Research on Safety Risk Assessment Technology of Expressway Traffic Operation

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Abstract. Based on the theory of expressway traffic safety and the analysis of accident causes, the risks of expressway traffic operation safety is identified, and a multilevel traffic safety risk assessment system is established. Combined with the advantages of traditional risk qualitative and quantitative analysis methods, the Fuzzy Analysis Theory is introduced in the Analytic Hierarchy Process, the Analytic Hierarchy Process (AHP) is established to weight each related index, and finally the Fuzzy Analytical Hierarchy Process (FAHP) is applied to estimate the risk probability and risk loss. And then according to the risk probability, risk loss assessment and its grade standard, the two-dimensional risk assessment matrix is used to measure the traffic operation risk level and give basic risk management and control criteria. And finally based on the above evaluation system, the traffic safety risk of an important bridge across the Yellow River on the expressway from Beijing to Shanghai is analyzed and assessed.

1. Introduction

By the end of 2017, the total mileage of expressways in China has reached 136,500 kilometers, ranking first in the world. Nearly 40% of China's cargo circulation depends on expressway transportation. The expressway has made great contributions to the development of the national economy, but the traffic accident death rate still stay high. At the end of 2017, the total mileage of national expressway was 4,773,500 kilometers, accounting for 2.9% of the total road mileage; while the number of expressway traffic accidents was more than 6,000, accounting for about 10% of the total traffic accident deaths.[1][2] The diversity, complexity and systematization of expressway traffic safety operation and management leads to more safety risks of highway traffic operation. In this way, the economic losses caused by safety risk accidents are increasing, which left risk decision making and management in great difficulty. China's safety risk identification and control technology in the field of expressway transportation is still in a blank, not only behind developed countries such as Europe and the United States, but also far from meeting the needs of transportation development in the new stage. Based on the analysis of the mechanism of traffic safety risk, this paper identifies the risk sources through the qualitative analysis method of Delphi and the statistical analysis method based on data such as traffic accidents, and gives the method of determining the risk grading standard, and then applies the method of Analytic Hierarchy Process to offer Muti-index synthesis assessment method.
2. Analysis and Identification of Influencing Factors of Expressway Operation Safety Risks

Risk identification is the basis of risk assessment and control management. Expressway traffic operation risk identification usually needs to solve two basic problems: one is what are the risk factors affecting expressway traffic operation, and another one is how to describe the characteristics of these risk factors in a comprehensive and detailed way and their adverse consequences on expressway traffic operations.

Commonly used risk identification methods in the field of risk management include Statistical analysis of related data, Safety checklist method, Brainstorming method, Delphi method, Work task analysis method and Fault tree analysis method, or the combination of two or more of them. [3] However, based on the unique attributes of the expressway operation industry and the relative lack of historical data on operational risk management, the problem of how to find relatively independent key risk factors from so many risk factors requires a more targeted risk identification method.

Based on the documentation research and the investigation of the safety risk management and control requirements of expressway operators, the risk factor identification method combining objective safety risk accident data analysis and subjective expert analysis method is adopted to break the limitation of data analysis and subjective analysis of risk factor and thus to improve the rationality of risk factor identification. At the same time, the risk factor identification method emphasizes the dynamic identification of risk factors and follows the rule that risks change with time and objective conditions.

Based on the statistical analysis of the influencing factors of the traffic safety risk accident case and the questionnaire from traffic safety management experts, we obtained the 15 expressway traffic safety risk factors index as shown in Figure 1.

![Figure 1. Indicators of influencing factors of expressway traffic safety risk](image-url)

- **Driver’s cause U1**
  - U11 Fatigue driving
  - U12 Expressway driving
  - U13 Awareness of safe driving and traffic rules compliance

- **Vehicle factors U2**
  - U21 Vehicle functions
  - U22 Vehicle overrun (load, height, width)
  - U23 Vehicle speeding

- **Road conditions U3**
  - U31 Road alignment (slope bend, bridge tunnels and etc)
  - U32 Road flatness
  - U33 Road anti-slip functions

- **Management factors U4**
  - U41 Traffic monitoring and controlling
  - U42 The setting of logo and marking
  - U43 The repair coverage of damaged road

