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Method of Grading Subway Stations Based on Evacuation Capability: A Quantitative Method

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Abstract

Stations are the main components of the subway systems. Despite the progress in the construction and maintenance, stations have always been exposed to the natural and man-made disasters. In such incidents, the station's evacuation capability has a direct relation with a passenger's life. Various factors affect the station's evacuation capability. Investigation of these factors and evaluation of the station's evacuation capability have important roles in protecting a passenger's life. For this purpose, the catastrophic events that lead to the evacuation of a station and the factors affecting the evacuation of the station are identified. Due to the difference in the catastrophic event probabilities at each station, the risk of catastrophic events is evaluated. Then the station score is calculated according to the value and weight of the evacuation factors and the wighted influence of the catastrophic events. Accordingly, the proposed model is implemented in the Tehran subway. Based on the results obtained, uncrowded stations, even though served by a small number of passengers, may also have a low evacuation capacity and lead to casualties in an emergency situation. This is due to the lack of emergency management and safety facilities. Also by assessing the risk of catastrophic events at stations and equipping stations on its basis, the degree of safety and evacuation capability can be improved more effectively. The sensitivity analysis of the evacuation factors show that the most effective way to increase the station's evacuation capability is to improve its status in management factors. Using the proposed model to evaluate the station's evacuation capability is an appropriate method for identifying the stations that have a poor evacuation capability.

1. Introduction

Subway systems are regarded as one of the main components of the today's modern societies and have become the first transportation option in many countries around the world. Subway systems are rapidly growing around the world due to high-capacity carriers, eco-friendly, low energy consumption, low transportation cost, quick travel time, accurate prediction of travel time, and high security.

Subway systems include five main components including tunnels and lines, stations and facilities, telecommunications and monitoring, trains, and energy supply facilities, among which station is considered as one of the main components of this system [1]. Despite the progress in the construction and maintenance, stations have been always exposed to natural and man-made disasters. Natural disasters such as floods, earthquakes and fires, and human factors like chemical and biological terrorist attacks are regarded as the risks that have always compromised the security of stations. Due to the high population density and other specific conditions, incidents at the subway stations may lead to fatalities and injuries [2]. In such incidents, the station evacuation capability has a direct relation with the passenger's life. The station evacuation capability is the ability that when an emergency situation is met, the passengers and subway station staff can be evacuated timely and effectively to safety areas [3]. The evacuation

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capability is one of the most important factors to be considered when a station is designed. Various factors affect the station's evacuation capability. Investigation of these factors and evaluation of the station's evacuation capability have important roles in protecting a passenger's life. In this regard, a large number of studies have been conducted during the recent decades.

Jiang et al. have modeled the emergency evacuation in a typical subway station in Beijing. The purpose of their study was to assess the station's evacuation capability under different conditions and to compare the results obtained with the code for the design of subway stations in China. Modeling was done by building the EXODUS software for 23 different evacuation scenarios. Their results showed that when the station was very crowded, the response time had little effect on the total evacuation time, and blocking that occurring often in the staircases and escalators was the main problem in evacuation of the station [4]. In another study, Jiang et al. have investigated the effect of the average minimum width of staircase used by the persons and maximum upstairs speed as two key parameters in evacuation through the staircase in subway stations. The evacuation process was modeled using the EXODUS software in two subway stations in China. They concluded that changing both of these parameters simultaneously could reduce the evacuation time by up to 50%. The changes in the evacuation time were different depending on the people density (people/m^2) in the station [5]. In addition, Jeon et al., by conducting experiments, have analyzed the station's evacuation performance in a situation where smoke has affected visibility. They conducted experiments in four different visibility conditions at underground facilities. The results obtained indicated that a change in visibility caused a change in the travel distance as well as the movement speed [6]. Congling et al. have investigated the evacuation capacity of a subway station using the computational models. They assessed the passengers' evacuation strategy at subway stations during fire and suggested a method for calculating the evacuation time in the subway stations. They finally provided guidelines and instructions for evacuating the passengers during a fire [7]. In addition, Su-li et al. have estimated the capacity of a subway station evacuation in emergency situations using the fuzzy network and prediction index by considering the quantitative and qualitative factors in their model [8]. In another study, Yoon et al. have carried out an evacuation experiment and used a questionnaire with 292 participants to analyze the evacuation time of the subway station during a fire. The results obtained showed that females were slower than males and those who had companience were slower than solo persons. The results obtained also indicated that those who had knowledge about evacuation operation and often thought about it were faster than the others [9]. Wan et al. have provided a method for the evacuation simulation in a subway station for bioterrorism. Their proposed method was based on the theory of social force model combined with the Gaussian Puff model that was suited to simulate a real situation of a sudden spread of a toxic gas. The results obtained showed that when a toxic gas was spread at a station, its influence on the passengers depended on the position as well as on the number of gas sources. The results also showed that more casualties would occur if the managers did not detect the toxic gas hazard and did not inform the passengers about it. Finally, the results showed that with increasing air flow rate at the station, the number of injuries was reduced [10]. Li et al. have investigated the features and characteristics of deep buried stations as well as the influence of these features on the station safety management. They also calculated the maximum optimal capacity and evacuation time in deep buried stations and compared the results with the values obtained from normal stations. The results obtained indicated that deep buried stations had a lower maximum optimum capacity and a longer evacuation time than normal stations [11]. Xie et al. have emphasized on the importance of establishing an emergency evacuation plan at the stations. They also discussed in detail about the evacuation strategies including the evacuation routes and evacuation safety zones [12]. Chilà et al. have proposed a methodology to calculate risk reduction in the transportation system under emergency conditions. They presented the main quantitative results of a long-lasting research project for which a unifying approach for the simulation and design of a transportation system under evacuation conditions was adopted. In this project, an intelligent transportation system (ITS) was implemented to monitor the real evacuation tests in a town where an emergency event had been simulated and experimented. Finally, the proposed model was calibrated and validated by means of the observed data obtained from ITS [13]. Wang et al. have designed a set of questionnaires and investigated the behaviors and panic-related psychology of evacuation crowds in subway stations during emergencies. The results obtained indicated that gender, education level, and carrying-on luggage had a strong correlation with the panic-related psychology and behaviors, while age and safety knowledge did not have a strong correlativity [3]. Wang has developed a model based on the artificial neural network for assessing the evacuation capability of subway stations. To this end, 14 indices were selected in three aspects of emergency early warning capability, emergency preparedness capacity, and emergency response capacity for assessment, and a model was applied at 18 subway stations in Beijing. The results obtained showed that the proposed model was effective in assessing the example subway emergency evacuation capability. The results also showed that the emergency evacuation capability of the subway line examined was general and close to good [14]. In another study, Wu et al. have estimated the capacity of a subway station evacuation in emergencies. They built a bi-level model in which the upper level maximized the utilization of the facility and the lower level minimized the evacuation time by determining how to guide passengers to arrive at safety zones. In order to validate the model, by taking the capacity estimation of the Fuxingmen Station in Beijing, they simulated the evacuation operation. The results obtained showed that capacity of the Fuxingmen Station was 1071 persons per minute in an emergency situation [15]. Shiwakoti et al. have explored the beliefs and perceptions of 1134 passengers about their behavior relating to the ability to get out safely during an emergency in subway stations. The results obtained showed that those who faced an emergency situation would be likely to quickly move to the station exit, wait for the staff guidance, help others with difficulties, choose the least crowded exit, and/or use the escalators. On the other hand, those who faced an emergency situation would be likely to do nothing and/or push others, if necessary, to get out safely [16]. Mei & Xie have developed a decision-making model based on fuzzy logic and the ELECTRE method for selecting the best evacuation strategy in a subway station. They also carried out a numerical example of emergency evacuation strategy in the Wuhan Guanggu Square station in China. The results obtained showed that their proposed model was reasonable and valid [17].

Considering all the above-mentioned studies, it can be seen that a comprehensive study of all types of catastrophic events at subway stations has not been made, and the studies are about one type of catastrophic event. Also studies have been conducted on the effects of one of the evacuation factors and effects of all evacuation factors. In this work, all types of catastrophic events that led to the evacuation of the station as well as all factors affecting the evacuation of station was investigated. Thus the present study aimed to develop a quantitative model for grading subway stations based on the evacuation capability. In this regard, the factors affecting the subway station evacuation operation (evacuation factors) as well as catastrophic events that lead to the station's evacuation were identified. The evacuation factors include the management factors, station characteristics, station facilities, emergency facilities, and human factors, and the catastrophic events including fire, earthquake, flood, and chemical and biological terrorist attacks and other terrorist attacks. Then the vacuation factors were weighted according to the type of event using the eigenvector method based on the positive pairwise comparison matrix. In the next stage, possible ranges for valuing the evacuation factors were defined. Due to the difference in likelihood and consequence of catastrophic events at each station, the risk of catastrophic events was evaluated using 6 criteria including probability of occurrence, finding ability, continuous repeating, manageability, uncertainty of estimates, and people's vulnerability. Then the station score was calculated according to the value and weight of the evacuation factors and wighted influence of the catastrophic events. The proposed model was implemented in the Tehran subway stations as a case study.

