

Research Article

Developing a Subway Fire Risk Assessment Model Based on Analysis Theory

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In order to effectively reduce the risk of subway fires and to improve the safety of passengers, a review of the background to subway fires employing literature and comparative analyses, computer simulation, expert consultation, and other research methods has been employed to conduct an in-depth study of subway fire risk assessment and control measures. A subway fire risk assessment model based on analysis theory was established. Firstly, a subway fire risk evaluation index system was developed, and the weight values of each level were determined using the interval analytic hierarchy process (IAHP), then the evaluation was derived using the fuzzy evaluation method, and the passenger distribution simulation was introduced to improve the objectivity of the evaluation. The results show that the fire evaluation of this subway system is safe. The results show that a subway fire risk assessment model may provide a scientific basis for establishing prevention and control measures, extinguishing methods, passenger safety evacuation schemes, and carrying out fire safety management activities during subway operations.

1. Introduction

In recent years, with the advancement of urbanization in China, the number of people living in cities is continuously increasing. Urban traffic congestion has, therefore, become a major problem that people must face when traveling, especially in some large and medium-sized cities, where congestion is more serious. As a new type of rail transit, the development of subway traffic symbolizes the rapid development of a city. Subways not only bring convenience to people when traveling but also have the characteristics of safety, punctuality, speediness, environmental protection, and large carrying capacity, as well as the advantages of saving land, reducing noise, saving energy, and reducing pollution. Subways are, therefore, gradually becoming an important tool for alleviating urban traffic congestion with its many advantages.

As one of the critical aspects of life in many modern cities, subway system security has become more important because of the cyclic nature of a network's operations. However, while subways bring convenience to people, the

fire safety of subway systems also faces severe challenges. Since subway stations and trains are densely populated public gathering places, once a fire starts and if there is no timely and effective control, it is bound to pose a serious threat to the safety of people's lives and property and has a significant impact on the smooth operation of urban transport. Therefore, fire is the key point of subway emergency rescue. Hence, in order to avoid or minimize the casualties and material losses caused by subway fires, and to ensure the subway operates in a safe environment, it is urgent to carry out the research on subway safety.

After a preliminary analysis of subway fire accidents, it has been found that subway fires are affected by many factors, including those associated with personnel, equipment, and the environment [1]. On the basis of the analysis of the influencing factors of subway fires, the risk of subway fire is assessed, and corresponding rectification schemes are suggested in advance according to the risk, so as to reduce the probability of subway fire, or to effectively deal with one if it occurs. Next, through the analysis of the causes and characteristics of subway fire accidents, an evaluation index

model is established and weighted. Finally, combined with specific examples, subway fire risk assessment is further studied.

2. Theoretical Background

The study of subway fire risk assessment has started with the emergence of subways. The occurrence of subway fire accidents in various countries around the world has promoted the study of subway fire safety and related evaluation measures, which requires the study of subway fire design codes and regulations, on the one hand, and the fire risk assessment and improvement through the subway system, on the other hand, which is also an effective way to guarantee the safety of people and property in the subway, and can be carried out in three aspects: qualitative, semiquantitative, and quantitative [2]. Huang [3] conducted a fire risk assessment of a subway using a hierarchical analysis process (AHP) and proposed four main factors that affect the fire risk of a subway station: passengers, fire safety management system, fire protection facilities, and subway structure. In order to assess the subway fire risk, An [4] established a multilevel extensible assessment method based on hierarchical analysis and expert survey method, which can be used to identify the weak points and management priorities of subway fire risk. Li [5] established the architecture of an urban underground transportation fire risk assessment system based on a time-series phased assessment approach and established a multilevel assessment index weighting model to propose evaluation criteria for judging fire risk. Lu [6] constructed a Bayesian network model to calculate the fire risk of the subway system and considered factors such as discarded cigarette butts, high temperature, spontaneous combustion of materials, fire in the subway system, and injuries to people and their interactions. Peng [7] used a fuzzy hierarchical integrated assessment model to evaluate the fire risk of subway stations, which considers the influence of multiple factors on station fires and portrays the relationship between the factors and the objects to which they belong by means of an affiliation function with fixed calculation steps that are easy to implement programmatically. Triadó [8] analyzed the causes and hazards of subway fires and assessed the evacuation evaluation index system of subway fire passengers in Barcelona, Spain, by the fuzzy comprehensive evaluation method. Krasyuk [9] used mathematical statistics combined with risk analysis theory to determine the most important factors causing subway fires and established an evaluation index system for subway fire risk assessment. This is a quantitative evaluation of the probability and impact of subway fires using fuzzy fault trees. Xie [10] established a fire risk assessment model for subway operations based on group topologizable fuzzy theory and used fuzzy mathematics and topologizable theory to make a comprehensive assessment of six aspects including fire sources, fire performance, fire extinguishing capability, evacuation capability, safety management situation, and environment in subway stations. Teodosiu [11] studied subway fires from three points of view: fuel content, safety management and evacuation of personnel and passengers,

and the safety of train equipment. Fridolf [12] analyzed the main influencing factors of subway fires from 21 categories of personnel, equipment, management, and environment and established a subway fire risk assessment model through neural networks. The neural network model was also optimized by a genetic algorithm. Wang [13] classified fire risk, analyzed the risk sources and risk parameters, calculated the index of subsystem or system, classified the fire risk of the system, and put forward the corresponding risk management countermeasures. Yu [14] analyzed the risk factors associated with subway fire accidents, and a subway fire risk assessment model was developed which employs a neural network with 21 main factors. Zhang [15] studied smoke flow and diffusion and temperature distributions resulting from subway fires, making use of the FDS (Fire Dynamics Simulator) is a computational fluid dynamics CFD model of fire-driven fluid flow. In order to minimize the hazards of smoke, a smoke emission scheme for subway fires was proposed. Wei [16] used FDS simulation software to analyze the effects of smoke temperature, visibility, and CO concentration on evacuation and developed a safety evacuation assessment model to analyze and verify whether people can evacuate safely under different fire conditions. Zhao [17] utilized the fire dynamics simulator (FDS) software to study the efficiency of different ventilation modes on smoke confinement in a T-type interchange subway station connecting Lines 1 and 2 of the Nanjing subway. An optimized ventilation mode is proposed based on the smoke diffusion, temperature, and visibility field. Yu [18] studied the identification of subway fire hazards by using a fault tree method. While classifying the identified hazards from the point of view of accident-causing theory and system safety analysis, an index system of subway fire risk assessment was developed, and in doing so, we established a subway fire risk assessment model using the FAHP-BP (Fuzzy Analytical Hierarchy Process, Back Propagation (BP) neural network) method.

