Research Article

Security Check Mutual Recognition between High-Speed Railway and Urban Rail Transit Based on Variable Fuzzy Set Theory

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At present, the secondary security check at the transfer station between high-speed railway and urban rail transit brings inconvenience to passengers. The aim of this study is to develop a methodology for evaluating the safety level of high-speed railway and subway stations by using variable fuzzy set theory, so as to determine the conditions for security check mutual recognition. In this research, considering transportation capacity, personnel and equipment, and environment and management, three aspects are considered to construct an evaluation index system for mutual recognition of high-speed railway and urban rail transit security check. Then, the variable fuzzy safety evaluation model has been established for high-speed railway and subway stations and their transport modes to analyse the feasibility of security check mutual recognition. Using the variable fuzzy set theory and the important consistency sorting theorem, the decision approach proposed in this study was tested for the high-speed rail station A and subway station B. As a result of using the methodology, the safety evaluation result of high-speed railway station A is 1.60, and the result of subway station B is 2.26. It is concluded that the safety of high-speed rail station A is higher than that of subway station B, and it is possible to enter the metro station without security check in one direction. The approach presented in this research can be used for judging the conditions for security check mutual recognition at interchange stations between high-speed railway and urban rail transit, which provides reference for the implementation of security check mutual recognition.

1. Introduction

In recent years, high-speed railway and rail transit have been in a stage of rapid development. With the gradual completion of the railway and urban rail transit network, there are a large number of seamless transfer stations in the road network. However, in China, whether it is to directly transfer to the subway from the high-speed railway station without leaving the station or to seamlessly transfer from the subway to the high-speed railway, the secondary security check is required. Although this approach ensures safety, it has an impact on the convenience of passengers and also causes a waste of time and resources generated by the secondary security check. Therefore, it is necessary to implement security check mutual recognition. Based on this, the government realizes that security check mutual recognition needs to be solved urgently. Therefore, in October 2019, the Ministry of Transport issued the “Urban Rail Transit Passenger Transport Organization and Service Management Measures,” which stipulate at the national level that the security check sites provided by stations connected with railway stations, long-distance passenger stations, airports, and so on should facilitate security check mutual recognition, so as to reduce repeated security checks and improve traffic efficiency and service levels.

However, there is still no clear definition of security check mutual recognition. According to the practice of the transportation industry, security check mutual recognition can be defined as follows. In order to avoid the second security check when passengers transfer between high-speed railway and urban rail transit, realize transfer and interoperability, and improve the efficiency of passenger transfer by reducing the number of security checks.

Meanwhile, the implementation of security check mutual recognition between rail transit stations requires firstly national and social guidance and hardware conditions for
direct passenger transfer. Secondly, through a comparative analysis of the regulations on prohibited and restricted items in rail transportation [1, 2], it is found that the content of the two regulations on prohibited and restricted items is basically the same. In principle, it provides a prerequisite for the security check mutual recognition between high-speed railways and urban rail transit. Since 2017, Chengdu East Railway Station, Beijing South Railway Station, Tianjin Railway Station, and other high-speed stations have implemented one-way check-free or two-way security check mutual recognition.

At present, the government or related industries do not have precise measurement standards and research methods for security check mutual recognition, and there are also no clear implementation standards to follow. Therefore, it is necessary to explore a reasonable and effective method to ensure the safety of passenger transportation under the condition of one security check. By comparing the safety requirements of high-speed railway and urban rail transit, the feasibility of implementing security check mutual recognition between the two is judged.

This paper proposes a safety evaluation method based on the station and its transportation mode, constructs safety evaluation indicators, and conducts related research on the feasibility of security check mutual recognition based on the variable fuzzy set theory, so as to provide a theoretical basis for implementing security check mutual recognition.

2. Literature Review

In an attempt to account for the importance of passenger transfer safety, many studies have been related to transportation safety, passenger travel satisfaction, and evaluation models.

2.1. Research on Transportation Safety. Behaviour-based safety involved measuring worker safety behaviors through peer observations or self-monitoring and providing feedback, to correct unsafe behaviours [3, 4]. Borrion et al. provided a framework for designers to identify the security functions in MRS in order to form an effective security system at the station [5]. Dai et al. analysed the problems existing in security inspection in China and gave suggestions for improving the quality of security inspection work [6]. Wang et al. used the fuzzy set qualitative comparative analysis method to study the causes of subway accidents and classified them into three types: low safety awareness, lack of supervision, and influence by others [7]. Han and Chao analysed the functional layout and transfer mode of Beijing South Railway Station and identified existing problems and made suggestions [8]. Wang obtained passenger flow data under different conditions through field investigations and analysed the reasons affecting his safety status. On this basis, the passenger flow security level of the station is divided, and corresponding optimization suggestions are proposed for the lower passenger flow security level [9].

