Research Article

Crash-Prone Section Identification for Mountainous Highways Considering Multi-Risk Factors Coupling Effect

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In order to identify crash-prone sections of the highways in mountainous areas professionally and exclusively, the common phenomena of "sharp turns", "continuous long downhill", "multiple tunnels", "dangerous roadside environment", and complex and changeable meteorological environment, which all imply risk factors of the mountainous highways, are comprehensively considered. Utilizing the improved classical coupling model, the coupling mechanism of the risk factors is revealed, and the coupling model of the traffic risk factors is constructed, by which the coupling degrees of multi-risk factors couplings are calculated respectively. Based on the coupling degrees of the above factors, the concept of vehicle operation risk index (*VORI*) of the mountainous highway is introduced and its numerical value is quantified as the basis for identifying the crash-prone sections. The 21 km of Songming to Huize section of the Songdai Highway in the Yunnan Province of China is selected as an example, and the good applicability of the identification model is verified.

1. Introduction

The highways in the mountainous regions in China have been remarkably improved with the rapid development of economy and society. However, because of the special geometrical and meteorological environment in the mountainous areas, multi-risk factors coupling effect occurs frequently on the same section, such as the coupling effects among the factors like "sharp turns", "continuous long downhill", "dangerous roadside environment", "high proportion of bridges and tunnels", the complicated and ever-changing meteorological environmental conditions, etc. [1]. Due to the limitation of terrain conditions in the mountainous areas, "sharp turns", "continuous long downhill", and "multiple tunnels" exist commonly and the definitions of them can be seen in Table 1. "Dangerous roadside environment" refers to the phenomena including the roadside safe distance being lower than the required distance, or dangerous objects existing within the safe distance, or unreasonable installation of roadside safety facilities [2]. "Dangerous roadside environment" is common on mountainous highways, and it is easy to result in fatal crashes like falling off a cliff or falling into a river [3]. The climate affected by the

high and various altitudes results in variations of all aspects of climate such as temperature, humidity, precipitation, and wind within a short distance and time [4]. Coupling effect refers to the phenomenon that in one common system, more components than one interact with each other or are associated with each other [5]. Mountainous highway traffic risk system is a complex and changeable dynamic system affected by the interactions of many risk factors described above with coupling effects [6]. Generally speaking, a single risk factor will not bring failure to the whole system, that is, unable to lead to the occurrences of crashes. However, when multiple risk factors are associated with each other or interact with each other, a series of errors will occur among the system, and it is easy to lead to the occurrences of crashes [7]. When the multi-risk factors on the mountainous highways occur at the same time or at the same site, the coupling effect occurs. The coupling effects can increase the harmfulness of the risk factors [8]. The total number of crashes, the severity of the crashes, and the loss of property in mountainous regions are generally higher than those in other nonmountainous areas [9]. So far, there is a lack of research on the coupling effects among multi-risk factors on mountainous highways, and a lack of

TABLE 1: Detailed information of the 8 risk factors.

Risk factor	Detailed information
Sharp turns	The radius of the circular curve of the highway is less than the minimum limit value of the circular curve corresponding to its designed speed, which can be seen in [11].
Continuous long downhills	The actual average longitudinal slope and slope length meet the definition standard, which can be seen in [12, 13].
Multiple tunnels	The actual length of the tunnel is more than 1000 m, which can be seen in [14].
	The distance between the actual continuous tunnel openings and the highway design speed meets the criteria, which can be seen in [15, 16].
Dangerous roadside environment	The roadside safety distance is lower than the standard requirement, which can be seen in [2].
	There are dangerous objects within the safe distance of the roadside [2].
	There are unreasonable installations of roadside safety facilities [2].
Rain	It is big rain with water film thickness greater than 0.120 mm [17].
Fog	The fog causes that the visibility is less than 200 m [18].
	The fog causes that the road adhesion coefficient is less than 0.4 [19].
Gale	Wind force is 5 and above [20].
Snow	The snow causes that the friction coefficient is less than or equal to 1/7 of dry road surface [21].
	The snow causes that the braking distance of the vehicle is more than 4 times of dry road surface [21].

research on the identification of technology and theory on highway crash-prone sections in mountainous areas [10]. At present, due to the lack of consideration of coupling effect between risk factors above, it is difficult to apply the relevant existing theories and standards of traffic crash-prone sections identification to the mountainous highways generally and exclusively.

