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Identification Method of Highway Accident Prone Sections Under Adverse Meteorological Conditions Based on Meteorological Responsiveness

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Abstract: To mitigate the prevalence of highway accidents in Southwest China during adverse weather conditions, this study introduces a novel method for identifying accident-prone sections in complex meteorological circumstances. The technique, anchored in data mining's support index, pioneers the concept of meteorological responsiveness, which includes the elucidation of its mechanisms and the development of computational methodologies. Historical meteorological data and accident records from mountainous highways were meticulously analyzed to quantify the spectrum of adverse weather impacts on driving risks. By integrating road geometry, weather data, and accident site information, meteorological events were identified, categorized, and assigned a meteorological responsiveness score. Outlier sections were processed for preliminary screening, enabling the identification of high-risk segments. The Meteorological Response Ratio Index was instrumental in highlighting and quantifying the influence of adverse weather on traffic safety, facilitating the prioritization of critical sections. The case study of the SC2 highway in Southwest China validated the method's feasibility, successfully pinpointing eight high-risk sections significantly affected by adverse weather, which constituted approximately 19.05% of the total highway length. Detailed analysis of these sections, especially those impacted by rain, fog, and snow, revealed specific zones prone to accidents. The meteorological responsiveness method's efficacy was further substantiated by correlating accident mechanisms under adverse weather with the road geometry of key sections. This approach stands to significantly enhance the safety management of operational highways.

Keywords: road engineering; adverse weather; risk identification; safety assessment; physical element analysis method

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1. Introduction

Since the 1980s, the scale of China's highway network has expanded rapidly, with the annual mileage increasing. According to the "2022 Statistical Bulletin on the Development of the Transportation Industry" [1], China's highway mileage has reached 177,300 km, ranking first globally. However, while highways offer efficient and convenient services, they also bring high accident and mortality rates, as well as substantial property losses. Traffic accident statistics and related research on highways [2] have indicated that adverse weather conditions are one of the main factors affecting traffic safety on highways. Therefore, reducing the impact of adverse weather on road traffic safety has significant theoretical and practical engineering value.

The impact of adverse weather on traffic safety dates back to the 1970s with studies on the daily variation of accident numbers under different weather conditions on California's highways [3,4]. Research on the impact of weather on road safety mainly focuses on three aspects: ① Keith [5] first compared the personal injury accident situations between rainy and non-rainy days, concluding the relationship between rainy days and a high number of accidents, thus introducing the concept of the relationship between weather and road traffic accidents. Zhu Xinglin et al. [6] analyzed the relationship between traffic accidents and meteorological factors and established a warning level for traffic safety meteorological factors, and on this basis, determined the weight coefficients using the entropy method and fuzzy matter-element. ② In research on the impact of various weather characteristics on road safety, Baker et al. [7] collected and analyzed data on vehicle accidents caused by strong winds during storms in the UK, studying the impact of various weather characteristics on road safety. Shi Maoqing [8] qualitatively analyzed the impact of various adverse weather conditions such as rain, snow, and fog on traffic safety and proposed a mechanism for preventing traffic accidents. Pan Yaying et al. [9] combined climatic characteristics to analyze traffic accidents within Lishui City and established a relationship between rainfall, snow depth, and wind speed with the occurrence of traffic accidents. ③ The coupling effect of different weather characteristic indicators and other factors on road traffic safety was analyzed. By comparing the personal injury accident situations between rainy and non-rainy days, Shankar et al. [10] explored the frequency of road accidents through multivariate analysis of road geometry, weather, and other factors. Zhang Chi et al. [11] analyzed the driving risk of passenger cars on flat curve sections in rainy and speeding conditions, exploring the dynamic water pressure on car tires under different water film thicknesses and speeds. Zhao Liang et al. [12] conducted research on the relationship between driver physiological responses and driving safety in three driving environments: clear, rainy, and snowy. Li Xiaolei et al. [13] comprehensively considered the coupling of fog with rain, snow, ice, and other complex factors, introduced the "field" theory, and constructed a risk field model for fog areas on highways.

Moreover, surrogate safety approaches have been increasingly utilized to identify likely crash-prone locations and improve overall road safety [14–17]. In the identification of accident-prone sections, Fan et al. [18] proposed that the core of identifying accident-prone sections mainly lies in: ① the selection of identification indicators; ② the determination of threshold values for identification indicators. Foreign countries first introduced the accident number method, including the absolute accident number method and the equivalent accident number method [19], followed by the quality control method [20], accident rate method [21], safety factor method [22], cumulative frequency curve method [23], and other methods for identifying accident-prone sections. Wright et al. [24] were the first to validate the effectiveness of various accident black spot identification methods and, based on the results of the effectiveness validation, proposed some suggestions to improve the quality of accident black spot identification methods, laying the foundation for subsequent research on the identification of accident-prone sections. Miranda-Moreno et al. [25] proposed a multiple test method based on the Bayesian framework for the identification of accident-prone sections. Jiang Hong et al. [26] proposed the cumulative frequency method based on research into domestic and foreign methods for identifying accident-prone sections. Pei Yulong et al. [27] used the principles of fuzzy mathematics to propose a fuzzy evaluation method for identifying accident-prone sections. Zhu Xinglin et al. [20] proposed the equivalent accident number-accident rate identification method based on existing methods for identifying accident-prone sections. Xie Lian et al. [28] proposed an accident-prone section identification method based on an improved clustering algorithm modeled on the idea of density clustering. In summary, different methods for identifying accident-prone

sections often use different identification indicators and determination conditions, so the characteristics and applicable ranges of each identification method also differ. A brief analysis and comparison of the advantages and disadvantages and applicable ranges of the various methods for identifying accident-prone sections proposed above is shown in Table 1.

Table 1. Evaluation of the applicability of identification methods for accident-prone road sections.