In addition, a large number of passengers gather and move in subway stations, and the passenger flow distribution has temporal and spatial distribution characteristics, and the interior of subway stations and subway cars is often very crowded during peak passenger flow, which may cause a large number of casualties in case of fire and other emergencies. The passenger evacuation risk in subway stations has also become a key issue in the evaluation of subway fire risk, and scholars have conducted a large number of studies. Mu [19] used the questionnaire method to conduct a random survey of passengers traveling in subway stations and used the chi-square test to correlate the statistical results of the questionnaire survey. Yi [20] proposed a method for calculating personnel exit selection under the influence of habit, panic, and herd mentality for the influence of personnel habit psychology and its impact on safe evacuation. Li [21] conducted a simulation study on passenger flow guidance and small group effect in the evacuation process of subway stations, and the results showed that passenger flow guidance and small group have significant effects on evacuation time, evacuation efficiency, bottleneck area, and detour distance. Lian [22] studied safe evacuation path

planning for crowded passengers based on a multiobjective particle swarm algorithm. Du [23] constructed a subway passenger evacuation model integrating ant colony algorithm and metacellular automaton by using metacellular automaton intelligent decision model. Li [24] found that stairs and gates are bottlenecks in the evacuation process through numerical simulation of subway evacuation. Li [25] investigated the interaction between fire and personnel evacuation and found that three factors, prolonging the evacuation time, limiting the range of activities, and changing the evacuation route of passengers, affect the effectiveness of subway evacuation.

Generally speaking, in terms of fire risk assessment index systems for subways, existing systems are not perfect, and their pertinence is not strong. Based on the existing research results of some underground buildings and the characteristics of subways, methods involving qualitative and quantitative evaluation have been applied to obtain a comprehensive assessment scheme of subway fire risk assessment. Moreover, design factors are added to improve subway fire risk evaluation indices, which provides guidance for the establishment of subway fire prevention and control procedures, firefighting, safe evacuation, and other measures.

3. Methodology

The objective of the research presented in this work is to develop an urban subway fire risk model. The methodology followed involves employing the analytic hierarchy process (AHP), which is a combination of qualitative and quantitative methods [26]. AHP converts the thinking process of decision-makers to a mathematical form and simplifies complex problems [27]. The work also employs fuzzy comprehensive evaluation (FCE), developed by Zadeh [28] in the 1960s. This covers six basic elements: evaluation factors, evaluation grades, fuzzy relation matrices, evaluation factor weight vectors, synthesis operations, and evaluation result vectors. The method proposed combines the advantages of hierarchical analysis for complex problems and the quantitative characteristics of the fuzzy comprehensive evaluation method, which has strong practicality for complex, nonquantitative problems such as subway fire risk evaluation and increases the objectivity of the evaluation relationship. And it draws on the process and ideas [29, 30] of quantitative simulation analysis of some fire initiating factors.

The improved AHP, namely, the interval analytic hierarchy process (IAHP) [31], is combined with set pair analysis theory to determine the weight of the evaluation indices used to evaluate the fire risk of urban subways. IAHP has the advantage of avoiding the chance of safety experts judging the subway fire risk factors.

In addition, in order to provide an objective evaluation basis for the fuzzy comprehensive evaluation, statistical methods are used to obtain the density of subway personnel, Pathfinder is used to simulate the number and distribution of passengers in subway stations, and the accuracy of the evaluation is enhanced based on the analysis results [32, 33].

4. Experiments

4.1. Analysis of Risk Factors for Subway Fire. The main factors affecting subway fire risk assessments include personnel, equipment, management, environment, and design, of which the most important are management and design. Subway administrators should manage the system in an objective manner and make use of a number of fire prevention and extinguishing methods to ensure the safety of life and property and to ensure the normal operation of the subway. The designer of a subway should consider the influence of subway fire from two aspects. One is fire prevention, and the other involves fire countermeasures. In terms of fire prevention factors, the trains themselves, especially the interiors and the materials they are built from, should meet the requirements of fire prevention, while the fire prevention aspects of a subway's design should include not using inflammable materials. In terms of fire countermeasures, the fire escape system, smoke drainage system, and other aspects of the safety evacuation system should be designed and constructed strictly in accordance with national standards, which to a certain extent will have an impact on the fire itself.

4.2. Numerical Simulation Model of Subway Station. In order to use Pathfinder for personnel distribution simulation, we firstly collected drawings and parameters of the subway station, and then AutodeskCAD is used to model the station and imported DWG format into Pathfinder software.

The subway station in this study is a double-decker island station, shown in Figure 1, with the lobby level at the first basement level, which is 72 m long, 18 m wide, and 3.6 m high, with two entrances on each side, each 5 m wide and 3 m high, and the platform level at the second basement level, which is 120 m long, 10 m wide, and 4 m high, connected to the lobby level by two staircases and two escalators. There is a smoke exhaust system on the top of the platform level, with 46 smoke exhaust openings, measuring 0.6 m × 0.5 m, arranged 4.5 m apart, and symmetrically distributed on both sides of the platform level.

4.3. Development of a Subway Fire Risk Evaluation Index System. The development of a subway fire risk assessment system should follow five principles, in that it needs to be systematic and scientific, allow comparability and operability, and be practical.

