Accident analysis of long and steep longitudinal highway slopes based on multi-source data under the background of Internet of Things

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ABSTRACT

Under the background of "Internet of Things + big data", the accident analysis and safety prevention of long and steep sections of highway have attracted the attention of academic circles. Reasonable analysis of safety influencing factors can contribute to ensuring traffic safety of highway projects and improve prevention technology. Therefore, based on multi-day and multi-source traffic accident data in Guizhou province, this paper constructs a Multinomial logit(MNL) model considering multiple accident causes. Firstly, data related to accident causes are screened out from multi-source data, and these data are divided into two categories of traffic accident characteristics and road environment characteristics. Secondly, based on the multi-day survey data, the MNL model was established by using python to conduct regression analysis on the relationship between the accident influencing factors and the accident severity under the general road section and the long and steep road section respectively, and the two were analyzed and compared based on the significance factors. Finally, the accident data of long and steep longitudinal slope sections are selected to do univariate regression analysis of the annual accident number and each influencing factor. An empirical experiment was carried out in Guizhou Province. The results show that the accident type, vehicle type and accident location are the obvious differences between the long and steep slope road accidents and the general road accidents. The coupling effect of slope length and slope, traffic flow and truck proportion have great influence on the number of annual accidents. This study can provide theoretical support for the improvement of highway accident prevention technology in mountainous areas.

Keywords: Long steep longitudinal slope, Accident cause analysis, Multi-source data, Multinomial logit, Elastic analysis, Intelligent prevention

1. INTRODUCTION

In recent years, with the rapid development of highway construction in China, the number of mountainous roads has continued to increase. However, the unique terrain and geological conditions of mountainous areas often result in more continuous longitudinal slope sections on mountainous highways. Research has shown that continuous longitudinal slopes are an important factor affecting traffic safety in highway projects, and with the increase of slope length and gradient, the accident rate significantly increases. Many experts and scholars have proposed corresponding improvement measures from road signs and markings, guardrail protection, and brake warning, in order to improve the safe traffic capacity of continuous long and steep longitudinal slope sections. However, compared to directly improving road facilities on long and steep longitudinal slope sections, comprehensive analysis of accident causes and influencing factors can provide more targeted theoretical support for accident prevention and remediation.

Initially, scholars mostly analyzed the accident characteristics of mountainous highways based on static indicators such as horizontal and vertical road alignments. Ahmed[1] developed a Bayesian layered model to study the impact of road geometry on collisions in highway sections. The results showed that locations with higher curvature, wider median, and increased number of lanes had lower collision rates. Shankar[2] explored the frequency of highway accidents based on multivariate analysis of road geometry, weather, and other seasonal effects, revealing that the important determining factor of accident frequency is the interaction between road geometry and weather. With the rapid development of highways, scholars have begun to consider the impact of continuous long and steep longitudinal slope sections on accidents[3]. Hong-zhi[4] analyzed the spatiotemporal distribution and vehicle type distribution of traffic accidents on long

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and steep downhill sections of highways, and established safety evaluation indicators for trucks using infrared observation instruments. The results showed that slope length and brake drum temperature are important factors affecting truck accidents. Wen-bin[5] established traffic simulation models with different actual loading rates and slope lengths through Vissim, and ultimately verified them during the renovation of the long and steep slope of the Expressway. Zheng[6] used the American safety analysis method to estimate the operational safety of long longitudinal slope highways in mountainous areas. The study showed that although the continuous long downhill of these mountain roads did not exceed the limit value, the maximum longitudinal slope length and slope value almost often reached the standard limit. Zhao[7] proposed recommended index values for continuous downhill gentle slope and slope length based on the requirements of effectively reducing vehicle operating speed and the braking performance curve of the leading vehicle model on downhill sections, which can be used as a reference for designers in design. In recent years, the rapid development of various mathematical models has led scholars to comprehensively consider the impact of various factors on accident rates. Huo[8] used a mixed logit model with mean variance heterogeneity to derive the safety effects of the interaction between multiple factors that affect the occurrence of car accidents, such as the increased risk of collision caused by sharp turns, and the increased speed is positively correlated with the distance the vehicle travels along steep slopes. Chen[9] developed three types of logit models to validate the influencing factors of highways, and the results showed that the combination of curves and slopes significantly increased the severity of highway accidents compared to individual curves and slopes. Fauzi[10] studied the frequent serious accidents on the highway and used the logit model to explore the relationship between influencing factors. Based on this, some geometric improvements were made to the road, such as preparing dedicated lanes for heavy vehicles after the new road alignment.