Identification Method	Merit	Weakness	Application Condition
Absolute Accident Number	① Concise and intuitive; ② Computationally simple	① Single evaluation factors; ② Traffic accident data requirements are relatively high	① Road sections with more comprehensive traffic accident data; ② Intersection section
Equivalent Accident Number	① The severity of the accident was considered	① Subjective; ② Evaluation factors are not comprehensive enough	① Section with more comprehensive traffic accident data
Accident Rate	① Traffic volume and road length are considered; ② Accuracy	① The particularity of some accidents is not considered	① Road conditions, traffic conditions change compared with the path section
Safety Coefficient	① Traffic accident data requirements are low; ② Computationally simple	① Lack of consideration of the accident attributes; ② Need for vehicle driving measured data, operability is not high	① Road section with more comprehensive vehicle driving data
Quality Control	① High accuracy; ② Traffic volume considered	① Large calculation volume; ② Lacks the consideration of the severity of the accident	① Various sections
Cumulative Frequency	① Concise and intuitive, intelligible ② Simple operation, strong practicability	① Factors such as traffic volume are not considered; ② Route division mode has a great influence on the results	① Road sections with obvious differences in accident conditions
Matrix	① Comprehensive accident rate method and accident number method	① The "low frequency high frequency" and "low frequency high frequency" sections cannot be directly judged	① Road conditions, traffic conditions change compared with the path section

Although accident-prone road sections account for a relatively small proportion of the entire road, they are characterized by a high number and concentration of accidents. As a "pain point" problem on the road, effective identification of accident-prone road sections is an important way to improve road traffic safety. This paper distinguishes from the conventional accident-prone roadway identification methods and takes weather conditions as the basic attribute into the identification of accident-prone highway roadways, forming a set of accident-prone highway identification methods for adverse meteorological conditions from a macroscopic point of view.

2. Methodology

2.1. Meteorological Event Responsiveness

This paper proposes a new method for identifying accident-prone highway sections under complex meteorological conditions by establishing the concept of meteorological risk responsiveness. The meteorological risk response index is the response degree based on traffic accident data, road design documents and meteorological data proposed by the accident-prone road section identification index; the main constituent parameters are: a meteorological event carrier, meteorological events, and a meteorological event response

mechanism. The numerical value of the response degree is used to characterize the impact of different meteorological events on each section of the highway, and at the same time, the accident-prone road sections that are affected by adverse meteorological influences are effectively screened.

(1) Meteorological event carrier. The event carrier of the meteorological event response degree is the route unit. According to the current status quo, there is no clear regulation on route division, and most consider the method of route division mainly based on experience and simplicity. Common road segmentation methods [29] include the average road segment method, uneven road segment method, fixed step method, dynamic step method, etc.

(2) Meteorological events. That is, the basic unit of meteorological risk responsiveness composition; its essence is the meteorological conditions as the basis for division of the meteorological event carrier on the accident division of the traffic accident set obtained, and the core of the meteorological event responsiveness is through the calculation of the number of responses to meteorological events to respond to the degree of impact of different weather on the roadway.

In view of the complexity of meteorological changes, this paper selects the changes in weather as the weather event division method and divides the set of traffic accidents occurring under the same type of consecutive meteorological conditions into one weather event in the time dimension, with the advantage of effectively analyzing the degree of impact of the same adverse weather on the same road section. The specific division method is to take the change in weather as the basis, on a certain route carrier, from the time of the traffic accident record to record the weather events; the same weather is recorded as one weather event, and when the weather changes, we restart the calculation as a new weather event. The set of weather events shown in Figure 1 can be represented as {rainy, sunny, cloudy, rainy, sunny, cloudy, foggy, snowy}.

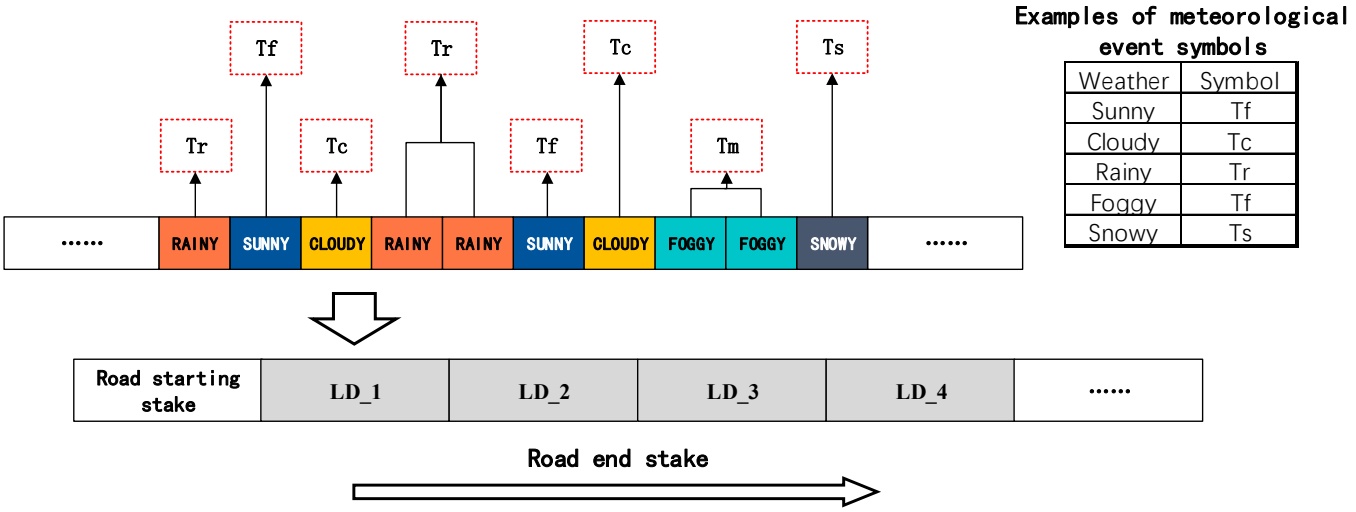


Figure 1. Classification method of meteorological events.

(3) Weather event response mechanism

Support in machine learning association rules, as a measure of the frequency of occurrence of itemsets in the total dataset, plays a key role in revealing the co-occurrence relationship between items in large datasets and is widely used in data mining research [30,31]. The versatility of the support degree method in dealing with large-scale and heterogeneous datasets makes it an ideal basic tool for identifying the association between factors such as meteorological conditions and complex alignments and the impact of traffic accident fre-

quency. Therefore, in order to investigate the association between highway traffic accidents and highway sections under meteorological conditions, this paper proposes the concept of responsiveness based on the idea of a support degree, which in turn evaluates the degree of connection between meteorology and accidents.

