Study on Evaluation of Beijing-Shanghai High-speed Railway Operation Safety

Zhuo Wang*, Xiaorong Deng

Beijing Jiaotong University, School of Traffic and Transportation, Beijing 100044;
*Corresponding author’s e-mail: zhwang1@bjtu.edu.cn

Abstract: The study aims to evaluate operation safety level of Beijing-Shanghai High-speed Railway in China. In order to do so, this research establishes a safety assessment index system of Beijing-Shanghai HSR based on AHP firstly. Then based on the fuzzy matter-element theory, with the concept of the Euclid approach degree (EAD), compound fuzzy matter-element for safety level evaluation is established. The results show that Beijing-shanghai HSR is a better operation safety level in China. According to the results, some suggestions on improving Beijing-shanghai HSR operation safety are proposed.

1. Introduction

Compared with other modes of transport, high-speed railway has many advantages, such as high speed, large transportation capacity, high comfort and low energy consumption, etc. After the completion of China's high-speed railway, high-speed railway carrying a large number of passengers. However, due to the high operating speed and the concentration of passengers, it is hard to dealt with the emergency at the first time. China has been building high-speed railways since 1999 and has a short development period. With the rapid development of China high-speed railway, safety issues will be exposed in terms of technology and management. On July 23, 2011, for example, a rear-end collision occurred in the eastern city of Wenzhou causing 40 deaths and more than 200 injuries. The reason for the accident is the disruption of signal transmission between the track circuit and the train operation control system because of lightning. The accident exposed both the design flaws in the signal system and the weaknesses in emergency treatment and security management.

How to improve the operation safety of high-speed railway is a problem that builders always confront with. Therefore, it is necessary to fully know the operation safety situation of high-speed railway, scientifically analyze the security risks of high-speed railway operation, and comprehensively evaluate high-speed railway operation safety level. This research takes the Beijing-Shanghai High-speed Railway as the research object. According to the historical accidents, analyze the safety factors of Beijing-Shanghai HSR. Several key high-speed railway lines are compared to evaluate the safety level of Beijing-shanghai high-speed railway in China.

2. Background

The Beijing-Shanghai High-speed Railway, with a total length of 1318 km, is the longest high-speed railway one-time constructed in the world by far. Beijing-shanghai high-speed rail occurred more than one accident since the operation.
Table 1 2011-2016 Beijing-Shanghai HSR typical accidents

| Time       | Accidents               | Causes                    |
|------------|-------------------------|---------------------------|
| 2011-7-10  | Train withdrawn from schedule | Heavy wind               |
| 2013-2-19  | Train withdrawn from schedule | Snowy conditions         |
| 2014-7-22  | Train delay              | Line fault                |
| 2016-11-29 | Train delay              | Factory accidents along the line |
| ---        | Train speed down        | Smoking                   |

Table 1 shows 2011-2016 Beijing-Shanghai HSR typical accidents. Combining with Accident-Causing Theory [1] and man-machine-environment system engineering, this article evaluates and analyzes the safety of the Beijing-Shanghai high-speed railway from personnel, equipment and environmental factors.

2.1. Passengers

The impact of passengers on the safety of high-speed railways is mainly reflected in the level of passengers' safety behaviors and passenger safety awareness [2]. The safety behavior of passengers includes carry dangerous goods and dangerous behavior. Passenger safety awareness refers to the understanding of HSR safety rules and regulations and the understanding of emergency response and emergency measures. The passenger safety awareness is related to the passenger component. Table 2 shows the occupations of passengers on the Beijing-Shanghai line [3]. The main components of passengers are business managers, technicians, tradesmen and workers. It can be seen from the occupations of passengers that most passengers have a high level of education, so as to infer that passengers' the safety behavior level and safety awareness are relatively high.

