Identification and Evaluation of Urban Rail Transit Operation Risk Factors Based on Entropy-AHP Hybrid Constrained DEA Method

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The whole society is increasingly aware of the importance of urban rail transit (URT) safety and risk management. In order to correctly identify and evaluate the risk factors of URT operation and then classify and take differential measures to deal with the risk factors, the risk sources of URT accidents were analyzed by fault tree analysis and the URT operation risk evaluation index system concerning 8 categories and 40 risk sources were constructed. The DEA (data envelopment analysis) method with entropy-AHP hybrid constraint was established, and the probability and consequences of URT operation risk were taken as decision variables to evaluate and rank various risk factors. The results show that decision-making units (DMU) 1 and 2, namely, vehicle system failure and signal communication system failure, are at the largest Pareto risk units, the probability of risk can be reduced by 50.08% and 41.7%, and the risk consequences can be reduced by 35.57% and 46.83%, respectively. Staff factors and environment and management factors are the other two units closest to the maximum risk surface. A risk factor distribution matrix was established, and 40 risk factors are divided into risk factors, leverage risk factors, conventional risk factors, and influential risk factors, which provide a basis for the classification and policy of rail transit risk management.

1. Introduction

With the urban expansion and traffic congestion, the scale of urban rail transit (URT) in China is sharply expanding. Both the length of lines and the number of passengers are rapidly increasing, and the proportion of rail transit travel in public travel is increasing day by day. By the end of 2019, the total mileage of URT in China had been 6,730.27 km, much higher than that of other countries such as Germany, the second longest with the URT mileage of 3,615.1 km. In 2018, Beijing surpassed Tokyo to become the city with the largest urban rail transit passenger volume in the world. In addition, Shanghai, Guangzhou, Shenzhen, and Hong Kong are among the top eight cities in the world in terms of passenger flow. City planners and policy-makers can effectively reduce car ownership and usage by rationally planning rail transit lines. This has a significant effect on alleviating urban traffic congestion [1], especially in densely populated countries like China [2]. However, the operation system of URT is easy to result in huge potential risks due to the characteristics of large passenger flow, narrow working space, various types of facilities, and large population density. Once a safety accident occurs in URT, it is difficult to evacuate the crowd and implement accident rescue measures, and the accident will have a huge impact on the economy and social politics [3, 4].

In recent years, due to the influence of various factors, such as complex social security incidents, natural disasters, viruses, terrorism, and so on, social public security has more and more attracted the countries’ attention, and the risk management of URT is more concerned by various circles of society and rail transit operation enterprises. Therefore, it is of theoretical and practical significance to correctly identify and evaluate the risk factors of URT operation safety, to carry out the corresponding measures according to the classified risks, and to ensure the production and operation safety of URT and the safety of passengers’ lives and properties.

The research ideas of this study are as follows: first, this research intends to use the fault tree analysis (FTA) method
to reveal the risk source factors of different types of accidents based on the statistical data of rail transit accidents and establish a rail transit operation risk factor evaluation index system. Second, a DEA method with entropy weight-AHP hybrid constraint is proposed for rail transit operation risk evaluation, and the distribution matrix of risk factors is obtained. After evaluating and ranking the risk decision-making units, the risk reduction ratio of each DMU is obtained, which provides a decision-making basis for rail transit risk management.

2. Literature Review

Due to the frequent occurrence of various disasters and risks, the safety and risk problems of urban rail transit have attracted much attention in academia [5]. How to prevent the risks of the railway system and the rail transit system is a very important issue, which has attracted extensive attention from the government management and academia. The society has become more and more aware of the importance of safety and risk management, and has paid more attention to the institutionalization of risk management approaches in order to prevent disasters and improve the safety of people in areas adjacent to risky activities [4]. The risks of rail transit are closely related to people’s lives, and scholars have carried out research from different angles. First, some literature analyzed the risk from the perspective of the cause of the subway accident. For example, the existing research literature explored the effect of metro passengers’ behaviors and their relationship with accidents [6], examined the impact of risk factors on the severity of subway operation interruption from the perspectives of society, operators, and passengers [7], and simulated the propagation and evolution of risks in the urban rail transit [8, 9]. Second, some literature proposed methods for monitoring the performance and risk of railway or subway systems. For example, the literature used resilience engineering (RE) to evaluate the performance of the railway transportation system to minimize risks in the event of sudden changes [10], proposed a risk monitoring method based on normal region estimation (NRE) to identify the risk of railway vehicle bearings [11], and developed an “operational risk index” to analyze the operational risk of a section of the railway network [12]. Third, some literature analyzed the risk of a certain subsystem of the railway or subway. For example, the literature analyzed the risk characteristics of crowd crushing and trampling accidents in subway stations [13, 14], analyzed the risk factors and characteristics of escalator-related injuries in metro stations [15], explored the safety risk interactions in rail stations, constructed [16] and analyzed the hazards of the urban rail transit dynamic operating system and the degree of influence between various factors [17], explored the safety factors of railroad grade crossings [18, 19], and identified the key risks of railway engineering projects [20]. In addition, some literature analyzed the risk and optimal allocation of maintenance costs of large-scale high-speed rail networks [21].

