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Article

Research on fire hazard assessment of metro baggage based on improved hierarchical analysis

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Abstract: Underground station passenger flow is large, the number of parcels carried by passengers is large and varied, and the parcels carried have an impact on the fire hazard and evacuation of the station. In order to determine the weights of the passenger luggage risk and environmental factor index system in the fire risk evaluation of underground stations in a more realistic way, an optimized and improved hierarchical analysis method for determining the judgement matrix is proposed, which improves the traditional nine-scaled method and adopts the three-scaled method for the four major categories of luggage, namely, handbags, rucksacks, portable power tools and trolley cases. The advantage of this method is that there is no need for consistency judgement in determining packages with a wide range of types and uncertain contents, thus simplifying the calculation. Meanwhile, the reasonableness and reliability of the method is verified by combining it with an actual metro station fire risk assessment system.

Keywords: subway fires; improved hierarchical analysis; fire assessment

1. Introduction

Available statistics show that fire accidents are one of the serious safety threats facing metros (Liu et al., 2022). The structure of metro stations is complex, and the stations are generally located underground, with a large number of equipment operating around the clock. According to statistics, the depth of most metro stations is more than 30 meters, and some stations are even 70 meters deep, which is a relatively closed underground system. Load-bearing structures are prone to deformation at high temperatures, leading to building falls, collapses and injuries to station occupants. In addition, the number of emergency evacuation routes and rescue evacuation routes in metro stations is relatively small, and external rescue personnel and internal evacuation of passengers travelling in opposite directions are prone to conflict in the metro up and down passages, escalators and other bottlenecks, which reduces the efficiency of the passage of rescue personnel and the evacuation of passengers to be evacuated. Moreover, even if there is a smoke exhaust system in such a space, the smoke will still gather in large quantities, and the toxicity and heat radiation of the toxic smoke produced by combustible combustion will make it difficult for rescuers to approach the part of the fire, thus prolonging the time to extinguish the open fire, and further increasing the difficulty of rescue (Ju et al., 2022).

In addition, metro stations are densely populated, the number of passengers increases dramatically during peak commuting periods, and passengers carry a lot of luggage on holidays, especially large flammable luggage and electronic products. This makes metro stations a high potential fire risk. There have been many serious fire incidents in the history of the metro and the current series of recorded fire incidents in the metro system clearly shows that the fire risk of passengers carrying luggage in metro stations and the impact of luggage on evacuation in the event of a fire is a major concern for station managers.

To ensure the efficiency of passenger travel and to effectively avoid the disclosure of personal information, very few countries worldwide have introduced security checks at metro stations. However, in order to reduce the potential fire risk posed by passengers' luggage to the metro system, security checks have been introduced in mainland China to check whether passengers are carrying flammable or explosive items, and the fire that occurred on 19 July 2013 at Huangbei Ling metro platform in Shenzhen, China, is strong evidence that passengers' luggage could have been the source of a metro fire (He and Elhami Khorasani, 2022). The fire was caused by the spontaneous combustion of two boxes of lithium batteries carried by a passenger, which burst into flames and smoke, causing panic among passengers.

Clothing, paper products and items containing lithium batteries (mobile phones and mobile power supplies) that passengers carry into metro stations are flammable and these items can pose a risk to station passengers if they burn. This paper defines passengers' luggage (e.g., backpacks, hand bags, portable electric vehicles, trolley cases, etc.) as mobile fire loads. The potential fire risk posed by passengers carrying mobile fire loads in metro stations therefore needs to be taken into account and studied by the relevant authorities as well as by researchers.