Table 2 Beijing-Shanghai HSR travel purpose and passenger occupation table (%)

| Classification       | Business trip | Visiting relatives | Tourism | Work | Study | Shopping | Trade | Others | Total |
|----------------------|---------------|--------------------|---------|------|-------|----------|-------|--------|-------|
| Administrator        | 5.13          | 0.45               | 2.38    | 0    | 0.45  | 0.07     | 0.15  | 0.15   | 8.77  |
| Manager              | 16.06         | 1.26               | 2.75    | 0.07 | 0.82  | 0.37     | 0.89  | 0.37   | 22.60 |
| Technician           | 12.04         | 1.19               | 2.9     | 0.15 | 1.12  | 0        | 0.15  | 0.07   | 17.62 |
| Worker               | 4.83          | 2.23               | 2.83    | 0.37 | 0.59  | 0.22     | 0.15  | 0.3    | 11.53 |
| Businessman          | 4.31          | 0.67               | 1.12    | 0    | 0.07  | 1.41     | 6.62  | 0.07   | 14.28 |
| peasant              | 0             | 0.67               | 0.37    | 1.49 | 0     | 0        | 0.45  | 0.07   | 3.05  |
| student              | 0             | 0.82               | 1.93    | 0.15 | 3.87  | 0        | 0.07  | 0.52   | 7.51  |
| retired people       | 0.45          | 1.78               | 1.04    | 0    | 0     | 0        | 0.15  | 0.15   | 3.42  |
| military and police  | 2.68          | 2.08               | 0.37    | 0    | 0.67  | 0        | 0     | 0.30   | 6.10  |
| Others               | 0.59          | 0.22               | 1.26    | 1.64 | 0.15  | 0.15     | 0.45  | 0.67   | 5.13  |
| **Total**            | **46.25**     | **11.38**          | **16.95**| **3.87**| **7.73**| **2.23** | **8.92**| **2.68**| **100**|

In addition, the main purpose of those passengers is to travel, business and visiting relatives. This leads to time non-equilibrium of passenger flow. During the Spring Festival, the passenger volume of Beijing-shanghai HSR reached up to 17.849 million a day. However, Beijing-Shanghai HSR transport capacity is 8000 million people per year and 219,200 daily. It is clear that the passenger volume during the Spring Festival greatly exceeded the transport capacity.

2.2. Equipment

Equipment includes rail and line, stations, communication signals, traction power supply system and vehicle power system. Beijing-Shanghai HSR rail line is the two-lane electrification, ballastless track and seamless rail. The proportion of viaduct is 86.5%. Viaduct can improve the ride comfort and safety of high-speed rail lines, so it can be used as an indicator for the safety of HSR. The design
speed of the Beijing-Shanghai HSR is 380 km/h and the operating speed is 300 km/h. Due to the high running speed, the maintenance of trains and lines under normal conditions and the train braking in emergency situations have a great impact on HSR safety.

2.3. Environment
In this section, the environmental conditions of Beijing-Shanghai HSR will be discussed from two aspects: the social environment and the natural environment.

2.3.1. Social Environment
Beijing-Shanghai HSR leads to the development of regional economy. In the six years since the operation of the Beijing-Shanghai HSR, it has stimulated the development potential of cities along the line and erected a "high-speed rail economic corridor". The illegal construction under the viaduct has brought security risks to the HSR operation. According to the statistics, there are 170 potential problems, 86 have been resolved.

2.3.2. Natural Environment
Beijing-Shanghai HSR is mainly in the eastern part of China, via Beijing, Tianjin, Jinan, Nanjing, Shanghai and other cities. The annual average rainfall in Tianjin and Beijing is more than 400ml; Nanjing and Shanghai more than 1200ml. Rainfall is one of the natural factors that affect the operation safety of HSR. The average winter temperatures in these cities such as Beijing and Tianjin range from -3 to 5 °C. Beijing-Shanghai HSR is affected by snowfall in winter. In addition, Beijing-Shanghai HSR also affected by cross-wind.

Beijing-Shanghai HSR uses traction power. Overhead lines as part of the traction power supply system is generally exposed to the natural environment, it was badly affected by the weather. There is heavy rainfall from June to September, the line is more likely to be struck by lightning. The lightning will be transmitted to the traction substation through overhead lines, causing the circuit breaker trip or even destroy equipment [4]. In addition, winter snowfall can also be harmful. Snowfall can not only cause rail icing and limit the speed of trains leading to train delays, but also cause overhead lines icing leading to rail lines paralyze.