A preliminary risk assessment index system is analyzed based on the current Code for Terrain Design, Code for Fire Prevention in Subway Design, Code for Design of Automatic Fire Alarm System, Comprehensive Ability of Fire Safety Technology, Code for Fire Prevention in Architectural Design, relevant fire codes for China and abroad, and the current domestic and foreign research literature [34]. On the basis of the preliminary establishment of the fire risk index system for the urban subway under consideration, a questionnaire survey is conducted to investigate the importance of the index, and the most important influencing factors are selected according to the grey theory. The final evaluation

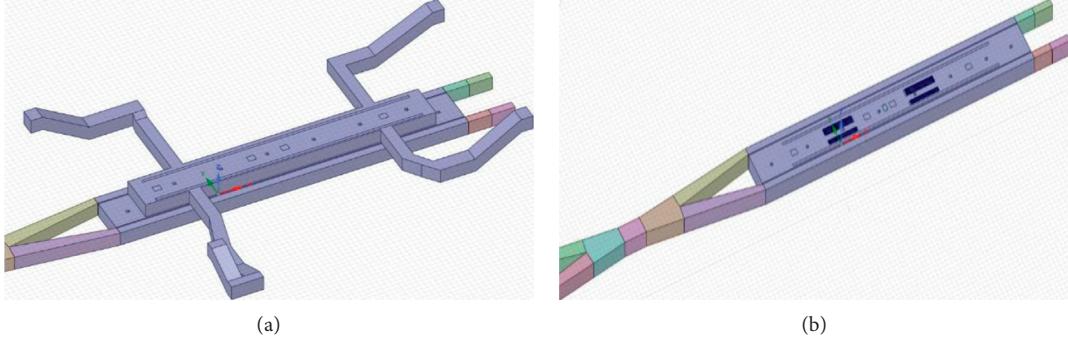


FIGURE 1: Station lobby level and platform level of the subway.

index system for subway fire risk has three levels, which are the target layer, the first-grade index layer, and the second-grade index layer. The target layer is the fire risk of an urban subway, and the first-grade index layer is the fire hazard control, the fire prevention capacity of the subway, the fire extinguishing capacity of the subway, the evacuation capacity, and the fire safety management. The second-grade index layer is in turn composed of 21 indices, which are outlined later in this work in Table 1.

4.4. Establishment of Subway Fire Risk Evaluation Index Model. The basic process of developing a subway fire risk assessment model includes five main aspects: establishing the objective of the subway fire risk assessment, determining the main factors of subway fire risk, developing the subway fire risk evaluation index system, undertaking a comprehensive evaluation of urban subway fire risk, and the risk control measures themselves. The main objective of a fire risk assessment of an urban subway system is to know the associated fire risk and to undertake targeted measures to reduce as much likelihood of the occurrence of fire as possible and to ensure the means of extinguishing the fire quickly and to rapidly and safely evacuate personnel and passengers. By analyzing the risk, characteristics, and causes of subway fires, the risk factors may be identified on the basis of relevant literature and codes. The identified risk factors have an important impact on the later risk assessment, which directly or indirectly determines the reliability of the risk assessment.

Establishing the fire risk assessment index of urban subways is an important link in risk assessment, and its development should follow the principles of being systematic, scientific, and practical. The preliminary index system is optimized, with the important factors of the index being selected by reasonable methods. In the process of establishing the index system, how to make the subway fire risk evaluation index system more reasonable and applicable becomes an urgent problem to be solved.

In a comprehensive evaluation of urban subway fire risk, the concrete object of the evaluation should be first determined; the structure of the hierarchical index system for fire risk is shown in Figure 2. The factors of the index system were then weighted by the interval analytic hierarchy process (IAHP). Then, the fuzzy comprehensive evaluation method

should be used to evaluate the urban subway fire risk, making use of a concrete example. Finally, the risk control measures should be determined according to the analysis of the evaluation results. After analyzing the results of the subway fire risk assessment, it is very important to put forward corresponding measures to mitigate against fire risk. Through relevant measures, the probability of such a fire can be reduced, so as to improve the safety of the subway.

The IAHP theory is used to transform the weight vectors of an interval form into weight vectors with exact values. From this, the weight of the subway fire risk evaluation index is obtained.

In IAHP, we first decompose the subway fire problem and establish a hierarchy. Then, a comparison is made of the relative importance of each indicator, by comparing it with each of the others, to establish a judgment matrix, and finally, the judgment matrix weights are solved and the combined weights of each subway fire risk evaluation index are calculated.

This method usually uses a 1–9 scale [26] method upon which the experts base their scores (see Table 2).

After the expert scores quantify the importance of the indicator, an interval number judgment matrix is constructed such that $A = (a_{ij})_{n \times n}$. A is the consistency interval matrix, where each element is made up of interval numbers represented by $a_{ij} = [a_{ij}^-, a_{ij}^+]$, which satisfies $a_{ji} = 1/a_{ij} = 1/a_{ij}^+ + 1/a_{ij}^-$.

Experts in subways and fire protection are then invited to score the developed risk evaluation index factors according to the 1–9 scale method (Table 2), and the interval number of judgment matrices was obtained by statistical analysis.

The interval number $a_{ij} = [a_{ij}^-, a_{ij}^+]$ of the relative importance degree between index factor i to index factor j is given by the k th expert as

$$a_{ij}^{(k)} = [a_{ij}^{-{(k)}}, a_{ij}^{+{(k)}}]. \quad (1)$$

Since each expert has different educational backgrounds, professional backgrounds, and experiences, it is necessary to give different score weights to each expert according to his or her level in order to make the evaluation more objective and convincing. WER (k) indicates the weight applied to the k th expert's response. The experts' weights for L experts are then expressed in a vector as

TABLE 1: Index weights of the subway fire risk evaluation index system.

First-grade index	Weight	Second-grade index	Weight
Personnel factor U ₁	0.067	Passenger safety awareness (u ₁₁)	0.211
		Fire awareness of subway staff (u ₁₂)	0.266
		Number of subway staff and their firefighting skills (u ₁₃)	0.171
Equipment factor U ₂	0.139	Emergency rescue capability of the subway staff (u ₁₄)	0.169
		Number and distribution of passengers (u ₁₅)	0.183
		Ventilation and smoke exhausting equipment (u ₂₁)	0.139
Environmental factor U ₃	0.293	Fire extinguishing equipment (u ₂₂)	0.163
		Environment and video surveillance equipment (u ₂₃)	0.108
		Fire detection and alarm equipment (u ₂₄)	0.205
Management factor U ₄	0.464	Mechanical and electrical equipment (u ₂₅)	0.175
		Communication equipment (u ₂₆)	0.210
		Fire compartment (u ₃₁)	0.290
Design factor U ₅	0.035	Fire prevention interval (u ₃₂)	0.251
		Fire load (u ₃₃)	0.190
		Construction of public fire facilities (u ₃₄)	0.102
Design factor U ₅	0.035	Nearest fire station distance (u ₃₅)	0.167
		Fire emergency preparedness plan (u ₄₁)	0.273
		Routine fire safety inspection (u ₄₂)	0.114
Management factor U ₄	0.464	Formulation and implementation of fire regulations (u ₄₃)	0.134
		Fire safety education and training for subway employees (u ₄₄)	0.106
		Publicity and popularization of subway fire safety knowledge (u ₄₅)	0.201
Design factor U ₅	0.035	Fire drill (u ₄₆)	0.173
		Design of safety evacuation system (u ₅₁)	0.401
		Design of smoke drainage system (u ₅₂)	0.232
Design factor U ₅	0.035	Design of emergency system (u ₅₃)	0.087
		Fire prevention and fire resistance of trains their component building materials (u ₅₄)	0.280

