Construction of accident rate model for tunnel group sections of expressway in mountainous areas

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Abstract: The main influential factors affecting the traffic safety of tunnel group sections of expressway in mountainous areas and their effect on the accident rate are analyzed. This paper analyzes the accident rate of the tunnel group sections of expressway from the aspect of the road alignment and the anti-sliding ability of the road surface. According to the principle of the road sections, the accident rate prediction models for four different sections are established, which are the curve section of the tunnel entrance, the straight section of the tunnel entrance, the curve section of the tunnel exit, and the straight section of the tunnel exit. For different types of road sections, the corresponding road data and independent variables are selected, multiple linear regression is performed by spss software, and an accident rate prediction model is constructed. The results show that under the worst condition of linear condition, the demand value of SFC side-way force coefficient is much larger than the specified value, the required anti-sliding performance of the road surface is the highest for the tunnel entrance straight section, and the anti-sliding performance of the road surface required for the tunnel exit curve section is the lowest. The reason for this is that the direct line segment is better than the curve line segment condition, resulting in faster driving speed, and therefore the demand for anti-sliding performance of the road surface is also higher.

1. Introduction

Due to the topographical, geological and socioeconomic limitations, the expressway in mountainous areas gradually emerged ultra ratio of bridge-tunnel sections, composed of special structures, such as tunnel groups, bridge and tunnel groups with totally different characteristics from the roads in the plain. A large number of accidents prove that, compared with the general road sections, the ultra ratio of bridge-tunnel sections had higher safety risks and greater difficulty in emergency rescue after the accidents, which have characteristics of wide range of impact and serious consequences. Therefore, it is still one of the important research directions in the field of traffic safety to study the characteristics of high ratio of bridge-tunnel sections of highway in mountainous regions and construct a traffic accident prediction model so as to reduce the number of accidents at the accident-prone locations.

Chuo[1] adopted the IHSDM accident prediction model to identify the accident-prone locations in road sections or areas, and proved that the accuracy of the model's output data. Marchionna[2] demonstrated from the opposite angle that the applicability of the model should be seriously discussed in road sections or areas with different characteristics. Choi[3] analyzed the road traffic and tunnel
accident data, calibrated the correction coefficients of middle strip type and middle strip width etc. in IHSDM, and obtained an accident prediction model applicable to the roads and tunnels in Korea. MA[4] established an accident frequency prediction model based on the time-space analysis and negative binomial distribution, summarized the highways and tunnels in China with different road infrastructure and safety conditions, considered the Poisson distribution model, the negative binomial distribution model. ZHANG [5] found in the research that the selection of dependent and independent variables, the form and type of model in the construction of the model are the main factors that affect the modeling accuracy. DENG [6] established a highway accident prediction model based on the BP neutral network, and finally the reliability of the prediction results of the model was verified.

For the accident prediction model, the scholars at home and abroad established several traffic accident prediction models on the basis of the generalized regressive model, the neural network model and IHSDM model etc., and obtained the prediction results mainly from the characteristics and features of the roads, such as the geometric alignment and cross sections etc. of the roads and tunnels. While on the other hand, how to combine the geometric alignment of the roads and tunnels with the anti-sliding performance of the road surface to construct a traffic accident prediction model still needs further research.

Characteristics of high ratio of bridge-tunnel sections of expressway in mountainous areas were analyzed with reference to documents and by collection of data. Through the analysis of the road alignment, vehicle velocity and anti-sliding ability of the road surface, the main factors that affect the traffic safety of the high ratio of bridge-tunnel sections of expressway in mountainous areas were obtained. Based on the analysis of the relationship between the division of road sections, road alignment indicators, anti-sliding performance indicators of road surface and the accident rate, a model applicable to the data in this paper was selected to construct a expressway accident prediction model and the accuracy of the model was tested accordingly. Besides, the demand value of anti-sliding ability of road surface under certain accident rate and road geometric alignment was calculated based on this model.