3. Evaluation indicators
After the analysis of Beijing-Shanghai HSR security conditions, a great many factors can influence the safety of HSR. Considering the previous research achievements and the difficulty of data acquisition, this research selects average daily passenger volume, passenger safety behavior level, proportion of bridges, operating speed, train technical merit, natural environment and social environment 7 indicators as the Beijing-Shanghai High-speed Railway safety evaluation index[6-8]. Since the evaluation indicators have both qualitative and quantitative indicators, this research uses analytic hierarchy process to evaluate the indicators.

3.1. Analytic Hierarchy Process
Analytic Hierarchy Process (AHP) is a hierarchical method that quantitatively expresses and deals with qualitative results of subjective judgment. The evaluation object is usually regarded as a whole composite system, and the system is divided into different levels according to the needs of decision-makers. AHP is particularly applicable to systems that are complex and lack quantitative data that consist of many interrelated and constrained factors [5]. The basic steps are as follows:

Step 1. Establish the index system. According to the evaluation object determine the evaluation index, and classify the evaluation indexes. Establish a hierarchical structure, the general hierarchy is divided into three layers: target layer, rule layer and index layer.

Step 2. Materiality judgment. Construct pairwise comparison judgment matrix

\[ C = \left( c_{ij} \right)_{nxn}. \]
Step 3. Calculate the weight of the indicator. Judgment matrix $C$ should satisfy $CW = \lambda_{\text{max}} W$. Then normalize eigenvectors. The normalized eigenvectors $\omega = [\omega_1, \omega_2, \cdots, \omega_n]^T$ are taken as the weight values of the corresponding elements of this level.

Step 4. Consistency check. By calculating the consistency index $CI$ and the average random consistency index $RI$ (look-up table available) to obtain concordance ratio $CR$. If $CR < 0.1$, then said the judgment matrix has a satisfactory consistency.

$$CI = (\lambda_{\text{max}} - n) / (n - 1) \quad (1)$$

$$CR = CI / RI \quad (2)$$

### 3.2. Index system construction

Based on AHP, this research establishes the safety assessment index system of Beijing-Shanghai HSR (see Fig. 1). In this research, the quantitative indicators of the Beijing-Shanghai HSR are average daily passenger volume, proportion of bridges and operating speed; qualitative indicators are passenger safety behavior level, train technical merit, natural environment and social environment.

![Beijing-Shanghai HSR safety assessment index system](image)

**Figure 1 Beijing-Shanghai HSR safety assessment index system**

### 3.3. Index analysis

Based on the historical data of the Beijing-Shanghai HSR and the research results at home and abroad [9-11], using AHP to calculate the subjective weights of the factors. After the consistency test, the weight and sort of the evaluation index of Beijing-shanghai HSR safety are shown in table 3.

**Table 3 Beijing-Shanghai HSR evaluation index weights and sort**

| Hierarchy | $B_1$ | $B_2$ | $B_3$ | Weights | Sort |
|-----------|-------|-------|-------|---------|------|
| $C_1$     | 0.0974| 0.5695| 0.3331| 0.0252  | 7    |
| $C_2$     | 0.6370| 0.0810| 0.2000| 0.1287  | 3    |
| $C_3$     | 0.1884| 0.7306| 0.6000| 0.0461  | 6    |
| $C_4$     | 0.1047| 0.2000| 0.1999| 0.1073  | 4    |
| $C_5$     | 0.4160| 0.4160| 0.4160| 0.1999  | 1    |
| $C_6$     | 0.1047| 0.2000| 0.0768| 0.1999  | 5    |
According to the evaluation results, the passenger, equipment and environmental in the rule layer account for the weights of 0.0974, 0.5695 and 0.3331, respectively. Equipment has the greatest impact on the safety of high-speed railways. Equipment status is the basis for the safe operation of HSR. The weight of environmental is higher than that of passengers, because environmental is more difficult to control than passengers. History has proven that the number of accidents caused by harsh environments is far greater than that caused by passengers.