The support degree indicates the frequency of occurrence of a certain itemset, i.e., the ratio of the number of transactions containing the itemset to the total transactions, as a measure of the frequency of occurrence of the item set in the total dataset. The basic form of support degree [32] expression is shown in Equations (1) and (2):

$$\text{Support } (X \rightarrow Y) = P(X \cup Y), \tag{1}$$

$$\text{Support}(X, Y) = \frac{P(X \cup Y)}{|D|} \times 100\% \tag{2}$$

Equations (1) and (2) $P(X \cup Y)$ denote the number of transactions containing both itemset X and itemset Y, and $|D|$ is the total number of transaction database records.

The stepwise support expression [29] is shown in Equation (3):

$$r_{ij} = \begin{cases} 1 & d_{ij} \leq \beta \\ 0 & d_{ij} > \beta \end{cases} \tag{3}$$

Equation (3) where d_{ij} is the observed value; r_{ij} is the degree of support; β is the observation number threshold and is a constant.

The value of the meteorological risk responsiveness is determined by calculating the number of meteorological event responses on each meteorological event carrier. The meteorological event response means that when the number of traffic accidents in a meteorological event reaches the specified threshold on a meteorological event carrier, it is defined as meeting the response conditions of the meteorological event, and the meteorological event is recorded as a response meteorological event, obtaining the meteorological response conditions formula as shown in Equation (4):

$$x_i = \begin{cases} 1 & T_i \geq \theta \\ 0 & T_i < \theta \end{cases} \tag{4}$$

where T_i is the number of traffic accidents of the ith meteorological event of a route unit; θ indicates the number of traffic accidents required to meet the response to the meteorological event, i.e., the threshold of the number of accidents. When the number of traffic accidents of the ith meteorological event reaches the threshold, it is defined as a response to the meteorological event, and the value of x_i is set to 1. Conversely, when the number of traffic accidents of the ith meteorological event does not reach the threshold, it is considered a non-response to the meteorological event, and the value of x_i is set to 0.

The response number of meteorological events is the sum of the response number of the meteorological event on the meteorological carrier (route unit), based on the above Formula (4); the response meteorological events of qx meteorological on the kth meteorological event carrier are summed up to obtain the total number of responses to qx meteorological events, and the specific formula is shown in Formula (5):

$$X(k)_{Tqx} = \sum x_i \tag{5}$$

In Equation (5): $X(k)_{Tqx}$ is the number of responses to the qx meteorological event on the kth meteorological event carrier; T_{qx} is the meteorological event symbol and qx is the meteorological type.

2.2. Calculation of Meteorological Risk Responsiveness

Meteorological risk responsiveness is mainly a response to the size of the impact of meteorological conditions on road traffic safety; it is the ratio of the number of responses of the calculated meteorological events on the meteorological event carrier to the total number of meteorological events of the calculated meteorological events on the same meteorological event carrier. The meteorological event responsiveness formula is shown in Equation (6):

$$R(k)_{qx} = X(k)_{Tqx} / X(k)_{qx} \quad (6)$$

In Equation (6), $R(k)_{qx}$ denotes the responsiveness of the meteorological event x on the ith meteorological event carrier; it denotes the number of events under meteorological event x on the kth meteorological event carrier.

From the above equation, the value of $X(k)_{Tqx} \in X(k)_{qx}$, $R(k)_{qx}$ is always in the interval of [0, 1]. From the perspective of correlation, the meteorological risk responsiveness indicates how much the number of meteorological events under which the response occurs accounts for the total number of such meteorological events, and the more the value tends to 1 indicates that the probability of traffic accidents occurring at the corresponding meteorological event carrier when the meteorological event occurs is higher, and vice versa, the lower the probability is.

3. Identification of Accident-Prone Roadways

3.1. Definition of Adverse Meteorological Conditions

Common meteorological conditions include sunny, rainy, cloudy, foggy, icy, and snowy. Among them, rain, fog, ice, and snow are the main meteorological factors affecting traffic accidents on mountain highways, which are very likely to pose a threat to driving safety [33]. These disasters mainly cause the highway road surface anti-skid ability and visibility to reduce, affecting the driver's ability to recognize a hazard and vehicle braking performance, which in turn leads to an increase in the risk of accidents. In this paper, with reference to the relevant China National Meteorological Administration issued specifications and standards [34,35], the minimum standards for the risk classification of the impact of rainfall and foggy and snowy weather on highways are summarized, and the results are shown in Table 2.

Table 2. Minimum standard for risk classification of adverse weather on highways.

	Discriminating Indicators	Influence Degree
Rainfall	Rainfall within 24 h/mm $\geq$ 10 mm	Certain impact
Fog	VisibilityL $\leq$ 200 m	Certain impact
Snowfall	Snow cover thickness of 1.0 cm $\leq$ H < 2.9 cm	Certain impact

3.2. Impact of Adverse Meteorological Conditions

According to the Annual Report of Road Traffic Accident Statistics of the Ministry of Public Security of China [36], more than 20% of highway traffic accidents every year occur under complex meteorological conditions such as rain, snow, and fog. The data of 3108 valid traffic accidents during the actual operation of a highway in Sichuan (hereinafter referred to as SC1 highway) from 2015 to 2020 were used as the basis of the study, of which the number of accidents in rain, fog, and snow totaled 593 cases, accounting for about 19%. The types of accident patterns under the three adverse meteorological conditions were statistically analyzed, and the statistical results are shown in Figure 2.

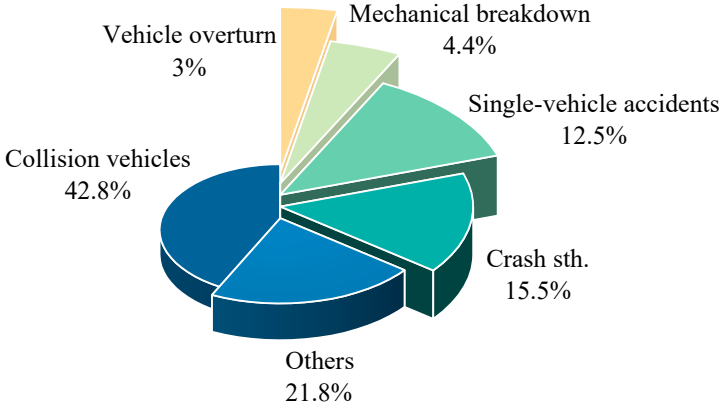


Figure 2. Accident types under adverse weather conditions.