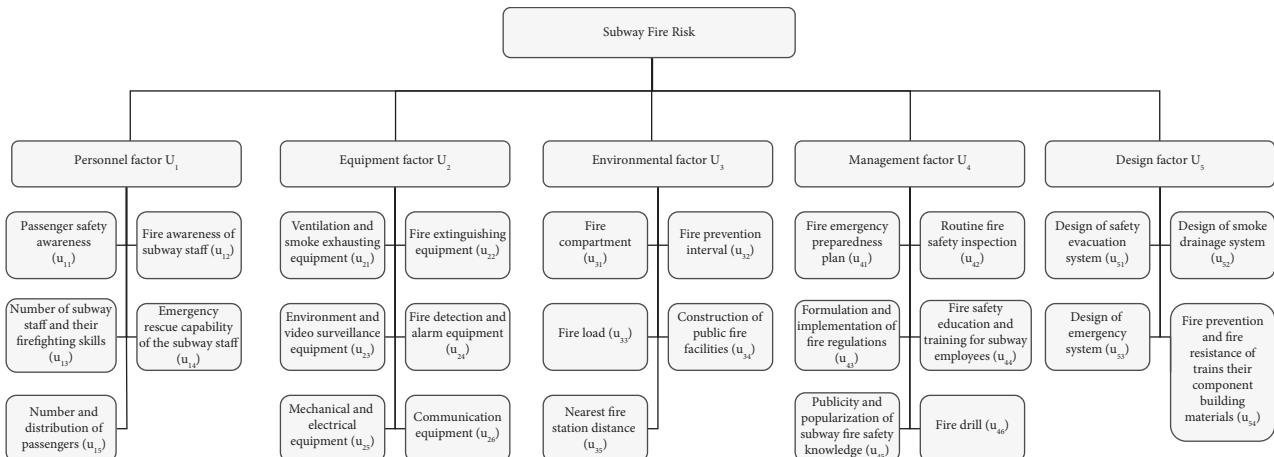


FIGURE 2: Index architecture diagram.

TABLE 2: The 1–9 scale method for rating the relative importance of two indicators.

Scale	Meaning
1	It suggests that when the two indicators are compared, the former is as important as the latter
3	It indicates that when the two indicators are compared, the former is a little more important than the latter
5	It means that when the two indicators are compared, the former is much more important than the latter
7	It means that when the two indicators are compared, the former is very strongly more important than the latter
9	It indicates that when the two indicators are compared, the former is much more important than the latter
2, 4, 6, and 8	These represent the intermediate values of the adjacent judgments
Reciprocal	If the ratio of the importance of index factor i to index factor j is a_{ij} , then the ratio of the importance of index factor j to index factor i is $a_{ji} = 1/a_{ij}$, which is reciprocal to each other

$$W_{EXP} = [W_{EXP}^{(1)}, W_{EXP}^{(2)}, \dots, W_{EXP}^{(L)}]. \quad (2)$$

The judgment matrix based on the interval numbers can then be obtained, which is given by

$$A = \begin{bmatrix} [1, 1] & [a_{12}^-, a_{12}^+] & \dots & [a_{1n}^-, a_{1n}^+] \\ \left[\frac{1}{a_{12}^+}, \frac{1}{a_{12}^-} \right] & [1, 1] & \dots & [a_{2n}^-, a_{2n}^+] \\ \vdots & \vdots & \ddots & \vdots \\ \left[\frac{1}{a_{1n}^+}, \frac{1}{a_{1n}^-} \right] & \left[\frac{1}{a_{2n}^+}, \frac{1}{a_{2n}^-} \right] & \dots & [1, 1] \end{bmatrix}, \quad (3)$$

where in equation (3), the various components are

$$a_{ij}^- = \sum_{k=1}^L (W_{ER}^{(k)} \cdot a_{ij}^{- (k)}), \quad (4)$$

$$a_{ij}^+ = \sum_{k=1}^L (W_{ER}^{(k)} \cdot a_{ij}^{+ (k)}). \quad (5)$$

After finding the experts' weights, it is possible to construct the interval number judgment matrix A according to equations (4) and (5) by the experts' scoring. The reciprocal of matrix A is guaranteed by the reciprocal rule outlined in Table 2 and the reciprocal consistency judgment matrix $M = (m_{ij})_{n \times n}$, which can be obtained by the use of the following formulation for its components m_{ij} :

$$m_{ij} = \sqrt[n]{\prod_{k=1}^{2n} \frac{a_{ik}^- \cdot a_{ik}^+}{a_{jk}^- \cdot a_{jk}^+}}. \quad (6)$$

The weight vector of $M = (m_{ij})_{n \times n}$ is marked as $W = (w_1, w_2, \dots, w_n)$, where w_j is the weight of the indicator j , and is calculated by the square root method:

$$w_j = \frac{1}{\sum_{i=1}^n m_{ij}}, \quad (7)$$

where $j = 1, 2, \dots, n$; thus, the weights of all n indicators can be determined.

By inviting subway fire safety experts to compare the relative importance of each indicator according to the 1–9 scale (Saaty, 1987), the judgment matrix in the form of interval numbers is given, and the weight coefficients of the first- and second-grade indices are determined. With the help of the Yaahp software [35] (a software tool based on hierarchical analysis and fuzzy integrated evaluation methods) in the calculation process, it is very convenient to derive the hierarchical structure model and to obtain the hierarchical model. The various matrices in the methodology are then generated automatically according to the hierarchical model. Finally, the results of the weight calculations can be produced.