The methodologies used in the existing literature for risk analysis include the classic dynamic model [8], fuzzy Petri net and fault tree analysis [14], Bayesian network model [16], and gray correlation analysis [17]. However, these methodologies cannot well measure the proportion of risk factors and risk consequences that can be reduced. The DEA model is widely used in economic efficiency evaluation [22]. Sivany-Stern (2000) [23] combined AHP and DEA to evaluate the inputs and outputs of the evaluation units, thus distinguishing between efficient and inefficient evaluation units. Hadad and Hanani (2011) [24] analyzed decision choices considering different factors based on AHP and DEA. The DEA method is a broad approach with different models for different application scenarios. The DEA can also be used for complex system safety and risk evaluation [25]. The DEA for risk evaluation is different from the models used in the literature [22–24]. The DEA is used for risk evaluation based on the “projection” of the DEA maximum risk surface and minimum risk surface to predict the possibility of risk reduction or increase in the decision unit, and rank the risks by the linear programming model of DEA. Compared with other risk evaluation methods, the hybrid DEA method can measure the reduction degree of the probability and consequence of each risk, thus making decisions on how to invest risk resources in the place where the maximum effect can be achieved.

Previous literature using DEA to analyze risk tends to use DEA alone or in combination with AHP, such as it used DEA to analyze outsourcing risks [26], used AHP-DEA to evaluate risks of bridge structures [27] and risks of failure of sewage pipes [28], and used fuzzy DEA to evaluate risks of supply chain [29]. However, there is great subjectivity and weight freedom for the evaluation system of a multilevel structure. The AHP is a subjective weight scoring method, which calculates the importance score by intercomparing the indexes. The entropy weight method is an objective weighting method based on the degree of dispersion and variation of evaluation data. The method, which is combined with the entropy weight method and AHP to constrain DEA, will modify the freedom and infinity of weights of the traditional DEA method. The entropy-AHP hybrid constrained DEA method was used to evaluate the operational risk of rail transit in this study, which avoids the shortcomings of the traditional DEA method and can extend the application of the DEA risk evaluation methodology to a certain extent.

Urban rail transit involves a wide range of risk sources. According to the previous analysis, the existing literature analyzes the causes and risk evolution of subway accidents [6–9], the risks of monitoring the performance of railroad or subway systems [10–12], and the risks of a subsystem such as railroad or subway [13–19]. The existing literature lacks a systematic analysis of risk factors from the perspective of rail transit operations. From the perspective of a rail transit operator enterprises’ consideration, operational risk management focuses on identifying risks and allocating appropriate resources to reduce the probability and consequences of risk. Therefore, this study intends to evaluate rail transit operation risk using the method of entropy-AHP hybrid constrained DEA to explore what percentage of probability and consequence of urban rail transit operation risk can be reduced and analyze which
3. Identification of Risk Factors of Rail Transit Operation-Based FTA

Scholars have analyzed the rail transit failure and safety factors, or analyzed the risk factors of accidents from the perspective of the rail transit subsystem, which provides a reference for the identification of operational risk factors of rail transit. According to the literature, the main faults of rail transit included seven categories, namely, vehicles, power supply, communication, maintenance management, passengers’ transportation, harmonic, and objective causes [3]. The basic elements that impacted the rail traffic safety were human, machine, environment, and management, and the machine risks mainly lay in the line, rail, equipment, and vehicles [17, 30]. Passengers and personnel are a significant factor in railway accidents [6, 31]. By summarizing some typical rail transit accident cases, we summarized the types of accidents that occurred in rail transit operations into the following: train accident of fire and explosions and terrorism, train derailment accident, train shutdown accident, train collision accident, rail falling accident, and trampling accident. By summarizing some typical rail transit accident cases, we summarized the types of accidents that occurred in rail transit operations into the following: train accident of fire and explosions and terrorism, train derailment accident, train shutdown accident, train collision accident, rail falling accident, and trampling accident.

The FTA (fault tree analysis) is a logical deductive system evaluation method used to describe the occurrence of accidents from results to causes. It can be used to analyze the causal relationship between the accident and the cause [32, 33]. In this study, the risk sources of rail transit were combined with the types of train accidents to find out the corresponding risk sources through the FTA method. Taking the accident of fire and explosions and terrorism as an example, the risk sources (secondary indicators) involved in the accident are as follows: fire caused by equipment failure ($y_{11}$), fire caused by equipment friction or train running arc ($y_{12}$), fire caused by wiring aging or short circuit ($y_{31}$), fire caused by the malfunction of train fire protection system ($y_{66}$), fire caused by inflammables ($y_{61}$), fire in the station commercial site ($y_{62}$), arson, or poison ($y_{71}$), and fire caused by illegal use of electrical equipment ($y_{81}$). The result of accident of fire and explosions and terrorism by FTA is shown in Figure 1, and the risk categories involved (first-level indicators) include the following: vehicle system failure, power supply system failure, electromechanical system failure, environment and management factors, passenger and external personnel factors, and staff factors. Similarly, the risk sources of other accidents are identified and classified as shown in Figures 2–6.