Comprehensive analysis of the above data shows that under adverse weather conditions, traffic accidents are mainly in the form of collisions, accounting for about 58% of the total number of accidents. The main cause of this phenomenon is that the anti-slip property of the road surface decreases significantly in rainy and snowy weather, and the friction resistance is weakened, which leads to easy skidding of the vehicle tires, thus seriously affecting the driver's normal control of the vehicle, causing the vehicle to deviate from the intended driving trajectory, and colliding with other vehicles or stationary objects. At the same time, on foggy days with low visibility, it is difficult for drivers to accurately judge the distance from the vehicle in front of them, and the braking reaction time is prolonged, so the chances of rear-end accidents increase dramatically.

In view of this, the identification of accident-prone road sections under specific climatic conditions and the development of targeted traffic safety measures and road improvement strategies accordingly are of great practical significance and wide application prospects for reducing the incidence of traffic accidents under adverse meteorological conditions, safeguarding road traffic safety, and enhancing the operational efficiency of roads.

3.3. Methods of Identifying Accident-Prone Road Sections

The identification method of accident-prone road sections under meteorological conditions proposed in this paper takes the meteorological risk responsiveness as the identification index, and effectively screens the accident-prone road sections that are greatly affected by adverse meteorological conditions by setting the responsiveness threshold. The specific hierarchy diagram is shown in Figure 3.

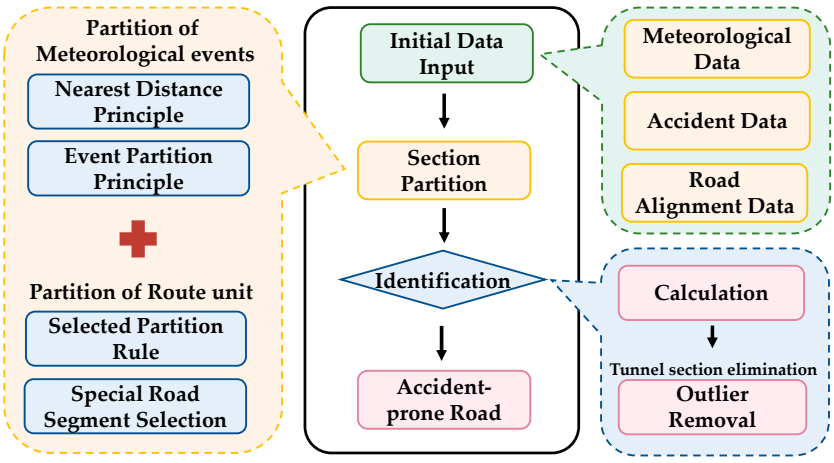


Figure 3. Identification hierarchy of accident-prone sections under meteorological conditions.

- The input layer is the data collection and organization stage of the identification model. The data collected and organized in the input layer are required to be accurate, and the data to be collected are mainly divided into three parts: meteorological data, traffic accident data, and road design data.
- The division layer is to classify and process the data collected and organized in the input layer and divide the meteorological time and meteorological event carriers required for the calculation of meteorological risk responsiveness, and the specific division methods and principles are as follows.
    1. Division of meteorological event carriers. According to the characteristics of the target road and the purpose of the study, the target road can be divided according to the average road section method; for longer road sections and more structures, the road section can be divided according to the combination of the length of the span of the structure and the uneven road section method.
    2. Meteorological event division. Process the meteorological data and traffic accident data, organize and classify the meteorological and accident data into each meteorological event carrier; then, according to the principles and methods of meteorological event division, divide the weather events into each meteorological event carrier, and finally calculate the number of adverse meteorological events on each meteorological event carrier.
- The identification layer carries out meteorological risk responsiveness calculation for each meteorological event carrier and identifies accident-prone road sections on target roads through a meteorological risk responsiveness, which is mainly divided into two parts.
    1. Meteorological risk responsiveness calculation. Based on the finished data, the number of meteorological events and meteorological event carriers, the adverse meteorological events on each meteorological carrier are calculated through the meteorological event response mechanism, the number of meteorological events that have responded to each adverse meteorological event is obtained, and the adverse meteorological risk responsiveness is calculated on each meteorological event carrier through Equation (6).
    2. Processing of road sections with abnormal values of meteorological responsiveness. We organize the calculated undesirable weather risk responsiveness, check whether there are abnormal prominent values, and when there are abnormal prominent values of weather risk responsiveness, check for these specific road sections.
- The output layer collects and organizes the results calculated in the identification layer and analyzes the results.
    1. Road section screening. Screening excludes tunnels and other special road sections that are less affected by adverse weather conditions.
    2. Meteorological risk response ratio calculation. As the value of the meteorological risk response degree is a reaction to the degree of macro-impact of different weather on road safety, in order to amplify and effectively analyze the degree of impact of adverse weather on road safety, the concept of the meteorological risk response ratio is proposed, and the meteorological risk response degree of sunny, cloudy, and other road sections with lower impact on road safety is set up as a control group, and the meteorological risk response ratio is the ratio of the risk response degree of the adverse meteorological group to the risk response degree of the control group. The meteorological risk response ratio is the ratio of the risk response of the adverse weather group to the risk response of the control group.

When the ratio is less than 1, it means that the influence on the road section by adverse weather is almost negligible; when the ratio is greater than 1, it indicates that the adverse weather has an influence on the target road section. The formula is shown in Equation (7):

$$N(k)_{qx} = \frac{R(k)_{qx}}{R(k)_{dz}} \quad (7)$$

In Equation (7), $N(k)_{qx}$ represents the meteorological risk responsiveness ratio of qx meteorological event on the kth meteorological event carrier; dz represents the meteorological event with less impact on traffic safety, and $R(k)_{dz}$ represents the meteorological risk responsiveness of the control meteorological event on the kth meteorological event carrier.

3. Result analysis: Based on the screened accident-prone road sections under adverse meteorological conditions, meteorological risk responsiveness and meteorological risk responsiveness ratio, accident-prone road sections are classified and analyzed, and the accident-prone road sections under meteorological conditions are derived in terms of the range of accident-prone road section stakes, and accident-prone road section accident-affecting factors and characteristics.