2.2. Research on Passenger Travel Satisfaction. Through several investigations, Cherry and Townsend found that passengers are highly dissatisfied with the existing transfer system. Through the research, it is found that the factors that have the greatest impact on the passenger transfer experience are the safety during the transfer process and the distance between the subway exit and the bus station [10]. Aydin et al. used statistical analysis and fuzzy analytic hierarchy process to provide a hierarchical customer satisfaction framework to evaluate customer satisfaction, which provides directions for future investment [11]. Baouni conducted a survey on passenger satisfaction of three rail transportation modes, light rail, underground heavy rail, and commuter rail, and determined the dimensions of service quality and user satisfaction [12]. Ding and Chen both analysed the existing problems of railway quality management and used relevant theoretical methods to establish a railway passenger transportation service quality evaluation system based on actual conditions [13, 14].

2.3. Research on Fuzzy Evaluation Models. The fuzzy comprehensive evaluation method is a comprehensive bid evaluation method based on fuzzy mathematics. It can better solve fuzzy and difficult-to-quantify problems, and it is suitable for quantitative analysis and qualitative research [15]. Because some of the evaluation factors are inherently vague, it is necessary to utilize a tool known as fuzzy set theory. Zadeh first introduced fuzzy set theory to deal with the vagueness of human thought [16]. Fuzzy set theory has been applied in many systems in recent scientific research [17, 18]. Zhou used the analytic hierarchy process and fuzzy comprehensive evaluation model to study the passenger flow safety situation of railway stations and, based on this, put forward some measures and suggestions to strengthen passenger flow safety management [19]. Miao constructed a railway station safety operation management evaluation model based on multilevel fuzzy comprehensive evaluation and obtained the physical and mental condition of station staff and the comprehensive environmental index inside the station which are important factors that affect the safe operation of the station [20]. Zhang et al. established an evaluation index model for the safety production management of an oilfield enterprise by utilizing an analytic hierarchy process (AHP) and fuzzy comprehensive evaluation (FCE) [21]. Tian et al. used the interval-valued intuitionistic fuzzy uncertain language to improve the classical TOPSIS [22]. Stolova used fuzzy linear programming method to solve the connection between intercity trains and examine routing of passenger trains. The approach presented can be used for other types of transport which could contribute to increasing transport sustainability [23, 24]. Wang introduced a fuzzy optimization model based on improved symmetric tolerance approach. It can allow for rescheduling high-speed railway timetable under unexpected interferences [25]. Jamil used fuzzy approach to solve the train routing and scheduling problem [26].

2.4. Research Ideas. From the literature review above, in the past considerable progress has been made in the transfer safety; however, almost all this work has focused on railways
or urban rail transit. Most papers are discussed only from the point of view of the station, with very little consideration being given to the relationship between the security level of the two systems of railway and urban rail and the comprehensive evaluation for security check mutual recognition.

In terms of methods, previous studies usually use AHP or other methods. In view of the shortcomings of previous research, this paper takes variable fuzzy evaluation model as its basic tool and uses the variable fuzzy set theory and the important consistency sorting theorem to determine the conditions for security check mutual recognition at transfer stations between high-speed railway and urban rail transit.

The variable fuzzy evaluation method can scientifically determine the relative membership degree of the index to the standard interval of the index at all levels and can obtain the evaluation level of the sample through the change model and its parameters and improve the credibility of the evaluation result. At the same time, this method organically combines qualitative and quantitative methods to avoid the shortcomings that all data in the evaluation process are determined by expert experience. This method treats the evaluation criteria as intervals rather than points and fully considers the fuzzy attributes of things.

This method can overcome the defect that AHP relies too much on subjective evaluation, makes the evaluation result more scientific and accurate, and can deal with the ambiguity of the evaluation level scientifically and reasonably. Based on the unified index standard, the variable fuzzy evaluation method based on the variable fuzzy set theory will not reduce the accuracy of the results due to the increase in the number of evaluation samples. This method also provides a more scientific sample evaluation grade by changing the model and parameters, which further improves the credibility of the results.

This paper is arranged as follows. The first step is to analyse the prerequisites of security check mutual recognition. In the second step, drawing on the idea of management “human-machine-environment-management,” this paper will conduct a security check mutual recognition evaluation index system of the two transportation modes and the two connected stations. In the third step, based on the variable fuzzy set theory and according to the qualitative and quantitative results of the high-speed railway station A and subway station B, the safety evaluation of two stations can be constructed. In the final step, the results are applied to the process of security check mutual recognition to verify the feasibility of the proposed method.

3. Materials and Methods

3.1. Security Check Mutual Recognition Evaluation Index System. Since security check mutual recognition is a relatively new concept, at present, there are no exact measurement standards and methods for research and judgment, and there are no clear implementation standard regulations to follow. This paper proposes a safety evaluation based on the station and its transportation mode and compares the safety evaluation results of the station and its transportation mode, so as to determine whether the security check mutual recognition can be carried out or determine the direction of exemption from one-way check.