2. Methodology

In the present work, the proposed grading model process includes the following steps (Figure 1):

- Identifying the factors that affect the evacuation capability of the subway stations in emergency situations (evacuation factors).
- Defining the possible ranges for valuing the evacuation factors.
- Identifying the catastrophic events that cause emergency situations and evacuation of the subway stations.
- Determining the weighted influence of each evacuation factor depending on the type of catastrophic event.
- Evaluating the risk of catastrophic events at subway stations.
- Estimating the specific score for each evacuation factor using the scenarios and defined possible ranges.

- Calculating the station evacuation capability overall score.
- Grading the subway station based on an overall score.

2.1. Evacuation factors

In order to achieve an accurate and a scientific assessment of the subway stations' evacuation capability, we categorized the influencial factors into five categories considering the management factors, station characteristics, station facilities, emergency facilities, and human factors.

2.1.1. Management factors

The management factors have five aspects: evacuation plan, evacuation drill and maneuver, command center, inspection and maintenance of the evacuation facilities, and staff training.

Evacuation plan (M1): Evacuation plans are developed to ensure limiting the loss of life and provide the most efficient evacuation time of all passengers [18]. The hazard evacuation plan must be developed for subway stations. An evacuation plan must include the potential impact areas for all known hazards, the number of people in the threatened area, facilities that may be impacted, potential evacuation routes, and evacuation assembly areas [19].

Evacuation drill and maneuver (M2): Evacuation drill and maneuver is a method of practicing how an area would be evacuated in a catastrophic event [20]. The relevant departments should organize evacuation drills and encourage people to participate in the drills to practice. One of the most important aspects of evacuation drill is familiarity of people with the self-rescue. In many situations, outside help comes too late. Thus self-rescue is really important and people should participate in relevant drills to become familiar with evacuation procedures and self-rescue [21].

Command center (M3): Incident Command Center (ICC) will prompt coordination and mobilization of equipment, supplies, staff, and control responsibility of facility for carrying out the rules of emergency management and preparedness operation [19].

Inspection and maintenance of evacuation facilities (M4): Evacuation facility should be inspected at regular intervals and, if necessary, repaired or changed. Timely inspection and maintenance of the evacuation facilities make it work well in the event of an emergency and to prevent increase in the evacuation time and risk of life loss [19].

Staff training (M5): Staff must be trained to take appropriate and immediate actions for crowd control under an emergency situation. Training should be done for both emergency response and transit system staff [22]. A proper training of staff can make them to carry out an emergency plan in an effective and timely manner, while making an optimum use of vehicles, equipment, and facilities. Training should emphasize on the location and operation of normal and emergency exit controls, communication equipment, and other safety features of the facilities [19].

2.1.2. Station characteristics

The station characteristics include the structural features of the station building, and have three aspects: depth, exit routes, and complexity of the station building.

Depth (S1): Station depth is one of the factors affecting the evacuation of subway stations. Development of urban communities and underground spaces makes urban rail transit to choose deep stations [23]. Deep stations have a more emergency evacuation time and a more intricate evacuation pathway than normal stations [11].

Exit routes (S2): At stations that do not have emergency exits, the passengers and staff should be evacuated through the exit corridors. Normally, subway stations must have at least two exit routes to permit a prompt evacuation of the passengers and staff during an emergency. If the number of people and size of the station building will not allow the safety evacuation operation, more than two exit routes are required [24], although some stations, due to the above ground conditions, may have one exit route that is not safe in case of an emergency. In addition to the number of exit routes, the distance from the initial location to the exits is a very important factor in the evacuation time and capability.

Complexity of station building (S3): Nowadays, the structure of a station has become more complex due to the type of its service functions. Complexity of a station building is one of the factors that increases the evacuation time. Evacuation from a large and complex subway station is usually slower than that for a normal station. This is due to the lack of knowledge of the detailed internal connectivity of the different parts of the station. As a result, a passenger may not be aware of all of the suitable paths for evacuation and may take his/her previous exit paths to evacuate or tend to ignore the emergency exits [25, 26].

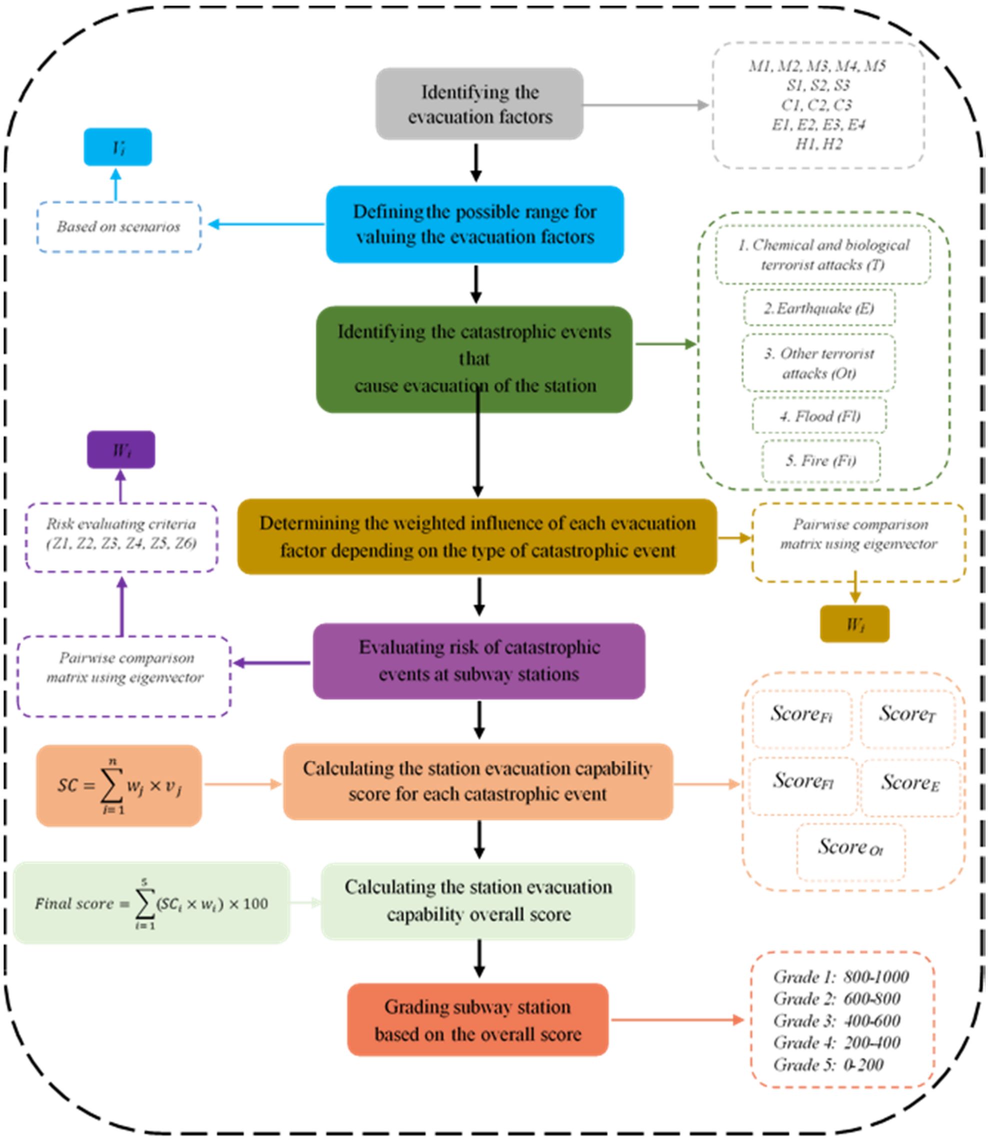

Figure 1. The main steps of the proposed model for grading subway stations.

2.1.3. Station facilities

The components related to evacuation in subway stations mainly include straight elevators, staircases and escalators, and ticket gate.

Straight elevator (C1): In an emergency, all people can not be evacuated from a station through stairs and escalators. Elderly, disabled, and frustrated people are among those who can not be evacuated from the station through staircases and escalators. Each subway station must have at least one designated barrier-free route facilitated with elevators leading into the above ground [27].

Stairs and escalators (C2): Nowadays, escalators have become a common means of vertical passengers traffic in subway stations, and often the existing stairways have been converted to escalators [28]. In an emergency situation, due to safety concerns, it has traditionally been planned that passengers should not use escalators and should use the stairs to evacuate from a station. However, the evacuation analysis has indicated that even the use of stopped escalators and stairs can simultaneously reduce the evacuation time compared to using stairs alone [29].