Crash-prone section can be described as black spot, crash-prone point or crash-prone location [22]. The general qualitative concept is that in a relatively long period of time (no less than 3 years), the number of crashes in the crash-prone section is much more than other normal sections nearby, or more potential safety risks exist compared with other normal sections, and the quantitative definition of crash-prone section has not yet been unified [23].

As with other normal highway crashes, the highway crash-prone sections in mountainous areas must be highway traffic risk points. The size of the amount of risks reflects the damage degree of highway traffic risks. The amount of risks should be considered in the light of actual risk factors, and different risk factors or multiple risk factors existing at the same time causing that the sizes of the risks to be various. Therefore, crash-prone section identification of the mountainous highways with the multi-risk factors coupling was the objective of this study. The identification of the crash-prone sections in the multi-risk coupling environment of the mountainous highways requires a comprehensive consideration of the coupling mechanism among various risk factors and calculating the coupling degrees of couplings. Then, based on the analysis of the above coupling degrees, the concept and calculation method of vehicle operation risk index (*VORI*) are introduced to measure the magnitude of the risks as a basis for the identification of crash-prone sections.

This article takes it into account that the essence of highway crash-prone section in the mountainous areas is the section with the greater road traffic risks [24]. The difference is that there are much more risk factors in the mountainous highways than in the nonmountainous highways. The 8 mountainous highway risk factors selected for research in this paper

included "continuous long downhills", "sharp turns", "dangerous roadside environment", "multiple tunnels", "rain", "gale", "snow", and "fog", and the detailed description of them can be seen in Table 1. This paper is based on the analysis of the coupling of multiple risk factors, and the coupling degree calculation method of each risk factor coupling is obtained using the classical coupling model. Then the concept and calculation method of *VORI* [25, 26] are put forward as the basis of the crash-prone section identification for mountainous highways. Therefore, it has certain theoretical value and practical significance for identifying the highway crash-prone section in mountainous areas because it considers multi-risk factors coupling effects and this is more in line with the actual driving situation on the mountainous highways.

2. Literature Review

In the aspect of mountainous highways environment, it was found that visibility and rainfall are closely related to the geometric characteristics by analyzing the influence of meteorological condition on road crash risks [27]. Ahmed et al. [4] developed Bayesian hierarchical models to model the crash frequencies on mountainous freeway segments, and they found that mountainous freeway segments with continuous long downhills, sharp turns, and segments with tunnels are more crash-prone along the study section. The research on coupling analysis of highway traffic risks is still in its infancy in China [1]. The influence mechanism of wind, rain and their coupling effect on traffic safety of mountainous expressway had also been analyzed [28]. Based on the mechanical analysis of vehicle and road coupling mechanism, safety guarantee technology of highway section in the mountainous area is studied [29]. It can be seen that the mountainous highway traffic risk and safety problems have already attracted the attention of numerous scholars particularly.

In the identification of highway crash-prone sections in mountainous areas, the main methods for identification of crash-prone sections include crash frequency (CF), equivalent property

damage only crash frequency, crash rate (CR), and empirical Bayesian approach (EB) [30–33]. The advantages and disadvantages of various methods are presented in Table 2 [30–33]. It can be seen that one of the most important and common disadvantage is seldom considering the coupling of multiple risk factors on mountainous highways, and the pertinence for the mountainous highway is not very strong [12]. Another important disadvantage is that large quantity of random road traffic accident data and the corresponding detailed data are needed, and it is difficult to obtain the data or the data are not recorded during the study period in many regions [30, 34]. The method proposed in this research can help improve these aspects.

3. Methodology

3.1. Modeling Idea.
Introducing the concept of *VORI* and its quantification method, then according to the numerical value of the *VORI* to assess the magnitude of the risk, and we can judge whether the mountainous highway crashes happen frequently or not. The concept of *VORI* and its quantitative calculation form can be derived from the coupling degree of the multiple risk elements coupling of mountainous highways based on the improved classical coupling model. Then, in the actual evaluation process, the road section is divided into several small unit highway sections, such as 8 km or 10 km (the average speed of driving on the mountainous highway is about 60 km/h, and 8 km is about the length of 8 minutes' driving). The sum of the existing multiple risk factors coupling degrees of each unit section is calculated, and the mountainous vehicle operation risk index is obtained by dividing the actual kilometers of the unit section. The modeling progress mainly includes three steps of obtaining coupling degree based on classical coupling model. Calculation of *VORI* is based on coupling degree, and hotspot identification is based on the value of *VORI*.