After the passenger has passed the inspection of the transportation mode A with higher safety requirements and during the transportation process of this transportation mode with higher safety, without endangering the life and property of oneself or other passengers, there is no need to conduct a second security check when directly transferring to another mode of transportation B with the same or lower safety requirements.

When determining the feasibility of mutual recognition of station security, this paper will conduct a unified analysis and comparison of the two transportation modes and the two connected stations and conduct a comprehensive safety evaluation. By drawing on the idea of “human-machine-environment-management” [27], this paper divides the indicators for evaluating safety in the transportation process into transportation capacity, personnel and equipment, and environment and management. [28] The result is shown in Figure 1.

3.1.1. Transportation Capacity. The influencing factors in terms of transportation capacity are passenger flow, passenger density in the car, concentration of passenger arrivals, and travel frequency.

The greater the passenger flow of station transportation is, the more difficult it is to manage, and the higher the possibility of uncertain factors is, resulting in greater security risk. As the number of passengers in the car increases, the personal space of each passenger decreases, and the comfort level of the passengers decreases. Therefore, the possibility of physical contact disputes and trampling increases, leading to increased safety risks. The greater the number of arriving passengers is, the more likely it is that congestion, passenger friction, trampling, and other accidents will occur. The smaller the interval between trains, the shorter the response and processing time left for the staff in the event of an emergency.

3.1.2. Personnel and Equipment. The influencing factors in terms of personnel and equipment are passenger safety awareness, working conditions of station staff, security check level, and train speed.

The weaker the passenger safety awareness, the smaller the processing capability in the event of an emergency, and the greater the corresponding potential safety hazard. The sense of responsibility and ability of station staff often affect the safety of the station or train operation. The higher the security check level of a station, the higher the safety of the station and the smaller the hidden safety hazard. In the event of an accident, the higher the speed of the train is, the shorter the reaction time the driver can take, and the longer the braking distance of the train after braking is.

3.1.3. Environment and Management. The influencing factors in terms of environment and management are station
location, train running position, passenger evacuation capacity at station, and emergency response ability of stations.

Compared with above-ground stations, underground stations may cause more serious consequences in the event of an accident, and it is more difficult to evacuate passengers. Therefore, the more closed the station is, the more safety requirements are required to ensure the safety of the lives and property of passengers in the station. The operation of trains is divided into two types: above-ground operation and underground (downhill) operation. Because the underground (under the mountain) operation is in a relatively more enclosed space, there are problems such as the inability of personnel to evacuate in time and the difficulty of rescue missions. Therefore, compared with above-ground operations, underground routes have greater safety risks, and higher standards of safety requirements are required. The stronger the station’s ability to evacuate passengers, the higher the safety of the station. The stronger the station’s ability to deal with emergencies, the better the treatment effect, and the smaller the corresponding potential safety hazards.

3.2. Variable Fuzzy Set Theory

3.2.1. Fuzzy Definition. The difference between objective phenomena and things under the condition of codimension and “this and the other” in the intermediary transition is called fuzziness. A concept that meets the definition of fuzziness is called a fuzzy concept.

3.2.2. Relative Difference Function. Let \( u \) be an element in the universe of \( U \) satisfying \( u \in U \); the relative membership degree of \( u \) for the attraction property \( A \) (binary opposition) is \( \mu_\Delta(u) \), and the relative membership degree for the repulsion property \( A^C \) is \( \mu_{\Delta^C}(u) \) [29, 30].

If we assume that

\[
D_\Delta(u) = \mu_\Delta(u) - \mu_{\Delta^C}(u),
\]

then it can be rewritten as

\[
D_\Delta(u) = 2\mu_\Delta(u) - 1.
\]

3.2.3. Variable Fuzzy Evaluation Model. According to the variable fuzzy set theory, the specific steps of the safety evaluation model for railway and urban rail transit stations are as follows.

According to the \( m \) indexes of the sample of safety evaluation mentioned above, the eigenvalue vector of the evaluation object can be constructed as [31]

\[
X = (x_1, x_2, x_3, \ldots, x_m).
\]

Let \( X_0 = [a, b] \) be an interval on the real axis, which is called the attraction domain of the fuzzy variable set \( V \). Satisfying \( 0 \leq D_\Delta(u) \leq 1 \), \( X = [c, d] \) is a region interval that contains a certain upper and lower bound of \( X_0 \) \( (X_0 \subseteq X) \). Intervals \([c, a] \) and \([b, d] \) are the repelling domains of fuzzy variable set \( V \), satisfying \( -1 \leq D_{\Delta^C}(u) \leq 0 \).