On the basis of the above research, this paper first processed the multi-day accident data of 7 expressways in Guizhou province, screened out the relevant data of accident causes, and then used python to build the MNL model for the relationship between the accident cause factors and the accident severity under the general road section and the long and steep slope road section respectively, and analyzed and compared the significant factors. The accident data of long and steep longitudinal slope sections are selected to establish the regression analysis between the annual accident number and various influencing factors. By digging deep into the factors affecting the accident of the long and steep longitudinal slope sections of the expressway, the theoretical support for the prevention and regulation of traffic accidents in mountainous areas is provided.

2. DATA SOURCE AND DESCRIPTION

2.1 Data sources

The accident data came from accident statistics tables recorded by traffic police departments on seven highway sections in Guizhou province, including the Guizun section of G75 Lanhai Expressway, the Huiluo section of G69 Yinlong Expressway, the Chongzun section of G75 Lanhai Expressway, the Banjiang section of G78 Shankun Expressway, the Xingyi section of S50 Huixing Expressway, the S25 Sijian Expressway, and the Zhensheng section of G60 Shanghai-Kunming Expressway. The selected highway section contains eight long and steep sections, and the traffic incidents of the study section from January 2016 to December 2018 are obtained from the accident statistics table. Due to the lack of correlation between the characteristics of road alignment and traffic flow and accidents in service areas, toll stations, and intersection ramps, this portion of accident data has been excluded. In addition, considering that most highways are closed roads, a small portion of accident data with types of pedestrian and livestock collisions has also been excluded.

The horizontal and vertical route shape data of the accident section are from the two-stage construction drawing design documents of Guizhou Province's highways. The horizontal curve data includes the starting and ending pile numbers of the road's horizontal curve, the radius of the horizontal curve, the length of the horizontal curve, turning, and turning angles. Vertical section data includes slope, slope length, and grade change point station number. In addition, it also includes data on road section structures such as tunnels, bridges, and service areas.

2.2 Data description

To construct a multiple logistic regression model to analyze the severity of accidents, the dependent variable of accident severity is divided into three categories based on the number of casualties: only property damage, injury accidents, and fatal accidents. The factors affecting road accidents are selected as the independent variables of the model. By studying the accident characteristics of long and steep longitudinal slope sections, two categories of traffic accident characteristics and road environment characteristics are selected as influencing factors. The characteristics of traffic accidents are selected as the independent variables of the model, including the type of accident, the type of vehicle involved, the number of vehicles involved, and the time of accident occurrence. The traffic environment characteristics mainly consider the selection of independent variables from the perspective of road alignment factors, road section types, and the location of long and steep longitudinal slope accidents.

Among them, the types of accidents include rear end collision, rollover, scraping, collision with fixed objects, and others. The severity of the situation that may be caused by these different types of accidents is also not entirely the same; The types of vehicles involved include trucks, trailers, small buses, and others. Among these types of vehicles, trucks have a larger load capacity and overall greater inertia compared to trailers. Accidents on long and steep longitudinal slopes can also cause more serious casualties; The number of vehicles involved includes single and multiple vehicles, and the number of vehicles involved can also intuitively reflect the severity of the accident; Accidents can be classified into six types: dawn, early morning, noon, afternoon, evening, and late night. Large trucks in China choose to travel at night, but insufficient lighting at night can easily lead to difficulty for drivers to recognize and cause dangerous accidents. Late night can have a higher severity and frequency of accidents. In terms of traffic environment characteristics, due to the consistent number and width of lanes in each section of the cross-section, the road alignment factor only takes the horizontal and vertical alignments as variables. Among them, the horizontal curve includes the radius and rotation angle of the circular curve. This article selects the radius of the circular curve and converts it into discrete variables, including straight lines ($R=\infty$), small radius curves ($R<1000$m), and general circular curves ($R \geq 1000$m). The vertical section feature indicators select slope and slope length to reflect the impact of different horizontal and vertical lines on accident rates; The types of accident sections are divided into tunnels, bridges, and general sections to reflect the impact of different road structures on accident rates and severity; The location of long and steep longitudinal slope accidents is comprehensively selected from the bottom section, middle section, and top section of the slope to analyze the impact of different locations of long and steep longitudinal slope accidents on the accident. The variable descriptions are shown in the Table 1.