4. Engineering Example Validation

In order to verify the effectiveness of the meteorological responsiveness method in the field of risk identification and its application potential in the field of practical engineering, this paper relies on a project for a highway in the southwest of China, hereinafter referred to as (SC2 highway), its position is shown in Figure 4. SC2 highway has a total length of about 131 km, a design speed of 80 km/h, four lanes in both directions, the standard roadbed width of 24.5 m .The climate along the whole route is changeable: there are adverse weather conditions such as heavy rain, ice and snow, and dense fog; the driving environment is complicated, and it is greatly affected by the adverse weather.



Figure 4. The experimental road.

4.1. Data Collection

The input layer data in the example road in this study were collected from the road data, traffic accident data, and meteorological data of SC2 highway.

4.1.1. Data Input

The data obtained for road design contains a series of parameters, encompassing stake numbers, horizontal and vertical alignment elements, as well as a variety of road structure

elements. Examples of these data are shown in Table 3 to meet the specific requirements of the study.

Table 3. Road design data collection example.

Serial Number	Stake Number	Horizontal Alignment Elements	Vertical Alignment Elements	Roadway Structure Elements
1	K1+000	Circular Curve	Sag Curve	Standard Section
2	K2+000	Straight	Crest Curve	Bridge
...	...	...	...	...
132	K132+000	Spiral Curve	Straight	Highway Tunnel

The study collects a total of 1001 cases of traffic accident data, of which the accident data under adverse weather conditions such as snow, rain, and haze account for a total of 206 cases, amounting to 20.58% of the overall accident data. Traffic accident data information mainly includes the time of traffic accidents; weather data at the time of traffic accidents; traffic accident stakeout locations; traffic accident patterns and causes; and types of vehicles involved in accidents, and the specific data collection format is shown in Table 4.

Table 4. Data of traffic accidents on SC2 highway.

Serial Number	Time of Accident	Location of Accident	Weather	Accident Pattern	Accident Vehicle Type
1	2018/6/3	K26+200	Rainy	Collision Vehicle	Small Car
2	2018/6/3	K49+000	Rainy	Collision Objects	Small Car
...	...	...	...	...	...
1001	2018/8/11	K38+500	Cloudy	No Records	Small Car

The meteorological data information collected for the study was obtained from the Mindful Weather platform, including all weather conditions from June 2018 to August 2021 at the start and end of the highway. The platform data characteristics provide high spatial and temporal resolution meteorological observations for this study. With the real-time weather data at 1 km × 1 km grid points updated 5-min by 5-min, and the day-by-day and hour-by-hour historical meteorological data this study is able to capture subtle weather changes and analyze their immediate impacts on traffic safety accordingly. The accuracy of the data meets the requirements of each meteorological vector within the scope of the subsequent study.

4.1.2. Data Segmentation

According to the road design information, accident data information and meteorological data information collected and organized in the input layer, the meteorological event carrier division and meteorological event division are carried out in the division layer.

(1) Meteorological event carrier division. Considering the domestic previous research and calculation needs, the average road section method is selected as the weather event carrier division method, and 1 km is selected as the length of the weather event carrier [34], with a total of 131 weather event carriers, numbered as LD_i, where i is the number of the route carrier, which is arranged sequentially from the starting point to the end point of the route. Based on the division mode of the average section method, the meteorological event carriers of SC2 highway are obtained, and the division results are shown in Figure 5.

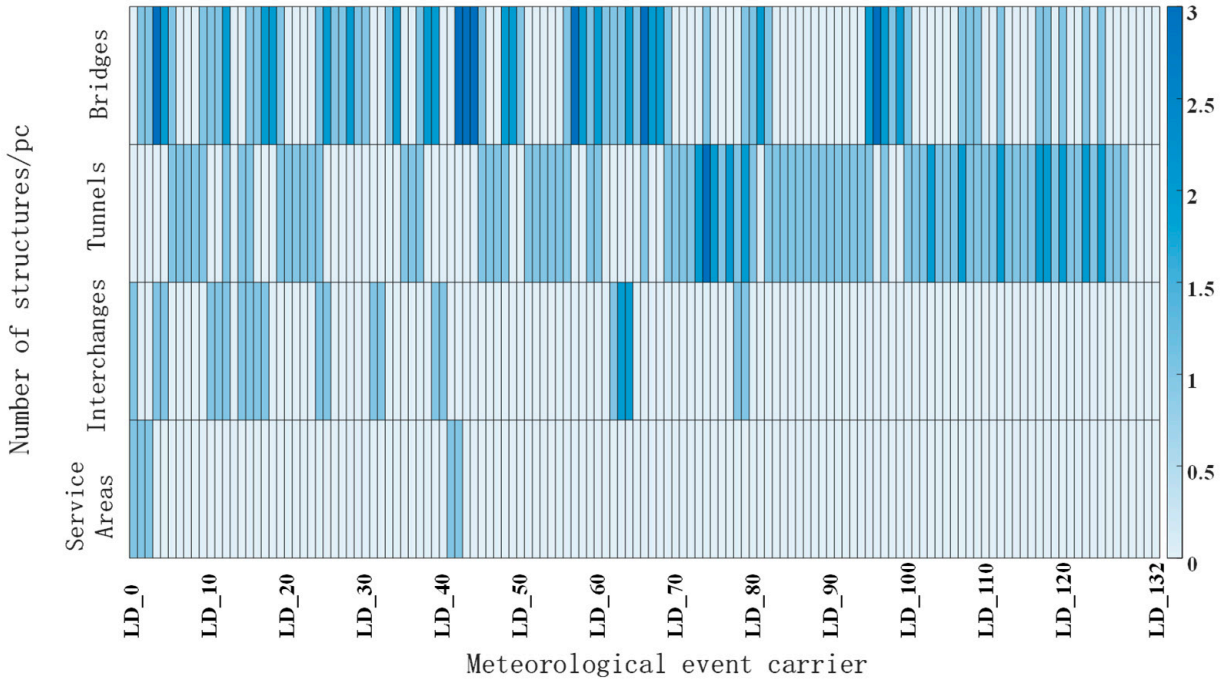


Figure 5. Schematic diagram of carrier distribution of meteorological events.