According to the evaluation index, the standard interval matrix \( I_{ab} \) of the safety evaluation index is determined as

\[
I_{ab} = \begin{bmatrix}
[a_{11}, b_{11}] & [a_{12}, b_{12}] & \cdots & [a_{1n}, b_{1n}] \\
[a_{21}, b_{21}] & [a_{22}, b_{22}] & \cdots & [a_{2n}, b_{2n}]
\vdots & \ddots & \ddots & \vdots \\
[a_{m1}, b_{m1}] & [a_{m2}, b_{m2}] & \cdots & [a_{mn}, b_{mn}]
\end{bmatrix}
\]

(4)

In the above formula, \( i \) is the indicator, \( i = 1, 2, \ldots, m \); \( h \) is the grade, \( h = 1, 2, \ldots, n \). Grade 1 is the optimal grade, and grade \( n \) is the worst grade.

Matrix \( I_{ab} \) is the standard value interval matrix of indicators at all grades, which is a known matrix; for the range value interval \([c_{ih}, d_{ih}]\) of index \( i \) for grade \( h \), it can be determined according to the upper and lower limits of the adjacent intervals on both sides of the standard value interval of all grades in matrix \( I_{ab} \).

Then, the range \( I_{cd} \) of the safety evaluation index can be written as

\[
I_{cd} = \begin{bmatrix}
[c_{11}, d_{11}] & [c_{12}, d_{12}] & \cdots & [c_{1n}, d_{1n}] \\
[c_{21}, d_{21}] & [c_{22}, d_{22}] & \cdots & [c_{2n}, d_{2n}]
\vdots & \ddots & \ddots & \vdots \\
[c_{m1}, d_{m1}] & [c_{m2}, d_{m2}] & \cdots & [c_{mn}, d_{mn}]
\end{bmatrix}
\]

(5)

According to matrix \( I_{ab} \), determine \( M \) as the point value of the attractive domain interval \([a_{ih}, b_{ih}]\); the relative membership degree is equal to 1, which can be expressed as

\[
I_{ab} = \begin{bmatrix}
[a_{11}, b_{11}, c_{11}] & [a_{12}, b_{12}, c_{12}] & \cdots & [a_{1n}, b_{1n}, c_{1n}] \\
[a_{21}, b_{21}, c_{21}] & [a_{22}, b_{22}, c_{22}] & \cdots & [a_{2n}, b_{2n}, c_{2n}]
\vdots & \ddots & \ddots & \vdots \\
[a_{m1}, b_{m1}, c_{m1}] & [a_{m2}, b_{m2}, c_{m2}] & \cdots & [a_{mn}, b_{mn}, c_{mn}]
\end{bmatrix}
\]

(6)

According to matrix \( I_{ab} \), determine \( M \) as the point value of the attractive domain interval \([a_{ih}, b_{ih}]\); the relative membership degree is equal to 1, which can be expressed as.

\[
I_{ab} = \begin{bmatrix}
[a_{11}, b_{11}, c_{11}] & [a_{12}, b_{12}, c_{12}] & \cdots & [a_{1n}, b_{1n}, c_{1n}] \\
[a_{21}, b_{21}, c_{21}] & [a_{22}, b_{22}, c_{22}] & \cdots & [a_{2n}, b_{2n}, c_{2n}]
\vdots & \ddots & \ddots & \vdots \\
[a_{m1}, b_{m1}, c_{m1}] & [a_{m2}, b_{m2}, c_{m2}] & \cdots & [a_{mn}, b_{mn}, c_{mn}]
\end{bmatrix}
\]

(6)
According to the positional relationship between the eigenvalue $x$ and $M$, if $x$ falls to the left of $M_{ih}$, the relative membership function calculation formula can be expressed as [28]

$$
\mu_{\Delta}(x_{ij})_{h} = 0.5 \left( 1 + \frac{x_{ij} - a_{ih}}{M_{ih} - a_{ih}}, x \in [a_{ih}, M_{ih}] \right)
$$

$$
\mu_{\Delta}(x_{ij})_{h} = 0.5 \left( 1 - \frac{x_{ij} - a_{ih}}{c_{ih} - a_{ih}}, x \in [c_{ih}, a_{ih}] \right)
$$

In the above formula, $i$ is the indicator, and $j$ is the sample.