- **Environment factors U5**
  - U51 Harsh weather (rain, fog, ice and snow)
  - U52 Geological disasters (landslides, falling rocks, mudslides)
  - U53 Maintenance, renovation and expansion of traffic control
3. Expressway Operation Safety Risk Assessment

The main task of risk assessment is to analyze the risk probability and risk loss of target indicators based on risk identification results, which is the most complicated and critical core step in the whole risk control technology process. The analysis methods of risk probability and loss are mainly divided into Qualitative methods (Expert investigation method) and Quantitative methods (Probabilistic analysis method, Decision tree method, Monte Carlo stochastic simulation method and Fuzzy comprehensive analysis method), and the result of traffic safety risk analysis with the quantitative method are more in line with the decision-making needs of expressway managers. [4][5]Probabilistic analysis method is difficult to implement due to the limited statistics on safety accidents. And at the same time, traffic safety risk assessment focuses on the impact of potential risks on traffic safety, so it is not necessary to dig deep into the logical relationship between influencing factors and to apply the Fault tree method. The combination of Analytic Hierarchy Process and Fuzzy Comprehensive Evaluation (AHP-FCE) is more suitable for the study of risk factor impact grading and risk decision hierarchy [6], and considering the uncertainty of risk analysis, it is also suitable for expressway traffic safety risk assessment. The main steps of this method include: establishing a hierarchical model of assessment index, constructing a risk index review set, establishing a hierarchy of evaluation index weights, establishing a membership matrix and a multilevel comprehensive evaluation algorithm.

3.1 The establishment of Hierarchical model of assessment index

Establishing a multilevel assessment model is one of the main steps of the Analytic Hierarchy Process, and most of its work has been finished in the process of risk identification. Based on the identification of expressway traffic safety risk sources, the target index \( U \) of expressway traffic operation safety risk is divided into m sub-indicators \( U^i, i=1, 2, 3, ..., m \), and the corresponding first-level indicator set \( U=(U^1, U^2, U^3, ..., U^m) \). And for each first-level indicator, it can also be further divided into n second-level indicators \( U^{ij}, j=1, 2, 3, ..., n \), and the corresponding secondary indicator set \( U^i=(U^{i1}, U^{i2}, U^{i3}, ..., U^{in}) \). In this way, the risk index is divided into two levels, and a three-level highway operation safety risk assessment index system is established as shown in Figure 1.

3.2 The Construction of Risk index review set

Risk index review set is a grading standard used to determine the level of each risk indicator in each risk factor group, \( V=(V_1, V_2, V_3, ..., V_5) \), and \( V_k \) represents different risk probabilities or loss levels. In the expressway operation safety risk assessment, it is more reasonable to divide the risk probability and loss into five grades (k=5) according to the cognitive law, that is, extremely low, low, medium, high, and extremely high. In order to better measure the final risk assessment results, it is necessary to give a risk probability and risk loss rating criteria. Tables 1 and 2 give a description of the different risk probabilities and risk loss levels [7].

| \( V_k \) | Score | Interval probability | Level | Description |
|------------|-------|----------------------|-------|-------------|
| extremely low | 0~0.2 | (0,10-6] | level one | It seems impossible, but there is still the possibility of occurrence |
| low | 0.2~0.4 | (10-6,10-3] | level two | Impossible, but there are still reasons to occur |
| medium | 0.4~0.6 | (10-3,10-2] | level three | Occurs many times |
| high | 0.6~0.8 | (10-2,10-1] | level four | Occur frequently |
| extremely high | 0.8~1.0 | (10-1,1] | level five | Occurs one after another |
### Table 2 Risk Loss Level Standard

