Safety Discrimination of Expressway Plane and Vertical Alignment Combination Based on Grey Clustering Method

Yifei Zhao¹, Xin Lei¹*
¹Highway School of Chang'an University, Xi'an, Shaanxi Province, 710064, China
*Corresponding author’s e-mail: 157441864@qq.com

Abstract. The combination design of plane and vertical alignment is one of the most important links in expressway alignment design, the quality directly affects the safety of corresponding sections. Therefore, it is of great practical significance to research the safety of plane and vertical alignment combination for expressway alignment design. Based on the collections of the plane and vertical alignment design data of the S26 Zhuji-Yongjia Expressway in Zhejiang Province and the historical data of the five-year traffic accidents, the paper uses the homogeneity method to divide the expressway alignment into the smallest unit modules. The grey clustering method is used to evaluate the safety of the plane and vertical alignment combination sections, and a discrimination model of the relationship between the plane and vertical alignment combination section and traffic safety is established. Combined with the severity of expressway traffic accidents, a method to judge the safety of different alignment combinations is given.

1. Introduction
With the gradual improvement of China's expressway network, expressway traffic accidents have also increased, and the number of casualties remains high, which has brought great negative impact on China's traffic safety operation and GDP growth. FU Rui and other scholars researched on a large number of data and found that the plane and vertical alignment of expressway will have a significant effect on the occurrence or severity of traffic accidents[1]. Matthew G. Karlaffi et al. used nonparametric statistical methods and proposed that highway geometry design and pavement type are the two most important factors for the accident rate[2]. As an important part of expressway, alignment has a decisive impact on traffic safety.

For in-service expressways, a model which can be used to judge the safety of different alignment combination sections is proposed, which has practical significance for later operation management and accident investigation. Through a large number of literature summary, it is known that the grey clustering method can objectively describe and evaluate uncertain systems with some known and effective information. This practical theoretical system has been used in many fields, such as observation and analysis of hydrological environment, macroeconomic analysis, e-commerce performance analysis, etc. In the field of transportation, this theory is basically used in traffic safety risk analysis[3].

2. Division of plane and vertical alignment combination sections
Firstly, some sections with abnormal accident data are eliminated, and the remaining sections are divided according to homogeneity method. The principle is shown in figure 1.
Using homogeneity method, taking the change point of plane and vertical alignment unit of expressway as the dividing point, the section is divided, the database is established based on the dividing sections and the accident history data. According to the stake mark\[4\] of the accident location, accident is linked with plane and vertical alignment combination of expressway, and the relationship between expressway plane and vertical alignment combination and traffic safety is researched.

3. Evaluation method and technical route
The grey clustering method is different from the commonly used discrimination methods, and only relies on accident data for direct discrimination. The severity of the accident is considered as the equivalent number of accidents. The number of accidents, deaths and injuries are converted into the equivalent number of accidents to measure the losses caused by accidents. The equivalent number of accidents is calculated according to equation (1):

$$ETAN = TAN + K_1F + K_2F + K_3J + K_4L$$

In equation (1): $ETAN$ — Equivalent number of accidents. $TAN$ — Total number of accidents. $F$ — Number of deaths caused by accidents. $J$ — The number of people who caused serious injury in the accident. $L$ — The number of people who caused minor injury in the accident. $K_1, K_2, K_3$ — Conversion coefficient of death accident, minor injury accident and serious injury accident. Its value is determined by the traffic police who deal with the accident at that time according to the impact on the society, generally range value of $K_1$ is (1.5,2.0), range value of $K_2$ is (1.2,1.5), range value of $K_3$ is (1.0,1.2).

Based on the grey clustering method, the technical route of road section safety research is relatively unified, that is, after defining the road section division, the number of accidents and casualties in the section is counted, and equivalent number of accidents is calculated annually. Then determining the grey class feature value, calculating the cluster vector, judging the grey class, and completing safety analysis of road section\[5\].

4. Grey Clustering Method for longitudinal evaluation of safety of plane and vertical alignment combination sections
Determining $n$ as the number of evaluation objects, determining the number of evaluation index items $m$, and determining the grey index $k$.