For the index layer, ranking first is train technical merit, with a weight of 0.4160 which is much higher than the other indicators. Basically, train malfunctions have a direct impact on the occurrence of accidents, and the train braking ability is related to the safety of passengers in emergency situations. For another, the natural environment and the passenger safety behavior level also have a great impact on HSR safety. The harsh natural environment often leads to the failure of the line equipment or the track which affect the operation of trains. This reminds managers of the importance of coping with bad weather. Passenger irregularities can also cause accidents. During the operation of Beijing-Shanghai HSR, there have been a number of train deceleration accidents caused by smoking on the train. Furthermore, the weight of average daily passenger flow volume and proportion of bridges are less than 0.05. Because the planning of the track line and carrying capacity of HSR is reasonable, and can meet the needs of actual transport.

4. Evaluation method

In order to analyze the safety level of Beijing-Shanghai HSR in China, Beijing-Shanghai, Beijing-Guangzhou, Harbin-Dalian and Lanzhou-Xinjiang HSR are compared in this research, which are important high-speed railway projects in China. Due to different indicators have different dimension, we need to unify the index values to get an intuitive assessment. Therefore, this research uses the fuzzy matter-element method for index evaluation.

4.1. Fuzzy Matter-element Method

Fuzzy matter-element method solves the problem of fuzzy incompatibility caused by the ambiguity of the value in the matter element. Fuzzy matter is a ternary ordered group of things, features, and fuzzy features. In the comprehensive evaluation, the thing is item M, the feature is evaluation index C, and the fuzzy feature is index value X, which constitute the following elements [12].

\[
R_{mn} = \begin{bmatrix}
M_1 & M_2 & \cdots & M_m \\
c_1 & \mu(x_{11}) & \mu(x_{21}) & \cdots & \mu(x_{m1}) \\
c_2 & \mu(x_{12}) & \mu(x_{22}) & \cdots & \mu(x_{m2}) \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
c_n & \mu(x_{1n}) & \mu(x_{2n}) & \cdots & \mu(x_{mn})
\end{bmatrix}
\]  

(3)

where, \( R_{mn} \) represents \( m \) things \( n \)-dimensional compound fuzzy matter-element; \( c_j \) represents the \( j \)th feature; \( M_i \) represents the \( i \)th thing; \( \mu(x_{ij}) \) represents the membership of the magnitude \( x_j (i = 1, 2, \cdots, m, j = 1, 2, \cdots, n) \) of the \( j \)th feature of the \( i \)th thing.

Generally, indexes are divided into the bigger the better and the smaller the better. And the different dimensions of the index will not affect the evaluation results. Eq. (4) and Eq. (5) are formulas for calculating the optimum degree of the indexes.

the bigger the better: \( \mu_j = x_{ij} / \max x_{ij} \)  

(4)

the smaller the better: \( \mu_j = \min x_{ij} / x_{ij} \)  

(5)
where, $\mu_{ij}$ represents the optimum degree of the $j$th feature of the $i$th thing; $x_{ij}$ represents the magnitude of the $j$th feature of the $i$th thing; $\max x_{ij}$ and $\min x_{ij}$ represent maximum and minimum values of $x_{ij}$.

### 4.2. Fuzzy Matter-element Decision Model

This article uses the Euclid approach degree (EAD) to evaluate the safety of high-speed railways. Approach degree refers to the degree of similarity between studied matter-element and standard matter-element. The larger the value, the closer they are. In order to use Euclid approach degree, it is necessary to establish a difference squared fuzzy matter-element between the studying fuzzy matter-element and the standard fuzzy matter-element. The standard fuzzy matter element refers to the maximum value or the minimum value of the degree of fuzzy goodness. According to the principle of determining the optimum degree, the degree of fuzzy goodness of the standard fuzzy matter element is 1. The calculation formulas of the fuzzy magnitude of difference squared fuzzy matter element $\Delta_{ij}$ are as shown in Eqs. (6) and (7).

- The bigger the better: $\Delta_{ij} = (1 - \mu_{ij})^2$, $i = 1, 2, \ldots, m$, $k = 1, 2, \ldots, n$  
- The smaller the better: $\Delta_{ij} = (\mu_{ij} - 1)^2$, $i = 1, 2, \ldots, m$, $k = 1, 2, \ldots, n$

Eq. (8) shows the calculation formula of Euclid approach degree evaluation index $\rho H_i$.

$$\rho H_i = 1 - \sqrt{\sum_{j=1}^{n} \omega_j \Delta_{ij}}, \quad i = 1, 2, \ldots, m$$

where, $\omega_j$ is the weight of the $j$th indicator. According to Eq. (8), a compound fuzzy matter-element based on Euclid approach degree $R_{\rho H}$ is constructed (see Eq. (9)).