A research work has shown that the use of static escalators causes more fatigue because of the wider tread and higher rise steps of an escalator compared to normal stairs [30]. Stairs and escalators are the components of a station that usually become the congestion bottlenecks over peak hours and evacuation of situation [31].

Ticket gate (C3): Ticket gate is a critical point in subway stations that influences the evacuation efficiency during an emergency. In an emergency situation, ticket gates may be very crowded and become a congestion bottleneck, and thus increase the evacuation time. The evacuation efficiency depends on three factors: location of ticket gates, and width and direction (one-way or two-way) of ticket gates [32].

2.1.4. Emergency facilities

Emergency facilities include the facilities that are designed to evacuate the station during an emergency, and may not be used during a normal condition. These facilities include emergency lighting, evacuation guiding sign, and emergency ventilation.

Emergency lighting (E1): In an emergency situation in subway stations, the lighting power may be cut-off, and the inside space becomes dark. In a low-visibility condition, the travel distance is increased and the walking speed is decreased. This will increase the evacuation time of a subway station [7]. Therefore, the existence of an efficient emergency lighting system in subway stations is essential.

Evacuation guiding signs (E2): Under an emergency situation, in the lack of an evacuation guidance sign, the passengers may feel difficult to identify the right direction to move. The research and experiments have shown that useful guiding signs for the passengers will increase the evacuation efficiency [33].

Emergency ventilation (E3): In the case of a catastrophic event such as a fire and release of a biological/chemical agent at the station, the ventilation system should work in such a way to provide suitable environmental conditions for passengers to evacuate the station. In response to any emergency situation, the ventilation equipment may be used to: (1) move chemical/biological agents, combustion and decomposition products, and heat in a preferred direction; (2) lessen the airborne concentration of chemical/biological agents, and combustion and decomposition products; and (3) lessen the heat build-up and air temperatures in the subway [34]. The emergency ventilation system improves the evacuation efficiency by reducing the risk of injuries and deaths for passengers as well as by improving the environmental conditions and visibility.

Emergency exits (E4): At some subway stations, the emergency exits are located on the two sides of the station in the tunnel. In this case, the passengers and staff on the platform can reach the surface via emergency exits in a significantly shorter time. Therefore, the existence of emergency exits as well as their location is an important factor in the evacuation time and capability.

2.1.5. Human factors

Human factors that affect the evacuation capability of subway stations are the passengers' density and evacuation speed.

Passengers density (H1): When the density of passengers is nearly 4 person/m^2, it is a crowd situation [35]. Under an emergency condition, the passengers' density is higher compared to a normal situation. A higher density of passengers will lead to a lower evacuating speed, congestion problem during evacuation, and reduction in the evacuation efficiency [33]. The density ranges at all levels of people evacuation are shown in Table 1.

Table 1. Density ranges at all levels of people evacuation level (people/m^2) (Wan *et al*., 2014).

State description	Evacuation level	Aisle	Stair	Queen area
Basic free status	Level one	< 0.43	< 0.71	< 1.08
Part behavior restricted	Level two	0.43-1.08	0.71-1.54	1.08-3.57
Limit big, almost a follow state	Level three	1.08-2.13	1.54-2.70	3.57-5.26
Very crowded, pedestrians blocking serious, badly need of guidance and control	Level four	> 2.13	> 2.70	> 5.26

Evacuation speed (H2): In a normal situation, the evacuation time decreases with speed growing. Under an emergency situation, the passengers try to move faster than a normal condition [4]. The Kohl & ILF Consulting Engineers have suggested that there are two types of walking speeds. One is walking speed on the platform and the other is walking speeds on solid stairs [21]. Helbing et al. have recommended an efficient average speed around 1.5 m/s through their dynamical model considering panic [36].

2.2. Possible ranges for valuing evacuation factors

For simplicity, the value range of each evacuation factor was considered between 1 and 10. Without designing scenarios for each evacuation factor, the valuing will not be based on an engineering judgment. Therefore, the scenarios were designed for the best to the worst conditions for each evacuation factor and the corresponding value was considered. The scenarios and values of evacuation factors are shown in Table 2.

Table 2. Rating of subway station evacuation factors.

Evacuation factor	Code	Scenarios	Value
Evacuation plan	**M1**	• All-hazard evacuation plan developed comprehensively and practically	8-10
		• All-hazard evacuation plan developed comprehensively and practically	6-8
		• A lot of flaw in plans that is less practical	3-6
		• Evacuation plan has not been developed	< 3
Evacuation drills and maneuvers	**M2**	• Carry out evacuation drills at a definite time, and achieve the purpose of drills very well	8-10
		• Carry out evacuation drills at a definite time, and achieve the purpose of drills	6-8
		• Carry out evacuation drills rarely and formally, and failed to achieve the goals	3-6
		• Never carry out drills	< 3
Command center	**M3**	• Station is equipped with command center and monitored permanently by the camera	7-10
		• Station is equipped with command center but does not have the conditions described above	4-7
		• No command center	< 4
Inspection and maintenance of evacuation facilities	**M4**	• Have a comprehensive inspection and maintenance system,and implemented effectively	8-10
		• Have advisable inspection and maintenance system,and being implemented	6-8
		• Have inspection and maintenance system,and implemented not strictly at all.	3-6
		• Maintain facility only when having a problem	< 3
Staff training	**M5**	• A comprehensive training system, and often carry out business training	8-10
		• A certain comprehensive training system	6-8
		• Only superficial training system	3-6
		• No training system	< 3
Depth	**S1**	• < 20 m	7-10
		• 20-50 m	4-7
		• > 50 m	< 4
Exit routes	**S2**	• Station has more than two exit routes, and distance from the initial location (platform) to the exit corridors is short	8-10
		• Station has more than two exit routes, and distance from the initial location (platform) to the exit corridors is long	6-8
		• Station has two exit routes, and distance from the initial location (platform) to the exit corridors is short	4-6
		• Station has two exit routes, and distance from the initial location (platform) to the exit corridors is long	2-4
		• Station has one exit route	< 2
Complexity of station building	**S3**	• Station building is very simple and small	7-10
		• Station building is relatively simple and has a medium dimension	4-7
		• Station building is very complex and large	< 4
Straight elevator	**C1**	• Number of elevators in station is adequate, and elevators are fire-resistant and equipped with emergency power generator	7-10
		• Station equipped with a straight elevator but does not have the conditions described above	4-7
		• No straight elevator	< 4
Stairs and escalators	**C2**	• Station is equipped with stairs and escalators. In an emergency, escalators are on and can be switched in the evacuation direction	8-10
		• Station is equipped with stairs and escalators. In an emergency, escalators are off	6-8
		• Station is equipped with stairs but not escalators	4-6
		• Some part of the station is equipped only with escalators. In an emergency, escalators are on and can be switched in the evacuation direction	2-4
		• Some part of the station is equipped only with escalators. In an emergency, escalators are off.	< 2
Ticket gate	**C3**	• No ticket gate	8-10
		• Bi-direction ticket gate with a standard width (0.55 m)	6-8
		• Bi-direction ticket gate with a non-standard width	4-6
		• One-way ticket gate with a standard width (0.55 m)	2-4
		• One-way ticket gate with a non-standard width	< 2

Table2. Continuation

Emergency lighting	**E1**	• Emergency lighting is designed in accordance with the standards, and provides the level of illuminance that is suitable for the anticipated emergency	7-10
		• There is emergency lighting at the station but not in accordance with the standards	4-7
		• No emergency lighting	< 4
Evacuation guiding signs	**E2**	• Evacuation guiding signs are in correct position and sensory-type so they can shine during the breaking of circuit system in an emergency situation	7-10
		• Evacuation guiding signs are in correct position but are not sensory-type, and their light may be inadequate during an emergency situation	4-7
		• No evacuation guiding sign	< 4
Emergency ventilation	**E3**	• Emergency ventilation system is designed according to the emergency situation and may include emergency fans, dampers, ductwork, and control systems	4-10
		• Emergency ventilation system is not designed	< 4
Emergency exits	**E4**	• Station has two emergency exits located on the two sides of the station in the tunnel	8-10
		• Station has two emergency exits that are not located on the two sides of the station in the tunnel	6-8
		• Station has one emergency exit	4-6
		• Station has no emergency exit	< 4
Passengers density*	**H1**	• Level one	8-10
		• Level two	6-8
		• Level three	3-6
		• Level four	< 3
Evacuation speed	**H2**	• > 1.2 m/s	8-10
		• 0.8-1.2 m/s	6-8
		• 0.5-0.8 m/s	3-6
		• < 0.5 m/s or > 1.5 m/s	< 3

*Based on Table 1.