Table 1. Description of variables.

Dependent variable	**Severity of traffic accidents**	**Death**
		Injured
		Property damage only
Characteristics of traffic accidents	Vehicle type	Goods train
		Trailer
		passenger car
		other
	Accident type	Reaching the tail
		Rollover
		scratch
		Impact fixture
		other
	Number of vehicles involved in the accident	Multiple vehicles
		Single vehicle
	Period of time	Dawn (3:00-7:00)
		Early morning (7:00-11:00)
		Noon (11:00-15:00)
		Afternoon (15:00-19:00)
		Evening (19:00-23:00)
		Late at night (23:00-3:00)

Traffic environment characteristics	Type of accident section	Tunnel
		Bridge
		General road section (base)
	slope	>3% (absolute value)
		0~3% (absolute value)
	Circular curve radius	R> 1000m
		R ≤ 1000m
		Straight line (base)
	Location of long and steep longitudinal slope accidents	Slope bottom section
		Middle section of the slope
		Slope top section
	Average longitudinal slope gradient at the point of accident	%
	Average length of longitudinal slope at the point of accident occurrence	m

3. MODEL CONSTRUCTION

3.1 Model specification

The characteristics of multinomial logit model make it well applicable to the analysis of traffic accident severity. The model structure is simple, and the effect of each influencing factor on the severity of the accident can be quantified. Meanwhile, the results of the model have good explanatory ability. Especially in the background of multi-source data, the model can screen out the significant factors of the cause of the accident well, and maximize the role of valuable data.

The multinomial logit model defines the choice utility value as U_{ij}, which represents the j accident consequence caused by i accident.

$$U_{ij} = \beta_j X_{ij} + \varepsilon_{ij} \tag{1}$$

Where:

β_j is the vector coefficient of accident consequence j;

X_{ij} is a vector composed of independent variables;

ε_{ij} is the error term that follows the Gumbel distribution.

From this, the expressions of multinomial logit models can be derived as follows:

$$P_i(j) = \frac{\exp\left(\beta_j X_{ij}\right)}{\sum_{j=1}^{J} \exp\left(\beta_j X_{ij}\right)} \tag{2}$$

python was used to build the model, mixed stepwise selection method was adopted, and the significance level was set at 0.05. When $p<0.05$, it indicated that the independent variable had a significant impact on the dependent variable, and the independent variable should be retained. By screening the independent variables such as vehicle type, accident type, number of vehicles involved, accident time and accident section type, the significant independent variables are determined and the coefficients of the independent variables are estimated to get the final model.

In order to more prominently reflect the particularity of the accident causes of the continuous long steep slope section of the mountain highway, the data of the general section and the data of the long steep slope section are used to build models respectively, and the significant factors of the models are analyzed and compared.

3.2 General road section

The multinomial logit model is used to regression the relationship between the influencing factors of general road accidents and the severity of accidents. Taking only economic loss accidents as the benchmark, the insignificant variables in the model estimation results are gradually eliminated, and finally the significant variables in the model and the estimated coefficients of injury and death accidents relative to only economic loss accidents are screened out. The results of the model are shown in the Table 2.