If the eigenvalue $x$ falls to the right of $M_{ih}$, the relative membership function calculation formula can be expressed as [32]

$$
\mu_{\Delta}(x_{ij})_{h} = 0.5 \left( 1 + \frac{x_{ij} - b_{ih}}{M_{ih} - b_{ih}}, x \in [M_{ih}, b_{ih}] \right)
$$

$$
\mu_{\Delta}(x_{ij})_{h} = 0.5 \left( 1 - \frac{x_{ij} - b_{ih}}{d_{ih} - a_{ih}}, x \in [b_{ih}, d_{ih}] \right).
$$

According to formula (7) and formula (8), the membership degree of each index to each evaluation grade is obtained. After normalization, the corresponding relative membership degree matrix $U$ is defined as follows:

$$
U = (\mu_{\Delta}(x_{ij})_{h})
$$

According to the variable fuzzy evaluation model, the comprehensive relative membership degree of sample $j$ to grade $h$ can be written as

$$
\mu_{U}^{j}_{h} = \left\{ \left[ \frac{\sum_{i=1}^{m} \omega_{i} \left( 1 - \mu_{\Delta}(x_{ij})_{h} \right)^{p}}{\sum_{i=1}^{m} \omega_{i}^{p} \mu_{\Delta}(x_{ij})_{h}^{p}} \right]^{\frac{1}{p}}, \frac{\alpha}{p} \right\}^{-1}
$$

In the above formula, $\mu_{U}^{j}_{h}$ is the comprehensive relative membership degree of the evaluation object for grade $h$; $\alpha$ is the model optimization criterion parameter; $\omega_{i}$ is the weight of indicator $i$; $p$ is the distance parameter, $p = 1$ is the Hamming distance, and $p = 2$ is the Euclidean distance.

When $\alpha = 1$, $p = 1$, the above formula is a fuzzy comprehensive evaluation linear model [33]; when $\alpha = 1$, $p = 2$, it is a rational model [34]; when $\alpha = 2$, $p = 1$, it is a sigmoid function [35]; when $\alpha = 2$, $p = 2$, it is a fuzzy optimal model [36].

It can be seen that the variable fuzzy model is equivalent to a model set of four parameter combinations, that is, a variable model set. According to four different combinations of parameters, a corresponding nonnormalized comprehensive relative membership degree matrix can be obtained.

Normalize formula (10) to obtain a comprehensive relative membership degree matrix, which can be rewritten as

$$
U = (\mu_{U}^{j}_{h}).
$$

We have

$$
\mu_{U}^{j}_{h} = \frac{\mu_{U}^{j}_{h}}{\sum_{h=1}^{c} \mu_{U}^{j}_{h}}.
$$

The evaluation grade is determined according to the grade characteristic value method. Consider the relative membership degree distribution sequence of the known evaluation object to grade $h$; the characteristic value of the grade variable $h$ is defined as follows:

$$
H = \frac{\sum_{h=1}^{c} U \times h}{4}.
$$

From this, the final comprehensive evaluation result of the evaluation grade can be expressed as

$$
H = \frac{\sum_{i=1}^{4} H_{i}}{4}.
$$

In the above formula, $i$ is the combination of parameters, $i = 1, 2, 3, 4$. According to the standard of grade discrimination, the results are defined as follows:

$$
\begin{cases}
1 \leq H \leq 1.5, \text{attributable to Grade } 1 \\
1.5 < H \leq h, \text{attributable to Grade } h, \text{ten } d \text{ to Grade } (h - 1) \\
h < H \leq h + 0.5, \text{attributable to Grade } h, \text{ten } d \text{ to Grade } (h + 1) \\
n - 0.5 \leq H \leq n, \text{attributable to Grade } n
\end{cases}
$$

**4. Results and Discussion**

Assume that a high-speed railway station A and a subway station B can meet the connection and have conditions to implement security check mutual recognition.

**4.1. Indicator Weight Determination**

Determine the index weights according to the importance ranking consistency theorem, and obtain the index weight importance ranking consistency scale matrix $E$ that passes the test. Use empirical knowledge to make binary comparison judgments on the importance of indicators, and then use the mood operator, the fuzzy scale, and the relative membership degree relationship to obtain the weight vector of each indicator for normalization [37]. The fuzzy mood operator, fuzzy scale, and relative membership degree relations are reported in Table 1.

According to the actual situation and expert experience, the indicators in the first grade are compared in pairs, and the ranking consistency scale matrix is established. If index A is more important than index B, it is assigned a value of 1.
Find the relative membership of the indicator to importance in Table 1. Transportation capacity is somewhat more important than personnel and equipment, so the relative membership degree found in Table 1 is 0.667. Transportation capacity is between rather and obviously more important than environment and management, so the relative membership degree found in Table 1 is 0.481. Through the above method, the relative membership degree of the index to the importance of \( \omega' = (1, 0.667, 0.481) \) is obtained.

In the same way, the weight of the secondary index and the weight of each index in the whole are obtained.

\( E_1 \) is the importance ranking consistency scale matrix of the second-grade index passenger flow, passenger density in the car, concentration of passenger arrivals, and travel frequency that passed the inspection.

The importance of the second-grade index of transportation capacity is as follows: passenger flow > travel frequency > passenger density in the car > concentration of passenger arrivals. Judging by analysis and consideration, the passenger flow is rather more important than passenger density in the car; it is between obviously and remarkably significant compared to the concentration of passenger arrivals and somewhat and rather more important than the travel frequency.