2. Data acquisition and analysis

2.1. Test section

G65 Baotou-maoming expressway is an important passage to the sea in central and western regions of China, and is an important economic and social link connecting the inland and coastal cities. Yuxiang section of Baotou-maoming expressway runs through the Daloushan Mountain, passes through Wuling mountainous area, and through high mountains and valleys, and karst caves. It is haily and misty in winter, windy in spring, and rainy in summer. Its geological and climatic conditions are quite complex. There are many long tunnels and bridge & tunnel groups and with a high proportion of bridges and tunnels. This paper selected Nanchuan-hongan section of G65 Baotou - maoming expressway.

The homogeneity method is helpful to determine the influence of geometric alignment on traffic safety, thus it is adopted in this paper for the division of road sections. Since the relationship between the test data of the road surface and the accidents will be discussed subsequently, the division of road sections in the test report should also be considered. If there is any difference, the sections divided by “homogeneity method” should be more detailed to ensure that the status of the road surface and data of each section is consistent. The principle of the division of road sections was shown in Figure 1.

In this paper, the data of stake number of Jiehong section K167+332~K1995+666 of Yuxiang super expressway was collected. The entrance and exit of each tunnel was divided as a road section. A total of 248 road sections were obtained, with 124 upward and 124 downward. The shortest road section was 65.55m, the longest was 4766.66m and the average length was 783.51m.
Figure 1. Principle of the division of road sections with homogeneity method

Table 1  Statistical indicator table of road sections of Yuxian super expressway

| Number of road sections | Shortest section (m) | Longest section (m) | Average length (m) |
|-------------------------|----------------------|---------------------|-------------------|
| 248                     | 65.55                | 4766.66             | 783.51            |

2.2. Geometric alignment data processing

The alignment elements were sorted out for this paper from the design documents of the expressway, including the horizontal alignment elements (length of straight section, length of horizontal curve, length of easement curve and radius of circular curve) and vertical alignment elements (falling gradient of vertical slope and length of vertical slope). The shortest straight section of Jiehong section of Yuxiang super expressway is 161.53m, the shortest horizontal curve is 63.42m, the smallest horizontal curve radius is 500m, the biggest slope is 4.75% and the longest vertical slope is 5300m. The horizontal and vertical alignment indicators were shown in Table 2.

Table 2 Summary of alignment indicators of Yuxiang super expressway

| Alignment indicators of expressway | Length of straight section (m) | Length of horizontal curve (m) | Length of easement curve (m) | Radius of circular curve (m) | Length of vertical slope (m) | Falling gradient (%) |
|-----------------------------------|--------------------------------|--------------------------------|-------------------------------|-------------------------------|-------------------------------|---------------------|
| Yuxiang super expressway Minimun value | 161.53                          | 63.42                           | 99.62                         | 500.00                        | 300.00                        | 0.30                |
| Yuxiang super expressway Maximun value | 7664.35                         | 2849.44                         | 452.70                        | 6800.00                       | 5300.11                       | -4.75               |
| Yuxiang super expressway Average value | 931.77                          | 525.47                          | 190.03                        | 1474.49                       | 1091.53                       | 1.86                |

2.3. Anti-sliding data

The anti-sliding performance of the road surface was evaluated with SRI and calculated with Formula 1.

\[
SRI = \frac{100 - SRI_{\text{min}}}{1 + a_0 e^{a_1 SFC}} + SRI_{\text{min}}
\]  

In the formula:  SFC is the side way-force-coefficient,  SRI min is the calibration parameter, which is 35.0;  a0 is the model parameter, which is 28.6;  a1 is the model parameter, which is -0.105.

In order to analyze the relationship between the SFC and the accident rate of the road section, this paper selected the SFC data from the test data, and regarded it as the basic data for subsequent analysis. The summary of the anti-sliding performance test data of Yuxiang super expressway was shown in Table 3.
Table 3  Summary of anti-sliding performance indicators of Yuxiang super expressway

| Driving direction | Minimum value | Maximum value | Average value | Standard difference |
|-------------------|---------------|---------------|---------------|---------------------|
| SFC               | 23.70         | 85.80         | 51.76         | 8.15                |
|                   |               |               |               |                     |
| Driving direction | Minimum value | Maximum value | Average value | Standard difference |
| SFC               | 14.50         | 75.70         | 51.13         | 9.51                |

2.4. Accident rate and its statistics

According to the data from the expressway law enforcement, there were 860 accidents from Nanchuan to Hongan section of Yuxiang super expressway in 2016. As mentioned previously, the section from Nanchuan to Hongan was divided into 248 road sections with the entrance and exit of each tunnel as a section, and there were 363 accidents in the section, with an average of 1.46 accidents. Based on the calculation, the lowest accident rate was 0, and the highest was 28.6.