Liu et al. (2023) and Wang et al. (2021) carried out numerical simulations of fires in metro stations. By analyzing the smoke temperature and velocity fields, the fire smoke flow in metro stations was investigated and the effect of fire smoke flow in metro stations on the assessment of metro stations was investigated. Nyimbili and Erden (2020) carried out numerical simulations of the environment in a metro station at the time of a fire in the station equipment. Yan and Wang (2021) carried out numerical simulations of two metro stations for the effect of weights of different ventilation conditions and compared and analyzed the evacuation of people and the distribution of safety assessments in the stations. Kumar et al. (2022) carried out numerical simulations of fires in metro stations for the case of metro platforms fitted with shielded doors and investigated the safety of the shielded doors. Lin et al. (2020) performed numerical simulations for the effect of ventilation on the assessment of fires in metro stations for the two Slusarczyk. Hysa (2021) and Rezaeifam et al. (2023) carried out numerical simulations of three major underground station fires in Los Angeles under two ignition power conditions, comparing the smoke removal effects of different ventilation modes.

There are many methods for underground fire risk assessment research, Hysa (2021) research combines the hierarchical analysis method and expert survey method to form a new multilevel topological assessment method to assess the weaknesses and management priorities of underground fire risk. Tong and Gernay (2021) established the structure of fire risk assessment system for urban underground transport based on the time sequence step-by-step assessment method, and established a multilevel assessment index weighting model, and put forward the evaluation criteria for judging the fire risk. Smith et al. (2020) established a genetic neural network model as an underground fire risk assessment model through experiments, and trained and optimized the model through actual sample data, which can be used for fire risk assessment. Di et al. (2021) assessed the fire risk of underground underground station system by combining field observation with a Bayesian network model through a combination of statistics and calculations in the field, where the endpoints are considered to be the discarded cigarette butts, high temperature, spontaneous combustion of materials, underground system fire, personnel injury and other factors and their interrelationships, and the results of the study show that the probability of personnel injury fluctuates with the probability of discarding cigarette butts, so the behavior of discarding cigarette butts should be paid attention to. Rahardjo and Prihanton (2020) combined with the use of the group topology of fuzzy theory in the Beijing metro station, and calculated a fire risk assessment model based on the statistical data of the Beijing metro station, and based on the actual working day of the metro fuzzy mathematics and topology theory of the station baggage fire. and topology theory to comprehensively assess the station luggage fire risk. Yuliatti et al. (2021) combined the actual statistics of Tokyo Metro to assess the fire risk of experimental metro stations on the basis of a fuzzy hierarchical integrated assessment model, which subdivided the influence of a variety of factors on the fire hazards of underground metro stations in the course of the study, and the affiliation function in the final conclusion portrayed the relationship of the importance between the influencing factors and the objects to which they belonged, with the advantage that the calculation steps are fixed and are easy to be realized in a programmable manner.

Currently, there are very few researchers on the risk assessment of mobile fire loads, and some researchers define them as parcels, baggage, temporary combustibles and portable fire loads, etc. Ye defined baggage as temporary combustibles. Ye defined the baggage carried by passengers as temporary combustibles, and conducted a field investigation in Chengdu metro station to obtain the number of temporary combustibles in the metro station and their distribution pattern on the platform. At the same time, the simulation of the underground fire caused by baggage was carried out, and the relationship between baggage and the fire risk at the underground platforms was obtained. KummMl defined the types of backpacks and baggage of the passengers in the underground stations based on the statistics of the field observation results, and defined them as the portable fire loads, and a series of combustion tests were carried out on the different types of portable fire loads, and the burning behavior patterns were obtained. Erdin and Çağlar (2021) conducted a field survey in Qingdao metro station, statistically derived the type, quantity and contents of passengers' baggage, and analyzed and calculated the intensive time period and distribution area of passengers' baggage fire loads.

The main shortcomings of the current research on hierarchical analysis of fire safety assessment in metro stations:

Most of these studies classify the response body into four aspects: personnel, equipment and facilities, environment and management according to the 4M theory. The main research areas are focused on personnel and equipment and facilities, and there are fewer studies on the assessment and evaluation of the fire safety of baggage in metro stations. 2. The existing relevant studies only classify the baggage in the car as a fire load in general, and there is no research on classifying the baggage in the metro station with different weights. 3. The relevant studies have a large amount of calculations and are subject to the subjective influence of the experts, and the precision of determining weights is lower. rate is low.