Combining literature and risk cases, the risk sources that lead to rail transit operation accidents are further explored. When using the fault tree for analysis, the initial risk factor indicators are more than those listed in Figure 1. During the research process, the opinions of first-line practitioners and experts of rail transit companies in multiple cities in the Pearl River Delta region were collected. After multiple rounds of expert feedback, the risk sources with inaccurate descriptions and relatively low-risk consequences and probability of occurrence were deleted. Finally, an evaluation index system of 40 risk source factors in 8 types of first-level indicators was constructed as shown in Table 1.

4. Methodology

4.1. The DEA Risk Assessment Method. The DEA method is a broad approach with different models for different application scenarios. In risk assessment, the DEA method predicts the growth trend of indicators through the “projection” of the DMU on the hyperplane. It predicts the possibility of risk reduction or increase in DMU by calculating the distance through the maximum and minimum risk surfaces. In the process of risk assessment, the probability and consequences of risk indicators of risk decision-making units are set as variables, and the risk factors are sorted and
evaluated by linear programming from the min-max risk surface, which is of great objectivity for the index value of risk factors.

The value of risk is assumed as \( R_{ij} = f(L, C) \). The \( L \) and \( C \) represent the probability and consequence of risk, respectively, and the vector \( R_j = (R_{1j}, R_{2j}, \ldots, R_{mj})^T \) is a kind of risk state value of DMU \( j \). When \( \lambda = (\lambda_1, \lambda_2, \ldots, \lambda_n)^T \geq 0, \sum_{j=1}^{n} \lambda_j = 1 \), the combination \( \sum_{j=1}^{n} R_j \lambda_j \) is a possible risk. When the number of reference points is enough, some hyperplanes are constructed by the maximum

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**Figure 2: Fault tree analysis of train derailment.**

**Figure 3: Fault tree analysis of train collision.**

**Figure 4: Fault tree analysis of train shutdown.**
risk states in the risk state set $T_{\text{max}}$. A binary relation $\propto$ on $T_{\text{max}}$ is defined as a partial order relation on set $P$, $V$ is a closed cam curve, and the risk vector $R_0$ of DMU is the maximal element of $(T_{\text{max}}, \propto_0)$. Vector $R_0$ is the Pareto optimal solution of the programming model $(VP)$ as equation(1).
Table 1: Index system of rail transit operation risks.

<table>
<thead>
<tr>
<th>NO.</th>
<th>First-level indicators</th>
<th>Secondary indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Vehicle system failure $Y_1$</td>
<td>Fire caused by equipment failure $y_{11}$, fire caused by equipment friction or train running arc $y_{12}$, trampling caused by equipment failure $y_{13}$, train suspension and derailment caused by mechanical equipment failure of vehicle $y_{14}$, train shutdown caused by vehicle body failure or damage $y_{15}$, train derailment or collision caused by vehicle braking system failure $y_{16}$, and rail falling caused by door damage $y_{17}$</td>
</tr>
<tr>
<td>2</td>
<td>Signal communication system failure $Y_2$</td>
<td>Train shutdown caused by a wireless communication system failure $y_{21}$, train derailment or collision caused by automatic train supervision failure $y_{22}$, train derailment or collision caused by automatic train operation system failure $y_{23}$, and train derailment or collision caused by onboard signal failure $y_{24}$</td>
</tr>
<tr>
<td>3</td>
<td>Power supply system failure $Y_3$</td>
<td>Fire caused by wiring aging or short circuit $y_{31}$, train derailment or collision caused by power supply line failure $y_{32}$, train derailment or collision caused by power supply equipment failure $y_{33}$, and train shutdown caused by power grid fluctuation $y_{34}$</td>
</tr>
<tr>
<td>4</td>
<td>Electromechanical system failure $Y_4$</td>
<td>Passenger crowding and trampling caused by elevator failure $y_{41}$, train shutdown caused by equipment monitoring system failure $y_{42}$, train shutdown due to screen door failure $y_{43}$, train shutdown caused by lighting system failure $y_{44}$, train shutdown caused by the failure of automatic ticket checking system $y_{45}$, and fire caused by the malfunction of train fire protection system $y_{46}$</td>
</tr>
<tr>
<td>5</td>
<td>Line and track fault $Y_5$</td>
<td>Train derailment caused by subgrade subsidence $y_{51}$, train shutdown or derailment caused by the damage of line or contact rail and components $y_{52}$, and train shutdown or derailment or collision caused by rail switch failure $y_{53}$</td>
</tr>
<tr>
<td>6</td>
<td>Environment and management factors $Y_6$</td>
<td>Fire caused by inflammables $y_{61}$, fire in the station commercial site $y_{62}$, trampling caused by emergency $y_{63}$, trampling caused by the defects of evacuation passages $y_{64}$, trampling caused by overload $y_{65}$, accidental falling on the track $y_{66}$, crashing down the track $y_{67}$, and train suspension due to natural disasters $y_{68}$</td>
</tr>
<tr>
<td>7</td>
<td>Passenger and external personnel factors $Y_7$</td>
<td>Arson or poison $y_{71}$, trampling triggered by terrorist attack $y_{72}$, train shutdown or derailment and collision caused by man-made sabotage to power supply equipment and signal equipment $y_{73}$, and suicide on the track $y_{74}$</td>
</tr>
<tr>
<td>8</td>
<td>Staff factors $Y_8$</td>
<td>Fire caused by illegal use of electrical equipment $y_{81}$, train shutdown or derailment or collision caused by man-made misoperation $y_{82}$, train shutdown or derailment and collision caused by illegal operation $y_{83}$, and train shutdown or derailment and collision caused by improper operation of the driver $y_{84}$</td>
</tr>
</tbody>
</table>

$$(VP) = \left\{ \begin{array}{l} V - \max(y_1, y_2, \ldots, y_m) \\ s.t. \quad Y \in T_{\text{max}} \end{array} \right. \quad (1)$$

$s_j$ is the residual variable or relaxation variable, and $S = (s_1, s_2, \ldots, s_m)^T$, $s_j \geq 0$.