(2) Meteorological event division. Based on the meteorological data, each meteorological event carrier has been divided into meteorological events. Since weather conditions such as sunny, cloudy, and foggy are not the main meteorological factors affecting driving safety, meteorological events such as sunny, cloudy, and cloudy that pose less risk to driving are uniformly set up as a control meteorological event group.

4.2. Calculation and Identification

4.2.1. Risk Identification

The identification layer carries out the calculation of meteorological risk responsiveness based on the meteorological event carriers and meteorological events delineated by the delineation layer, and screens and reviews the meteorological risk responsiveness anomalies.

Meteorological risk response calculation. Meteorological event response calculation first needs to set the meteorological risk response threshold. The meteorological risk response threshold is based on the average number of accidents of meteorological carriers, that when a single meteorological carrier under the conditions of a meteorological event occurs more than the average number of traffic accidents, the meteorological event of the meteorological carrier there is a greater impact, in order to ensure that the identification effect is more accurate, the meteorological risk response threshold in the average number of accidents of the meteorological carriers above the value of the specific calculations, see Formula (8):

$$\begin{cases} T = [\frac{N}{n \times m}] + 2\ ,\ 0.5\ \le T - [\frac{N}{n \times m}]\ <\ 1 \\ T = [\frac{N}{n \times m}] + 1\ ,\ \ 0\ \le T - [\frac{N}{n \times m}]\ <\ 0.5 \end{cases} \tag{8}$$

Equation (8) where T is the meteorological risk responsiveness threshold; N is the total number of traffic accidents; n is the number of meteorological event carriers; and m is the number of meteorological event categories.

The study collected a total of 1001 cases of traffic accidents and a total of 131 meteorological event carriers; as can be seen from the provisions of the division of the layer, the need for four groups of meteorological events and meteorological control group for the

calculation of meteorological risk responsiveness, that is, rain, snow, fog adverse meteorological events group and clear, cloudy, cloudy meteorological events control group, through the calculation of the average number of events for each meteorological carriers is 1.91, the application of Equation (8) after the calculation of the $T = 3$; therefore The meteorological risk response threshold of this study is taken as 3.

4.2.2. Results

Based on the results of the meteorological risk responsiveness of each route carrier calculated by the discriminant layer, the accident-prone sections of the SC2 highway affected by adverse meteorological conditions are obtained.

In general, special sections such as tunnels are less affected by adverse weather conditions and should be filtered out initially. Section filtering is performed based on the type of tunnel sections provided in the structural data. On this basis, a 40-km stretch from K15 to K55 is selected for computational output, and the processed results are shown in Figure 6.

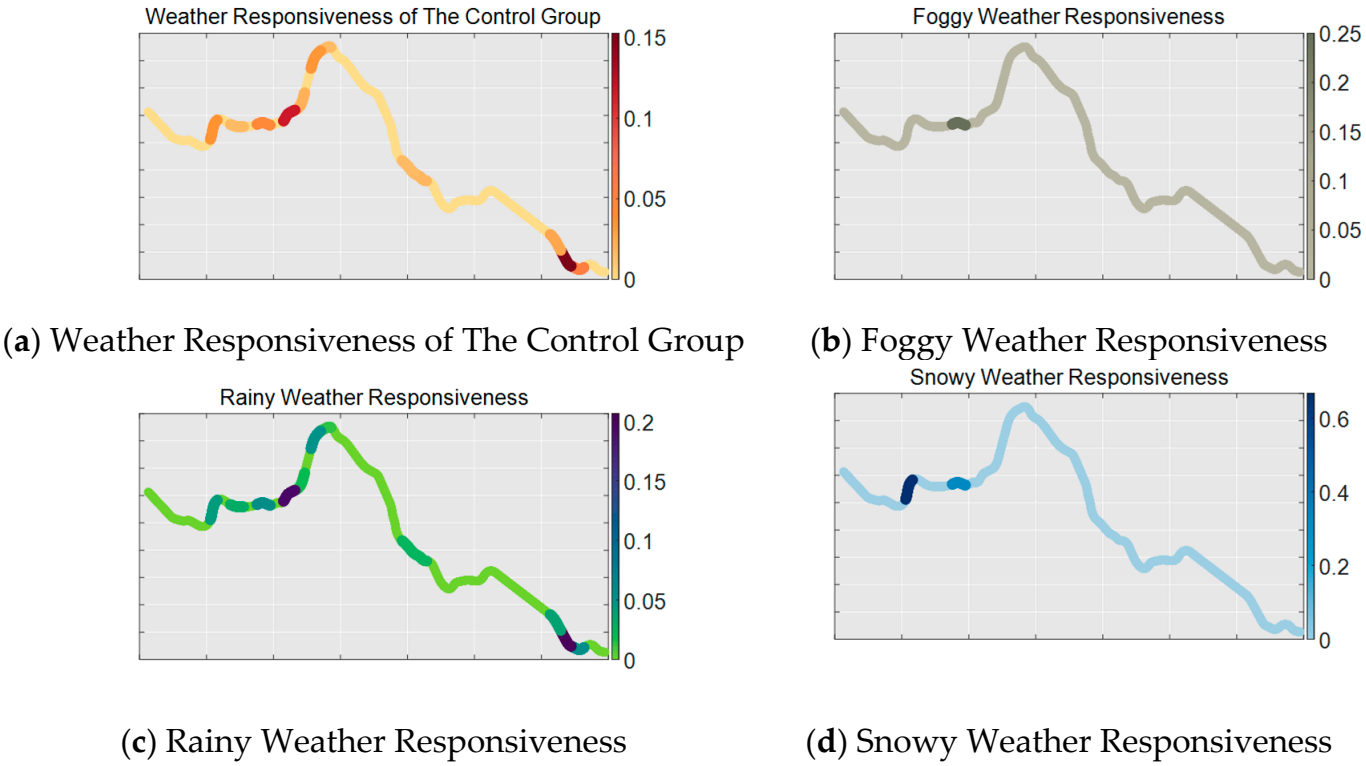
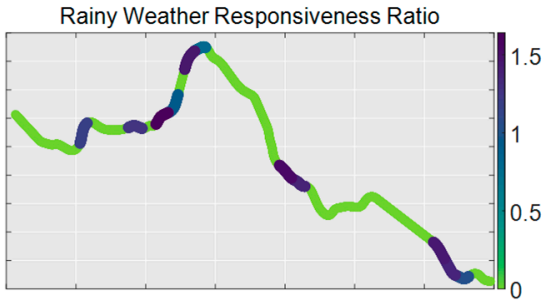


Figure 6. Calculation results of meteorological events.