Table 2. Multinomial logistic regression results for general road section

variables		**Injury accident**		**Fatal accident**	
		coefficient	**P**	**coefficient**	**P**
Slope length		-0.00021***	.0000	-0.00086***	.0000
Slope gradient		-0.17341***	.0000	-0.3568***	.0000
Accident type	Reaching the tail	0.45572***	.0000	-	-
	Roll over	0.56704***	.0000	-	-
	scratch	-0.46501*	.0959	-	-
	Impact fixture (base)	-	-	-	-
Period of time	Dawn	-1.54168***	.0000	-2.04787***	.0000
	Early morning	-1.54598***	.0000	-2.40329***	.0000
	Noon	-1.31574***	.0000	-2.76078***	.0000
	Afternoon	-1.15614***	.0000	-2.20132***	.0000
	Evening	-1.24324***	.0000	-1.8812***	.0000
	Late at night (base)	-	-	-	-
Vehicle type	Goods train	0.12271	.1730	0.30782	.1460
	Trailer	0.27552	.4622	1.02596*	.0831
	passenger car (base)	-	-	-	-
Type of accident section	Tunnel	-0.23848*	.0545	-	-
	General section (base)	-	-	-	-
Circular curve radius	<1000m	-	-	-0.46063**	.0287
	≥1000m	-0.1769*	.0934	-	-
	Straight line（base）	-	-	-	-

Note：***, ** and * represent significance levels of 1%, 5% and 10% respectively.

As can be seen from Table 2, significant factors in the severity analysis of injury accidents are longitudinal slope length, slope, accident type, accident time, vehicle type, section type and circle curve radius. The greater the longitudinal slope and the longer the longitudinal slope, the lower the probability of injury. Among accident types, rear-end and rollover accidents result in a higher probability of injury than hitting a fixed object, while scratch accidents result in a lower probability of injury. The accident time showed that the accident severity was higher in the late night time. The tunnel is negatively correlated with the accident severity. The regression coefficient of the radius of the circular curve shows that the accident severity will decrease in the section with larger radius of the circular curve.

In the analysis of death accident severity, the significant factors were longitudinal slope length, slope, accident time, vehicle type, section type and circle curve radius. The higher the longitudinal slope degree and the longer the longitudinal slope, the lower the probability of death accident. The pattern of accident time is similar to that of injury accidents. Scenarios involving a vehicle type of trailer have an increased risk of fatality. The circle curve with small radius is negatively correlated with the accident severity.

3.3 Long and steep longitudinal slope section

The benchmark type is also selected as economic loss accident, and the results of the model are shown in Table 3.

Table 3. Multinomial logistic regression results for long and steep longitudinal slope section

variables		Injury accident		Fatal accident	
		coefficient	P	coefficient	P
Slope length		-0.00020***	.0000	-	-
Slope gradient		-0.22335***	.0000	-0.36054***	.0369
Accident type	Reaching the tail	0.55315***	.0000	-	-
	Roll over	1.12371***	.0000	-	-
	Impact fixture (base)	-	-	-	-
Period of time	Dawn	-1.73886***	.0000	-2.00763***	.0000
	Early morning	-1.43353***	.0000	-1.191745***	.0000
	Noon	-1.43019***	.0000	-3.18481***	.0000
	Afternoon	-1.22491***	.0000	-1.73903***	.0000
	Evening	-0.97404***	.0000	-1.65812***	.0000
	Late at night (base)	-	-	-	-
Vehicle type	Goods train	0.47471***	.0051	1.18700**	.0107
	Trailer	1.28273**	.0277		
	passenger car (base)	-	-	-	-
accident location	Middle slope	-	-	-1.36243***	.0061
	Top of slope	-	-	-2.37866**	.0388
	Base of slope（base）	-	-	-	-
Note：***, ** and * represent significance levels of 1%, 5% and 10% respectively.					

As can be seen from the table, significant factors in the severity analysis of injuries on long and steep longitudinal slopes are longitudinal slope length, slope, accident type, accident time, vehicle type and road section type. The greater the longitudinal slope and the longer the longitudinal slope, the lower the probability of injury. Rear-end collisions and rollover accidents have a higher risk of injury than collisions with fixed objects. Similar to the general road, the probability of injury accidents is greater in the early morning than at other times. The impact of vehicle types on the probability of injury accidents on long and steep slopes is different from that on general road sections, and trucks and trailers are more likely to cause injury accidents. The probability of injury in the tunnel is less than outside the tunnel.

In the analysis of death accident severity, the significant factors were longitudinal slope, accident time, vehicle type and long steep slope accident location. The greater the longitudinal slope degree and the longer the longitudinal slope length are, the lower the probability of injury accident is. The influence of accident time on death accident is the same as that of injury accident. In terms of vehicle type, truck has a significant positive effect on the probability of death accident. In addition, the accident severity of the middle and lower sections of the long and steep longitudinal slopes has increased compared with that of the upper reaches.