4.2. Introducing Entropy Weight and AHP to Constrain DEA.

The DEA method solves the risk assessment through linear programming, but there is no way to evaluate the multilevel evaluation index. In order to work out this problem, the analytic hierarchy process (AHP) is introduced to deal with the multilevel evaluation index. The AHP is a subjective weight scoring method, which calculates the importance score by intercomparing the indexes. The entropy weight method is an objective weighting method based on the degree of dispersion and variation of evaluation data. The method which is combined with the entropy weight method and AHP to constrain DEA will modify the freedom and infinity of weights of the traditional DEA method.

4.2.1. Analytic Hierarchy Process. First, the comparison matrix $H = (h_{ij})_{n \times n}$ is constructed according to the importance ratio between performance indicators, where $h_{ij}$ is the importance ratio between index $i$ and index $j$.

Then, the comparison matrix satisfies the following equation:

$$\sum_{j=1}^{n} h_{ij} = 1, h_{ij} \geq 0.$$
\[ HW = \lambda_{\text{max}} W_i. \]  

\( \lambda_{\text{max}} \) is the maximum eigenvalue. The evaluation vector \( W \) has \( n \) components \( W_i \), and each one is the weight of the corresponding factor.

At last, the consistency checking is conducted on the weight results to determine whether they meet the consistency requirement, concerning the values of consistency index (CI) and the consistency ratio (CR). If CR is less than 0.10, then the comparison matrix satisfies the consistency requirement. The formulas of CI and CR are as follows:

\[ CI = \frac{(\lambda_{\text{max}} - n)}{(n - 1)}, \]  

\[ CR = \frac{CI}{RI}. \]  

4.2.2. Entropy Weight Method. First, the decision evaluation matrix \( X = (x_{ij})_{nm} \) is standardized by

\[ z_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^2}}. \]  

The proportion of \( z_{ij} \) in the index \( j \) in the evaluation matrix is calculated as equation (7), and the contribution degree of all indicators of the evaluation matrix to the attribute is calculated as equation (8).

\[ p_{ij} = \frac{z_{ij}}{\sum_{j=1}^{n} z_{ij}} \quad (j = 1, 2, \ldots, m), \]  

\[ e_j = -k^* \sum_{i=1}^{n} P_{ij} \ln(P_{ij}). \]  

In equation (8), \( k \) is related to the number of samples \( m \). Generally, there is \( k = 1/\ln(m) \), so there is \( 0 \leq e_j \leq 1 \). The consistency degree of contribution of each calculation is calculated as \( d_j = 1 - e_j \), so the entropy weight of each attribute is obtained as equation (9):

\[ U_j = \frac{d_j}{\sum_{j=1}^{n} d_j}, \quad j = 1, 2, \ldots, m. \]  

The entropy weight and AHP weight are integrated to get the hybrid weight as follows:

\[ U_j^* = \frac{(\alpha w_j + (1 - \alpha) U_j)}{2}. \]  

The appropriate value \( \alpha \) is taken to obtain \( U_j^* \), and the weighted values of \( R_j \) are introduced in equations (2) and (3) for DEA calculation.

5. Identification and Evaluation of Rail Transit Risk Factors

5.1. Determination of the Value of Probability and Consequence of Risk. The decision variables of rail transit risk are assumed as \( R_j = F(L, C) \), where \( L \) and \( C \) represent the probability and consequence of risk, respectively. The probability of accident occurrence of the urban rail transit is expressed by value 1 to 5, in which the value 1 indicates that the risk is extremely unlikely to occur; the value 2 indicates a rare probability of the risk occurrence; the value 3 indicates that the risk event may occur; the value 4 indicates that the risk event is likely to occur; and the value 5 indicates that the risk event repeatedly occurs. The consequence of rail transit risk is expressed by values 1 to 7, where the value 1 refers to the minor accident with personal injury and system failure; the value 2 refers to a common accident with a few people slightly injured and system damaged; the value 3 represents big risk accident with many people slightly injured and system seriously damaged; the value 4 represents serious accident that causes many people injured or disabled; the value 5 represents very serious accident that causes casualties; the value 6 represents a major disastrous accident with multiple deaths; and the value 7 refers to a catastrophic accident with a large number of deaths.

During the investigation, the investigation team collected a total of 112 score sheets on the probability and consequences of risk factors. The respondents are first-line employees and experts of rail transit companies and research institutions in multiple cities in the Pearl River Delta region. Among them, 53.33% are the frontline staff, 17.27% are management personnel, 14.24% are technical personnel, and 15.16% are researchers. The 112 survey scores were averaged to get the initial risk value, as shown in Table 2.

