Value
1	0.081 8
2	0.061 4
3	0.050 9
4	0.095 8
5	0.069 5
6	0.057 4
7	0.106 2
8	0.089 1
9	0.083 0
Risk Ranking	7,4,8,9,1,5,2,6,3

the driving speed of each group remains unchanged, and the curve radius keeps increasing. In contrast, the comprehensive evaluation coefficients of groups 1 to 3, 4 to 6, and 7 to 9 show an upward trend, of which driving speed in a group gradually increases. The most dangerous section has a driving speed of 100 km·h^{-1} and a curve radius of 250 m; the safest section has a driving speed of 60 km·h^{-1} and a curve radius of 450 m. Therefore, traveling at higher speeds through narrower curves is more dangerous. The tendencies in Tab. 14 and Tab. 15 are reasonably consistent with the reality.

5 Auxiliary Decision-making for Passenger Cars and Trucks

As mentioned above, the use of fuzzy comprehensive evaluation method to investigate driving risk for passenger cars and trucks provides some logical conclusions. However, this analysis assumes that the driving speed ranges of passenger cars and trucks are the same, which turns out to be not true. The purpose of taking the same value was to verify the accuracy of fuzzy comprehensive evaluation; therefore, the differences in operating speeds of passenger cars and trucks are needed to be considered. In addition, the complex distributions of Chinese vehicle types on expressways, and the proportions of passenger cars and trucks are not identical; therefore, the effect of vehicle type is required to be considered.

5.1 Effect of Operating Speeds

In 2008, Fu[15] measured the operating speeds for different curve radii and vehicle types when the design speed is 80 km·h^{-1}. Parts of these results of operating speed under different curve radii are given in Tab. 16.

Tab. 16 Theoretical Operating Speed Values at Design Speed of 80 km·h^{-1}

表 16 设计速度为 80 km·h^{-1}的理论运行速度值

Curve Radius R/m	Operating Speed of Passenger Cars v_C/(km·h^{-1})	Operating Speed of Trucks v_T/(km·h^{-1})
250	76.9	76.9
300	80.6	80.0
350	84.0	80.0
400	87.2	80.0
450	90.1	80.0

Operating speed refers to the speed that intermediate skilled drivers can safely maintain control of vehicles under the conditions of good weather, and actual highway and traffic conditions[16]. Therefore, the values of V_{85} for passenger cars and trucks are set as Tab. 16.

Regarding passenger cars, the minimum speed is 60 km·h^{-1}; the maximum speed is 120 km·h^{-1}, and V_{85} is column 2 listed in Tab. 16; for trucks, the minimum speed is 60 km·h^{-1}; the maximum speed is 100 km·h^{-1}, and V_{85} is column 3 listed in Tab. 16. Tab. 17 and Tab. 18 show the listed probabilities of risk for passenger cars and trucks respectively under actual conditions.

The comprehensive evaluation matrix for single factor evaluation is computed and normalized to the comprehensive evaluation values. The final normalized results are presented in Tab. 19 and Tab. 20.

Tab. 17 Probability of Each Risks Level with Different Curve Radii for Passenger Car Under Actual Conditions

表 17 实际情况下小客车不同圆曲线半径下每种风险等级发生概率

R/m	Probability of Risk at Grade 1 to 8
250	0,0.45,0.40,0.02,0.02,0.02,0.01,0.08
300	0.05,0.50,0.30,0.03,0.02,0.02,0.01,0.07
350	0.17,0.44,0.25,0.02,0.03,0.02,0.02,0.05
400	0.24,0.40,0.22,0.03,0.03,0.02,0.02,0.04
450	0.30,0.37,0.19,0.04,0.02,0.03,0.02,0.03

Tab. 18 Probability of Each Risks Level with Different Curve Radii for Truck Under Actual Conditions

表 18 实际情况下大货车不同圆曲线半径下每种风险等级发生概率

R/m	Probability of Risk at Grade 1 to 8
250	0,0,0.43,0.43,0.05,0.06,0.03,0
300	0,0.09,0.55,0.25,0.07,0.04,0,0
350	0,0.30,0.55,0.09,0.06,0,0,0
400	0,0.49,0.41,0.09,0.01,0,0,0
450	0,0.68,0.25,0.07,0,0,0,0

Tab. 19 Normalized Synthesis Evaluation Results for Passenger Cars Under Actual Conditions