3.2. Model Specification and Limitation.
This paper only considers the highway traffic risks, the multi-risk factors coupling effect and the highway crashes on the mountainous highways, which are caused by the special geometrical conditions of mountainous highways and the adverse and ever-changing weather conditions which will be encountered in the actual driving environment. The risk factors considered in this paper are either directly or indirectly due to the mountainous highways' special geometrical or meteorological factors, and no other relevant factors are considered, such as driver characteristics and vehicle characteristics. The lack of consideration of the risk factors in the aspect of drivers and vehicles is the limitation. However, if the selected road sections that need identifying are generally continuous, the risk factors belonging to the drivers and the vehicles do not affect the final results, especially the error in traffic volume and vehicle proportions can be ignored.

3.3. Modeling Process

3.3.1. Coupling Degrees Based on Classical Coupling Model.
The weight of the index is determined by analytic hierarchy process (AHP) according to the reference of similar research area with complex risk system [35, 36]. Using the 1–9 proportion scale

method, "1" means that i is as important as j, and "9" means that i is more important than j extremely, and the relative importance of the two factors a_{ij} is obtained by comparing the two elements and $a_{ji} = 1/a_{ij}$, and the comparison matrix A can be obtained. Then, the consistency test is used to obtain the consistency ratio (*CR*). Once *CR* is less than 0.1, the resulting comparison matrix satisfies the condition. Then the maximum eigenvalue of the comparison matrix (A) is λ_{max}, and the eigenvector is w, and the normalized vector is the weight of the influencing degree of each risk component. And $A = \left(a_{ij}\right)_{m \times m}$, m is quantity of constituent elements, namely, order of the matrix. Consistency index $CI = (\lambda_{max} - m)/(m - 1)$, and consistency ratio $CR = CI/RI$, and the consistency indicators reference is as summarized in Table 3.

Before the coupling degrees are calculated by coupling degree model, it is necessary to evaluate each risk factor involved in the coupling. This paper uses the improved coupling degree model based on the expert scoring method to quantify the risk factors. Expectation value (E_x), entropy (E_n), and excess entropy (H_e) are used to describe the representative value, measure, and degree of dispersion respectively. $\overline{X}$ is the mean of data sample x_i, and the formulas are as follows:

$$\text{Entropy}: E_n = \sqrt{\frac{\pi}{2}} \frac{1}{n} \sum_{i=1}^{n} |x_i - E_x|, \tag{1}$$

$$\text{Excess entropy}: H_e = \sqrt{S^2 - E_n^2}. \tag{2}$$

The method of expert scoring is used for the merits including simplicity, and consideration of evaluation items that can be quantitatively calculated and those that cannot be quantitatively calculated. So the multi-risk factors coupling effect can be taken into consideration for crash-prone section identification of mountainous highways. Because of the rich experience of the experts' engaging in the relevant field research for numerous years, this method has been used in many similar areas of research with complex risk system like urban rail transit operation risk system [37]. The expert scoring method also has many disadvantages, but according to the current reference of relevant research methods and considering the research objective and the content of this paper, the expert scoring method is selected to carry out this research, and optimizing the research method is one of the most important future research directions. Crash data method is used for the verification of the proposed method. The evaluation matrix of risk components is obtained by expert scoring method [37]:

$$B = \begin{bmatrix} b_{11} & \cdots & b_{1j} & \cdots & b_{1m} \\ \vdots & \ddots & \vdots & \vdots & \vdots \\ b_{i1} & \cdots & b_{ij} & \cdots & b_{im} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ b_{n1} & \cdots & b_{nj} & \cdots & b_{nm} \end{bmatrix}, \tag{3}$$

m represents the quantity of risk components, and n represents the number of expert groups. The element of any row of the

TABLE 2: Advantages and disadvantages of the previous traditional methods for identifying crash-prone sections [30–33].