| $V_k$            | Score  | Level   | Description                                                                                                                                 |
|------------------|--------|---------|---------------------------------------------------------------------------------------------------------------------------------------------|
| extremely low    | 0~0.2  | level one | There are few or no injuries; the losses are less than 50,000 yuan; no or few road facilities are damaged; the operator has no faults and no bad impact on his corpore reputation; no or less environmental damage. Zero death or no more than one severe injury; property losses are 50,000 to 500,000 yuan; road facilities are slightly damaged; the operator has no fault but it has minor social impact (such as road congestion); temporary severe damage to the environment. Two people die and ten people are severely injured under; property losses are 500,000 to 3 million yuan; local road facilities are severely damaged and it needs to be temporarily closed and repaired; operators take secondary civil liabilities, and adverse social reactions within a small area, and it causes slight reputation impact; long-term impact on the environment. Three to ten people die; property losses amount to 3 million to 30 million yuan; road facilities are severely damaged, requiring long-term closed maintenance; the operator have major civil liability, causing large adverse social repercussions and bad corporate reputation; serious environmental damage. More than ten people die; property losses are more than 30 million yuan; major damage to key road facilities (bridges, tunnels and etc.), requiring long-term closed maintenance; the operator take the primary responsibility, and it causes social repercussions and it damages corporate reputation; permanent and serious impact on environment. |
| low              | 0.2~0.4| level two |                                                                                                                                              |
| medium           | 0.4~0.6| level three|                                                                                                                                              |
| high             | 0.6~0.8| level four |                                                                                                                                              |
| extremely high   | 0.8~1.0| level five |                                                                                                                                              |

#### 3.3 Establishment of a Hierarchy of evaluation index weights

Weight analysis is another important content of the Analytic Hierarchy Process method. The hierarchy of evaluation index weights is a standard that indicates the importance of each level of risk index in each set of factors, and its establishment process includes: the discriminant matrix construction of the hierarchical index priority relationship, the fuzzy consistency discriminant matrix construction and the weight level calculation.

#### 3.3.1 Discriminant matrix of indicator priority relationship

The priority relationship matrix reflects the priority relationship between each of the two index in the same level of risk factors. It usually uses the Expert survey method to compare and analyze the importance of different indicators at the same level of traffic safety risks to establish this model. For example, the judgment matrix for the secondary indicator set is:

$$
a = \begin{bmatrix}
    a_{11} & a_{12} & \cdots & a_{1n} \\
    a_{21} & a_{22} & \cdots & a_{2n} \\
    \vdots & \vdots & \ddots & \vdots \\
    a_{n1} & a_{n2} & \cdots & a_{nn}
\end{bmatrix}
$$

(1)

Where: $a_{ij}$ (i = 1, 2, 3, ..., n; j = 1, 2, 3, ..., m) is the relative importance of the index factor $U_e$ to the $U_e$ (e = 1, 2, 3, ..., m). There are many Numerical scales methods used in the existing research to compare
the two pairs, and each has its own advantages and disadvantages [8]. This paper uses the 3-scale method to get $a_{ij}$:

$$a_{ij} = \begin{cases} 
0.5 & \text{if } t(i) = t(j) \\
1.0 & \text{if } t(i) > t(j), i,j=1,2,3,...,n \\
0 & \text{if } t(i) < t(j) 
\end{cases}$$  \hspace{1cm} (2)

Where: $t_i$, $t_j$ are the importance in the comparison of indicator factors $U_i$ and $U_j$. The 3-scale method is a complementary scale and is in harmony with people's logical thinking.

3.3.2 Construction of Fuzzy consistency matrix. The judgment matrix of the medium-transitiveness of the fuzzy consistency matrix is more suitable for the mental characteristics of people's decision-making thought, and the fuzzy consistency judgment matrix is effective in its function. The introduction of the fuzzy consistency judgment matrix can avoid the consistency check procedure caused by the subjectivity of judgment. Many scholars have studied and proved the consistency of fuzzy judgment matrices, see Li Yong, Hu Xianghong [9], Zhang Sen, et al. [10]. The fuzzy consistent judgment matrix $A=\left( a_{ij} \right)_{n\times n}$, where $a_{ij}$ is a priority judgment matrix.

$$A_{ij} = \frac{k_i}{2n} - \frac{k_j}{2n} + 0.5 \quad K_i = \sum_{j=1}^{n} a_{ij} \quad i=1,2,3,...,n$$  \hspace{1cm} (3)

3.3.3 Calculation of the Weight coefficient. There are several methods for solving the weight coefficient vector from the relational judgment matrix [8]. In this paper, the weight consistency judgment matrix $A$ is applied to calculate the weight based on the row normalization method. Firstly, the elements $A_{ij}$ in $A$ are normalized in columns to get a matrix $E = \left( e_{ij} \right)_{n\times n}$.