2.3. Catastrophic events

By studying the statistical analysis of incidents at subway stations, the catastrophic events that may lead to a station evacuation include:

- Fire
- Earthquake
- Flood
- Chemical and biological terrorist attacks
- Other terrorist attacks (bombings, hostage-taking, etc.)

2.4. Weighted influence of each evacuation factor depending on type of catastrophic events

Each evacuation factor has a different effect on the evacuation process depending on the type of catastrophic events. For example, the emergency ventilation system plays a very small role in the evacuation of a station due to a flood, while in the event of a fire, it is one of the most critical factors. Given these changes, we can not consider the overall weight for each factor. Therefore, each factor takes 5 different weights depending on the 5 types of catastrophic events.

There are several methods available for calculating the weight of the alternatives. Saaty has introduced the scaling method for priorities using a positive pairwise comparison matrix in the hierarchical process [37]. Saaty has also indicated that among the commonly used methods for deriving priority such as least squares, logarithmic least squares, eigenvector, and approximation method, eigenvector captures transitivity uniquely and is the only way to obtain the correct ranking on a ratio scale of the alternatives of a decision [38].

Assume the objects by $A_1, \ldots\ldots, A_n$ and their weights by $w_1, \ldots\ldots, w_n$. The pairwise comparisons may be represented by a matrix, as follow:

$$\begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_n \end{array} \begin{array}{c} \begin{array}{cccc} A_1 & A_2 & \cdot & A_n \end{array} \\ \begin{bmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} & \cdots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & \frac{w_2}{w_2} & \cdots & \frac{w_2}{w_n} \\ \vdots & \vdots & & \vdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \cdots & \frac{w_n}{w_n} \end{bmatrix} \end{array} \quad (1)$$

This is a 'reciprocal matrix' that has all the positive elements and has the reciprocal property.

$$a_{ji} = \frac{1}{a_{ij}} \quad (2)$$

In order to assess the scale ratio, w_i/w_j, Saaty has given an intensity scale of importance, as shown in Table 3 [37].

In the eigenvector method, after creating the reciprocal matrix, the following steps are performed to determine w_i:

- Creation of the $(A - \lambda I)$ matrix, where λ is the eigenvalue and I is the identity matrix.
- Calculation of λ from the following equation:

$$det(A - \lambda I) = 0 \quad (3)$$

- Selection of the largest value of λ (λ_{max}) and calculation of w_i by the following equation:

$$(A - \lambda_{max} I) \times w = 0 \quad (4)$$

When many pairwise comparisons are performed, some inconsistencies may typically arise. Saaty has proved that for a consistent reciprocal matrix, the largest eigen value is equal to the number of comparisons or $\lambda_{max} = n$. Then he has given a measure of consistency called "Consistency Index (CI)" as a deviation or degree of consistency using the following formula [37]:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (5)$$

A perfectly consistent decision-maker should always obtain $CI = 0$ but small values of inconsistency may be tolerated, in particular, if:

$$IR = \frac{CI}{RI} < 0.1 \quad (6)$$

where IR is the inconsistency rate and RI is the random index and its value for small problems, are shown in Table 4.

Table 3. The scale and its description (Saaty, 1977).

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Weak importance of one over another	Experience and judgment slightly favor one activity over another
5	Strong importance	Experience and judgment strongly favor one activity over another
7	Demonstrated importance	An activity is strongly favored and its dominance is demonstrated in practice
9	Absolute importance	Evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between two adjacent judjments	When compromise is required

Table 4. Random index (RI) Value (Saaty, 1998).

n	1	2	3	4	5	6	7	8	9	10
Random Index (RI)	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

2.4.1. Pairwise comparison matrices of evacuation factors

In order to determine the weighted influence of evacuation factors, a questionnaire was designed and provided to the experts. In this questionnaire, the experts were asked to evaluate the importance of the evacuation factors relative to each other according to the type of catastrophic event and the numbers given in Table 3. The number of participants was 30. The pairwise comparison matrices of evacuation factors for the catastrophic events are shown in Tables 5 to 9. The elements of these matrices are the mean scores given by the participants.

Some of the evacuation factors like H1, H2 and S1, S2 may have correlation but they are considered separately. This is for two reasons: first, they have a great role in the evacuation of the station, and secondly, these factors are not always interdependent. For example, with decrease in the passengers' density, the evacuation speed will not always increase. At uncrowded stations where evacuation maneuvers have not been conducted, the speed of a passenger may be very low in case of violence between them.

In order to tackle the correlated factors and avoid iteration, the participants were asked to consider these factors independently in the questionnaire.

Table 5. Pairwise comparison matrix of evacuation factors in case of fire.

	M1	M2	M3	M4	M5	S1	S2	S3	C1	C2	C3	E1	E2	E3	E4	H1	H2
M1	1	1.7	2.2	4.3	3.7	4.3	3.2	3.7	4.5	4.4	6.1	4.2	5.3	1.2	2.9	4.1	5.9
M2	0.6	1	2.5	4.1	2.2	4.1	4.4	4.6	5.4	5.9	6.7	3.9	5.2	0.5	3.7	3.5	4.8
M3	0.5	0.4	1	1.3	0.4	1.2	1.2	1.1	4.2	3.7	7.2	5.2	5.1	0.1	1.2	4.2	4.9
M4	0.2	0.2	0.8	1	0.4	1.2	0.3	0.3	4.3	3.9	5.2	3.2	4.8	0.1	0.3	2.8	4.2
M5	0.3	0.5	2.7	2.3	1	4.9	2.9	2.4	4.0	2.4	4.9	2.5	2.9	0.1	2.7	3.7	4.2
S1	0.2	0.2	0.8	0.9	0.2	1	1.7	1.2	3.7	3.7	5.2	0.5	3.5	0.1	1.5	4.5	4.7
S2	0.3	0.2	0.8	3.7	0.3	0.6	1	3.4	4.7	4.3	5.9	2.0	3.5	0.1	0.7	4.4	5.3
S3	0.3	0.2	3.3	3.3	0.4	0.8	0.3	1	4.2	3.8	4.8	0.3	4.6	0.1	0.2	5.3	5.8
C1	0.2	0.2	0.2	0.2	0.3	0.3	0.2	0.2	1	0.5	1.8	0.5	0.2	0.1	0.2	0.3	1.7
C2	0.2	0.2	0.3	0.3	0.4	0.3	0.2	0.3	2.1	1	1.7	0.1	0.2	0.1	0.2	3.5	3.9
C3	0.2	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.6	0.6	1	0.1	0.2	0.1	0.1	2.2	0.5
E1	0.2	0.3	0.2	0.3	0.4	2.0	0.5	3.0	2.0	8.3	8.3	1	3.1	0.1	0.1	3.2	4.7
E2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.2	5.5	6.4	6.5	0.3	1	0.1	0.1	2.5	2.8
E3	0.8	2.0	7.7	7.7	8.3	8.3	8.8	8.5	8.8	8.3	8.8	8.8	8.9	1	8.1	8.3	8.8
E4	0.3	0.3	0.8	4.0	0.4	0.7	1.4	4.5	4.8	5.0	9.1	10.0	7.0	0.1	1	4.8	5.0
H1	0.2	0.3	0.2	0.4	0.3	0.2	0.2	0.2	3.8	0.3	0.4	0.3	0.4	0.1	0.2	1	2.1
H2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.6	0.3	2.1	0.2	0.4	0.1	0.2	0.5	1

Table 6. Pairwise comparison matrix of evacuation factors in case of earthquake.