The road accident rate was mostly 0 to 3 times, the number of sections with 0-1 accident rate was 117, accounting for 47.18%, the number of sections with 1-2 accident rate was 30, accounting for 12.10%, the number of sections with 2-3 accident rates was 29, accounting for 11.69% and the number of sections with over ten accident rate was 14, accounting for 5.65%.

2.5. Relationship between radius of horizontal curve and accident rate

The fitting relationship between the radius of horizontal curve and accident rate was shown in Figure 2. It can be seen from the figure that the higher the radius of horizontal curve was, the lower the accident rate was. These two elements had a clear adverse relationship. In addition, when the radius of horizontal curve was relatively small, the accident rate decreased rapidly with the increase of the radius of horizontal curve, and when the radius of horizontal curve was relatively big, the accident rate decreased slowly with the increase of the radius of horizontal curve.

The relationship model between the accident rate and radius of horizontal curve obtained from the results of regression analysis was shown in Formula 2.

\[ y = 34.11e^{-4.6-0.8R}, R^2 = 0.923 \]

In the formula:  
- \( y \) is accident rate, times/year/km;  
- \( R \) is radius of horizontal curve, m.

2.6. Relationship between length of horizontal curve and accident rate

The relationship model between the accident rate and length of horizontal curve obtained from the results of regression analysis was shown in Formula 3.
In the formula:

\[ y = 34978L - 1.25, R^2 = 0.720 \]  

In the formula: \( y \) is accident rate, times/year/km;

\( L \) is length of horizontal curve, m.

From the model curve, it can be seen that the accident rate decreased with the increase of the length of horizontal curve. When the horizontal curve was shorter than 1000m, the accident rate increased significantly. The several largest accident rates all incurred when the horizontal curve was shorter than 1000m. When the horizontal curve was longer than 1500m, the accident rate decreased slowly and showed a stable tendency.

**Figure 3. Relationship between length of horizontal curve and accident rate**

2.7. Relationship between length of straight section and accident rate

The relationship between the length of straight section and accident rate was shown in Figure 4.

\[ y = 6E - 0.7L^2 - 0.005L + 11.4, R^2 = 0.70 \]  

In the formula: \( y \) is accident rate, times/year/km;

\( L \) is length of straight section, m.

**Figure 4. Relationship between the length of straight section and accident rate**

From the above figure, it can be seen that the accident rate had a quadratic parabola relationship with the length of straight section. When the straight section was 3000m-5000m, the accident rate was the lowest. When the straight section was shorter than 1000m or longer than 7000m, the accident rate raised significantly, which showed that too short or too long straight section shall have certain adverse effect on traffic safety. Therefore, in the design of the road, too short or too long straight alignment should be avoided.

2.8. Relationship between falling gradient of vertical slope and accident rate

The fitting relationship between the falling gradient of vertical slope and accident rate was shown in Figure 5. It can be seen from the figure that the accident rate increased with the increase of the falling gradient, and the downhill section changed more obviously than the up slope. Under the same falling gradient, the accident rate of the downhill section was higher than that of the up slope section, which
showed that the downhill section had a higher driving risk than the up slope section. It was mainly because that the driving speed on downhill section was greater than the up slope section, especially for the trucks, the accident rate would be relatively higher.

\[ y = 0.574i - 0.354i + 3.566, \quad R^2 = 0.429 \]  

(5)

In the formula:  
- \( y \) is accident rate, times/year/km;  
- \( i \) is falling gradient of vertical slope, %.

Figure 5.  Relationship between falling gradient of vertical slope and accident rate

2.9. Relationship between length of vertical slope and accident rate

The relationship between the length of vertical slope and accident rate was shown in Figure 6.

\[ y = 139.2L - 0.49, R^2 = 0.12 \]  

(6)

In the formula:  
- \( y \) is accident rate, times/year/km;  
- \( L \) is the length of vertical slope, m.