Through the above judgment results and Table 1, \( \omega'_1 = (1, 0.538, 0.379, 0.60) \); weight after normalization \( \omega_1 = (0.40, 0.21, 0.15, 0.24) \).

\( E_2 \) is the importance ranking consistency scale matrix of the second-grade index passenger safety awareness, working conditions of station staff, security check level, and train speed that passed the inspection.

The importance of the second-grade index of personnel and equipment is as follows: security check level > working conditions of station staff > passenger safety awareness > train speed. Judging by analysis and consideration, the security check level is slightly more important than the working conditions of station staff, between somewhat and rather more important than passenger safety awareness, and between rather and obviously more important than train speed.

Through the above judgment results and Table 1, \( \omega'_2 = (0.60, 0.818, 1, 0.481) \); weight after normalization \( \omega_2 = (0.21, 0.28, 0.34, 0.17) \).

\( E_3 \) is the importance ranking consistency scale matrix of the second-grade index station location, train running position, passenger evacuation capacity at station, and emergency response ability of stations that passed the inspection.
The importance of the second-grade index of environment and management is as follows: train running position > station location > passenger evacuation capability. Judging from analysis and consideration, the train running position is somewhat more important than the station location, rather more important than the passenger evacuation capability, and between rather and obviously more important than the emergency response capability.

Through the above judgment results and Table 1, \( \omega_5 = (0.66, 0.53, 0.48) \); weight after normalization \( \omega'_5 = (0.25, 0.37, 0.20, 0.18) \).

The index weights of high-speed railway station A and subway station B are summarized in Table 2.

It can be seen from Table 2 that three of the twelve secondary indicators have larger weights and are more important in station safety. They are passenger flow, security check level, and travel frequency.

4.2. Station Safety Evaluation. The indicators in this paper include both qualitative and quantitative indicators. This paper uses the same criteria to determine the evaluation interval, weights, and eigenvalues. The qualitative indicators in this paper are the concentration of passenger arrivals, the working conditions of station staff, the security check level, the station location, the passenger evacuation capability at station, and the emergency response capacity of the stations. The characteristic values of the qualitative indicators are based on objective reality combined with expert scores. The rest are quantitative indicators. In addition, the characteristic values of the quantitative indicators are obtained through data collection and on-site investigation. Combining actual conditions and expert opinions, the evaluation intervals of these qualitative and quantitative indicators are divided into five intervals (90, 100), (80, 90), (60, 80), (40, 60), and (0, 40) based on a percentile system. The higher the score, the higher the security level, and the characteristic value of each index is given.

According to the above calculation results, the index weights and characteristic values of high-speed railway station A and subway station B are obtained as shown in Table 3.

According to formula (4), the attractive interval matrix of the evaluation index is determined as

\[
I_{ab} = [90, 100][80, 90][60, 80][40, 60][0, 40].
\]

According to formulas (5) and (6), the corresponding rejection interval \( I_{cd} \) and the point value interval matrix \( I_m \) can be determined as

\[
I_{cd} = [80, 100][60, 100][40, 90][0, 80][0, 60],
\]

\[
I_m = (100, 88, 70, 45, 0).
\]

According to formulas (7) and (8), the relative membership vector of the passenger flow of high-speed railway station A can be calculated, and the normalized result is (0.21, 0.56, 0.23, 0, 0).

Similarly, the normalized membership matrix of index \( i \ (i = 1, 2, 3 \ldots 12) \) of high-speed railway station A to level \( h \ (h = 1, 2, 3, 4, 5) \) can be obtained.

\[
(\text{station } A), U = \left( \mu_A(x_{ij}) \right)_h = \begin{bmatrix}
0.21 & 0.56 & 0.23 & 0 & 0 \\
0.80 & 0.35 & 0 & 0 & 0 \\
0.09 & 0.52 & 0.39 & 0 & 0 \\
0.54 & 0.46 & 0 & 0 & 0 \\
0.21 & 0.56 & 0.23 & 0 & 0 \\
0.80 & 0.35 & 0 & 0 & 0 \\
0.70 & 0.40 & 0 & 0 & 0
\end{bmatrix}
\]

(22)
According to formula (10), the comprehensive relative membership matrix of high-speed railway station A can be written.

\[
(\text{station} A) = \begin{bmatrix}
0.48 & 0.46 & 0.09 & 0 & 0 \\
0.46 & 0.47 & 0.15 & 0 & 0 \\
0.46 & 0.42 & 0.01 & 0 & 0 \\
0.42 & 0.45 & 0.03 & 0 & 0
\end{bmatrix}
\]  \hspace{1cm} (23)

After normalization, the comprehensive relative membership matrix of high-speed railway station A can be rewritten.

\[
(\text{station} A) = \begin{bmatrix}
0.46 & 0.44 & 0.10 & 0 & 0 \\
0.42 & 0.44 & 0.14 & 0 & 0 \\
0.46 & 0.47 & 0.15 & 0 & 0 \\
0.42 & 0.42 & 0.01 & 0 & 0 \\
0.42 & 0.45 & 0.03 & 0 & 0
\end{bmatrix}
\]  \hspace{1cm} (24)

According to formulas (13) and (14), the final comprehensive evaluation result of the high-speed railway station A can be expressed.

\[
\bar{H} = \frac{(1.64 + 1.72 + 1.49 + 1.59)}{4} = 1.60. \hspace{1cm} (25)
\]

Table 3: Station index weight and characteristic value table.