	M1	M2	M3	M4	M5	S1	S2	S3	C1	C2	C3	E1	E2	E3	E4	H1	H2
M1	1	0.8	3.2	6.2	1.1	6.9	7.5	2.3	8.1	5.2	5.6	5.8	4.2	8.3	6.3	2.1	2.8
M2	1.3	1	4.5	7.2	2.3	7.3	7.2	2.6	8.1	6.2	5.2	6.4	4.9	8.5	7.1	2.5	3.1
M3	0.3	0.2	1	5.2	0.5	5.5	4.8	1.5	7.0	5.1	5.2	5.7	3.5	8.1	2.1	0.4	2.9
M4	0.2	0.1	0.2	1	0.2	0.8	0.4	0.2	6.8	5.1	5.1	5.1	0.5	7.8	0.2	0.3	2.2
M5	0.9	0.4	2.2	5.8	1	5.1	4.1	2.2	7.8	5.8	5.2	6.3	2.2	7.2	4.5	1.6	4.1
S1	0.1	0.1	0.2	1.3	0.2	1	1.4	0.3	6.9	3.1	4.1	4.9	4.5	7.1	5.3	1.2	2.5
S2	0.1	0.1	0.2	2.6	0.2	0.7	1	0.5	6.1	3.1	4.1	4.2	4.4	7.1	5.5	2.8	2.1
S3	0.4	0.4	4.3	4.3	0.5	3.5	1.9	1	7.5	4.1	5.1	5.6	4.9	7.9	6.2	2.1	3.4
C1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	1	0.3	0.2	0.4	0.2	0.6	7.3	5.3	4.1
C2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.2	3.2	1	0.5	1.9	0.5	4.1	6.8	0.2	0.5
C3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	4.5	2.1	1	2.1	0.2	1.8	6.4	0.2	1.2
E1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	2.3	0.5	0.5	1	0.2	1.8	7.9	0.2	0.2
E2	0.2	0.2	0.3	2.2	0.5	0.2	0.2	0.2	5.0	1.9	4.8	5.0	1	6.5	8.3	0.2	1.4
E3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.8	0.2	0.6	0.6	0.2	1	8.5	6.7	0.2
E4	0.2	0.1	0.5	6.7	0.2	0.2	0.2	0.2	0.1	0.1	0.2	0.1	0.1	0.1	1	2.5	2.3
H1	0.5	0.4	2.3	3.1	0.6	0.9	0.4	0.5	0.2	4.5	6.3	6.3	4.8	0.1	0.4	1	4.3
H2	0.4	0.3	0.3	0.5	0.2	0.4	0.5	0.3	0.2	2.2	0.9	4.8	0.7	6.3	0.4	0.2	1

Table 7. Pairwise comparison matrix of evacuation factors in case of flood.

	M1	M2	M3	M4	M5	S1	S2	S3	C1	C2	C3	E1	E2	E3	E4	H1	H2
M1	1	1.5	2.2	5.1	3.1	6.1	5.1	2.1	6.4	4.2	7.1	6.5	3.5	8.1	6.6	2.5	2.9
M2	0.7	1	2.1	5.7	3.1	5.8	4.8	3.5	6.2	4.2	6.2	6.1	3.1	8.2	6.3	1.5	3.5
M3	0.5	0.5	1	5.1	0.5	3.5	0.5	0.4	5.8	3.9	4.2	5.8	3.5	7.9	3.2	0.4	0.8
M4	0.2	0.2	0.2	1	0.2	0.5	0.9	0.2	1.9	0.4	1.3	5.2	0.4	7.1	0.2	0.3	0.6
M5	0.3	0.3	2.1	5.3	1	2.2	1.0	0.5	6.0	4.3	4.1	5.1	3.6	7.1	4.5	1.5	1.7
S1	0.2	0.2	0.3	2.1	0.5	1	0.8	0.2	4.1	4.1	4.6	5.0	2.1	7.2	4.3	0.5	2.1
S2	0.2	0.2	1.9	1.2	1.0	1.3	1	0.2	2.2	3.5	3.7	5.1	4.5	7.5	0.5	2.5	3.7
S3	0.5	0.3	4.1	4.1	2.2	4.3	4.3	1	3.2	3.1	3.8	5.3	2.4	7.8	4.3	1.6	2.1
C1	0.2	0.2	0.2	0.5	0.2	0.2	0.5	0.3	1	0.4	0.3	1.2	0.2	6.1	0.2	0.2	0.4
C2	0.2	0.2	0.3	2.5	0.2	0.2	0.3	0.3	2.8	1	1.2	3.3	0.7	6.7	0.3	0.3	0.5
C3	0.1	0.2	0.2	0.8	0.2	0.2	0.3	0.3	3.1	0.8	1	3.1	0.5	6.9	4.6	0.3	1.1
E1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.9	0.3	0.3	1	0.2	1.7	0.2	0.2	0.2
E2	0.3	0.3	0.3	2.3	0.3	0.5	0.2	0.4	5.1	1.5	2.0	5.3	1	4.6	0.2	0.2	1.5
E3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.6	0.2	1	0.1	0.1	0.1
E4	0.2	0.2	0.3	4.5	0.2	0.2	2.0	0.2	5.0	3.3	0.2	6.3	5.6	8.3	1	0.3	0.3
H1	0.4	0.7	2.3	3.4	0.7	1.9	0.4	0.6	4.7	3.6	3.3	6.5	4.7	8.0	3.3	1	3.7
H2	0.3	0.3	1.2	1.6	0.6	0.5	0.3	0.5	2.3	1.9	0.9	5.2	0.7	7.2	3.3	0.3	1

Table 8. Pairwise comparison matrix of evacuation factors in case of chemical and biological terrorist attacks.

	M1	M2	M3	M4	M5	S1	S2	S3	C1	C2	C3	E1	E2	E3	E4	H1	H2
M1	1	1.3	2.4	5.7	3.9	4.6	5.3	3.2	5.8	5.1	8.3	7.8	4.9	0.8	3.9	4.2	6.1
M2	0.8	1	2.1	5.3	3.2	4.6	3.5	2.4	5.2	4.9	6.5	7.2	3.1	0.5	3.0	4.2	5.7
M3	0.4	0.5	1	4.1	0.4	2.3	3.8	1.8	4.9	4.9	5.9	6.8	2.8	0.1	2.9	2.8	4.7
M4	0.2	0.2	0.2	1	0.2	2.1	0.7	0.7	3.5	3.1	3.8	5.1	1.2	0.1	0.1	3.5	3.9
M5	0.3	0.3	2.5	4.3	1	4.2	2.5	1.5	3.2	2.9	5.8	5.8	2.1	0.1	4.3	4.1	4.9
S1	0.2	0.2	0.4	0.5	0.2	1	0.5	0.3	1.7	1.1	3.9	4.6	1.7	0.1	0.2	2.1	2.8
S2	0.2	0.3	0.3	1.5	0.4	2.2	1	1.7	3.8	3.3	4.6	3.7	0.5	0.1	0.1	3.1	3.9
S3	0.3	0.4	1.4	1.4	0.7	3.9	0.6	1	4.1	3.5	5.2	4.2	1.4	0.1	0.1	3.1	4.2
C1	0.2	0.2	0.2	0.3	0.3	0.6	0.3	0.2	1	0.3	1.2	2.2	0.2	0.1	0.1	0.2	1.3
C2	0.2	0.2	0.2	0.3	0.3	0.9	0.3	0.3	3.2	1	2.5	4.1	0.6	0.1	0.1	1.5	2.1
C3	0.1	0.2	0.2	0.3	0.2	0.3	0.2	0.2	0.9	0.4	1	1.2	0.2	0.1	0.1	0.2	1.2
E1	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.2	0.5	0.2	0.9	1	0.2	0.1	0.1	0.3	0.7
E2	0.2	0.3	0.4	0.8	0.5	0.6	2.0	0.7	4.2	1.6	4.1	4.6	1	0.1	0.2	0.3	1.1
E3	1.2	2.1	8.3	8.4	8.4	8.8	8.6	8.6	8.9	8.8	8.8	8.7	8.5	1	0.1	8.9	8.9
E4	0.3	0.3	0.3	8.0	0.2	6.5	7.0	7.2	8.2	8.2	8.5	8.0	4.5	7.8	1	7.9	8.2
H1	0.2	0.2	0.4	0.3	0.2	0.5	0.3	0.3	4.7	0.7	4.7	3.8	3.9	0.1	0.1	1	4.4
H2	0.2	0.2	0.2	0.3	0.2	0.4	0.3	0.2	0.8	0.5	0.9	1.4	0.9	0.1	0.1	0.2	1

Table 9. Pairwise comparison matrix of evacuation factors in case of other terrorist attacks.