Method	Advantage	Disadvantage
Crash frequency (CF)	It is the simplest identifying method. It performs better than other methods with more appealing theoretical arguments.	Large quantities of random road traffic accident data are needed, and it is difficult to explain the contributing factors in this manner. Crash count does not always give an unbiased estimate of the long-term expected number of crashes because crash counts can randomly fluctuate during the observation period.
Equivalent property damage only crash frequency	It measures weights crashes according to the severity (fatal, injury and property damage only) to develop a combined frequency and severity score for each site.	Large quantity of random road traffic accident data are needed, and it is difficult for explaining the contributing factors in this manner. Crash count does not always give an unbiased estimate of the long-term expected number of crashes because crash counts can randomly fluctuate during the observation period.
Crash rate (CR)	It normalizes the crash frequency with exposure measured by traffic volume. Road segment traffic volume is measured as vehicle-kilometers travelled for the study period and this method reflects crash risk for the individual road user.	Large quantity of random road traffic accident data and the corresponding traffic volume data are needed, and it is difficult for explaining the contributing factors using this way. Crash count does not always give an unbiased estimate of the long-term expected number of crashes because crash counts can randomly fluctuate during the observation period.
Empirical Bayesian approach (EB)	It can control the random fluctuations in the recorded number of crashes. It can overcome the limitations of the conventional methods by accounting not only for regression-to-the-mean effects, but also for traffic volume changes and for time trends in accident occurrence due to changes over time in factors such as weather, accident reporting practices and driving habits.	Large quantity of random road traffic accident data and the corresponding detailed data are needed as well.

TABLE 3: Consistency index reference.

m	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.89	1.12	1.24	1.32	1.41	1.45

matrix is the result of the evaluation of the m indexes by the same expert, and any column element is the result of the evaluation of the same index by all experts. Supposing that E_{xij} is the expected value under multi-risk factors coupling environment, and A_{ij} and B_{ij} are the upper and lower bounds for the expected value respectively, so the efficacy function (U_{ij}) of the risk factors to the whole traffic risks is:

$$U_{ij} = \frac{E_{xij} - B_{ij}}{A_{ij} - B_{ij}}. \tag{4}$$

It is assumed that the weight of each risk element (w_{ij}) is obtained by AHP, so the ordered contribution degree (U_i) of any risk factor to the whole multiple risk factors coupling environment is:

$$U_i = \sum_{j=1}^{m} w_{ij} U_{ij}. \tag{5}$$

The coupling degree of m risk components is C_m[38]:

$$C_m = \left\{ \frac{U_1 \cdot U_2 \cdot U_3 \ldots U_m}{\left[\prod (U_i + U_j) \right]} \right\}^{1/m}. \tag{6}$$

Coupling degree $C \in [0, 1]$, a rank of coupled states in physics can be obtained: when $C \in [0, 0.3]$, weak coupling; when $C \in [0.3, 0.7]$, moderate coupling; when $C \in [0.7, 1]$, strong coupling.

3.3.2. Calculation and Grade Division of VORI. In the actual calculation process, 24 hours (one day) is used as the time unit. Taking the effects of seasonal changes into account, the total requirements measured by a given section is one year (365 days or 366 days). Assuming that the actual need of highway length to calculate is x km (Generally less than 10 km. The smaller, the more precise, and can reflect the actual situation of highway traffic risks much more accurately. But not less than 500 m in principle, for example, due to the factor such as the definition of long continuous downhill needs long road section as the minimum dimension. Too long length of each section is not conducive to the accuracy of model analysis). In various practical situations, there exists various multi-risk factors couplings, and any coupling degree is C_i, and there are n coupling effects in this section, so the total coupling degree of the whole section is $C_{\text{total}} = \int_o^x C_i d_i$, and the actual *VORI* for a year is:

$$\gamma_{\text{year}} = \begin{cases} \dfrac{C_{total}}{x} = \dfrac{\int_0^x C_i d_i}{x} & \text{if } x \leq 10 \text{ km} \\[3mm] \left(\dfrac{x-10}{10} + 1 \right) \times \dfrac{C_{\text{total}}}{x} = \left(\dfrac{x-10}{10} + 1 \right) \times \dfrac{\int_0^x C_i d_i}{x} & \text{if } 10 < x < 20 \text{ km.} \end{cases} \tag{7}$$

In the actual calculation process, the risk factors of topography and geology are relatively fixed, but the risk factors of meteorological environment are complex and ever-changing. Due to the limitations of the experimental conditions and considering the continuous effect of rain, snow, and ice on the highway surface, this paper chooses 24 hours per day as a time unit.

3.3.3. Hotspot Identification Based on VORI. The identification method of the crash-prone section in this paper is based on the above mentioned *VORI*. The section whose *VORI* is higher indicates that more stealthy and explicit risks and their coupling effects are more dangerous. And in the actual driving behavior, it is easy to result in crashes in mountainous areas, which is the highway crash-prone section. After obtaining a year's actual road *VORI* in Section 3.3.2, divided by the actual number of days in the year, the daily average highway vehicle operation risk index is obtained.