Collecting raw data, evaluating matrix $D_0$, such as equation (2), $d_{ij}^0$ represents the original value of the jth evaluation index in the ith evaluation object, $i = 1,2,\ldots,n; j = 1,2,\ldots,n$.

$$D_0 = \begin{pmatrix} d_{11}^0 & \cdots & d_{1m}^0 \\ \vdots & \ddots & \vdots \\ d_{n1}^0 & \cdots & d_{nm}^0 \end{pmatrix}$$
Carrying out dimensionless treatment on accident indicators and ensuring that all values after dimensionless treatment are between \((0,1)\), and processing the original data according to equation (3) and equation (4). The matrix after dimensionless processing is \(D_i\).

\[
d_{ij} = \frac{d^0_{ij}}{\max_{1 \leq i \leq n} \{d^0_{ij}\}}
\]

\[(3)\]

\[
D_i = \begin{pmatrix}
\frac{d_{i1}}{d_{i1}} & \cdots & \frac{d_{im}}{d_{i1}} \\
\vdots & \ddots & \vdots \\
\frac{d_{in}}{d_{i1}} & \cdots & \frac{d_{im}}{d_{in}}
\end{pmatrix}
\]

\[(4)\]

According to the grey index \(k\), the evaluation grade is divided into three grades: the section with better safety condition, the section with general safety condition and the section with worse safety condition. At the same time, the cumulative distribution curve of the initial data is drawn. According to the cumulative frequency curve, the values of \(A^1_j, A^2_j, A^3_j\) are 30\%, 50\%, 70\%, \(j = 1, 2, \ldots, m\), so as to determine safety conditions on each section. Then, determining the whitening weight function of grey classes belonging to different evaluation indexes.

After dimensionless processing, the numerical values are concentrated between \((0,1)\), the whitening weight function \(f(x) \in (0,1)\).

The whitening weight function of the section with better safety condition:

\[
f^1_j \left( d_{ij} \right) = \begin{cases}
1, & d_{ij} \in \left[ 0, A^1_j \right] \\
\frac{A^2_j - d_{ij}}{A^2_j - A^1_j}, & d_{ij} \in \left[ A^1_j, A^2_j \right] \\
0, & d_{ij} \notin \left[ 0, A^1_j \right]
\end{cases}
\]

\[(5)\]

The whitening weight function of the section with safety condition:

\[
f^2_j \left( d_{ij} \right) = \begin{cases}
0, & d_{ij} \in \left[ A^1_j, A^3_j \right] \\
\frac{d_{ij} - A^1_j}{A^3_j - A^1_j}, & d_{ij} \in \left[ A^1_j, A^2_j \right] \\
\frac{A^3_j - d_{ij}}{A^3_j - A^2_j}, & d_{ij} \notin \left[ A^2_j, A^3_j \right]
\end{cases}
\]

\[(6)\]

The whitening weight function of the section with worse safety condition:

\[
f^3_j \left( d_{ij} \right) = \begin{cases}
0, & d_{ij} \in \left[ A^1_j, A^2_j \right] \\
\frac{d_{ij} - A^2_j}{A^3_j - A^2_j}, & d_{ij} \in \left[ A^2_j, A^3_j \right] \\
1, & d_{ij} \geq A^3_j
\end{cases}
\]

\[(7)\]

Analyzing what kind of grey classes each index belongs to and distinguishing its clustering coefficient.

\[
u^j_i = \frac{A^j_i}{\sum_{j=1}^{m} A^j_i}
\]

\[(8)\]
In the equation (8): $u^t_j$ - The clustering coefficients of the evaluation objects are classified into the item $t$ grey class according to the item $j$ evaluation index; $A^t_j$ - The item $j$ evaluation index belongs to the eigenvalues of the item $t$ grey class; $j=1,2,\ldots,m; t=1,2,\ldots,k$.

Determining the clustering values of each grey class, expressing the clustering values by clustering coefficient vectors, and judging the grade of road sections.

$$\sigma'^t_i = \sum_{j=1}^{m} f^t_j \left( d^t_j \right) u^t_j$$  \hspace{1cm} (9)

In the equation (9): $\sigma'^t_i$ - Section $i$ belongs to the clustering value of item $t$ grey class; $f^t_j \left( d^t_j \right)$ - Item $j$ evaluation index belongs to the function value of whitening weight function at whitening value of item $t$ grey class; $i=1,2,\ldots,n; j=1,2,\ldots,m; t=1,2,\ldots,k$.

$$\sigma_i = \left( \sigma^1_i, \sigma^2_i, \ldots, \sigma^k_i \right)$$  \hspace{1cm} (10)

In the equation (10): $\sigma_i$ — Cluster coefficient vector of section $i$.

$$\sigma^*_i = \max_{1 \leq t \leq k} \left\{ \sigma'^t_i \right\}$$  \hspace{1cm} (11)

The corresponding assignment of the whole alignment is carried out to get the safety condition of the corresponding section $i$, and the whole road section is classified as the section with better safety condition, the section with general safety condition and the section with worse safety condition[6].