	M1	M2	M3	M4	M5	S1	S2	S3	C1	C2	C3	E1	E2	E3	E4	H1	H2
M1	1	0.4	1.2	7.3	0.5	6.2	4.5	3.5	6.2	5.7	6.9	7.8	6.4	8.2	2.1	0.9	2.1
M2	2.4	1	3.7	7.8	1.9	6.8	4.3	3.7	6.2	6.4	7.5	7.2	7.1	8.7	2.2	1.9	2.8
M3	0.8	0.3	1	6.5	0.8	6.1	3.8	2.3	4.1	4.2	6.4	6.5	6.1	7.9	0.2	2.1	3.4
M4	0.1	0.1	0.2	1	0.2	0.2	0.2	0.2	0.5	0.3	0.5	0.2	0.2	4.1	0.1	0.1	0.1
M5	2.1	0.5	1.3	6.3	1	7.2	5.5	6.9	6.2	5.7	6.4	6.8	5.5	8.1	2.3	1.7	2.3
S1	0.2	0.1	0.2	4.2	0.1	1	3.1	0.2	2.1	2.5	3.5	5.7	4.1	7.8	0.1	0.2	0.3
S2	0.2	0.2	0.3	5.9	0.2	0.3	1	2.1	4.1	4.9	5.1	4.2	5.1	7.5	0.2	2.1	3.4
S3	0.3	0.3	5.9	5.9	0.1	4.2	0.5	1	4.2	4.1	5.3	5.7	2.1	8.3	0.2	0.4	1.8
C1	0.2	0.2	0.2	2.2	0.2	0.5	0.2	0.2	1	0.5	1.2	4.6	0.2	7.4	0.1	0.2	0.2
C2	0.2	0.2	0.2	3.2	0.2	0.4	0.2	0.2	2.1	1	4.1	5.2	1.6	7.3	0.1	0.2	0.2
C3	0.1	0.1	0.2	1.9	0.2	0.3	0.2	0.2	0.8	0.2	1	5.1	0.4	6.8	0.1	0.2	0.2
E1	0.1	0.1	0.2	5.0	0.1	0.2	0.2	0.2	0.2	0.2	0.2	1	0.2	6.1	0.1	0.1	0.1
E2	0.2	0.1	0.2	5.6	0.2	0.2	0.2	0.5	4.3	0.6	2.3	5.4	1	7.1	0.2	0.2	0.2
E3	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	1	0.2	0.1	0.1
E4	0.5	0.5	6.6	7.7	0.4	8.3	5.9	6.3	7.7	7.1	8.3	8.3	6.7	6.7	1	4.6	5.2
H1	1.1	0.5	0.5	7.2	0.6	4.2	0.5	2.3	6.3	4.3	5.3	7.0	4.1	8.5	0.2	1	4.1
H2	0.5	0.4	0.3	6.8	0.4	3.8	0.3	0.6	5.5	5.0	4.4	6.8	5.0	7.1	0.2	0.2	1

2.4.2. Calculating weighted influence of each evacuation factor using eigenvector method

Table 10 shows the calculated weight of evacuation factors according to the type of catastrophic events using the eigenvector method.

2.5. Evaluating risk of catastrophic events at subway stations

Probability of the catastrophic events in subway stations is not the same and depends on factors such as the surrounding environment, geographical location, crowding level, and safety systems. For example, by improving the level of security at a subway station, the probability of terrorist attacks is decreased or it is likely that there is a higher probability of flood at stations located near lakes and rivers. On the other hand, considering the term "probability" is not enough to assess the catastrophic events, and the consequence should be considerd. Thus in order to assess the catastrophic events at subway stations, we will evaluate their risk (the possibility of losing something of value) level at a subway station.

Table 10. The calculated weight of evacuation factors using the eigenvector method.

Catastrophic event / Evacuation factor	Earthquake	Flood	Other terrorist attacks	Chemical and biological terrorist attacks	Fire	Inconsistency rate
M1	0.129	0.155	0.102	0.136	0.125	0.04
M2	0.144	0.150	0.143	0.109	0.113	0.08
M3	0.088	0.071	0.086	0.075	0.043	0.03
M4	0.043	0.024	0.011	0.029	0.025	0.08
M5	0.105	0.082	0.137	0.090	0.053	0.04
S1	0.057	0.056	0.040	0.022	0.042	0.03
S2	0.060	0.067	0.057	0.032	0.042	0.02
S3	0.084	0.104	0.039	0.038	0.040	0.05
C1	0.029	0.015	0.021	0.012	0.011	0.05
C2	0.026	0.025	0.027	0.018	0.012	0.06
C3	0.026	0.032	0.020	0.009	0.010	0.08
E1	0.020	0.011	0.023	0.009	0.075	0.03
E2	0.046	0.033	0.028	0.025	0.057	0.05
E3	0.031	0.007	0.019	0.193	0.243	0.02
E4	0.026	0.047	0.119	0.167	0.079	0.06
H1	0.055	0.080	0.074	0.025	0.017	0.08
H2	0.03	0.041	0.054	0.011	0.015	0.04

2.5.1. Risk evaluating criteria

Accuracy of the risk evaluating methods depends on the inclusiveness of the studied factors. Most risk evaluating studies have used the terms "likelihood" and "consequence" (probability-impact risk rating matrix) to evaluate a risk. One of the problems with this method is to ignore the importance of low probability and high impact risks. Actually, in this method, the low probable and high impact risks are assumed to be equivalent to those with a high probability and a negligible effect. Therefore, we used 6 criteria including the probability of occurrence, finding ability, continuous repeating, manageability, uncertainty of estimates, and people's vulnerability to evaluation of the risks more accurately. Table 11 presents the risk evaluating criteria, where the positivity of a criterion indicates an increase in risk and vice versa.

Table 11. The risk evaluation criteria.

Criterion	Code	Effectiveness	Description
Probability of occurrence	Z1	+	Indicates the expectation of a risk
Finding ability	Z2	-	Ability to identify the risk at the time of occurrence
Continuous repeating	Z3	+	Indicates repeating and continuity of the risk
Manageability	Z4	-	Ability to manage and response to the risk
Uncertainty of estimates	Z5	+	Indicates the uncertainty of risk assessment
People's vulnerability	Z6	+	Severity of the risk to people

2.5.2. Calculating weighted influence (risk level) of catastrophic events on subway stations

In order to determine the weighted influence of the catastrophic events, due to the different characteristics of the stations, each should be studied separately. To this end, a questionnaire should be designed and provided to the experts that have a comprehensive knowledge about the characteristics of that station. The questionnaire should be designed in such a way that the experts can evaluate the risk level of each catastrophic event at a subway station according to the type of criteria and the numbers given in Table 11 and 3, respectively. An example of a designed questionnaire is shown in Appendix 1. The calculation method used to determine the weighted influence (risk level) of each catastrophic event on subway stations use the eigenvector method based on the positive pairwise comparison matrix, as described in Section 2.4.

2.6. Calculating station evacuation capability score

The final score of a station is equal to the sum of the multiplication of the score earned by the station in each type of catastrophic event in the weighted influence (risk level) of each catastrophic event, as follow:

$$Final\ score = \left[(Score_{Fire} \times w_{Fire}) + (Score_{Flood} \times w_{Flood}) + (Score_{Earthquake} \times w_{Earthquake}) + (Score_{Terrorist\ attack} \times w_{Terrorist\ attack}) + (Score_{Other\ terrorist\ attack} \times w_{Other\ terrorist\ attack})\right] \times 100 \tag{7}$$

or:

$$Final\ score = \sum_{i=1}^{5}(SC_i \times w_i) \times 100 \tag{8}$$

where i is the index corresponding to the type of catastrophic event, w is the weighted influence (risk level) of the i-th catastrophic event, and SC is the station's rating of the i-th catastrophic event calculated as follows:

$$SC = \sum_{j=1}^{n} w_j \times v_j \tag{9}$$

where w and v are the weight (based on Table 10) and value (based on Table 2) of the j-th evacuation factor, respectively.

2.7. Grading subway station based on overall score

According to the rating of evacuation factors (Table 2) and Equation 8, the maximum score of the station evacuation capability will be 1000. Thus the station can be graded according to Table 12.

Table 12. Grading of subway station based on evacuation capability.

Scoring range	Grade	State description
0-200	5	Can be expected that during emergency, station's evacuation will be difficult and endanger people's lives
200-400	4	During emergency, station's evacuation will be probably difficult and may endanger people's lives
400-600	3	During emergency, station's evacuation might be difficult and endanger people's lives at some time
600-800	2	During emergency, station's evacuation might be difficult at some time but not endanger people's lives
800-1000	1	Can be expected that during emergency, station's evacuation will be done without problems

3. Application of proposed model

3.1. Tehran subway system

The Tehran subway is a rapid transit system serving Tehran, the capital of Iran. The length of the subway lines operated is 221 km and the number of operational stations is 118 in 5 lines (Figure 2). The Tehran subway carries more than 3 million passengers every day [39]. Due to the fact that the Tehran subway stations have been built over the years, they have various facilities, and therefore, different evacuation capabilities during emergencies.

3.2. Grading Tehran subway stations

In Tables 13 and 14, the relevant scores (based on Table 2) and calculated weight (risk level) of each catastrophic event on 16 stations in 4 different lines of the Tehran subway are presented.

Table 13. Scores of stations studied in Tehran subway.