$$e_{ij} = \frac{A_{ij}}{\sum_{i=1}^{n} A_{ij}}$$  \hspace{1cm} (4)

Secondly, the elements in $E$ are added to the vector $F=\left(\ldots\right)$, and the vector $F$ is dimension-ed and normalized to obtain the weight coefficient vector $W=\left(\ldots\right)^T$.

$$w_{ij} = \frac{f_{ij}}{\sum_{e=1}^{n} f_e} \quad j = 1,2,3,...,n$$  \hspace{1cm} (5)

The weight coefficient vector $W$ of the first-level indicator set $U$ can be calculated by the same method. For some specific hierarchical structures, the weight of the first-level indicator can also be directly specified through expert investigation opinions.

3.4 Establishment of Membership matrix

The Membership matrix is a matrix used to describe the degree of membership of each risk index for each level of the comment set, and it is the basis of the evaluation result.

$$R = \begin{bmatrix} 
    r_{11} & r_{12} & \cdots & r_{1k} \\
    r_{21} & r_{22} & \cdots & r_{2k} \\
    \vdots & \vdots & \ddots & \vdots \\
    r_{n1} & r_{n2} & \cdots & r_{nk} 
\end{bmatrix}$$  \hspace{1cm} (6)

Where: $r_{ij}$ (i = 1, 2, 3, ..., n; j = 1, 2, 3, ..., k) is the membership of the i-th index with respect to the j-th comment level. For the index factors that can be quantified, the membership degree can be calculated
from the index feature values through the membership function [11]; but for most systemic risk analysis problems, the index factors are often difficult to quantify, so it can be obtained by statistical means using Expert survey methods. Table 3 gives the results of the Expert survey of the driver's factor membership probability for the driver's indicator set $U_i = (U_{i1}, U_{i2}, U_{i3})$.

Table 3 Driver's factor risk probability membership degree questionnaire

| The driver Factors | Score | Lower | Low | Medium | High | Extremely high |
|-------------------|-------|-------|-----|--------|------|----------------|
| $U_{i1}$ (fatigue) | 0.09  | 0.14  | 0.21| 0.29   | 0.50 |                |
| $U_{i2}$ (experience) | 0.16 | 0.18  | 0.23| 0.22   | 0.20 |                |
| $U_{i3}$ (consciousness) | 0.15 | 0.11  | 0.11| 0.40   | 0.29 |                |

3.5 Multilevel comprehensive evaluation
The multi-level comprehensive evaluation refers to the process of calculating the evaluation sets of each level from the bottom layer to the target layer based on the obtained membership degree matrix and weight set, and finally obtaining the risk estimation result of the target indicators.

3.5.1 Comprehensive evaluation of secondary index. From the second-level index weight set and the membership degree matrix $R_i$, the second-level index evaluation set $B_i$ can be obtained:

$$B_i = W_i^T \cdot R_i = \left[ W_{i1} + W_{i2} + \cdots + W_{in} \right] \cdot \begin{bmatrix} \Gamma_{i1} & \Gamma_{i2} & \cdots & \Gamma_{ik} \\ \Gamma_{i1}^{21} & \Gamma_{i2}^{22} & \cdots & \Gamma_{ik}^{2k} \\ \vdots & \vdots & \ddots & \vdots \\ \Gamma_{i1}^{m1} & \Gamma_{i2}^{m2} & \cdots & \Gamma_{ik}^{m k} \end{bmatrix} = \left[ b_{i1}, b_{i2}, \cdots, b_{ik} \right]$$

$i=1,2,\ldots,m$

In the formula: "," is a fuzzy operator. In this paper, the Zadeh operator, which is determined by the main factor, highlights the influence of the main factors and ignores other secondary factors [12].

$$b_{ij} = \frac{1}{n} \left( W_{ij} \cdot \Gamma_{ij} \right)$$

$i=1,2,\ldots,m$  $j=1,2,\ldots,n$  $e=1,2,\ldots,k$

The Dimensional normalization of the $B_i$.