3.4 Comparative analysis

Through the analysis of the factors affecting the accident severity of the long and steep longitudinal slope section and the general section, the characteristics of the long and steep longitudinal slope accident are further revealed. Taking the general road section as a contrast, the difference variables of the two causes are analyzed, and the difference of the influence factors on the accident severity between the long steep slope section and the general road section is obtained.

In terms of the influence of slope degree and slope length on the accident severity, they show the same characteristics. With the increase of slope and slope length, the accident severity decreased. The reason for this phenomenon may be that on the road with higher slope, the driver will be more careful, and the road safety facilities will be better, resulting in less serious accidents.

From the impact of accident type on accident severity, it can be seen that, different from general road sections, rollover accidents on long steep road sections are more likely to cause casualties than rear-end accidents. In terms of vehicle type impact, there is a clear difference between the two. Accidents involving trucks and trailers have a greater casualty rate on long and steep slopes. The analysis of the accident location of the long and steep slope shows that the accident severity is higher in the section at the bottom of the long and steep slope. The longer the vehicle travels on a long steep slope, the more times it brakes, the higher the brake drum temperature, and the greater the risk of losing control.

4. ACCIDENT CAUSE ANALYSIS

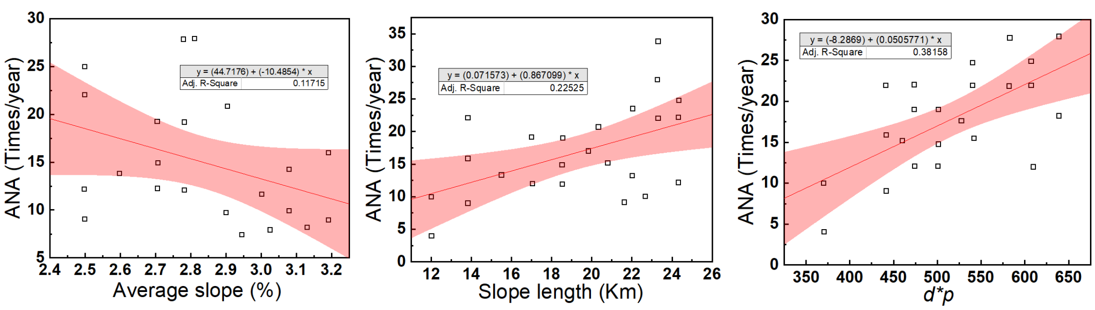
4.1 Data filterings

In the previous chapter, a comparative analysis was conducted to investigate the differences in accident causation between the two road sections through the construction of a multinomial logit model. The sources of accident data in this chapter remain consistent with those in the previous chapter. However, for a separate analysis of the influencing factors of accidents on long and steep longitudinal slopes, only accident data from such slopes have been selected. The data for the roadway segment comprises of traffic volumes and longitudinal and vertical alignments. The longitudinal and vertical alignments were extracted from the highway design drawings, whilst the traffic flow data were calculated from the toll station data.

4.2 Factor analysis

1) The Effect of longitudinal line shape on the number of annual accidents

According to the above analysis, the factors that have a greater impact on the safety of long and steep slopes in road environment are mainly longitudinal slope degree and longitudinal slope length. In addition, foreign scholars' studies on long and steep slopes show that the product of cumulative slope length *d* and average slope *p* of long and steep slopes has a certain correlation with accident risk. Therefore, based on the collected accident data of several long and steep longitudinal slope sections, this paper studies the relationship between the average longitudinal slope degree, longitudinal slope length and their coupling with the Annual number of accidents (ANA) of these sections, and the results are shown in the Figure 1.