5.2. Weight Calculation. The AHP method is used to determine the weight, and the comparison matrix of first-level index weight was obtained as follows.

The weight coefficients corresponding to the first-level index were obtained as follows:

\[ W = (0.175, 0.203, 0.104, 0.139, 0.066, 0.118, 0.143, 0.053)^T. \]  

According to the calculation process of the AHP method, the greatest eigenvalue \( \lambda_{\text{max}} \) was 8.047, and the random consistency test ratio was obtained as CR = 0.005 < 0.1. According to the consistency test results, the weight evaluation data are trustworthy. Similarly, the weight of each secondary index was deduced, and after normalization, the weight vector of AHP was obtained as shown in Table 2. Taking the initial value of probability and consequence of risk as the evaluation matrix, and according to the calculation principle of entropy weight, the entropy weight was obtained as shown in Table 2. Finally, taking the weight constraint value \( \alpha = 0.5 \), the hybrid weight \( U_j^* \) was obtained.

5.3. Calculation of Maximum and Minimum Risks. According to the initial value and weight of risk, the risk index data of DMU 1 to 9 were obtained as shown in Table 3. Thus, the DEA model \( (D) \) is constructed. The model formula of DMU 1 is shown as equation (12).
Equation (12) was constructed based on equation (2) of the DEA method. Similarly, the formula of DMU 2 ~ 8 can be obtained. The Pareto optimal solutions \( s_1 \) and \( s_2 \) corresponding to the risk index of DMU 1 ~ 9 can be calculated by the model (D) of the DEA method using the linear programming method to solve the problem, and the objective function value of linear programming of DMU 1 ~ 9 can also be obtained as shown in Table 4.

Similarly, according to the DEA model (D1), the minimum risk decision of DMU 1 ~ 9 was obtained as shown in Table 5. The surface distribution map of maximum risk (Figure 7) was obtained by using the risk decision data of the DEA model (D).

### Table 2: Index weight of each risk factor and initial risk value.

<table>
<thead>
<tr>
<th>Factor</th>
<th>( y_{11} )</th>
<th>( y_{12} )</th>
<th>( y_{13} )</th>
<th>( y_{14} )</th>
<th>( y_{15} )</th>
<th>( y_{16} )</th>
<th>( y_{17} )</th>
<th>( y_{21} )</th>
<th>( y_{22} )</th>
<th>( y_{23} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability of risk</td>
<td>2.86</td>
<td>1.71</td>
<td>2.12</td>
<td>2.32</td>
<td>2.12</td>
<td>2.19</td>
<td>2.04</td>
<td>2.21</td>
<td>1.67</td>
<td>1.83</td>
</tr>
<tr>
<td>Consequence of risk</td>
<td>5.37</td>
<td>3.13</td>
<td>3.85</td>
<td>3.8</td>
<td>3.55</td>
<td>5.03</td>
<td>3.07</td>
<td>3.04</td>
<td>4.13</td>
<td>5.71</td>
</tr>
<tr>
<td>AHP weight</td>
<td>0.034</td>
<td>0.02</td>
<td>0.024</td>
<td>0.017</td>
<td>0.03</td>
<td>0.037</td>
<td>0.014</td>
<td>0.052</td>
<td>0.041</td>
<td>0.063</td>
</tr>
<tr>
<td>Entropy weight</td>
<td>0.033</td>
<td>0.012</td>
<td>0.019</td>
<td>0.019</td>
<td>0.016</td>
<td>0.028</td>
<td>0.013</td>
<td>0.015</td>
<td>0.02</td>
<td>0.035</td>
</tr>
<tr>
<td>Hybrid weight</td>
<td>0.033</td>
<td>0.016</td>
<td>0.021</td>
<td>0.018</td>
<td>0.023</td>
<td>0.033</td>
<td>0.013</td>
<td>0.033</td>
<td>0.03</td>
<td>0.049</td>
</tr>
</tbody>
</table>

### Table 3: Risk index data of each DMU.

<table>
<thead>
<tr>
<th>DMU</th>
<th>First-level index</th>
<th>Probability of risk</th>
<th>Consequence of risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Vehicle system failure</td>
<td>0.357</td>
<td>0.667</td>
</tr>
<tr>
<td>2</td>
<td>Signal communication system failure</td>
<td>0.306</td>
<td>0.809</td>
</tr>
<tr>
<td>3</td>
<td>Power supply system failure</td>
<td>0.300</td>
<td>0.469</td>
</tr>
<tr>
<td>4</td>
<td>Electromechanical system failure</td>
<td>0.235</td>
<td>0.435</td>
</tr>
<tr>
<td>5</td>
<td>Line and track fault</td>
<td>0.178</td>
<td>0.430</td>
</tr>
<tr>
<td>6</td>
<td>Environment and management factors</td>
<td>0.335</td>
<td>0.660</td>
</tr>
<tr>
<td>7</td>
<td>Passenger and external personnel factors</td>
<td>0.273</td>
<td>0.581</td>
</tr>
<tr>
<td>8</td>
<td>Staff factors</td>
<td>0.320</td>
<td>0.719</td>
</tr>
</tbody>
</table>
The risk consequence can be called key risk factors, including probability of occurrence and serious consequences, which influence risk. Namely, the key risk, leverage risk, conventional risk, and four different matrices are divided into four categories, including occurrence, which can be called leverage risk factors, in- cluding slight consequences but relatively high accident probability. (Z_hey can be called influential risk factors. For these risk factors in the light of the secondary indicators are distributed according to a matrix, as shown in Figure 8. Among them, the key risk factors in the first quadrant and the leverage risk factors in the second quadrant are the key objects of safety management.