5. An example of safety discriminant calculation for plane and vertical alignment combination sections

The section K159+250~K172+990 of S26 Zhuji-Yongjia Expressway in Zhejiang Province was selected as the calculation example section. It can be seen from statistical analysis that the accident rate of the plane-vertical alignment combination (the annual average number of accidents per unit length[7]) is small, and the correlation between different combination and accident rate is good. Taking the expressway as an example, the calculation of grey clustering method has certain representativeness.

5.1. Preliminary work

Determining the number $n$ of evaluation targets, determining the number $m$ of evaluation indicators, and discriminating the grey index $k$. The section K159+250~K172+990 of S26 Zhuji-Yongjia Expressway is divided into 30 sections by the homogenous method, $n=30$. The number of accidents, the equivalent number of accidents and the accident rate are used as the evaluation indexes, $m = 3$. The grade of grey class is three grades, $k=3$.

Integrating the original values of the data, and minimizing three evaluation indexes of dimensionless processing, as shown in table 1.

| No. | Number of accidents | Accident rate | Equivalent number of accidents | No. | Number of accidents | Accident rate | Equivalent number of accidents |
|-----|---------------------|---------------|--------------------------------|-----|---------------------|---------------|--------------------------------|
| 1   | 0.053               | 0.072         | 0.041                          | 16  | 0.000               | 0.000         | 0.000                          |
| 2   | 0.316               | 0.068         | 0.248                          | 17  | 0.632               | 0.660         | 0.657                          |
| 3   | 0.263               | 0.059         | 0.207                          | 18  | 0.000               | 0.000         | 0.000                          |
| 4   | 0.211               | 0.071         | 0.215                          | 19  | 0.053               | 0.098         | 0.041                          |
| 5   | 0.000               | 0.000         | 0.083                          | 20  | 0.000               | 0.000         | 0.000                          |
| 6   | 0.211               | 0.115         | 0.215                          | 21  | 0.158               | 0.179         | 0.124                          |
| 7   | 0.842               | 0.478         | 0.744                          | 22  | 0.053               | 0.086         | 0.041                          |
| 8   | 1.000               | 0.421         | 1.000                          | 23  | 0.000               | 0.000         | 0.000                          |
| 9   | 0.053               | 0.057         | 0.041                          | 24  | 0.000               | 0.000         | 0.000                          |
5.2. Determining grey class eigenvalues
Based on the dimensionless data, the cumulative frequency curve is estimated by SPSS data processing software: the cumulative frequency curve of number of accidents is \[ y = -0.0008x^2 + 0.0561x - 0.0635, R^2 = 0.9982 \]; the cumulative frequency curve of accident rate is \[ y = -0.0004x^2 + 0.0477x - 0.085, R^2 = 0.9845 \]; and the cumulative frequency curve of equivalent number of accidents is \[ y = -0.00009x^2 + 0.0459x - 0.0566, R^2 = 0.9802 \].

Substituting the 30%, 50%, and 70% cumulative frequency node values into the above equations and yielding a grey eigenvalue matrix:

\[
\begin{bmatrix}
A_1^1 & A_2^1 & A_3^1 \\
A_1^2 & A_2^2 & A_3^2 \\
A_1^3 & A_2^3 & A_3^3
\end{bmatrix}
= \begin{bmatrix}
0.213 & 0.425 & 0.535 \\
0.165 & 0.368 & 0.432 \\
0.274 & 0.369 & 0.555
\end{bmatrix}
\]

5.3. Determining whitening weight function and grey clustering coefficient of evaluation index
According to the grey eigenvalue matrix, substituting data into equation (5), equation (6) and equation (7), obtaining the whitening weight functions of three evaluation indexes. Then calculating clustering coefficient by equation (8), the matrix of grey clustering coefficient is obtained as follows:

\[
\begin{bmatrix}
u_1^1 & u_2^1 & u_3^1 \\
u_1^2 & u_2^2 & u_3^2 \\
u_1^3 & u_2^3 & u_3^3
\end{bmatrix}
= \begin{bmatrix}
0.182 & 0.362 & 0.456 \\
0.171 & 0.381 & 0.447 \\
0.229 & 0.308 & 0.463
\end{bmatrix}
\]