To compare with the actual situation, this paper collected the actual road crash data in the whole section in 2015 (from January 1, 2015 to December 31, 2015), the method of vehicle operation risk index based on multi-risk factors coupling is compared with the common method of calculating the equivalent crash number (*ECN*). The formula of *ECN* is [36]:

$$ECN = K_1 F + K_2 J + CN. \tag{8}$$

Among them, F is the number of deaths; J is the number of the injuries; CN is the number of crashes occurring; K_1 and K_2 are 2 and 1.5, respectively.

4. Case Study and Result Analysis

4.1. Study Area and Data Collection. Because of the special geometrical and meteorological environment and high crash rate, the 21 km of Songming to Huize section of the Songdai Highway in the Yunnan Province of China is selected as an example, as shown in Figure 1. This section is with many narrow roads, long and sharp ramps, and the average longitudinal slope is 3.5%, and the average horizontal slope is 7%, including 3 curved tunnels. It is common that more than 5 crashes occur in one day in this section, which is one of the total sections where more than thousands of people died because of the crashes, since the highway was opened to traffic. More than 120 days are foggy or with agglomerate fog in a year on the section above K70, and heavy rain, sleet, snow, and other extreme weather occur frequently, which lowers the visibility of the section. The actual risk factors, the number of crashes, injuries, and death for the whole section in 2015 are collected and analyzed through data collection and field survey, and 8 risk factors were selected and was combined with the actual situation of the highway. Fourteen experts in the field of road traffic safety were invited to evaluate the risk components by expert scoring questionnaires. Ten of them are associate professors and the other four are professors, and they are all from the South China University of Technology or Kunming University of Science and Technology. All of them have obtained their doctorates in the field of road traffic safety and driver
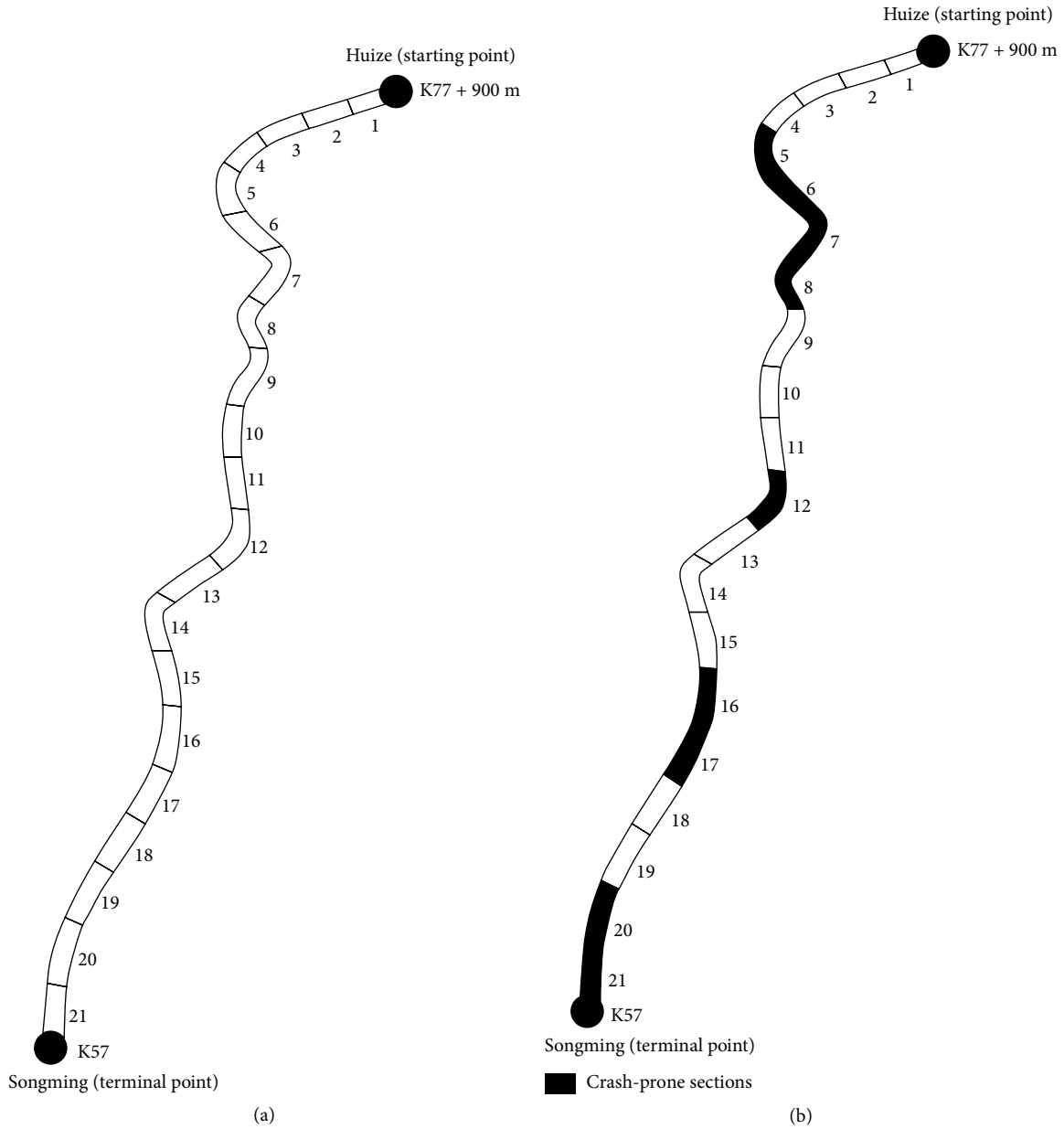
(a)