Considering the different experience, professional, and educational backgrounds, knowledge level, position, and the cognitive tendency of each expert taking part in the study, the following weights were assigned, where W_{ERP} indicates all (in this case, six) expert's weights:

$$W_{EXP} = (0.3, 0.2, 0.15, 0.15, 0.1, 0.1). \quad (8)$$

Based on the importance of the indicators given by the experts, the interval number judgment matrix A was obtained following equations (3) to (5):

$$A = \begin{bmatrix} [1.00, 1.00] & [0.18, 0.29] & [0.14, 0.20] & [0.19, 0.34] & [2.10, 4.75] \\ [3.45, 5.56] & [1.00, 1.00] & [0.14, 0.20] & [0.19, 0.34] & [5.40, 7.15] \\ [5.00, 7.14] & [5.00, 7.14] & [1.00, 1.00] & [0.15, 0.21] & [6.75, 8.55] \\ [2.95, 5.26] & [2.90, 5.15] & [4.76, 6.67] & [1.00, 1.00] & [4.55, 6.75] \\ [0.21, 0.48] & [0.14, 0.19] & [0.12, 0.15] & [0.15, 0.22] & [1.00, 1.00] \end{bmatrix}. \quad (9)$$

The consistency judgment matrix was obtained by applying equation (6) and is expressed as

$$M = \begin{bmatrix} 1.00 & 0.48 & 0.23 & 0.15 & 1.91 \\ 2.07 & 1.00 & 0.47 & 0.30 & 3.95 \\ 4.36 & 2.11 & 1.00 & 0.63 & 8.32 \\ 6.88 & 3.33 & 1.58 & 1.00 & 13.14 \\ 0.52 & 0.25 & 0.13 & 0.08 & 1.00 \end{bmatrix}. \quad (10)$$

$$W = (0.067 \ 0.139 \ 0.293 \ 0.464 \ 0.035) \quad (11)$$

while according to equation (7), the weight vector of the consistency judgment matrix is given by

From the resulting weight vector presented above, the weight of the first-grade indexes is obtained, where the

management factors are considered to have the greatest impact on fire risk levels. In the same way, the weights corresponding to the second-grade indexes can be obtained, with Table 1 presenting the weights' statistics of the subway fire risk evaluation index system.

4.5. Fuzzy Comprehensive Evaluation Process. After obtaining the weights of each indicator with the IAHP [36], the fuzzy comprehensive evaluation method was used to select the most objectively reasonable risk state within the fire risk assessment set of an urban subway system. The fire risk assessment set is expressed as $Y = (Y_1, Y_2, \dots, Y_m)$, which contains m levels of risk status, from very safe to very dangerous. In the urban subway fire risk assessment example, we use five-level risk evaluation, expressed as

$$Y = (Y_1, Y_2, Y_3, Y_4, Y_5) = (\text{Safest, Safer, Moderately safe, Relatively dangerous, Very dangerous}). \quad (12)$$

The index system shown in Figure 1 can then be used to analyze subway fire risk. U is the first-grade factor set, and U_i is the second-grade factor set. The various factors are outlined in

$$U = (U_1, U_2, \dots, U_n), \quad (13)$$

$$U_i = \{u_{i1}, u_{i2}, \dots, u_{iK}\}, \quad i = 1, 2, \dots, n, \quad (14)$$

where U_i contains K factors.

The fuzzy relation matrix of the evaluation index R is then determined by a single-factor evaluation of the indicators at each level, which is carried out sequentially, with the following set of single-factor evaluations of the first-grade factors:

$$R = \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1m} \\ r_{21} & r_{22} & \dots & r_{2m} \\ \dots & \dots & \ddots & \dots \\ r_{n1} & r_{n2} & \dots & r_{nm} \end{bmatrix}, \quad (15)$$

where r_{ij} represents the fuzzy affiliation of the indicator factor U_i to the fire risk assessment set Y_j , and it expresses the results of the fire risk evaluation of the index U_i . Suppose that 10 experts were invited to score the subway fire risk according to its specific situation, leading to 5 experts scoring the safety level of the "equipment factor" as "very safe", 4 experts finding it "relatively safe", and 1 expert finding it "generally safe". This evaluation indicator will then be scored as [0.5, 0.4, 0.1, 0.0, 0.0].

where B represents the evaluation result vector, whose components b_i show the degree of the subjection of the evaluated index to the fuzzy set of the indices Y_i as a whole, W represents the weight vector of the index, which is obtained according to equation (6), and R represents the fuzzy relation matrix.

The fuzzy comprehensive evaluation is then carried out following equation (10), expressed as

4.6. Subway Passengers Distribution Statistics. In order to improve the coverage of passengers' evacuation simulation, a typical situation with a more crowded evening peak was conducted. First, the number of people in the evening peak period of the subway was counted, and the comprehensive statistics for several times yielded that the average density of the passengers inside the train in the evening peak was 2.68 persons/m², the average density of the passengers waiting in the platform was 0.492 persons/m², and the density of the passengers in the station hall was 0.243 persons/m².

In city X, the Y-line subway uses model B. The area of a single car is 53 m², and the total area of 6 cars is 318 m², with the density data; the number of passengers in a train is 864. The area available for waiting in line at the platform is about 1466 m², and the number of passengers at the platform is 721. The area for waiting in line at the hell is about 1508 m², and the number of people at the lobby level is 378. Therefore, the total number of passengers at the station during peak hours is about 1940.

By investigating the composition of the passengers in the subway station, youth: middle-age: elderly = 3.11 : 4.87 : 2.02, where the ratio of male to female is 1.04 : 0.96. The distribution of passengers is random, and the related parameters are set in Table 3.

4.7. Simulation of Passengers' Evacuation in Subway Station. Pathfinder simulation software is used to simulate the passengers' evacuation in the subway station, and the passengers' evacuation behavior after the fire is simulated by setting the parameters of evacuees and buildings. Pathfinder software can implement 2 types of simulation for passengers' movement patterns, namely, SFPE mode and Steering mode. In this paper, we use the Steering mode, which is closer to reality, and the analysis process is shown in Figure 3.

With the end condition of evacuating all the passengers in the subway station, the evacuation simulation can obtain the distribution and density of passengers with time, as in Figure 4; the passenger congestion mainly occurs at the stairway entrance, which lasts from 4 s to the end of 260 s. The passenger moves to the station hall level through the stairs or escalators connected to the platform level, the width of the stairs is 2.5 m, and the width of the escalators is 1.0 m. There are 2 staircases and 2 escalators, the length of each staircase is 8 m, and the length of each escalator is 10 m.