5.4. Determining grey class of each section and summary of calculation results
The values of table 1 are substituted into equation (9), and the grey clustering values of the three evaluation indicators are obtained. By analogy with the above calculation methods, the grey classes of 30 sections as shown in table 2:

Table 2. Computation table of grey class.

| No. | Clustering coefficient vector | Grey class | No. | Clustering coefficient vector | Grey class |
|-----|-------------------------------|------------|-----|-------------------------------|------------|
| 1   | 1.000 0.000 0.000            | 1          | 16  | 1.000 0.000 0.000            | 1          |
| 2   | 0.670 0.333 0.000            | 3          | 17  | 0.000 0.000 1.000            | 1          |
| 3   | 0.864 0.143 0.000            | 1          | 18  | 1.000 0.000 0.000            | 1          |
| 4   | 0.980 0.005 0.000            | 1          | 19  | 1.000 0.000 0.000            | 1          |
| 5   | 1.000 0.000 0.000            | 1          | 20  | 1.000 0.000 0.000            | 1          |
| 6   | 0.980 0.005 1.000            | 1          | 21  | 1.000 0.000 0.000            | 1          |
| 7   | 0.000 0.000 1.000            | 3          | 22  | 1.000 0.000 0.000            | 1          |
| 8   | 0.000 0.000 1.000            | 3          | 23  | 1.000 0.000 0.000            | 1          |
| 9   | 1.000 0.000 0.000            | 1          | 24  | 1.000 0.000 0.000            | 1          |
| 10  | 0.101 0.453 0.439            | 2          | 25  | 1.000 0.000 0.000            | 1          |
| 11  | 1.000 0.000 0.000            | 1          | 26  | 1.000 0.000 0.000            | 1          |
| 12  | 0.000 0.000 1.000            | 3          | 27  | 1.000 0.000 0.000            | 1          |
| 13  | 1.000 0.000 0.000            | 1          | 28  | 0.650 0.005 0.275            | 1          |

5
According to the grey theory, section 7, 8, 12, 17 and 30 are sections with worse safety condition. Section 7 is a combination section of straight alignment and large longitudinal slope, section 8 and 12 are a combination section of circular curve and large longitudinal slope, and section 7 and 8 constitute long downhill section. Section 17 is a combination section of small radius circular curve and vertical curve. Section 30 is a bridge section where the composite grade does not meet the requirements. Section 10 is a section with general safety condition, after verification, section 10 is a combination section of circular curve and long downhill section. The safety condition of other sections is judged to be better by grey class calculation.

It can be seen that the discrimination model established by grey clustering method has good practical application, and grey class and section safety condition consistent with statistical results.

6. Conclusion
By collecting the expressway route design data, traffic accidents and traffic composition data of Zhejiang Province, the expressway alignment is divided into the smallest unit modules by the homogeneity method. The grey clustering method is used to evaluate the safety of each plane and vertical alignment combination section, and the discrimination model of the relationship between plane and vertical alignment combination section and traffic safety is established. Combined with the different severity of expressway traffic accidents, a method to judge the safety of different alignment combinations is given. The section K159+250~K172+990 of S26 Zhuji-Yongjia Expressway is selected as the calculation example to verify the reliability of the discrimination method.

References
[1] Fu, R., Guo, Y.S., Yuan, W. (2011) The correlation between gradients of descending roads and accident rates. Safety Science., 49(3): 416-423.
[2] Matthew, G.K., Loannis, G., (2002) Effects of road geometry and traffic volumes on rural roadway accident rates. Accident Analysis and Prevention., 34: 357-365.
[3] Li, Z.M. (2015) The Application of Multi-level Grey Clustering Model on the Comprehensive Evaluation of River Health. Chongqing Jiaotong University, Chongqing.
[4] Zhang, X.M. (2016) Study of Relationship Between Road Alignment and Accident Rate Along with Induction Factors on Freeway. Harbin Institute of Technology, Harbin.
[5] Wang, J., Lu, X.F. (2016) Highway Black Spot Verification and Cause Analysis Based on Cluster Analysis. Technology of Highway and Transport., Vol. 32 No. 5: 114-119.
[6] Sha, M.H. (2018) Study on the Setting of Safety Facilities for Accident Prone Points in Mountain Area. Southwest Jiaotong University, Chengdu.
[7] Wang, H., Meng, H.Y., Guan, Z.Q. (2011) Research on Relationship Between Traffic Accident Rate and Geometric Alignment for Mountainous Freeway. Highway Engineering., Vol, 36 No. 4: 89-92.