According to the fitting curve and relationship model, the value of \( R^2 \) was 0.12, which showed that the correlation between the length of vertical slope and accident rate was small. It was mainly because that the main factor affecting the accident rate was the vertical slope of vertical section, which also showed that the samples with large accident rates existed in different slope sections. Therefore, the length of vertical slope was not selected as an independent variable in the model fitting.

Figure 6.  Relationship between length of vertical slope and accident rate

2.10. Relationship between SFC and the accident rate

The anti-sliding performance indicators of road surface directly affects the driving safety of the vehicles at high-speed, mainly in braking performance and braking distance. After statistical analysis, the relationship between the accident rate and SFC was shown in Figure 7.
After regression analysis, the relationship between the calibrated accident rate and SFC was shown in Formula 7.

\[ y = -0.044SFC + 4.984, R^2 = 0.565 \]  

In the formula: \( y \) is accident rate, times/year/km; 
SFC is side-way force coefficient.

According to the fitting curve and model, the accident rate had a negative linear correlation with SFC. The higher the SFC value was, the lower the accident rate was, and thus the stronger anti-sliding ability of the road surface and higher of driving safety.

3. Verification and calculation of the model

3.1. Verification of the model

In order to determine whether the influencing factors in the regression model are correlated, a collinearity diagnosis should be conducted for the variables introduced in the model. The analysis result by SPSS software was shown in Tables 4 to 7.

### Table 4. Collinearity diagnosis for accident rate prediction model of curve section of tunnel entrance

| Model | Dimension | Characteristic value | Condition index | (Constant) | Variance proportion |
|-------|-----------|----------------------|-----------------|------------|---------------------|
|       |           | Radius of horizontal curve |               | .00        | .00                 |
|       |           | Length of horizontal curve |               | .00        | .00                 |
|       |           | Falling gradient of vertical slope |       | .00        | .00                 |
| 1     | 1         | 4.337                | 1.000           | .00        | .00                 |
| 2     | .625      | 2.635                | .00             | .00        | .00                 |
| 3     | .332      | 4.584                | .00             | .06        | .01                 |
| 4     | .126      | 6.547                | .00             | .63        | .00                 |
| 5     | .024      | 8.888                | .75             | .01        | .05                 |

\( ^a \)Dependent variables: accident rate.

### Table 5. Collinearity diagnosis for accident rate prediction model of straight section of tunnel entrance

| Model | Dimension | Characteristic value | Condition index | (Constant) | Variance proportion |
|-------|-----------|----------------------|-----------------|------------|---------------------|
|       |           | Length of straight section |               | .02        | .00                 |
|       |           | Falling gradient of vertical slope |       | .00        | .00                 |
| 1     | 1         | 3.489                | 1.000           | .00        | .00                 |
| 2     | .387      | 3.002                | .00             | .49        | .00                 |
| 3     | .123      | 5.317                | .00             | .49        | .04                 |
| 4     | .042      | 8.510                | .66             | .00        | .06                 |

\( ^a \)Dependent variables: accident rate.
Table 6. Collinearity diagnosis for accident rate prediction model of curve section of tunnel exit

| Dimension | Characteristic value | Condition index | (Constant) Radius of horizontal curve | Length of horizontal curve | Falling gradient of vertical slope | SFC |
|-----------|----------------------|-----------------|---------------------------------------|---------------------------|-----------------------------------|-----|
| 1         | 4.385                | 1.000           | 0.00                                  | 0.00                      | 0.00                              | .00 |
| 2         | .569                 | 2.775           | 0.00                                  | 0.01                      | 0.01                              | .00 |
| 3         | .226                 | 4.990           | 0.00                                  | 0.69                      | 0.06                              | .02 |
| 4         | .139                 | 5.097           | 0.00                                  | 0.28                      | 0.67                              | .02 |
| 5         | .107                 | 6.209           | 0.85                                  | 0.02                      | 0.06                              | .44 |

* Dependent variables: accident rate.