The risks in the first quadrant are the key risk factors, and the probability and consequences of these risk factors are relatively large, so these factors should be paid attention to, dynamically inspected, and strictly prevented. These factors include fire caused by illegal use of electrical equipment, train shutdown or derailment, and collision caused by illegal operation, fire caused by wiring aging or short circuit, train derailment, or collision caused by power supply line failure, fire caused by equipment failure, train shutdown or derailment caused by the damage of line or contact rail and components, train shutdown or derailment or collision caused by rail switch failure, fire caused by inflammmables, train shutdown or derailment and collision caused by man-made sabotage to power supply equipment and signal equipment, arson or poison, and passenger crowding and trampling caused by elevator failure.

The risk factors in the second quadrant have a relatively low probability of occurrence but serious risk consequences. They can be called leverage risk factors. For these leverage risks, emergency contingency plans must be formulated to improve emergency response capabilities. In addition, these risk factors should be regularly checked and eliminated to nip them in the bud. Leverage risk factors include fire caused by illegal operation, train derailment or collision caused by on-board signal failure, train derailment or collision caused by automatic train operation system failure, trampling triggered by terrorist attack fire caused by the malfunction of train fire protection system, train shutdown or derailment and collision caused by improper operation of the driver, train derailment caused by subgrade subsidence train derailment or collision caused by vehicle braking system failure, train shutdown or derailment and collision caused by man-made misoperation, fire in the station commercial site, and crashing down the track.

The risk factors in the third quadrant have a low probability of occurrence and slight consequences, which

<table>
<thead>
<tr>
<th>DMU</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s_1$</td>
<td>0.000</td>
<td>0.000</td>
<td>0.006</td>
<td>0.071</td>
<td>0.128</td>
<td>0.000</td>
<td>0.033</td>
<td>0.000</td>
</tr>
<tr>
<td>$s_2$</td>
<td>0.000</td>
<td>0.000</td>
<td>0.340</td>
<td>0.374</td>
<td>0.379</td>
<td>0.070</td>
<td>0.228</td>
<td>0.052</td>
</tr>
<tr>
<td>Objective function value</td>
<td>0.000</td>
<td>0.000</td>
<td>-0.346</td>
<td>-0.445</td>
<td>-0.506</td>
<td>-0.070</td>
<td>-0.260</td>
<td>-0.052</td>
</tr>
</tbody>
</table>

Table 4: Maximum risk decision values of $s_1$ and $s_2$ calculated by the model $(D)$.

<table>
<thead>
<tr>
<th>DMU</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s_1$</td>
<td>0.179</td>
<td>0.128</td>
<td>0.121</td>
<td>0.057</td>
<td>0.000</td>
<td>0.156</td>
<td>0.095</td>
<td>0.141</td>
</tr>
<tr>
<td>$s_2$</td>
<td>0.237</td>
<td>0.379</td>
<td>0.039</td>
<td>0.005</td>
<td>0.000</td>
<td>0.230</td>
<td>0.151</td>
<td>0.289</td>
</tr>
<tr>
<td>Objective function value</td>
<td>-0.416</td>
<td>-0.506</td>
<td>-0.160</td>
<td>-0.062</td>
<td>0.000</td>
<td>-0.386</td>
<td>-0.246</td>
<td>-0.430</td>
</tr>
</tbody>
</table>

Table 5: Minimum risk decision values of $S_1$ and $S_2$ calculated by the model $(D_1)$.

5.4. Analysis of Risk Factor Distribution Matrix. Taking the probability of risk occurrence as the X axis and risk consequence as the Y axis, the matrix distribution chart of risk factors was established as shown in Figure 8. The risks in four different matrices are divided into four categories, namely, the risk key, leverage risk, conventional risk, and influential risk.

The risk factors in the first quadrant are those with a high probability of occurrence and serious consequences, which can be called key risk factors, including $y_{81}, y_{31}, y_{11}, y_{52}, y_{61}, y_{73}, y_{71}, y_{32}, y_{63}, y_{53}$, and $y_{41}$.

The risk factors in the second quadrant are those with serious consequences but relatively low probability of occurrence, which can be called conventional risk factors, including $y_{24}, y_{72}, y_{46}, y_{62}, y_{81}, y_{31}, y_{16}, y_{62}$, and $y_{67}$.

The risk factors in the third quadrant are those with slight consequences and relatively low probability of occurrence, which can be called conventional risk factors, including $y_{44}, y_{13}, y_{21}, y_{15}, y_{17}, y_{45}, y_{12}, y_{66}, y_{22}, y_{64}$, and $y_{65}$.