Therefore, in the process of constructing the hierarchical analysis index system, full consideration should be given to the fact that the underground environment is constantly changing. In particular, the underground does not pass time with the change of the number of passengers with the change of luggage. In particular, different baggage size, type, material, content and so on all have different assessment impact on the metro station. Therefore, a simple and accurate fire hazard weighting study of the main baggage in the metro is an important guide for on-site safety management in metro stations.

2. Application of improved hierarchy method for mobile fire load hazard assessment in metro stations

After years of development, the hierarchical analysis method has been derived from the improved hierarchical analysis method, fuzzy hierarchical analysis method, expandable fuzzy hierarchical analysis method and grey hierarchical analysis method, etc., and according to the actual situation of the research, each has its own scope of application.

Hierarchical analysis is a tool that helps to determine the relationship between indicators at different levels, and to obtain the weights of each level and each indicator in the indicator system by means of expert judgement of the importance of the indicators at the same level to each other. Therefore, the key of AHP method is to determine the hierarchical relationship.

Improved hierarchical analysis is based on the judgment matrix is not easy to determine the situation, by improving the judgment scale to help decision makers more easily to construct a good quality judgment matrix. The improved hierarchical analysis method is used in this paper to determine the fire risk of passenger baggage and the weights of each evaluation index in the metro station fire risk evaluation index system.

The key step in assessing fire hazards in the underground using hierarchical analysis is to construct a judgment matrix A. The elements of matrix A, a_{ij} represent the relative importance of the row elements A_i to the column elements A_j of the matrix (Nuthammachot and Stratoulias, 2019). Usually, a_{ij} can be taken as 1, 2, 3, ..., 9 and its inverse, the larger the value, the stronger the relative importance, this method is called the nine-scale judgment method. Although the nine-scale method is carefully divided, the differences between them are not easy to grasp, especially in the classification and evaluation of underground luggage, due to the diversity of luggage and the complexity of the types of items in luggage, it is very easy to produce some relying on the objective impression of experts to set the weight value, lacking the support of scientific data, resulting in the inaccuracy of subsequent research work.

In this paper, after verifying the usefulness of such switching state statements for assessing the simplicity, efficiency and accuracy of the construction matrix of fire hazards of passenger-carried baggage in metro stations, a three-scale judgement method is proposed, i.e., three numbers, 2, 0 and 1, are used to describe the problems of "big hazards", "small hazards", and "many hazards". In this paper, before the expert scoring, first show the experts the experimental underground station statistics of passenger flow data information, the number of types of baggage statistical information with matching X-ray security check statistics, the experts of the research based on the collated data analysis, to weight scoring, to avoid the bias of subjective will. The experts in this paper come from 30 industry experts, of which 10 are management experts of metro companies with rich experience in metro site management, 10 are professors of related disciplines in universities, and the last 10 are experts in the field of hierarchical analysis algorithms.

Comparative projections using the traditional luggage fire hazard index system. The following table shows the comparison matrix constructed by the nine scale methods: the value $a_{ij} =$ in the matrix is obtained from data or expert opinions. The comparison matrix after the three-scale transformation is shown in **Table 1** below:

Table 1. Three scale construction comparison matrix.

	Handbag	**Backpack**	**Portable electric vehicle**	**Luggage**
Handbag	1	2	2	2
Backpack	0	1	2	2
Portable electric vehicle	0	0	1	0
Luggage	0	0	2	1

The transformed comparison matrix (which we define as B) requires the following transformations to construct the true judgment matrix A.

$$\begin{gathered} a_{ij} = \frac{r_i - r_j}{r_{max} - r_{min}} \times (b_m - 1) + 1, \qquad r_i \geq r_j \\ a_{ij} = 1, \qquad r_{max} = r_{min} \\ a_{ij} = \left[\frac{\left|r_i - r_j\right|}{r_{max} - r_{min}} \times (b_m - 1) + 1\right]^{-1}, \qquad r_i < r_j \end{gathered} \tag{1}$$

In equation $r_i = \sum a_{ij}\, r_{max} = max(r_i), r_{min} = min(r_i) \quad b_m = \frac{r_{max}}{r_{min}}$.