	Station (Line)															
Index	A (1)	B (1)	C (1)	D (1)	E (2)	F (2)	G (2)	H (2)	I (3)	J (3)	K (3)	L (3)	M (4)	N (4)	O (4)	P (4)
M1	3	4	5	3	5	6	5	5	6	6	6	6	5	5	5	4
M2	3	4	6	2	6	6	5	4	6	7	7	6	7	7	6	5
M3	2	3	3	2	5	5	5	3	7	7	7	7	5	5	5	5
M4	5	5	5	5	6	6	6	5	7	7	7	7	6	6	6	6
M5	4	4	6	3	5	7	5	4	5	7	7	5	7	7	5	4
S1	8	8	8	5	4	7	4	4	4	5	6	4	5	5	5	5
S2	2	6	6	1	6	6	6	2	1	7	7	7	5	6	8	8
S3	7	5	3	6	4	3	4	6	6	5	6	6	3	5	6	6
C1	1	5	5	1	5	6	6	1	2	7	7	7	4	6	5	4
C2	3	5	5	4	5	5	6	3	7	7	7	6	6	6	6	5
C3	7	3	2	7	3	4	3	5	4	5	6	4	4	4	4	4
E1	2	3	3	2	4	4	4	3	5	6	7	6	5	5	4	4
E2	3	4	5	3	5	5	3	3	6	6	6	6	5	5	5	4
E3	3	5	6	3	6	7	6	5	7	7	7	7	5	6	6	6
E4	2	2	2	2	2	2	2	2	2	7	7	7	3	3	3	3
H1	5	5	2	8	2	2	3	6	6	5	7	6	2	2	4	6
H2	5	5	3	8	3	2	3	6	6	5	7	6	2	2	4	6

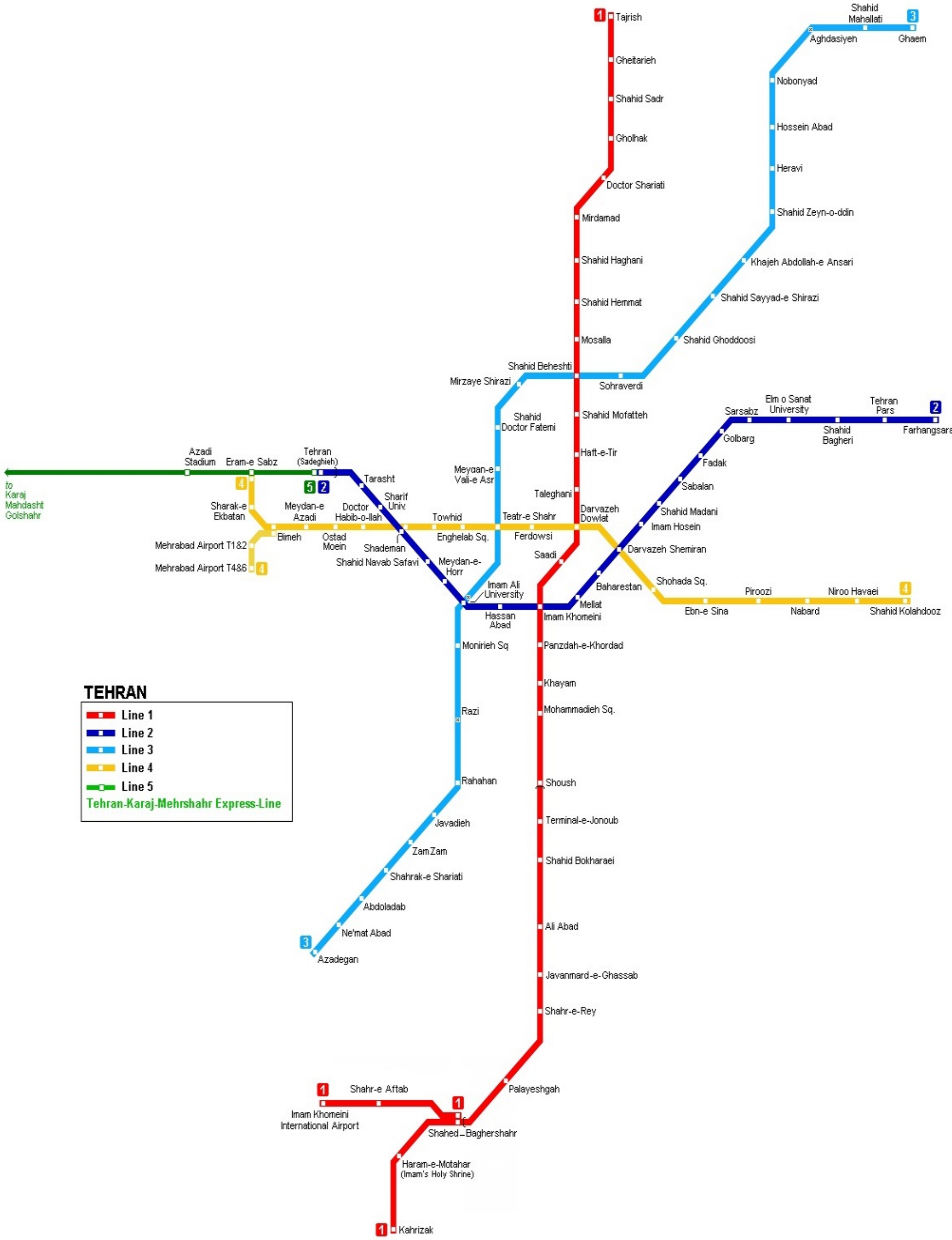

Figure 2. Tehran subway map (Tehran Urban and Suburban Railway Operation Co, 2018).

4. Results and discussion

4.1. Analyzing results of grading studied stations

Given the characteristics of the stations under study, it can be said that the proposed model evaluates the evacuation capability with a good accuracy. The total score and grading of the stations studied in the Tehran subway are presented in Table 15. The results tabulated in this table are as follow:

- Among the stations studied, stations A and D have the lowest evacuation capability score, and stations K and J have the highest. The reason for this difference in the evacuation capability is the early time stations D and A were built and the big gap of construction technology compared with stations K and J that were built in later periods in Tehran.
- Some of the studied stations (such as C, E, and G) are important transfer points in lines and serve a large number of passengers. These stations typically lead to a poor emergency evacuation capability. Therefore, these stations require efficient evacuation facilities and emergency management.
- According to Table 10, the management factors have a main influence on the evacuation capability of subway stations. Thus stations such as J, K, and L that have a higher score of management factors have higher overall scores.
- Stations D, A, and H with the lowest scores have only one exit route to the ground, and in an emergency prevent the passengers from getting out of the station quickly. Station I also has only one exit route. In fact, if this station, like the other stations in line 3 had 4 outputs, it would be in grade 2.

Table 14. Calculated weight (risk level) of each catastrophic event on subway stations.

Station \ Catastrophic event	Earthquake	Flood	Other terrorist attacks	Chemical and biological terrorist attacks	Fire	Inconsistency rate
A	0.213	0.043	0.187	0.185	0.372	0.05
B	0.32	0.035	0.23	0.1	0.31	0.08
C	0.369	0.046	0.201	0.146	0.238	0.08
D	0.306	0.045	0.206	0.167	0.276	0.07
E	0.238	0.087	0.18	0.12	0.369	0.08
F	0.21	0.29	0.1	0.1	0.3	0.08
G	0.222	0.22	0.13	0.12	0.309	0.08
H	0.23	0.14	0.12	0.11	0.4	0.05
I	0.267	0.082	0.197	0.181	0.273	0.08
J	0.2	0.19	0.2	0.18	0.23	0.06
K	0.23	0.2	0.19	0.19	0.19	0.04
L	0.329	0.205	0.082	0.171	0.209	0.07
M	0.15	0.201	0.19	0.209	0.25	0.03
N	0.1	0.2	0.25	0.25	0.2	0.06
O	0.16	0.2	0.21	0.2	0.23	0.08
P	0.21	0.3	0.13	0.12	0.24	0.02

- Stations B and C have been built almost simultaneously with stations A and D but have higher grades than those stations. The reason for this is that at these stations, measures have been taken to increase the level of safety such as construction of escalators and elevators, installation of emergency lights, and guiding signs and maneuvering.
- At all the surveyed stations, the scores obtained for different types of catastrophic events are approximately equal, which indicates that the stations are safe or unsafe against all types of catastrophic events. In this case, the risk level of the catastrophic events can increase or decrease the station's grade.
- Stations D, A, H, B, G, and C have the lowest scores among the surveyed stations. Between these stations, B, G, and C are interchanges, serving to transfer passengers between lines and handle more passengers than regular stations, and stations D, A, and H have the lowest passengers' density among all the surveyed stations and very few passengers use them. This indicates that as crowded stations, due to high passengers' density, they have a low evacuation capability in emergencies, and uncrowded stations may also be at risk in an emergency situation due to the lack of emergency management, safety facilities, and equipment. In fact, when a catastrophic event occurs, at first sight, it is expected that the highest casualty rate will be at crowded stations, while the uncrowded stations may have the highest casualties due to the lack of emergency management, safety facilities, and equipment.

Table 15. Total score and grade of stations studied in Tehran subway.