<table>
<thead>
<tr>
<th>Serial number</th>
<th>First-grade indexes and weights</th>
<th>Second-grade indexes and weights</th>
<th>Overall weight</th>
<th>Characteristic value A</th>
<th>Characteristic value B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Transportation capacity (0.47)</td>
<td>Passenger flow (0.40)</td>
<td>0.1880</td>
<td>87</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Passenger density in the car (0.21)</td>
<td>0.0987</td>
<td>96</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Concentration of passenger arrivals (0.15)</td>
<td>0.0705</td>
<td>82</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Travel frequency (0.24)</td>
<td>0.1128</td>
<td>91</td>
<td>81</td>
</tr>
<tr>
<td>2</td>
<td>Personnel and equipment (0.31)</td>
<td>Passenger safety awareness (0.21)</td>
<td>0.0651</td>
<td>87</td>
<td>82</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Working conditions of station staff (0.28)</td>
<td>0.0868</td>
<td>96</td>
<td>95</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Security check level (0.34)</td>
<td>0.1504</td>
<td>92</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Train speed (0.17)</td>
<td>0.0527</td>
<td>87</td>
<td>80</td>
</tr>
<tr>
<td>3</td>
<td>Environment and management (0.22)</td>
<td>Station location (0.25)</td>
<td>0.0550</td>
<td>92</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Train running position (0.37)</td>
<td>0.0814</td>
<td>91</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Passenger evacuation capacity at station (0.20)</td>
<td>0.0440</td>
<td>94</td>
<td>92</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Emergency response ability of stations (0.18)</td>
<td>0.0396</td>
<td>96</td>
<td>97</td>
</tr>
</tbody>
</table>

Table 4: The characteristic value of high-speed railway station A.

<table>
<thead>
<tr>
<th>Parameter combination</th>
<th>Membership</th>
<th>Grade 1</th>
<th>Grade 2</th>
<th>Grade 3</th>
<th>Grade 4</th>
<th>Grade 5</th>
<th>(H)</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\alpha = 1)</td>
<td>Relative membership</td>
<td>0.48</td>
<td>0.46</td>
<td>0.09</td>
<td>0</td>
<td>0</td>
<td>1.64</td>
<td></td>
</tr>
<tr>
<td>(p = 1)</td>
<td>Membership after normalization</td>
<td>0.46</td>
<td>0.44</td>
<td>0.10</td>
<td>0</td>
<td>0</td>
<td>1.72</td>
<td>1.60</td>
</tr>
<tr>
<td>(\alpha = 1)</td>
<td>Relative membership</td>
<td>0.46</td>
<td>0.47</td>
<td>0.15</td>
<td>0</td>
<td>0</td>
<td>1.49</td>
<td></td>
</tr>
<tr>
<td>(p = 2)</td>
<td>Membership after normalization</td>
<td>0.42</td>
<td>0.44</td>
<td>0.14</td>
<td>0</td>
<td>0</td>
<td>1.56</td>
<td></td>
</tr>
<tr>
<td>(\alpha = 2)</td>
<td>Relative membership</td>
<td>0.46</td>
<td>0.42</td>
<td>0.01</td>
<td>0</td>
<td>0</td>
<td>1.56</td>
<td>1.60</td>
</tr>
<tr>
<td>(p = 1)</td>
<td>Membership after normalization</td>
<td>0.52</td>
<td>0.47</td>
<td>0.01</td>
<td>0</td>
<td>0</td>
<td>1.56</td>
<td></td>
</tr>
<tr>
<td>(\alpha = 2)</td>
<td>Relative membership</td>
<td>0.42</td>
<td>0.45</td>
<td>0.03</td>
<td>0</td>
<td>0</td>
<td>1.56</td>
<td></td>
</tr>
<tr>
<td>(p = 2)</td>
<td>Membership after normalization</td>
<td>0.47</td>
<td>0.50</td>
<td>0.03</td>
<td>0</td>
<td>0</td>
<td>1.56</td>
<td></td>
</tr>
</tbody>
</table>

Table 5: The class characteristic value of subway station B.