3.5.2 Comprehensive evaluation of primary indicators. From the second-level index evaluation set $B_i$, the first-level membership degree matrix $R$ can be obtained.

$$R = \begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ B_n \end{bmatrix} = \begin{bmatrix} W_{11} \circ R_{11} \\ W_{21} \circ R_{21} \\ \vdots \\ W_{n1} \circ R_{n1} \end{bmatrix} = \left[ \Gamma_{ie} \right]_{m \times k}$$

Considering the first-level index weight set $W$, the first-level index evaluation set $B$ can be obtained.

$$B = W^T \cdot R = \left( w_1, w_2, \cdots, w_m \right) \cdot \begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ B_n \end{bmatrix} = \left( b_1, b_2, \cdots, b_n \right)$$
The Dimensional normalization of the $B_i$.

When $W$ can only be given by expert experience, $B$ can be obtained by:

$$B = W^T \cdot R = \left(W_1, W_2, \ldots, W_m\right) \cdot \left(B_1, B_2, \ldots, B_m\right)$$

(11)

3.5.3 Comprehensive assessment of target index. For some complex problems, the hierarchical model may have multiple intermediate layers. According to the above steps, the assessment is performed from the bottom layer to the upper layer, and the evaluation set $B$ can be obtained. The score set $G = (0.1, 0.3, 0.5, 0.6, 0.9)$ is established from the middle value of the comment set $V$ score interval, and the risk estimation result $D$ of the target index $U$ can be obtained as in the formula (12).

$$D = B \cdot G^T = \left(b_1, b_2, \ldots, b_k\right) \cdot \left(g_1, g_2, \ldots, g_k\right)$$

(12)

4. Expressway Operation Safety Risk Assessment and Control

Based on the risk identification and estimation, the risk assessment used the comprehensive risk probability estimation result and the risk loss estimation result, combined with the corresponding risk assessment model, comprehensively evaluates the risk, determine the overall level and severity level of the system risk. And finally gives corresponding risk control measures. The expressway operation safety risk assessment model applies to a two-dimensional evaluation model, as shown in Table 4, and Table 5 gives the control measures for different risk levels.

### Table 4 Risk Assessment Model

| Risk portability \ Risk loss score | 0.2–0.4 | 0.4–0.6 | 0.6–0.8 | 0.8–1.0 |
|-----------------------------------|---------|---------|---------|---------|
| Score                             | I       | II      | III     | IV      |
| 0.2–0.4                           | I       | I       | II      | III     |
| 0.4–0.6                           | I       | II      | III     | III     |
| 0.6–0.8                           | I       | II      | III     | IV      |
| 0.8–1.0                           | II      | III     | IV      | IV      |
| 0.2–0.4                           | III     | III     | IV      | IV      |

### Table 5 Risk Control Criteria

| Risk level | Acceptance criteria | Control criteria |
|------------|---------------------|------------------|
| I          | Can be ignored      | Lower risk, no need to take risk response and monitoring measures |
| II         | Can be accepted     | Moderate risk, no need to take risk response measures but need to take monitoring measures |
| III        | Not expected        | High risk, must take risk response and monitoring measures to reduce risk level |
| IV         | Cannot be accepted  | Extremely high risk, must attach great importance to risk aversion, otherwise should reduce risk to undesired levels at all costs |

5. Case Analysis

A Yellow River Highway Bridge, as a prime large bridge on the Beijing-Shanghai expressway, is an critical cross section of the Beijing-Shanghai and Beijing-Taibei Expressway, with a total length of 5,750 meters, a main bridge length of 947.66 meters, and an approach bridge length of 4,152.98 meters. It is 35.5 meter in width, 6 lanes in both directions, and it has a design speed of 120 km/h. It is an expressway bridge with high design standards and large building scale on the Yellow River. At present, it has more than 67,600 traffic flows. With such a huge traffic flow, it always causes frequent traffic safety accidents,
congestion in bad weather, and difficult operation and management. Therefore, it is very important to strengthen the safety risk assessment based on the safety risk influencing factors of the bridge.

5.1 Establishment of a weight set
According to the results of the Expert survey and the formulas from (1) to (5), the weight set $W_i$ of the secondary index set $U_i$ of the traffic safety risk can be obtained.