For **Table 2** $r_1 = 7, r_2 = 5, r_3 = 1, r_4 = 3, r_{max} = 7, r_{min} = 1, b_m = 7$ can be obtained after conversion according to Equation (1), such as $a_{12} = \left(\frac{7-5}{7-1}\right) \times (7-1) + 1 = 3$.

Table 2. Optimal transfer matrix C.

	Handbag	**Backpack**	**Portable electric vehicle**	**Luggage**
Handbag	0	0·331	1.011	0.680
Backpack	−0.331	0	0.680	0.349
Portable electric vehicle	−1.011	−0.680	0	−0.331
Luggage	0	0.331	1.011	0.680

Comparing the judgement matrix after conversion and the matrix of the expert's decision, there is almost no difference between the two, which shows the feasibility and ease of operation of the method (Wang, 2019).

After determining the judgement matrix, it is necessary to determine the weight of each factor. Conventional methods are power method, square root method and product method, regardless of which method must be consistency test, this paper does not carry out in-depth research. In this paper, we will use a method to calculate the weights directly through the optimal transfer matrix C and the consistency-adjusted judgement matrix A*. This method not only does not require consistency test but also is not complicated.

First, calculate the optimal transfer matrix *C* according to Equation (2)

$$c_{ij} = \frac{1}{n}\sum_{k=1}^{n}\left(log\frac{a_{ik}}{a_{jk}}\right), \forall i, jk = 1,2,\ldots,n \tag{2}$$

For example, **Table 3** can be calculated as:

$$c_{11} = \frac{1}{4}\left[lg\frac{1}{1} + lg\frac{3}{3} + lg\frac{7}{7} + lg\frac{5}{5}\right] = 0$$

$$c_{12} = \frac{1}{4}\left[lg\frac{1}{1/3} + lg\frac{3}{1} + lg\frac{7}{5} + lg\frac{5}{3}\right] = 0.331$$

...

$$c_{21} = \frac{1}{4}\left[lg\frac{1/3}{1} + lg\frac{1}{3} + lg\frac{5}{7} + lg\frac{3}{5}\right] = -c_{21} = -0.331$$

Then, according to Equation (3), the judgment matrix after consistency adjustment is calculated A*

$$a_{ij}^{*} = 10^{c_{ij}} \tag{3}$$

Table 3. Final judgment matrix A.

	Handbag	Backpack	Portable electric vehicle	Luggage
Handbag	1	2.143	10.257	4.786
Backpack	0.467	1	4.786	2.234
Portable electric vehicle	0.097	0.209	1	0.467
Luggage	0.209	0.448	2.143	1

Finally, calculate **Table 4** according to Equation (4) to obtain the weight vector *wj* of each index.

$$W_j = 1\backslash\sum a_{ij}^{*} \tag{4}$$

$$W_{handbag} = \frac{1}{1 + 0.467 + 0.097 + 0.209} = 0.564$$

$$W_{backpack} = \frac{1}{2.143 + 1 + 0.209 + 0.448} = 0.263$$

$$W_{portable\ electric\ vehicle} = \frac{1}{10.257 + 4.786 + 1 + 2.143} = 0.055$$

$$W_{handbag} = \frac{1}{4.786 + 2.234 + 0.467 + 1} = 0.118$$

The result is compared with the conventional algorithm as follows:

Table 4. Comparison of weight calculation results between improved analytic hierarchy process and conventional algorithm.

	Handbag	Backpack	Portable electric vehicle	Luggage
Improved Method	0.564	0.263	0.055	0.118
Conventional Method	0.558	0.263	0.057	0.122

It can be seen that the improved hierarchical analysis method is not only easy to operate, but also can fully meet the requirements in the calculation results.