(b)

FIGURE 1: Identification result of highway crash-prone sections.

behavior. The youngest of them is 35 years old and the oldest is 54. And the risk assessment matrix is:

$$
B = \begin{bmatrix}
7 & 6 & 4 & 6 & 2 & 9 & 1 & 8 \\
8 & 5 & 9 & 6 & 3 & 8 & 1 & 7 \\
7 & 5 & 6 & 4 & 2 & 9 & 1 & 8 \\
7 & 6 & 7 & 5 & 1 & 7 & 2 & 9 \\
6 & 7 & 8 & 5 & 1 & 7 & 3 & 9 \\
6 & 4 & 8 & 4 & 2 & 8 & 1 & 7 \\
8 & 5 & 9 & 3 & 3 & 7 & 2 & 6 \\
8 & 6 & 9 & 4 & 4 & 8 & 3 & 7 \\
7 & 7 & 6 & 3 & 4 & 9 & 2 & 8 \\
7 & 5 & 7 & 2 & 3 & 6 & 4 & 8 \\
6 & 5 & 7 & 3 & 5 & 6 & 1 & 8 \\
6 & 5 & 9 & 5 & 2 & 4 & 3 & 8 \\
9 & 4 & 8 & 4 & 2 & 7 & 1 & 6 \\
9 & 5 & 6 & 4 & 2 & 7 & 1 & 8
\end{bmatrix}. \quad (9)
$$

Based on the risk assessment matrix, the comparison matrix described in Section 3.3.1 can be obtained. Then we carried out consistency test, and obtained $CR < 0.1$. This is consistent with the consistency check described in Section 3.3.1. The coupling degree of the two factors coupling among risk factors is calculated as shown in Figure 2 [38]. The coupling degree means the correlation between the factors and the degree of danger when the coupling effect occurs. The larger the coupling degree is, the more likely the coupling effect will occur and more serious the crash will be.