$W_1 = (0.463, 0.312, 0.225)^T$, $W_2 = (0.303, 0.352, 0.345)^T$, $W_3 = (0.351, 0.301, 0.348)^T$, $W_4 = (0.417, 0.289, 0.294)^T$, $W_5 = (0.579, 0.217, 0.204)^T$.

The weight set of the first-level indicator set $U$ is directly given by expert experience $W = (0.50, 0.10, 0.15, 0.10, 0.15)$.

5.2 Establishment of a membership matrix
According to the risk factor expert survey results of the driver factor set, the risk probability membership matrix $R_i$ of the driver factor set $U_1$ is

$R_1 = 
\begin{array}{ccccc}
0.09 & 0.14 & 0.21 & 0.29 & 0.50 \\
0.16 & 0.18 & 0.23 & 0.22 & 0.20 \\
0.15 & 0.11 & 0.11 & 0.40 & 0.29 \\
\end{array}$

The other secondary indicator membership matrix $R_i$ can be obtained by the same method.

5.3 Comprehensive assessment of traffic safety risks
Taking the risk probability estimation as an example, from the calculated $W_i$ and $R_i$ and the formulas (7) to (8), the second-level index evaluation set $B_i$ can be obtained.

$B_1 = (0.326, 0.326, 0.101, 0.065, 0.182)$, $B_2 = (0.316, 0.255, 0.195, 0.099, 0.135)$

$B_3 = (0.273, 0.237, 0.227, 0.126, 0.137)$, $B_4 = (0.283, 0.283, 0.155, 0.167, 0.112)$

$B_5 = (0.321, 0.155, 0.264, 0.139, 0.121)$.

From equations (9) to (11), the first-level index assessment set $B$ is $B = (0.50, 0.10, 0.15, 0.10, 0.15) \cdot (B_1, B_2, B_3, B_4, B_5)$, $T = (0.394, 0.112, 0.189, 0.113, 0.192)$.

From equation (12), the safety risk probability of the bridge traffic operation is $DP = B \cdot (0.1, 0.3, 0.5, 0.7, 0.9) = 0.4194$. In the same way, the safety risk loss score of the bridge traffic operation is $Dl = 0.4316$.

5.4 Security Risk Assessment and Control Measures
According to the risk probability and risk loss estimation assessment results, and the risk two-dimensional evaluation model in table 5, it is known that the bridge traffic safety risk is classified as level III, which is an undesired risk zone. Risk response measures and monitoring measures must be taken to reduce the risk level. In order to achieve the above objectives, risk control measures such as restricting driving behavior, improving road conditions, improving transportation facilities and strengthening traffic management should be adopted to reduce traffic risk.

6. Summary
Based on the statistical analysis of the influencing factors of expressway traffic safety risk, this paper identifies the main factors affecting the safety of high-speed traffic operation. And then the construction of a risk assessment index of influencing factors through traffic safety data analysis, the introduction of fuzzy comprehensive evaluation theory to highway traffic operation and the application of a systematic assessment of safety to achieve the following results:
(1) Through objective data statistics and subjective mechanism analysis, this paper identifies various risk indicators in five aspects: driver behavior, vehicle performance, road conditions, management factors and road environment that affect expressway traffic safety, and it has constructed an indicator system for traffic safety risk assessment.

(2) Combining the advantages of Analytic Hierarchy Process and Fuzzy Comprehensive Evaluation, the Fuzzy Analytic Hierarchy Process (FAHP) is used to establish the expressway traffic safety risk assessment. The weight of index factors is obtained by Analytic Hierarchy Process method and Fuzzy consistency judgment matrix is introduced to ensure it consistency. All those have effectively improved the uncertainty in traffic safety risk assessment.

(3) Establishing the correspondence between different risk probabilities, risk loss levels and risk estimation scores to obtain risk probability and risk loss level standards. And then establishing a highway traffic safety risk assessment method based on two-dimensional evaluation model to give basic risk control guidelines.

(4) Through the above research, a set of assessment methods for potential traffic safety risks in the highway operation phase has been established. According to the actual construction of a significant trans-Yellow River bridge project of Beijing-Shanghai Expressway, the assessment system was used to analyze and evaluate its traffic safety risks. The case study has showed that the proposed theory and method can effectively analyze the traffic safety risks of expressway or some critical sections.

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