(a) Average slope regression analysis (b) Slope length regression analysis (c) Coupled regression analysis

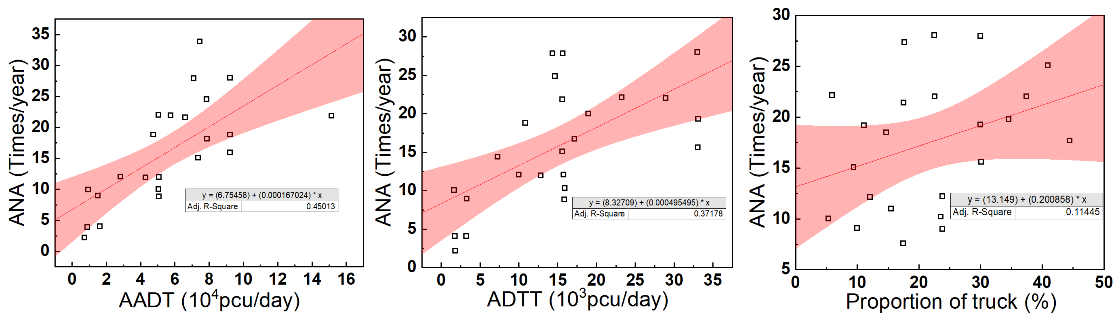
Figure 1. Relationship between longitudinal linear shape and annual number of accidents.

Note: The red band area in the figure is the 95% confidence interval, and the same is true below.

The relationship between the analyzed average slope and longitudinal slope length of the long and steep longitudinal slope sections and the annual number of accidents is relatively discrete, without obvious statistical characteristics, and the linear relationship is weak. As can be seen from the trend line, with the increase of the average slope, the annual accident number has a slight downward trend. With the increase of longitudinal slope length of long and steep longitudinal section, the annual accident number also increases. The product of cumulative slope length and average slope of long and steep longitudinal slope has a certain correlation with accident risk, showing relatively strong linear characteristics. This phenomenon suggests that the longitudinal slope and slope length should be considered comprehensively when preventing accidents on long and steep longitudinal slope sections, and more safety facilities should be added in the sections where the product of the two is larger.

2) The Effect of traffic flow on the number of annual accidents

The influencing factors of traffic include traffic flow, truck proportion, etc. Due to the particularity of long and steep slope, truck traffic flow is also included in the range of variables. In addition to considering the overall traffic flow impact, truck flow is taken as a separate variable to study its impact on accidents. Traffic flow is expressed by AADT (Average Annual Daily Travel) and truck flow is expressed by ADTT (Average Annual Daily Travel of Truck). The increase of the proportion of trucks will form a bottleneck of traffic flow, which will reduce the stability of traffic flow and increase the risk of accidents. In order to measure the impact of trucks on the safety of long and steep slopes, the proportion of trucks is used as a variable. The results are shown in the Figure 2.



(a) AADT regression analysis (b) ADTT regression analysis (c) Truck ratio regression analysis

Figure 2. Relationship between traffic flow and annual number of accidents.

The annual number of accidents presents a relatively obvious linear positive correlation with the annual average daily traffic volume and the annual average daily traffic volume of trucks. The number of accidents increased as the proportion of trucks increased, but the statistical correlation between the two was weak. It is suspected that when the proportion of trucks increases, drivers will increase their vigilance accordingly, resulting in a weak increase in the number of accidents. This suggests that safety prevention departments can reduce the probability of accidents by controlling the traffic flow and the proportion of trucks on dangerous roads.

5. CONCLUSIONS

Based on the accident data of seven expressways with multiple long and steep slopes in Guizhou Province, this paper uses python to build MNL models for different sections, studies the different accident causes of two types of sections, and makes univariate regression analysis on multiple factors of long and steep slopes. The following conclusions are reached:

1) Based on the processing and screening of multi-day and multi-source accident data, it is found that the causes of highway accidents in mountainous areas mainly include vehicle type, accident type, accident time, and horizontal and vertical line shape of road sections.

2) Based on the accident data, python was used to build MNL models for different types of road sections, and the significance analysis and comparison were conducted. It was found that the accident type, vehicle type and accident location of the long and steep slope road sections were significantly different from those of the general road sections.

3) The results show that the coupling effect of longitudinal slope length and slope, traffic flow and truck proportion have obvious influence on the annual accident number. This provides some reference for the safety prevention department to

determine the high-risk section, and also indicates that it is feasible to control the traffic volume input and the proportion of trucks in the dangerous section to reduce the probability of accidents.

Due to the limitation of data and the limitation of accident analysis methods, the analysis of accident causes in different road sections is still relatively simple. In the next step, different models and simulation software can be combined to deeply explore the causes of accidents on long and steep longitudinal slopes, so as to provide more effective guidance for the safety prevention of mountain highways.

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