*4.2. Calculation of **VORI** and the Identification.* The first and essential step in the calculation is road segmentation. In order to ensure the accuracy of the calculation, the highway is divided by the method of fixed length, each 1 km as a section starting at the beginning. Through the calculation results of coupling degrees, the vehicle operation risk index of highways
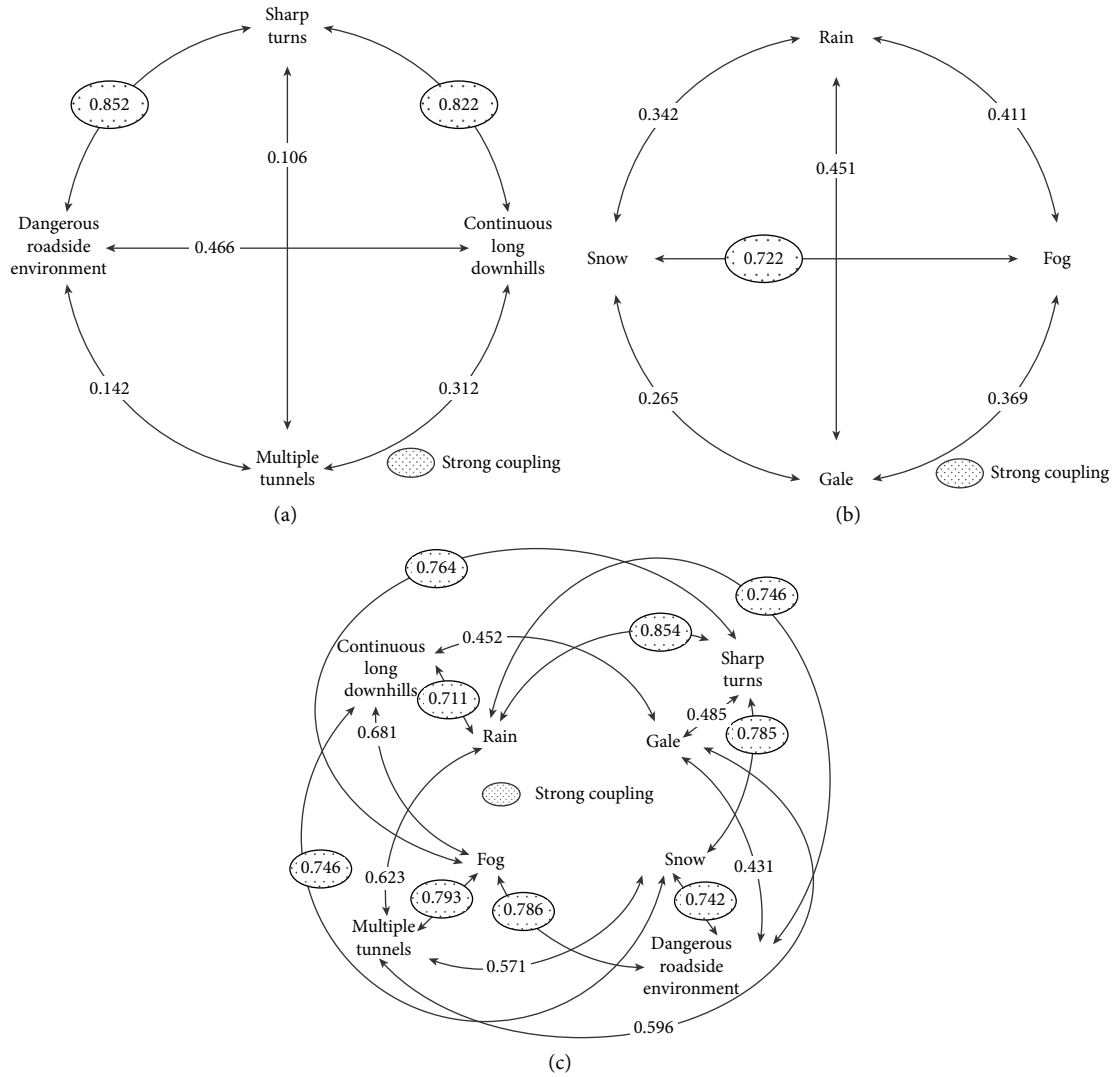
FIGURE 2: Distribution of coupling degrees of two factors coupling effects among risk factors.

is substituted by the actual risk factors of each section. The actual length of each selected sections is 1 km, so the total coupling degree and the highway vehicle operation risk index value are equal. The road section with a *VORI* larger than 1000 is identified as a crash-prone section, and the result is shown in Figure 1.

The coupling degrees of the multi-risk factors coupling and the actual highway vehicle operation risk index of the 21 sections are obtained as shown in Figure 3. Identification line 1 means the identification method proposed in this article, and the sections above the line are recognized as crash-prone sections. Identification line 2 means the identification method of *ECN*, which is used for comparison with the proposed methods for verification. Because the selected 21 km is a continuous section, the error in traffic volume and model proportion can be negligible [39].

The relationships between the values of γ_{year} and *ECN* corresponding to the 21 research sections and the fitted line can be seen in Figure 4. Figures 3 and 4 shows that the obtained values by using the two kinds of crash-prone section identification methods are highly correlated. Moreover, the results of

the two identification methods (If $\gamma_{year} > 1000$ or *ECN* > 10, the crash-prone sections) are basically consistent, which verifies the reliability and applicability of the proposed method.