$$R_{\rho H} = \begin{bmatrix} M_1 & M_2 & \cdots & M_m \\ \rho H_1 & \rho H_1 & \rho H_2 & \cdots & \rho H_m \end{bmatrix}$$

### 5. Results

In this research, the Beijing-Shanghai, Beijing-Guangzhou, Harbin-Dalian and Lanzhou-Xinjiang four high-speed railway lines are defined by Line 1, Line 2, Line 3 and Line 4. Table 4 describes the 7 evaluation indicators of four lines. Herein, the quantitative safety indicators (average daily passenger volume, proportion of bridges and operating speed) are described according to Table 5. And qualitative indicators (passenger safety behavior level, train technical merit, natural environment and social environment) are evaluated by experts, the evaluation criteria is shown in Table 6.

| Indicators                              | High-speed railway |
|-----------------------------------------|--------------------|
|                                        | Line 1 | Line 2 | Line 3 | Line 4 |
|-----------------------------------------|--------|--------|--------|--------|
| Average daily passenger volume $C_1$ (unit: million people) | 24.7   | 9.6    | 27.4   | 1.04   |
| Passenger safety behavior level $C_2$  | 0.6    | 0.6    | 0.6    | 0.45   |
| Proportion of bridges $C_3$ (unit: %)   | 86     | 73.3   | 81     | 9.53   |
| Operating speed $C_4$ (unit: km/h)      | 300    | 300    | 310    | 250    |
| Train technical merit $C_5$              | Good   | Good   | Good   | Good   |
| Natural environment $C_6$                | Common | Very poor | Poor | Very poor |
| Social environment $C_7$                 | Good   | Good   | Good   | Common |
Table 5 Description of quantitative index evaluation criteria

| Indicators                                      | Excellent | Good  | Common | Poor  | Very poor |
|------------------------------------------------|-----------|-------|--------|-------|-----------|
| Operating speed (unit: km/h)                    | 200       | 201-250 | 251-300 | 301-350 | >350       |
| Proportion of bridges (unit: %)                 | ≥ 60% and <60% | ≥ 40% and <50% | ≥ 30% and <40% | <30% |
| Average daily passenger volume (unit: million people) | ≥ 10 and <20 | ≥ 20 and <30 | ≥ 30 and <40 | >40 |

Table 6 Description of qualitative index quantitative criteria

| Grade                                  | Excellent | Good  | Common | Poor  | Very poor |
|----------------------------------------|-----------|-------|--------|-------|-----------|
| Score                                  | 0.9       | 0.75  | 0.6    | 0.45  | 0.3       |

Based on the qualitative and quantitative criteria, the four high-speed railway line evaluation indicators were quantified and compared with the standard line (defined by Line 0) which evaluated as "Excellent", and then establish the compound fuzzy matter-element $R_{mR}$. According to Eq.(8) a compound fuzzy matter-element based on Euclid approach degree $R_{pH}$ are figured out. The value and sort of $R_{pH}$ of four high-speed railway lines are shown in table 7.

Table 7 Comprehensive evaluation results of four high-speed railway lines

| Line               | $R_{mR}$ | Sort |
|--------------------|----------|------|
| Line 0             | 1.00     | 0.0000 |
| Line 1             | 0.67     | 0.7462 |
| Line 2             | 1.00     | 0.6287 |
| Line 3             | 0.67     | 0.6717 |
| Line 4             | 1.00     | 0.5802 |

Generally, the Beijing-Shanghai HSR in the four lines in the most safe and have a good level of operation safety in China. However, Lanzhou-Xinjiang HSR has the lowest safety level relatively. There has a lot of room for Lanzhou-Xinjiang HSR to improve. According to comparison with the standard line, the proportion of bridges, train technical merit and social environment of Beijing-Shanghai HSR are good. The index values of average daily passenger volume and operating speed are slightly lower than that of the standard line, and the weights in HSR safety indicators are also low. They can be enhanced by strengthening the management of passenger and the maintenance of line and train. Moreover, the index values of natural environment and passenger safety behavior level are slightly lower than that of the standard line, but they have high weights in HSR safety indicators. As a result, these two aspects can be regarded as the key point to improve the safety level of the Beijing-Shanghai HSR. Here are some suggestions to improve the safety of Beijing-Shanghai.
HSR. For example, strengthening the safety early warning system of the Beijing-Shanghai HSR, improving emergency equipment and emergency measures and enhancing passenger safety education to enhance passenger safety awareness.