The passenger usage of lobby level in Figure 5 shows that the gates near the stairs and escalators hinder evacuation and reduce evacuation efficiency. Due to the location of the gates, the evacuation paths through the two subway entrances on the lower side of the figure are short, and a concentration of people occurs here during the evacuation of passengers. In particular, the effect of passenger concentration is more obvious in the lower right side of the figure. At 47.2 s, the flow rate of passengers at the lower right side of the subway entrance reaches a peak of 1.05 persons/s. At 174.2 s, the trend of passengers flowing through the subway entrances is stable. It can be seen from Figure 5 that the effect of subway evacuation can be optimized if the location of the gates is changed or the flow of people is guided by some facilities like fences.

The simulation shows that the total time taken to evacuate all members to the ground is 449 s. The relationship

between the number of evacuees and the time is shown in Figure 6.

4.8. Fuzzy Comprehensive Evaluation Process with Simulation. Due to the complexity of subway fire, experts' evaluation of risk should be based on more subway information, which includes basic subway information, such as structure and facilities; see Section 4.2; it also includes some research and analysis results, such as the distribution of subway passengers; see Sections 4.5 and 4.6.

The fuzzy comprehensive evaluation of the second level factors is carried out first, and then the subordination matrix of the first level factors is constructed according to the evaluation results.

Before conducting the subway fire risk assessment, the passenger distribution statistics of the subway station under study were conducted, see Section 4.5, and the simulation of the passenger density at different time periods was carried out in Pathfinder software, as shown in Figures 4 and 5. Based on the results of this study, experts can more accurately evaluate the number and distribution of passengers (u_{15}) factor.

On this basis, 12 experts evaluated the other 4 indicators of personnel factor U_1 , including passenger safety awareness (u_{11}), fire awareness of subway staff (u_{12}), number of subway staff and their firefighting skills (u_{13}), and emergency rescue capability of the subway staff (u_{14}).

The affiliation matrix of personnel factor U_1 is obtained as follows:

$$R_1 = \begin{bmatrix} 0.167 & 0.250 & 0.500 & 0.083 & 0.000 \\ 0.417 & 0.083 & 0.500 & 0.000 & 0.000 \\ 0.083 & 0.250 & 0.583 & 0.083 & 0.000 \\ 0.167 & 0.167 & 0.500 & 0.167 & 0.000 \\ 0.083 & 0.333 & 0.417 & 0.167 & 0.000 \end{bmatrix}. \quad (17)$$

The affiliation degree of personnel factor U_1 to the total evaluation result was obtained by fuzzy comprehensive evaluation as follows.

$$B_1 = W_1 \cdot R_1 = (0.211, 0.266, 0.171, 0.169, 0.183) \begin{bmatrix} 0.167 & 0.250 & 0.500 & 0.083 & 0.000 \\ 0.417 & 0.083 & 0.500 & 0.000 & 0.000 \\ 0.083 & 0.250 & 0.583 & 0.083 & 0.000 \\ 0.167 & 0.167 & 0.500 & 0.167 & 0.000 \\ 0.083 & 0.333 & 0.417 & 0.167 & 0.000 \end{bmatrix}, \quad (18)$$

$$= (0.204, 0.207, 0.499, 0.091, 0.000).$$

The evaluation of the design of smoke drainage system (u_{52}) can be easily carried out according to the layout of the ventilation structure of the subway; firstly, the effect of

smoke drainage system is three-dimensional [37], as shown in Figure 7; based on this study experts can evaluate the design of smoke drainage system (u_{52}) more accurately.

On this basis, 11 experts evaluated the other 3 indicators of design factor U_5 ; the constructed design factor affiliation matrix is as follows.

$$R_5 = \begin{bmatrix} 0.182 & 0.273 & 0.364 & 0.091 & 0.091 \\ 0.091 & 0.182 & 0.455 & 0.182 & 0.091 \\ 0.091 & 0.273 & 0.364 & 0.182 & 0.091 \\ 0.182 & 0.273 & 0.364 & 0.091 & 0.091 \end{bmatrix}. \quad (19)$$

$$\begin{aligned} B_1 &= W_1 \cdot R_1 = (0.401, 0.232, 0.087, 0.280) \\ &= (0.153, 0.252, 0.385, 0.120, 0.091). \end{aligned}$$

Similarly, a fuzzy comprehensive evaluation of all five second-grade indexes was performed. The fuzzy relation matrix of the first-grade evaluation index is then obtained and is expressed as

$$R = \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} = \begin{bmatrix} 0.204 & 0.207 & 0.499 & 0.091 & 0.000 \\ 0.493 & 0.394 & 0.100 & 0.000 & 0.000 \\ 0.100 & 0.210 & 0.414 & 0.209 & 0.101 \\ 0.304 & 0.420 & 0.201 & 0.103 & 0.000 \\ 0.153 & 0.252 & 0.385 & 0.120 & 0.091 \end{bmatrix}. \quad (21)$$

$$\begin{aligned} B &= W \cdot R = (0.067, 0.139, 0.293, 0.464, 0.035) \\ &= (0.258, 0.334, 0.276, 0.119, 0.033). \end{aligned}$$

The results of the analysis in this paper used the maximum membership degree principle. That is, according to the maximum value of the evaluation result vector B , we find the corresponding evaluation level in the subway fire risk assessment set Y . From the final evaluation results given by the result, it can be seen that the maximum membership degree corresponding to the fire risk level is “Safer.”

This result indicates that the overall fire safety of the subway lines under study is “Safer,” but there are still three first-grade indexes in the “Moderately safe” category, which indicates that there is a need for improvement in personnel, environment, and design. The evaluation results of three indexes are still “Moderately safe”, which means that

The affiliation degree of design factor U_5 to the total evaluation result was obtained by fuzzy comprehensive evaluation as follows.

$$\begin{bmatrix} 0.182 & 0.273 & 0.364 & 0.091 & 0.091 \\ 0.091 & 0.182 & 0.455 & 0.182 & 0.091 \\ 0.091 & 0.273 & 0.364 & 0.182 & 0.091 \\ 0.182 & 0.273 & 0.364 & 0.091 & 0.091 \end{bmatrix}, \quad (20)$$

The final fuzzy comprehensive evaluation results were obtained as follows:

$$\begin{bmatrix} 0.204 & 0.207 & 0.499 & 0.091 & 0.000 \\ 0.493 & 0.394 & 0.100 & 0.000 & 0.000 \\ 0.100 & 0.210 & 0.414 & 0.209 & 0.101 \\ 0.304 & 0.420 & 0.201 & 0.103 & 0.000 \\ 0.153 & 0.252 & 0.385 & 0.120 & 0.091 \end{bmatrix}, \quad (22)$$

improvement is needed in personnel, environment, and design. According to the weight value of each criterion, the improvement should be made in the order of priority environment, personnel, and design.