表 19 实际情况下小客车归一化的综合评判结果

I	R/m	Comprehensive Evaluation
1	250	0,0.45,0.40,0.02,0.02,0.02,0.01,0.08
2	300	0.05,0.49,0.31,0.03,0.02,0.02,0.01,0.07
3	350	0.17,0.44,0.25,0.02,0.03,0.02,0.02,0.05
4	400	0.24,0.40,0.22,0.03,0.03,0.02,0.02,0.04
5	450	0.30,0.37,0.19,0.04,0.02,0.03,0.02,0.03

Tab. 20 Normalized Synthesis Evaluation Results for Trucks Under Actual Conditions

表 20 实际情况下大货车归一化的综合评判结果

J	R/m	Comprehensive Evaluation
1	250	0,0,0.43,0.43,0.05,0.06,0.03,0
2	300	0,0.10,0.51,0.27,0.08,0.04,0,0
3	350	0,0.32,0.52,0.10,0.06,0,0,0
4	400	0,0.48,0.42,0.09,0.01,0,0,0
5	450	0,0.60,0.31,0.09,0,0,0,0

5.2 Effect of Vehicle Type

Obviously, the distribution of vehicle types varies for each expressway and time of day; therefore, the influence should be considered. A comprehensive evaluation that considers vehicle types obeys the following formulae

$$G'_{IJ}=A'_{1k}G''_{IJ} \quad (11)$$

$$A'_{1k}=(a_1,a_2) \quad (12)$$

where I, J is the row number of Tab. 19 and Tab. 20 respectively; a_1 and a_2 represent the proportions of passenger cars and trucks types, respectively, and $a_1+a_2=1$. Here, the proportions of passenger cars and trucks are divided into 21 groups, each group with a 5% gradient, being 100% and 0%, 95% and 5%, etc.; G''_{IJ} is a comprehensive evaluation matrix which is combined from the ith row in Tab. 19 and the jth row in Tab. 20.

5.3 Evaluation Coefficient Model Considerations of Passenger Cars and Trucks

G'_{IJ} was normalized to obtain normalized fuzzy comprehensive evaluation results that considered the vehicle types of passenger cars and trucks. As a reminder, there are 5 groups with each group having 21 normalized fuzzy comprehensive evaluation values.

The coefficient matrix is selected considering passenger cars and trucks as $(0.03, 0.06, 0.08, 0.11, 0.14, 0.17, 0.19, 0.22)^T$. 105 discrete data in 5 groups is used to establish the regression model, which can be expressed as

$$M=f(R,x) \quad (13)$$

where M represents the comprehensive evaluation coefficient; x represents the proportion of passenger cars.

Using MATLAB to perform the regression analysis of the 105 data, the following regression equation is obtained

$$M=-0.000\,135R-0.007\,414x+0.132\,115, r^2=0.93 \quad (14)$$

The comprehensive evaluation coefficient decreased as the curve radius increased, indicating that wide corners pose less risk. For a fixed curve radius, the comprehensive evaluation coefficient decreased as the proportion of passenger cars increased, indicating that low truck traffic poses less risk. Therefore, the comprehensive evaluation coefficient had an inverse relationship with both curve radius and proportion of passenger cars.

6 Conclusions

(1) The factors that might have an impact on sideslip of vehicles on sharp turns sections are analyzed based on fuzzy synthesis evaluation and statistics knowledge with a combination of two mathematical models. The result indicates that only driving speed and circular curve radius will have a significant impact on sideslip of vehicles on sections with sharp turns.

(2) The regression model was developed based on regression coefficient value. The degrees of risk on different sections can be judged by employing this regression model, which have a practical function in assisting decision-makers to make decisions.

(3) In this reaseach, the danger of sharp turn sections at a design speed of 80 km·h^{-1} was studied, without considering the cases of other design speeds. At the same time, it only considers a single circular curve, and reverse curves, complex circular curves and other factors in actual highway are not considered. In the next phase of study, such situations should be taken into account in order to improve the conclusions.

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2015 年度中国公路学会科学技术奖颁奖大会在西安召开

2016 年 6 月 12 日，2015 年度中国公路学会科学技术奖颁奖大会在西安召开，此次共颁发特等奖 5 项、一等奖 18 项、二等奖 69 项、三等奖 70 项。

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