3. Engineering verification

The engineering and construction as well as the actual conditions of the experimentally verified metro stations are as follows: The length of the main body of the station is 276.2 meters, the width is 43.4 meters, the width of the platform is 14 meters, and the effective platform length is 120 meters. The underground main building area is 24,872.96 square meters, as of July 2023, the station has a total of 7 entrances and exits, the design flow of the interchange hall is 29,100 people/h, according to statistics, the average daily flow of the station is about 17,000 people, the average daily scanning and collecting passenger parcel information is 10,000 sheets. The amount of parcels in the peak period can be up to 40,000 pieces. In summary, the underground station has the possibility and sensitivity of baggage fire hazards and the impact of passenger evacuation, so it carries out the fire hazard assessment of passenger baggage management (Liu et al., 2023).

According to the research method and theory of this paper, the weight of fire load in the fire risk indicator system of this metro station is calculated and summarized in the following **Table 5**:

Table 5. Summary of the calculation of fire load weights for the fire risk indicator system for metro stations.

Domain of discourse	Evaluation system (Level 1)	Weight	Evaluation system (Level 2)	Weight	Evaluation system (Level 3)	Weight
Fire risk assessment of luggage in subway station	Subway passengers carry their belongings	0.58	Handbag	0.564	Attache case	0.44
					Hand luggage bag	0.44
					Portable plastic bag	0.12
			Backpack	0.263	Backpack	0.28
					Laptop bag	0.39
					One shoulder haversack	0.11
					Mountaineering bag	0.11
			Portable electric vehicle	0.055	Electric wheelchair	0.4
					Folding electric bicycle	0.48
					Electric balance car	0.12
			Luggage	0.118	Soft and hard surface Case	0.36
					Trolley bag	0.34
					Folding shopping cart	0.23
					Baby carriage	0.07

According to the theory of third-order arithmetic proposed in this paper, the results that will be obtained match well with the feedback from the actual on-site operators at the station as well as the results obtained in comparison with the actual management of the site. In order to further serve the operation and management of the metro station using the methodology of this thesis, the seven aspects of fire hazards in the metro station were calculated and constructed as follows **Table 6**—Metro Station Fire Hazard Construction Matrix. The results of the study show that the operational management of the station is excellent in controlling the fire hazards, and the possibility of fire is low, which is in line with the safety management requirements of the metro station. The matrix has practical guidance for the management of fire hazards in underground stations.

Table 6. Fire hazard construction matrix for metro stations.

	Equipment factors	Management factors	Material factors	Personnel factors	Safe driving	Environmental factor	Informational factors
Equipment factors	1	1	0.5832	2.322	0.2033	4.7422	4.9509
Management factors	1	1	4.553	1	0.206	4.9864	4.6363
Material factors	2.0196	0.2196	1	1	0.3324	2.9522	4.7691
Personnel factors	0.4307	1	1	1	0.2123	4.7825	4.8616
Safe driving	4.9195	4.8534	3.0082	4.7113	1	5.151	6.9619
Environmental factor	0.2109	0.2005	0.3387	0.2091	0.1941	1	2.6089
Informational factors	0.202	0.2157	0.2097	0.2057	0.1436	0.3833	1

4. Summary

At present, the main difficulty in the practical application of the hierarchical analysis method for fire risk assessment of metro stations lies in how to reasonably determine the index system and the weight of each evaluation index, especially the fire load of the station under environmental factors.

For this reason, this paper adopts the three-scale method, which is easy to operate, to determine the judgement matrix of the weights of the four indicators of each evaluation station for the four major categories of mobile loads, namely, handbag, backpack, trolley case and portable electric vehicle. The results of the study show that, firstly, the improved hierarchical analysis method is more objective and stable, and the method is easy to operate, reliable, and versatile, and has application value in many comprehensive evaluations of system engineering. Secondly, the accurate determination of the weights of luggage fire hazards in metro stations can play a guiding role in the safety management of metro station sites. Finally, the determination of the weights of major luggage fire hazards in metro stations will improve the assessment volume of fire protection and evacuation in metro stations.

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