5. Discussion

In this work, a subway fire risk assessment model based on analysis theory is constructed, by combining the use of interval hierarchical analysis and fuzzy comprehensive evaluation method. The use of interval numbers in fuzzy mathematics to express the uncertainty of expert evaluation of subway fires overcomes the uncertainty bias of the traditional analytic hierarchy process (AHP), which uses the

TABLE 3: Evacuation parameters of passengers in subway.

	Gender	Age	Shoulder width (mm)	Walking speed (m/s)
Youth	Male	<40	330~417	1.225
	Female		302~387	1.183
Middle age	Male	40~65	328~415	1.164
	Female		305~390	1.115
Elderly	Male	>65	320~415	0.915
	Female		302~387	0.955

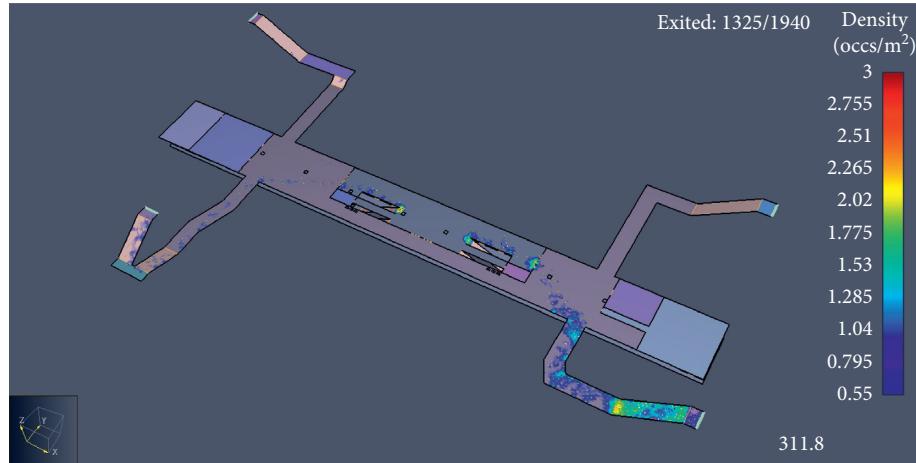


FIGURE 3: Simulation of passengers' evacuation in subway stations.

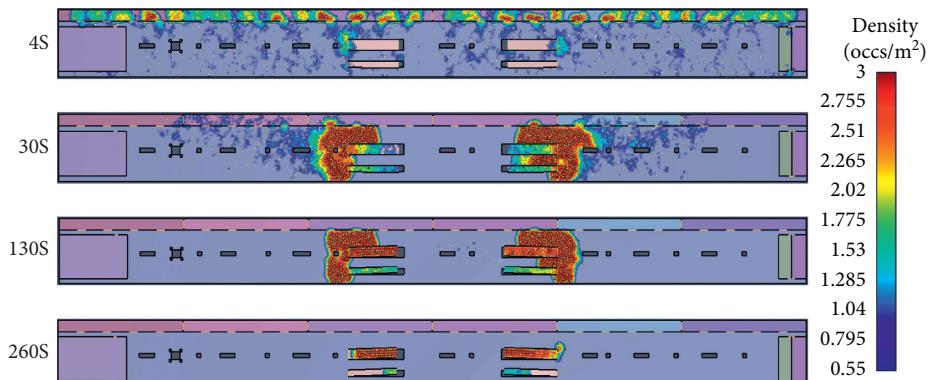


FIGURE 4: Passenger density at platform level during evacuation.

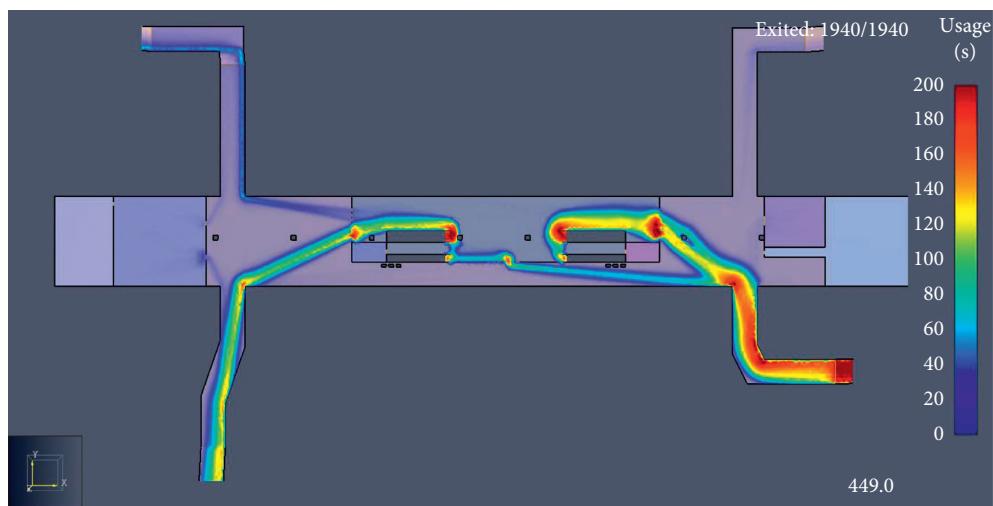


FIGURE 5: Passenger usage of lobby level during evacuation.