The risk factors in the fourth quadrant have relatively slight consequences but relatively high accident probability. They can be called influential risk factors, including $y_{33}, y_{42}, y_{43}, y_{34}, y_{63}, y_{74}, y_{68}, y_{73}$, and $y_{14}$.

6. Discussion

6.1. Analysis and Discussion of the Quadrants of Risk Factors. The risk factors in the light of the secondary indicators are distributed according to a matrix, as shown in Figure 8. Among them, the key risk factors in the first quadrant and the leverage risk factors in the second quadrant are the key objects of safety management.

The risks in the first quadrant are the key risk factors, and the probability and consequences of these risk factors are relatively large, so these factors should be paid attention to, dynamically inspected, and strictly prevented. These factors include fire caused by illegal use of electrical equipment, train shutdown or derailment, and collision caused by illegal operation, fire caused by wiring aging or short circuit, train derailment, or collision caused by power supply line failure, fire caused by equipment failure, train shutdown or derailment caused by the damage of line or contact rail and components, train shutdown or derailment or collision caused by rail switch failure, fire caused by inflammmables, train shutdown or derailment and collision caused by man-made sabotage to power supply equipment and signal equipment, arson or poison, and passenger crowding and trampling caused by elevator failure.

The risk factors in the second quadrant have a relatively low probability of occurrence but serious risk consequences. They can be called leverage risk factors. For these leverage risks, emergency contingency plans must be formulated to improve emergency response capabilities. In addition, these risk factors should be regularly checked and eliminated to nip them in the bud. Leverage risk factors include fire caused by illegal operation, train derailment or collision caused by on-board signal failure, train derailment or collision caused by automatic train operation system failure, trampling triggered by terrorist attack fire caused by the malfunction of train fire protection system, train shutdown or derailment and collision caused by improper operation of the driver, train derailment caused by subgrade subsidence train derailment or collision caused by vehicle braking system failure, train shutdown or derailment and collision caused by man-made misoperation, fire in the station commercial site, and crashing down the track.

The risk factors in the third quadrant have a low probability of occurrence and slight consequences, which
can be called conventional risk factors. The conventional risk factors should be normally managed, paying attention to the normalized and standardized management of the operation process, and regular inspection shall be carried out to eliminate potential risks.

The risk factors in the fourth quadrant are called influential risk factors. These have a high probability of occurrence, but the consequences of the risk are not serious. In terms of safety countermeasures against these risk factors, it is necessary to establish standardized operation guidelines, strengthen patrol inspections, and increase the speed of risk resolution.

### 6.2. Maximum and Minimum Risk Surface Analysis of Risk DMU

According to the maximum risk decision data calculated by the model \((D_1)\) in Table 4, the Pareto optimal solutions \(s_1\) and \(s_2\) of the DMU 1 and DMU 2 are 0, which shows that the risk of decision-making units 1 and 2 is in the Pareto state of maximum value. It indicates that, compared with the other six risk indicators, the risk probability and consequences of vehicle system failure and signal communication failure risk are in the maximum value state, that is, for the risk DMU 1 and 2, the risk probability and consequences cannot continue to increase at the same time. According to the risk surface analysis, vehicle system failure (DMU 1) and signal communication system failure (DMU 2) are the maximum risks. They are on the maximum risk surface, and the next risk DMUs include staff factors (DMU 8), environment and management factors (DMU 6), passenger and external personnel factors (DMU 7), power supply system failure (DMU 3), electromechanical system failure (DMU 4), and line and track fault (DMU 5). Therefore, it is necessary to pay special attention to controlling the risk sources of DMU 1 and 2, and correspondingly reducing the possibility and the consequences of risk.

In accordance with the DEA model \((D_1)\), the minimum risk decision data were obtained (Table 5). According to the minimum risk decision data calculated by the model \((D_1)\), the Pareto optimal solutions \(s_1\) and \(s_2\) of the DMU5 are 0, showing that the risk of unit 5 is in the Pareto state of maximum value. It also indicates that, compared with the other seven risk indicators, the risk probability and consequences of line and track risks reach the minimum value, showing that the risk probability and consequences cannot continue to decrease at the same time. From the minimum risk surface data, the reduction ratio of risk probability and risk consequence data of each index can be obtained. The risk probability of DMU 1 can be reduced by 0.179/0.357 = 0.50.88%, and the risk consequence of DMU 1 can be reduced by 0.237/0.667 = 35.57%. According to the same calculation method, the risk probability of DMU 2 can be reduced by 41.7% and the risk consequence of DMU 2 can be reduced by 46.83%. According to the similarity principle, the risk reduction ratio of other DMU can be obtained as shown in Table 6.