6. Conclusions and future work
This research analyzes the security conditions of Beijing-Shanghai High-speed Railway based on the typical historical accidents, and establishes a hierarchical structure model of the safety influential factors of high-speed railway by AHP. In the process of model establishment, the influence of the same index on multiple rule layers is considered to make the evaluation result reasonably. In order to observe the safety level of the Beijing-Shanghai High-speed Railway in China, a compound fuzzy matter-element model for safety level evaluation is established. In the model, the idea of Euclid approach degree was introduced to reflect the extent of closeness between four key high-speed railway lines in China including the Beijing-shanghai High-speed Railway and standard line.

The results show that Beijing-Shanghai High-speed Railway have a good level of operation safety in China. However, there are still some aspects should be improved, such as safety early warning system, emergency equipment, emergency measures and passenger safety education. Due to the lack of data support, the selection of safety evaluation index of the Beijing-Shanghai High-speed Railway is not comprehensive. Some management factors, such as the quality of flight attendants and drivers, are not considered in this study. In addition, the quantitative methods of qualitative indicators are subjective and may differ from reality. Our further research will focus on the selection of evaluation indicators and the improvement of evaluation methods to reduce the impact of subjective factors on evaluation results.

References
[1] Reilly J, Brown J, 2004, Management and Control of Cost and Risk for Tunneling and Infra-structure Projects, *Tunnelling and Underground Space Technology incorporating Trenchless Technology Research*, Vol.19(4), pp.330-330.
[2] Feng Y et al., 2013, An Analysis on the Relationships between the High-speed Railway Safety Factors Based on the Structural Equation Model, *Journal of Beijing Jiaotong University: Social Sciences Edition*, Vol.12(4), pp.75-83.
[3] Xiao Z, 2008, The Research on Application of Revenue Management in Railway Passenger Marketing, *Beijing Jiaotong University*, F532.6-533/201, pp.20-21.
[4] Zhao L, 2014, Study on Lightning Protection Reconstruction Plan of Catenary in Beijing-Shanghai High-speed Railway, *Shanghai Railway Science & Technology*, 2014, Issue 02, pp.44-45.
[5] Guo Z, Sang X and Li H, 2011, AHP-Based Safety Assessment Model for Rail Transit System, *China Railway Science*, Vol.32(3), pp.123-125.
[6] Wang Y et al., 2011, Design of the Simulation Platform for Safety Safeguard of High-Speed Trains Operation, *China Railway Science*, Vol.32(6), pp.134-140.
[7] Ma S et al., 2007, Determining Method of Index Weight for Synthetic Evaluating Road Environment, *Journal of Chang’an University: Natural Science Edition*, Vol.27(4), pp.37-41.
[8] Zheng L et al., A Comprehensive Evaluation of High-speed Railway Operation Safety Based on an Integrated Method, *Journal of Transport Information and Safety*, Vol.33(3), pp.65-70.
[9] Hu Q, Gao N, 2014, High Speed Railway Environment Safety Evaluation Based on Measurement Attribute Recognition Model, *Computational Intelligence and Neuroscience*, Vol.2014, PP.1-10.
[10] Ji X, Cheng W and Yanu J, 2009, Evaluation Model for Railway Human Factors Safety Based on Information Extraction, *Innovation Management and Industrial Engineering*, Vol.2009, pp.216-218.
[11] England, 2007, The railway strategic safety plan 2009-2014, *England: Rail Safety and Standards Board*.
[12] Zhang B, 1997, Fuzzy Matter-element Analysis, *Beijing: Petroleum industry press*.
[13] Wang Y, Wu L and Cai M, 2015, Operation Safety Assessment of Rail Transit Based on Entropy Weight Fuzzy Matter Element, *Transportation Standardization*, Vol.1(6), pp.51-57.