Table 7. Collinearity diagnosis for accident rate prediction model of straight section of tunnel exit

| Dimension | Characteristic value | Condition index | (Constant) Length of straight section | Falling gradient of vertical slope | SFC |
|-----------|----------------------|-----------------|---------------------------------------|-----------------------------------|-----|
| 1         | 3.424                | 1.000           | 0.02                                  | 0.00                              | .00 |
| 2         | .460                 | 2.727           | 0.02                                  | 0.59                              | .00 |
| 3         | .115                 | 5.448           | 0.00                                  | 0.29                              | .05 |
| 4         | .082                 | 7.955           | 0.53                                  | 0.09                              | .23 |

* Dependent variables: accident rate.

It can be seen from the tables that the characteristic values were all greater than 0, the condition index values were all less than 10, and the variance proportions of the variables were less than 1, thus it can be concluded that there were no collinearity problems among the introduced variables, and the model results obtained from the regression analysis were accurate.

3.2. Calculation of the model

3.2.1. Calculation model of the anti-sliding performance indicators of road surface

Based on the accident rate prediction model constructed above and the set accident rate, the SFC can be calculated reversely, i.e. under certain radius of curve section, length of curve (straight)section and falling gradient of vertical slope, the required SFC below specified accident rate could be obtained. The calculation model of SFC was as follows.

1) Curve section of tunnel entrance

\[
SRI = \frac{26.014 - 1.505R - 0.563L + 2.429i - y}{0.542}
\]  

(8)

In the formula:  
y is accident rate (times/year/km);  
R is radius of horizontal curve (km);  
L is length of horizontal curve (km);  
i is falling gradient of vertical slope(%);

2) Straight section of tunnel entrance

\[
SRI = \frac{36.560 - 1.181R - 4.654L + 1.527i - y}{0.204}
\]  

(9)

In the formula:  
y is accident rate (times/year/km);  
L is length of straight section (km);  
i is falling gradient of vertical slope(%);  
SFC is anti-sliding performance index of road surface.

3) Curve section of tunnel exit

\[
SRI = \frac{36.560 - 1.181R - 4.654L + 1.527i - y}{0.805}
\]  

(10)
In the formula:  
\[ y \text{ is accident rate (times/year/km);} \]
\[ R \text{ is radius of horizontal curve (km);} \]
\[ L \text{ is length of horizontal curve (km);} \]
\[ i \text{ is falling gradient of vertical slope(%)}; \]
\[ SFC \text{ is anti-sliding performance index of road surface.} \]

4) Straight section of tunnel exit

\[
SRI = \frac{54.394 + 0.39L + 4.889i - y}{1.403}
\]  

In the formula:  
\[ y \text{ is accident rate (times/year/km);} \]
\[ L \text{ is length of straight section (km);} \]
\[ i \text{ is falling gradient of vertical slope(%)}; \]
\[ SFC \text{ is anti-sliding performance index of road surface.} \]

3.2.2. Calculation of required value of SFC

In accordance with the JTGD20-2017 Design Specification for Expressway Alignment:

1) Length of straight section between two circular curves: When the design speed is greater than or equal to 60km/h, the minimum straight section between the circular curves at the same direction should be no less than 6V, and no less than 2V at the opposite direction.

2) The maximum radius of the circular curve should not exceed 10000m.

3.2.3. Suppose that the accident rate is 1, and put the values of the different combinations of conditions into the SFC calculation model.

See Table 8 for the calculation results

| Section type | Curve section of tunnel entrance | Straight section of tunnel entrance | Curve section of tunnel exit | Straight section of tunnel exit |
|--------------|----------------------------------|------------------------------------|-----------------------------|--------------------------------|
| 1            | 57.56                            | 69.78                              | 47.76                       | 48.58                          |
| 2            | 62.77                            | 76.04                              | 50.19                       | 52.05                          |
| 3            | 67.70                            | 82.31                              | 52.48                       | 55.52                          |
| 4            | 72.33                            | 88.58                              | 54.66                       | 59.00                          |