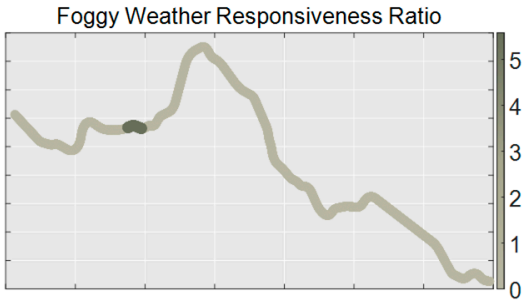
In order to further screen the accident-prone road sections under adverse meteorological conditions, and at the same time to provide data and reference for road section analysis and safety and security programs, the meteorological risk responsiveness ratio is calculated based on Equation (8) for the data in Figure 6, and the specific calculation results are shown in Figure 7.

From the above figure, it can be seen that the rainy weather risk responsiveness ratio of LD_42 and LD_39 road sections is less than 1; the rainy weather risk responsiveness ratio of LD_17 road section is approximated to be 1, which indicates that compared with the general meteorological conditions such as sunny, cloudy, and foggy, the road section is less affected by rainy adverse meteorological conditions, and it does not conform to the definition of accident-prone road sections subject to adverse meteorological conditions, and it should be

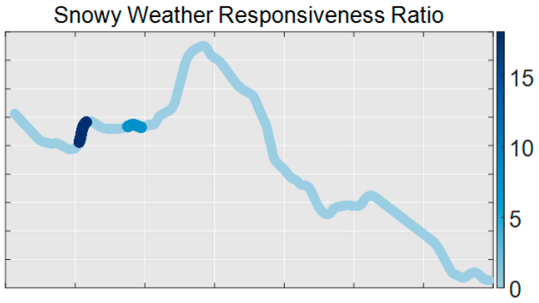
sifted out and ultimately, the responsiveness ratio = 1 is used as the discriminative index for screening; the obtained accident-prone roadway table is shown in Table 5.



(**a**) Rainy Weather Responsiveness Ratio



(**b**) Foggy Weather Responsiveness Ratio



(**c**) Snowy Weather Responsiveness Ratio

Figure 7. Calculation results of meteorological risk response ratio of SC2.

Table 5. Accident-prone sections of SC2 highway under adverse weather conditions.

Route Unit	Rainy Weather Risk Response/Ratio	Foggy Weather Risk Response/Ratio	Snowy Weather Risk Response/Ratio
LD_18	20.63%/1.35	0.00%/0.00	0.00%/0.00
LD_19	3.75%/1.42	0.00%/0.00	0.00%/0.00
LD_30	2.50%/1.37	0.00%/0.00	0.00%/0.00
LD_31	2.50%/1.53	0.00%/0.00	0.00%/0.00
LD_40	5.00%/1.45	0.00%/0.00	0.00%/0.00
LD_43	19.38%/1.64	0.00%/0.00	0.00%/0.00
LD_45	5.63%/1.26	25.00%/5.58	33.33%/7.44
LD_49	4.38%/1.19	0.00%/0.00	66.67%/18.17

4.3. Analysis of Results

The data processing and calculations at all stages have screened out eight high-risk road sections of SC2 highway that are greatly affected by adverse meteorological conditions, accounting for about 19.05% of the non-tunnel road sections along the whole route. According to Table 4, when the road section has fog and snow adverse risk meteorological responsiveness, its value is significantly higher than the meteorological risk responsiveness under rainy day adverse meteorological conditions, indicating that at the macro level, the degree of influence of fog and snow adverse meteorology on road traffic safety is much higher than that of a rainy day. LD_18 and LD_43, which have the largest meteorological responsiveness in rainy days, and LD_45 and LD_49, which have the largest meteorological responsiveness in fog and snow, were selected for key analysis, and the risk responsiveness radar charts are shown in Figure 8.

According to the results of Figure 8, the response of LD_18 and LD_43 road sections to the control group and the adverse meteorological risk in rainy days is much higher than that of other road sections. Referring to the level longitudinal line indexes of LD_18 and LD_43 in the level longitudinal data, the minimum radius of the level curve of LD_18 is 560 m, the maximum longitudinal slope is −3.34%, and the road section exists as an S-curve; the minimum radius of the level curve of LD_43 is 720 m, the maximum longitudinal slope is 3.50%, and the road section exists as an S-curve. The minimum radius of level curve of LD_18 is 560 m, the maximum longitudinal slope is −3.34%, and there is an S-shaped curve in the road section; the minimum radius of level curve of LD_43 is 720 m, and the maximum longitudinal slope is 3.50%. Both road sections have low level and longitudinal linear indexes, which is in line with the characteristics of accident-frequent road sections.

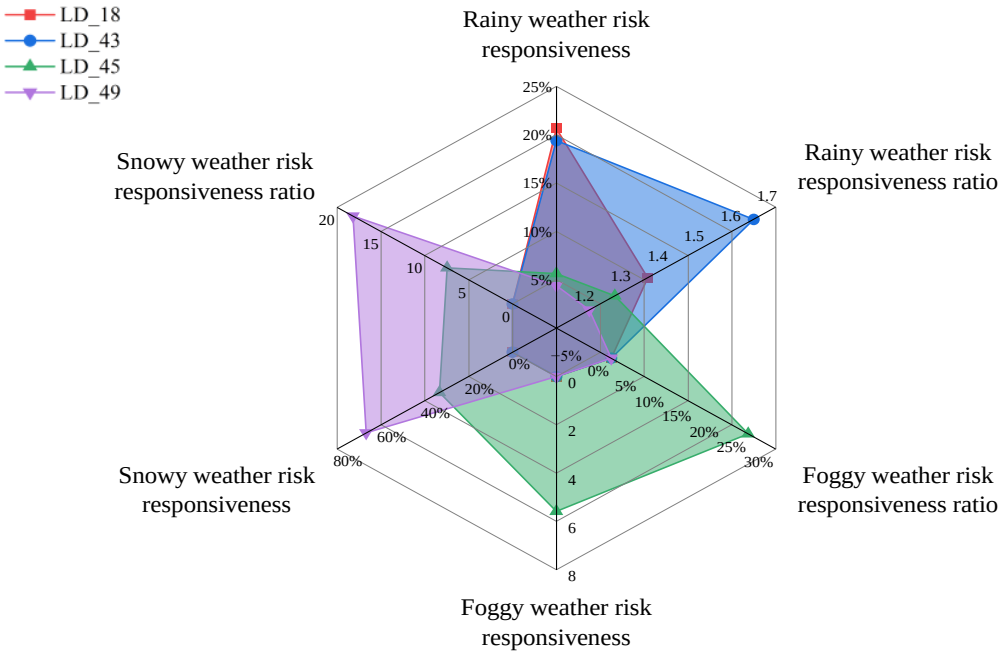


Figure 8. Radar chart of meteorological risk response.