### 7. Enlightenment

According to the occurrence probability and the consequence severity of the risk sources, the risk factors are divided into four categories in this study, that is, the key risk, leverage risk, conventional risk, and influential risk. The key risk factors in the first quadrant should be focused on and implementing with key management measures. For the key factors, patrol inspection and registration should be strengthened, and dynamic monitoring and management should be carried out in time. The probability of risks in the second quadrant is small, but the risk consequences are serious, so it can be called leverage risk. Therefore, it is necessary to formulate an emergency plan to leverage risk, improve the emergency response capacity, and regularly check and eliminate these risks to prevent them from happening. Xu et al. [9] pointed out that the guidance and evacuation facilities in the station are very important when rail transit is at risk. From the perspective of preventing accidents, it is of great importance to formulate an emergency plan. The conventional risk factors located in the third quadrant should be normally managed through standardized management in various projects, equipment operations, and regular inspection so as to eliminate hidden dangers. The influential risk in the fourth quadrant includes the risks that are more likely to occur daily but with relatively slight risk consequences, so standardized operating procedures should be adopted to reduce the probability of risk occurrence and increase the speed of accident resolution. From the perspective of the first-level indicators, special attention should be placed to controlling the risk sources of DMU 1 and 2, and correspondingly reducing the possibility and consequences of risks. Second, emphasis should be placed on controlling the risks of DMU 8 and 6. The greatest effect can be achieved by focusing on investing risk resources in these DMUs.

Urban rail transit involves a wide range of risk sources. The existing literature analyzes the analysis of rail transit from some perspectives but lacks a systematic analysis of risk factors from the perspective of rail transit operations. From the perspective of a rail transit operator enterprises’ consideration, operational risk management focuses on identifying risks and allocating appropriate resources to reduce the probability and consequences of risk. This study explored the causes of different types of rail traffic accidents through the FTA method and constructed an evaluation system with 8 types of risk level indicators totaling 40 risk factors, which can help rail transit operation enterprises and supervisory
departments to correctly identify and evaluate the risk factors of urban rail transit operation safety, so as to ensure the safety of urban rail transit production and operation and the safety of passengers’ lives and properties, and the research of this study is a major topic with theoretical and practical significance.

Methodologically, unlike the methods used in the existing literature analyzing rail transportation risks, this study utilizes a DEA method with entropy-AHP hybrid constraints, which is able to measure the reduction degree of probability and consequence of risk, and thus makes decisions favoring the investment of risk resources where they can achieve the greatest effect. The entropy-AHP hybrid constrained DEA method uses the objectivity of the entropy method and the subjectivity of the AHP method to synthesize constrained DEA, which avoids the shortcomings of the traditional DEA method, and extends the application of the DEA risk assessment methodology to a certain extent. The entropy-AHP hybrid constraints the DEA method taking the probability and consequence of risk occurrence as decision, and the linear programming model of DEA was constructed to evaluate and rank the risk decision-making units. The results show that vehicle system failure and signal communication system failure are at the maximum risk. They are the first-level factors to be considered in the management of rail transit operation risk and should be paid more attention to. The next risk DMUs include staff factors, environment and management factors, passenger and external personnel factors, power supply system failure, electromechanical system failure, and line and track fault. Through the decision analysis of the minimum risk surface, the reduction ratios of risk probability and risk consequence of each risk decision-making unit were obtained. These results are of great guiding significance for rail transit risk management, and it is helpful to take differential measures and policies based on risk categories and characteristics of analysis. The risk factor distribution matrix was constructed according to the occurrence probability and the consequence severity of the risk sources, the risk factors are divided into four categories, and the key risk factors and leverage risk factors should be paid attention to. Through the decision analysis of the minimum risk surface, the reduction ratios of risk probability and risk consequence of each risk decision-making unit were obtained. These results are of great guiding significance for rail transit risk management, and it is helpful to take differential measures and policies based on risk categories and characteristics of analysis. The research results are conducive to investing resources in risk factors that can achieve more obvious results, which is of positive significance for optimizing the efficiency of risk resource allocation.

Based on the results of the analysis, it is urgent to establish a management system that can help rail transit operators deal with risks. The recommendations were proposed as the following: (1) a risk classification manual and a guide on how to respond to risks should be prepared. (2) A risk prevention and monitoring mechanism should be established for rail transit safety management. (3) A standardized risk decision-making mechanism and emergency management system should be established. (4) The maintenance of equipment should be strengthened, especially the maintenance of vehicle system, signal and communication system, and the investment of resources should be strengthened in key risk sources.

8. Conclusion
This study explored the causes of different types of rail traffic accidents through the FTA method and constructed an evaluation system of 40 risk factors in 8 types of risk indicators. The first-level indicators of rail transit operational risks are summarized into 8 major types of risks, that is, vehicle system failure, signal communication system failure, power supply system failure, electromechanical system failure, line and track fault, environment and management factors, passenger and external personnel factors, and staff factors. The risk factor evaluation index system proposed in this study can help rail transit operating companies and regulatory authorities to correctly identify and evaluate the risk factors of urban rail transit operation safety, so as to ensure the safety of urban rail transit production and operation, and the safety of passengers’ lives and property. Hence, this research is a major subject of theoretical and practical significance. Using the risk evaluation method of entropy-AHP hybrid constrained DEA, the research results point out which decision-making units have the greatest risk, can reduce the most proportion, and establish a classification matrix of risk factors, which provides theoretical guidance for risk management in rail transit operation enterprises. The research results show that the applicability of the evaluation index proposed in this study and the scientificity of the analysis method provide a new idea for rail transit operation risk management, and this research method can also be applied to other risk management fields in the future. There are many risk factors in rail transit operations. This study only selects typical factors for quantitative analysis and cannot fully cover all risk factors. Therefore, future research can be further classified and refined.

Data Availability
The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest
The authors declare no conflicts of interest.

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