<table>
<thead>
<tr>
<th>Parameter combination</th>
<th>Membership</th>
<th>Grade 1</th>
<th>Grade 2</th>
<th>Grade 3</th>
<th>Grade 4</th>
<th>Grade 5</th>
<th>(H)</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\alpha = 1)</td>
<td>Relative membership</td>
<td>0.35</td>
<td>0.26</td>
<td>0.24</td>
<td>0.08</td>
<td>0.07</td>
<td>2.26</td>
<td></td>
</tr>
<tr>
<td>(p = 1)</td>
<td>Membership after normalization</td>
<td>0.35</td>
<td>0.26</td>
<td>0.24</td>
<td>0.08</td>
<td>0.07</td>
<td>2.26</td>
<td></td>
</tr>
<tr>
<td>(\alpha = 1)</td>
<td>Relative membership</td>
<td>0.34</td>
<td>0.28</td>
<td>0.38</td>
<td>0.15</td>
<td>0.18</td>
<td>2.64</td>
<td>2.26</td>
</tr>
<tr>
<td>(p = 2)</td>
<td>Membership after normalization</td>
<td>0.26</td>
<td>0.21</td>
<td>0.29</td>
<td>0.11</td>
<td>0.13</td>
<td>1.79</td>
<td>1.79</td>
</tr>
<tr>
<td>(\alpha = 2)</td>
<td>Relative membership</td>
<td>0.22</td>
<td>0.11</td>
<td>0.09</td>
<td>0.01</td>
<td>0.00</td>
<td>1.79</td>
<td></td>
</tr>
<tr>
<td>(p = 1)</td>
<td>Membership after normalization</td>
<td>0.50</td>
<td>0.25</td>
<td>0.22</td>
<td>0.02</td>
<td>0.01</td>
<td>1.79</td>
<td></td>
</tr>
<tr>
<td>(\alpha = 2)</td>
<td>Relative membership</td>
<td>0.21</td>
<td>0.14</td>
<td>0.27</td>
<td>0.03</td>
<td>0.05</td>
<td>1.79</td>
<td></td>
</tr>
<tr>
<td>(p = 2)</td>
<td>Membership after normalization</td>
<td>0.31</td>
<td>0.20</td>
<td>0.39</td>
<td>0.04</td>
<td>0.06</td>
<td>2.34</td>
<td></td>
</tr>
</tbody>
</table>

According to formula (10), the comprehensive relative membership matrix of high-speed railway station A can be written.
comprehensive relative membership degree and grade characteristic value of subway station B under the four parameter combinations. The calculation results are shown in Tables 4 and 5.

The variable fuzzy model is equivalent to a model set of different parameter combinations. When the values of $\alpha$ and $p$ are equal to 1 or 2, the result of the variable model set is shown in Figure 2. The average value of the calculation results under the combination of the four parameters is taken as the final safety evaluation result. Therefore, the safety evaluation result of high-speed railway station A is 1.60. According to formula (15), the affected grade belongs to grade 2 and tends to grade 1. The safety evaluation result of subway station B is 2.26. According to formula (15), the affected grade belongs to grade 2 and tends to grade 3.

It can be seen that, regardless of the combination of the four parameters or the final result, the safety grade of the high-speed railway station A is higher than that of the subway station B. Therefore, it is feasible for passengers to transfer to the subway in one direction without contacting with the outside world after getting off the train at high-speed railway station A.

5. Conclusions

(1) In the present study, a methodology for solving security check mutual recognition between high-speed railway and urban rail transit has been developed based on variable fuzzy set theory.

(2) An index system for evaluating the security level of subway and high-speed railway is established from three aspects: transportation capacity, personnel and equipment, and environment and management, including twelve evaluation indexes.

(3) Through the expert brain storming discussion, the important consistency sorting theorem method is used to calculate the weights, among which passenger flow, security check level, and travel frequency are more important, and the weights are 0.1880, 0.1504, and 0.1128, respectively.

(4) This paper uses variable fuzzy set theory to calculate the safety level of high-speed railway station A and subway station B, respectively. The variable fuzzy model is equivalent to a model set of four parameter combinations. Take the average of the results of the four parameter combinations when $\alpha$ and $p$ are equal to 1 and 2, respectively, to obtain the final result. The safety evaluation result of high-speed railway station A is 1.60, and the affected grade belongs to grade 2 and tends to grade 1. The safety evaluation result of subway station B is 2.26, and the affected grade belongs to grade 2 and tends to grade 3. According to the calculation results, passengers arriving at high-speed railway station A can get off the CRH and enter the urban rail transit station without inspection in one direction without contacting with the outside world.

(5) The research method can provide theoretical basis for high-speed railway and urban rail transit stations that plan to implement security check mutual recognition and provide reference for the research and judgment of the implementation of stations that have implemented security check mutual recognition and plan optimization.

(6) Further study can further improve the selection of indicators affecting the safety level of railway and urban rail transit.

Data Availability

The data used to support the findings of this study are included within the paper.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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References