5. Conclusion

A method of identifying crash-prone sections is proposed, which takes the common geometrical and meteorological risk factors of the mountainous highways into account. Based on the coupling degree of coupling of multiple risk factors, the concept of *VORI* of mountainous highway is derived and quantified, which is used as the basis for identifying the crash-prone sections. The 21 km of the Songming to Huize section of the Songdai Highway with high crash rate in the Yunnan Province of China is selected as an example, and the calculation result is comparatively validated with the method of *ECN*. The obtained values by using the two kinds of crash-prone section identification methods are highly correlated and the identification results are basically consistent, which verifies the reliability and applicability of the method proposed in this paper. Because of consideration of
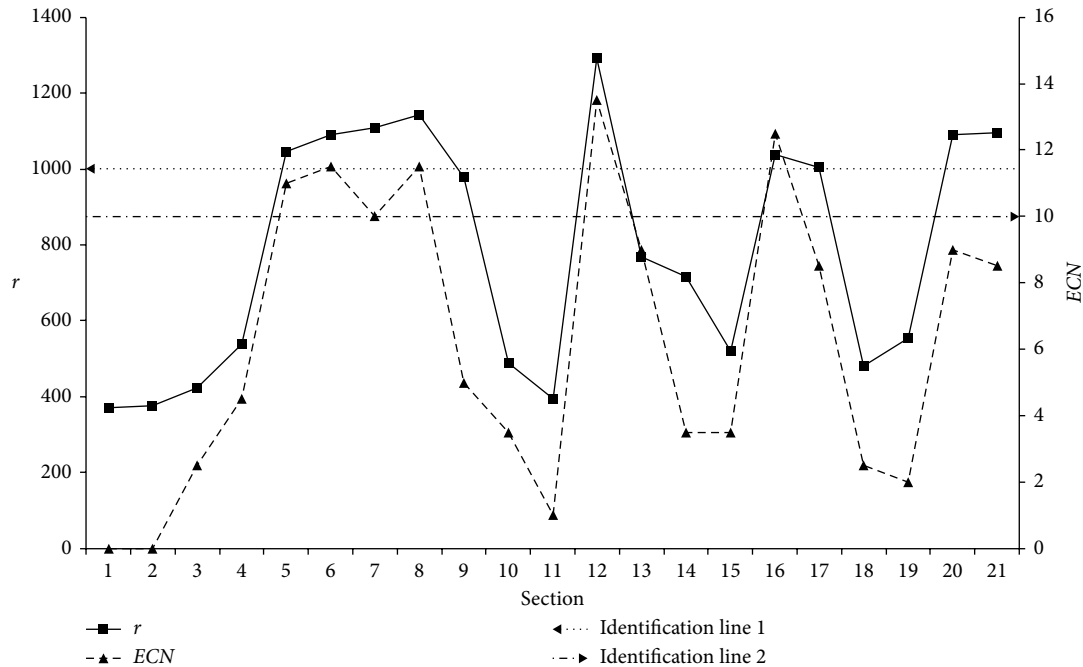
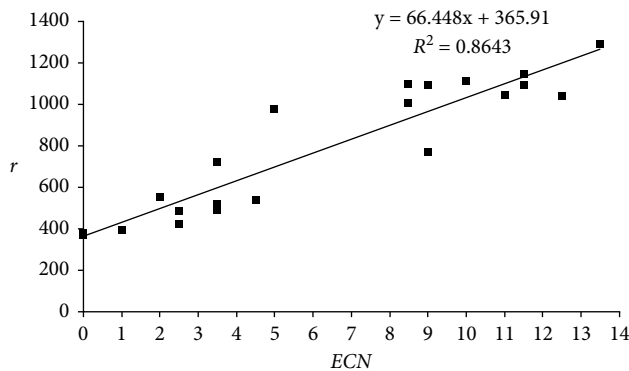FIGURE 3: Identification and validation of crash-prone sections.

FIGURE 4: The relationships between the values of r and ECN corresponding to the 21 research sections.

multiple risk factors, the proposing method can be used for the identification of crash-prone sections in mountainous areas accurately. Based on the quantitative research method of mountainous highway traffic risk and crash-prone section identification proposed in this paper, highway traffic risks in mountainous areas can be classified and managed according to the coupling degree between the risk factors. In order to decrease the risks or improve the crash-prone sections, we can prevent the coupling effects of high coupling degrees from occurring.

Data Availability

"The evaluation matrix of risk components obtained by expert scoring method" data used to support the findings of this study are included within the article. "The actual road crash data in the 21 km of Songming to Huize section of the Songdai Highway in Yunnan Province of China in 2015 (from January 1, 2015 to December 31, 2015)" data used to support the findings of this study are currently under embargo while the research findings are commercialized. Request for data, 12 months after publication of this article, will be considered by the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interests regarding the publication of this paper.

Acknowledgments

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