To control the accident rate below 1 (time/year/km), the anti-sliding performance index under different working conditions must meet the value sin Table 22. From the data in the table, it can be found that under the worst condition of linear condition, the demand value of SFC lateral force coefficient is much larger than the specified value (see Table 9), and the required anti-sliding performance of the road surface is the highest for the tunnel entrance straight section, and the anti-sliding performance of the road surface required for the tunnel exit curve section is the lowest. The reason for this is that the direct line segment is better than the curve line segment condition, resulting in faster driving speed, and therefore the demand for anti-sliding performance of the road surface is also higher.

| Average annual rainfall (mm) | Technical test index value |
|------------------------------|---------------------------|
|                              | SFC60                     |
| Greater than 1000            | Greater than or equal to 54|
| 500-1000                     | Greater than or equal to 0.55|
| 250-500                      | Greater than or equal to 45|

Note: 1. SFC60 - the side-way force coefficient measured at a driving speed of 60 km/h. 2. Texture depth TD (mm)—determined by sand patch method.
4. Conclusions
Based on the data of Yuxiang super expressway and targeted at the tunnel entrance and exit, this paper divides the Nanchuan-Hongan section into 248 road sections, and statistically analyzes the accident data, road alignment data, and SFC of each road section, analyzes the relationship between the accident rate and the road alignment and SFC, and calibrates and verifies the accident rate prediction model with the linear regression tool of SPSS software. The conclusions are as follows:

(1) As the radius of the horizontal curve increases, the accident rate decreases. There is a clear adverse relationship between the two.

(2) As the increase of the length of horizontal curve, the accident rate decreases. When the horizontal curve is shorter than 1000m, the accident rate increases significantly. The several largest accident rates all incurred when the horizontal curve was shorter than 1000m. When the horizontal curve is longer than 1500m, the accident rate decreases slowly and shows a stable tendency.

(3) When the straight section is 3000m-5000m, the accident rate is the lowest. When the straight section is shorter than 1000m or longer than 7000m, the accident rate rises significantly.

(4) The length of vertical slope has a low correlation with the accident rate and the accident rate has a negative linear correlation with SFC. The higher the SFC value is, the lower the accident rate is, and thus the stronger anti-sliding ability of the road surface and higher of driving safety.

(5) The required anti-sliding performance of the road surface is the highest for the tunnel entrance straight section, and the anti-sliding performance of the road surface required for the tunnel exit curve section is the lowest. The reason for this is that the direct line segment is better than the curve line segment condition, resulting in faster driving speed, and therefore the demand for anti-sliding performance of the road surface is also higher. By specifying the accident rate and different working conditions, SFC is calculated by accident rate prediction model, and the minimum value of SFC required to meet the accident rate of 1 (time/year/km) is obtained.

Acknowledgments
This paper is supported by National Natural Science Foundation of China (Project approval number: 51608084), Project of Chongqing Science & Technology Commission (cstc2017shms-zdyfX0070), Project of Chongqing Transport Commission (SW-2016-263) and Project of Chongqing Expressway Co,Ltd(CK-KY-0001).

References
[1] Chuo K, Saito M.(2009)Applicability of FHWA Crash Prediction Module to selecting candidate locations for safety audits of two-lane rural expressways. J.Transportation Research Record Journal of the Transportation Research Board.2137(2137):20-28.
[2] Marchionna A, Perco P, Falconetti N.(2012)Evaluation of the Applicability of IHSDM Crash Prediction Module on Italian Two-Lane Rural Roads. J.Procedia-Social and Behavioral Sciences.53:932-941.
[3] Choi E, Kim E, Cho H, et al.(2014)Development of a Korea expressway safety evaluation prototype model on the concept of IHSDM crash prediction module. J.International Journal of Urban Sciences.18(1):61-75.
[4] MA, Z.L, ZHANG, Y.Y.(2015)Research on models for predicting severity of traffic accident in expressway tunnel. J.China Safety Science Journal.25(5):75-79.
[5] ZHANG, T.J.(2010)Analysis of Poisson Traffic Accident Prediction Models and Their Application. J.Journal of Highway and Transportation Research and Development.27(6):132-137.
[6] DENG, X.Q.(2016)An Accident Prediction Model for Expressway Based on BP Neural Network. J.Journal of Transport Information and Safety.7(1): 95-99.