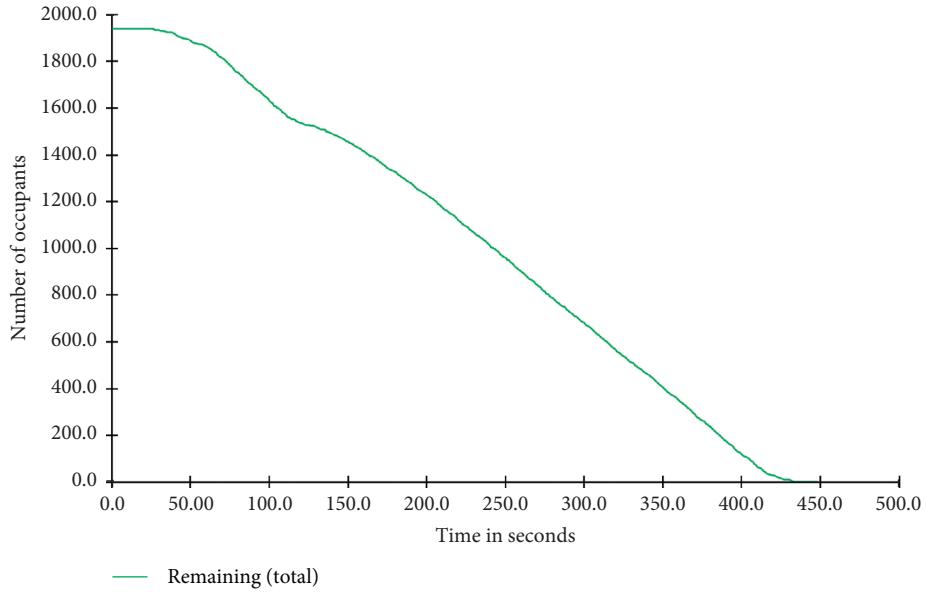


FIGURE 6: The number of passengers in the subway station during the evacuation process.

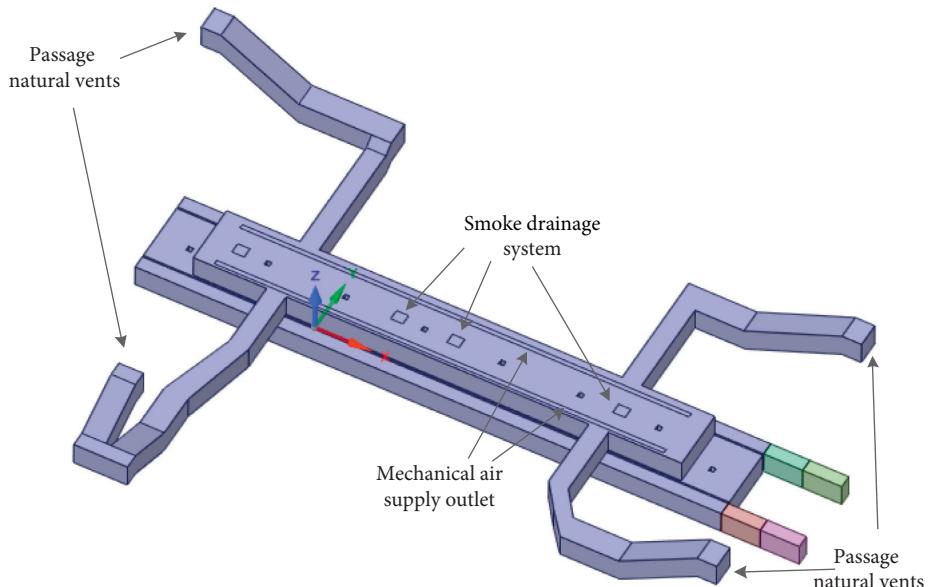


FIGURE 7: Subway station smoke drainage system.

exact number to describe the importance degree between indicators, and makes the evaluation results more objective and reasonable. On the other hand, the interval number instead of the exact number reflects the perception of things and is also more in line with people's objective understanding of risk.

The introduced fuzzy comprehensive evaluation method is based on the affiliation theory to transform qualitative evaluation into the quantitative evaluation and uses fuzzy numbers to make an evaluation of the subway fire risk which is subject to many factors, which has the characteristics of

clear results and strong system and can better solve such fuzzy and difficult to quantify problems of subway fire.

In addition, in order to make better use of the fuzzy comprehensive evaluation method and to improve the objectivity and comprehensiveness of the evaluation, we used statistical analysis and numerical simulation to analyze the subway situation, in particular, the distribution of passenger and the emergency evacuation time for the subway fires that affect more. Through the statistics of passengers in the evening peak, we obtained the result that the number of people will reach 1940; through the numerical

simulation of the evacuation process of people in that time, we can obtain the conclusion that 1940 people need 449 s to complete the evacuation. These data are of high reference value for fuzzy comprehensive evaluation.

The analysis process of line Y subway in X city as an example shows that, for such nondeterministic problems, the fuzzy mathematics can better identify the hierarchical and recursive relationships among indicators and, to a certain extent, reduce the impact caused by human subjective errors in the analysis.

The resulting subway fire risk assessment model has some shortcomings. The indicators affecting the fire risk of the urban subway are very complicated, and the research in this paper needs to be further developed to decompose the evaluation indicators, take into account more aspects of the impact, and build a more complete fire risk indicator system. On the other hand, the technical analysis process of the method is more complicated after the number of indicators increases and the levels increase, and the assessment process needs to be further optimized.

6. Conclusions

Given the potential for subway fires, a subway fire risk evaluation index system is proposed and analyzed, and a subway fire risk evaluation model combined with the IAHP and fuzzy comprehensive evaluation method is established. In order to improve the objectivity and accuracy of the evaluation, Pathfinder was used to simulate the distribution of people in metro stations. The following points are emphasized.

First, by using the IAHP, the weight vectors of the interval form are transformed into the weight vectors with exact values, and the weight of the subway fire risk evaluation index is obtained. Then, the fuzzy comprehensive evaluation method is used to establish the urban subway fire risk evaluation model. The methodology developed in this paper can be used to evaluate the fire risk of all types of subways. In order to validate the method when taking the Y-line subway in city X as an example, the risk evaluation index system and its weight values are calculated, and the evaluation results were analyzed. Through this case study, according to the principle of maximum membership degree, the fire risk level of the Y-line subway is “Safer”.

The simulation analysis shows that the evacuation risk level increases with the increase of the passengers’ density and subway bearing in the subway station; determining the evacuation risk level by the passengers’ density on the subway platform is conducive to taking corresponding control measures under different risk levels to control the passengers’ density in the station and reduce the evacuation risk.

There are still some deficiencies in the resulting subway fire risk assessment model. First, the urban subway fire risk evaluation index system needs further improvement by decomposing the evaluation indicators. Second, the establishment of an urban subway risk assessment model needs to be simplified. Therefore, reducing the complexity of the weighting method and making the evaluation process and results clearer to understand need further study.

Data Availability

The data are available and explained in this article; readers can access the data supporting the conclusions of this study.

Conflicts of Interest

The authors declare no conflicts of interest.

Authors’ Contributions

All authors approved the final version of the manuscript.

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