The accident-prone road sections LD_45 and LD_49 under foggy and snowy adverse meteorological conditions have a much larger adverse meteorological risk response and response ratio than other road sections. Combined with the flat and longitudinal line of the two road sections, the minimum radius of the plane curve of the LD_45 road section is 551.15 m, and the maximum longitudinal slope is −1.80%; the minimum radius of the plane curve of the LD_49 road section is 560 m, and the maximum longitudinal slope is 3.78%. LD_45 section and LD_49 section plane line index in all the accident-prone sections in the lowest standard; at the same time, LD_45 section in the existence of downhill, combined with fog, snow adverse meteorological conditions of the accident mechanism, in line with the theoretical logic. Combined with the above analysis, it can be concluded that LD_18, LD_43, LD_45, and LD_49 are the key accident-prone sections.

4.4. Method Validation

For further validation of the proposed methodology, data on 414 valid accidents from January to December 2022 were collected and analyzed for their spatial and temporal distribution, as shown in Figure 9.

After comparison, it is found that the key accident-prone road sections under adverse meteorological conditions identified by this method are basically consistent with the actual distribution, and the key road sections predicted by the method are more accurate.

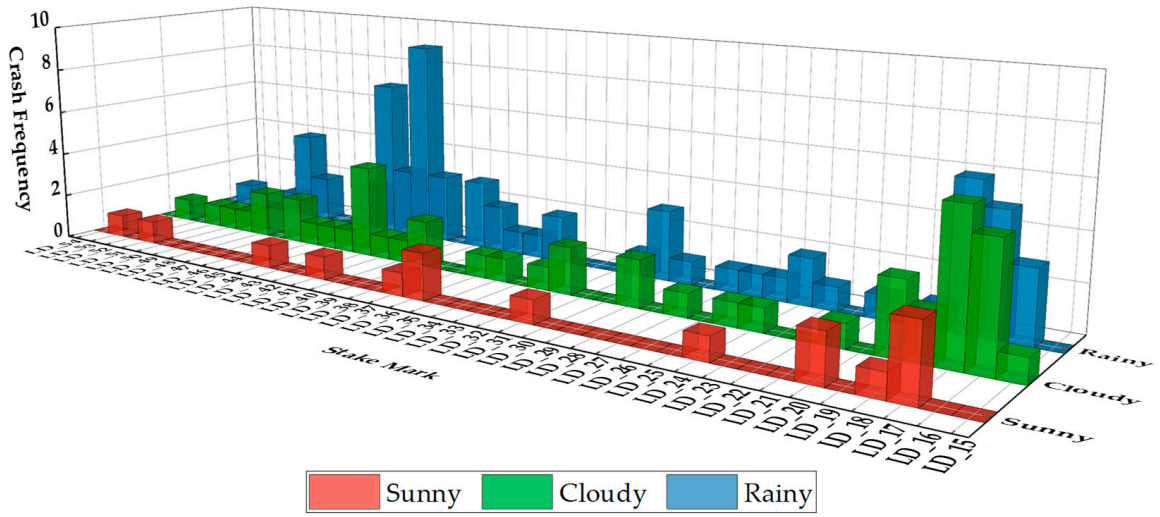


Figure 9. Distribution of accident conditions under different meteorological conditions.

5. Discussion

Due to the limitation of the dataset, the accident type is more prominent under rainfall conditions in the study area. For the accident-prone road sections proposed by the identification results, it is recommended to focus on verifying the road section drainage, traffic signs and marking lines, increasing the density of water-discharging holes in bridge sections, and paving permeable asphalt pavement in the rest of the road sections under the conditions of reconstruction and expansion, so as to improve the pavement drainage system and ensure that the rainwater and melting snow can be removed quickly and effectively.

Restricted by the research conditions, research time and other factors, at this stage, this paper only selects part of the representative meteorological characteristics of the indicators as the basis for risk assessment, which is applicable to non-tunnel road sections of mountain highways that are highly affected by meteorological factors. In future research, other risk-related influencing factors will be introduced for in-depth study to further improve the accuracy and applicability of model identification; the meteorological unit used in the case study of this article is relatively simple and has high requirements on the temporal and spatial accuracy of meteorological data. Its applicability needs to be improved, and a more scientific and reasonable division of meteorological units will be explored in subsequent research.

6. Conclusions

Based on the analysis of driving safety under adverse meteorological conditions, this paper proposes the concept of meteorological risk responsiveness with the help of the support index in data mining and specifies its detailed composition parameters as the identification index of accident-prone road sections. Based on the identification method of traditional accident-prone road sections, we clarify the meteorological response mechanism and the calculation method of meteorological risk responsiveness, and construct the identification model of accident-prone road sections under meteorological conditions through the structure of "input layer-division layer-identification layer-output layer".

Taking SC2 highway as the experimental road, applying the process of identifying accident-prone road sections under adverse meteorological conditions, identifying eight road sections affected by adverse meteorological conditions and analyzing the causes of accidents in four key road sections, verifying the effectiveness of the accident-prone model by comparing the identification results with the actual situation in different years, indicating that the currently constructed accident-prone road sections based on meteorological

responsiveness can be used in identifying and evaluating accident-prone road sections and their causes. It shows that the currently constructed weather responsiveness-based accident-prone road section identification method has reference value in identifying and characterizing the accident-prone key road sections under complex meteorological conditions, which can be applied to engineering practice to a certain extent, and provides an effective basis for the optimization of drainage and the improvement of traffic safety facilities in key road sections of highways during the operation period.

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