Station	Line	Total score					Grade
		Score$_{(E)}$	Score$_{(Fl)}$	Score$_{(Ot)}$	Score$_{(T)}$	Score$_{(Fi)}$	
K	3			670.229			2
		66.3	66.2	67.71	67.7	67.4	
J	3			639.632			2
		62.79	61.75	63.93	66.2	65.09	
L	3			613.9611			2
		59.82	59.73	60.56	63.56	62.98	
I	3			531.6174			3
		53.53	52.75	50.18	52.78	55.33	
N	4			521.01			3
		53.43	51.13	50.53	52.31	54.11	
F	2			519.337			3
		52.33	49.46	48.64	52.25	55.04	
O	4			518.671			3
		53.08	52.53	50.01	50.95	52.94	
P	4			495.302			3
		49.93	50.35	47.99	47.77	49.87	
M	4			491.3145			3
		50.26	48.01	48.57	49.06	50.24	
E	2			470.1536			3
		47.48	45.5	44.01	46.78	49.38	
C	1			469.2459			3
		47.32	45.43	44.33	46.21	49.23	
G	2			458.5023			3
		46.22	44.54	43.24	45.74	47.51	
B	1			428.126			3
		44.41	44.46	41.52	40.51	43.37	
H	2			408.106			3
		41.06	42.55	39.07	39.54	40.93	
A	1			347.2325			4
		38.16	39.7	35.24	32.11	33.22	
D	1			330.1983			4
		35.24	37.87	34.39	30.02	30.56	

4.2. Effect of catastrophic event risks on stations final score and grade

The risks of catastrophic events at subway stations are not the same and depend on several factors. This difference can increase or decrease the station's final score. The station's status in evacuation capability should be proportional with the catastrophic events that have a higher risk. In fact, the station should be more capable of evacuating in the catstrophic events with higher risks. The total score and grade of the stations studied in the Tehran subway without regarding the risk of catastrophic events are shown in Table 16.

By comparing Tables 15 and 16, the effect of the catastrophic event risks on the final score of the stations can be investigated. By comparing these two tables, it can be seen that the factor of risk in the calculation process will increase the final scores of stations F and P compared to stations O and M, respectively. The reason is that, for example, station F has the lowest score for the lowest risk of a catastrophic event and has the highest score for the highest risk of a catastrophic event. At station O, this condition is reverse, and the highest score is for the lowest risk catastrophic event. This description also applies to stations P and M.

Considering the above-mentioned cases, the risk of catastrophic events is one of the important factors in the station's evacuation capability score. In fact, it can be said that by assessing the risk of catastrophic events at stations and equipping stations on its basis, the degree of safety and evacuation capability can be improved more effectively, and it is better to assess the risk of catastrophic events before taking any steps to equip the stations with safety facilities.

Table 16. Total score and grade of stations without regarding risk of catastrophic events.

Station	Line	Total score	Score$_{(E)}$	Score$_{(Fl)}$	Score$_{(Ot)}$	Score$_{(T)}$	Score$_{(Fi)}$	Grade
K	3	335.31	66.3	66.2	67.71	67.7	67.4	2
J	3	319.76	62.79	61.75	63.93	66.2	65.09	2
L	3	306.65	59.82	59.73	60.56	63.56	62.98	2
I	3	264.57	53.53	52.75	50.18	52.78	55.33	3
N	4	261.51	53.43	51.13	50.53	52.31	54.11	3
O	4	259.51	53.08	52.53	50.01	50.95	52.94	3
F	2	257.72	52.33	49.46	48.64	52.25	55.04	3
M	4	246.14	50.26	48.01	48.57	49.06	50.24	3
P	4	245.91	49.93	50.35	47.99	47.77	49.87	3
E	2	233.15	47.48	45.5	44.01	46.78	49.38	3
C	1	232.52	47.32	45.43	44.33	46.21	49.23	3
G	2	227.25	46.22	44.54	43.24	45.74	47.51	3
B	1	214.27	44.41	44.46	41.52	40.51	43.37	3
H	2	203.15	41.06	42.55	39.07	39.54	40.93	3
A	1	178.43	38.16	39.7	35.24	32.11	33.22	4
D	1	168.08	35.24	37.87	34.39	30.02	30.56	4

4.3. Sensitivity analysis of evacuation factors

As explained in Section 2.1, the factors affecting the subway station evacuation during emergencies can be categorized into five categories: considered management factors, station characteristics, station facilities, emergency facilities, and human factors. The sensitivity analysis was performed to investigate the effect of the evacuation factors on the station's evacuation capability.

The effect of increasing one unit of each evacuation factor on the final score of the station is presented in Table 17. According to this table, the highest percentage increase in the final score of the station is related to the management factors.

Table 18 shows the effect of increasing 2 units of evacuation factor values on the final score of the station. Regarding this table, it can be seen that increasing 2 units of management factor values will upgrade the evacuation capability of the 6 stations from 16 studied stations (highlighted case in Table 18), while increasing 2 units of emergency facilities will upgrade one station. Increasing two units of other factors will not affect the studied stations grade.

According to Tables 17 and 18, the management factors have the most effect on the final score and grade of the station. In fact, it can be said that the most effective way to increase the evacuation capability of a given station is to improve the status of that station in management factors. It should be noted that improving the status of management factors at a station, in addition to being more efficient, is the most convenient and least costly way to increase the station's evacuation capability. For example, it is almost impossible to change the station's characteristics or improving station's status in emergency facilities, require a lot of money and also installing new equipment. But management factors can be improved with proper planning and accurate study of the station's condition.

Table 17. New score of studied stations for increasing one unit of evacuation factor values.

Station	Score	Increasing one unit of management factors		Increasing one unit of station characteristics		Increasing one unit of station facilities		Increasing one unit of emergency facilities		Increasing one unit of human factors	
		Score	Percentage increase	Score	Percentage increase	Score	Percentage increase	Score	Percentage increase	Score	Percentage increase
A	347.2	390.6	12.5	361.3	4.1	352.5	1.5	378.0	8.9	353.7	1.9
B	428.1	472.6	10.4	443.2	3.5	433.9	1.4	454.8	6.2	435.5	1.7
C	469.2	514.8	9.7	484.7	3.3	475.3	1.3	494.6	5.4	476.7	1.6
D	330.2	375.0	13.6	345.1	4.5	336.0	1.7	357.4	8.2	337.4	2.2
E	470.2	513.6	9.2	485.0	3.2	475.6	1.2	498.8	6.1	477.1	1.5
F	519.3	564.0	8.6	536.1	3.2	525.2	1.1	544.2	4.8	527.2	1.5
G	458.5	503.0	9.7	474.7	3.5	464.3	1.3	484.6	5.7	466.1	1.7
H	408.1	451.5	10.6	423.5	3.8	413.5	1.3	437.1	7.1	414.9	1.7
I	531.6	576.3	8.4	546.6	2.8	537.3	1.1	559.0	5.1	538.8	1.4
J	639.6	684.7	7.0	655.2	2.4	645.4	0.9	665.3	4.0	647.5	1.2
K	670.2	715.8	6.8	686.1	2.4	676.2	0.9	694.7	3.7	678.3	1.2
L	614.0	657.3	7.1	628.8	2.4	619.3	0.9	642.6	4.7	621.5	1.2
M	491.3	537.2	9.3	506.9	3.2	497.3	1.2	515.4	4.9	499.7	1.7
N	521.0	565.9	8.6	535.7	2.8	526.6	1.1	547.9	5.2	529.0	1.5
O	518.7	563.6	8.7	534.0	3.0	524.4	1.1	544.9	5.1	526.5	1.5

5. Conclusions

Todays, the subway system is expanding around the world due to the problems related to population growth, traffic, and air pollution. Subway systems consist of several components among which station is the main component. Despite the progress in the construction and maintenance, stations have been always exposed to natural and man-made disasters. In such incidents, the station evacuation capability has a direct relation to a passenger's life. The evacuation capability is one of the most important factors to be considered when designing a station. Various factors affect the station's evacuation capability. Investigation of these factors and evaluation of station evacuation capability has an important role in protecting a passenger's life.

Table 18. New score of studied stations for increasing two units of evacuation factor values.

Station	Score	Grade	Increasing two units of management factors		Increasing two units of station characteristics		Increasing two units of station facilities		Increasing two units of emergency facilities		Increasing two units of human factors	
			Score	Grade	Score	Grade	Score	Grade	Score	Grade	Score	Grade
A	347.2	4	433.9	3	375.5	4	357.7	4	408.7	3	360.3	4
B	428.1	3	517.1	3	458.4	3	439.8	3	481.4	3	442.8	3
C	469.2	3	560.4	3	500.2	3	481.3	3	519.9	3	484.1	3
D	330.2	4	419.9	3	360.1	4	341.7	4	384.6	4	344.5	4
E	470.2	3	557.0	3	499.9	3	481.1	3	527.5	3	484.0	3
F	519.3	3	608.6	2	552.9	3	531.0	3	569.1	3	535.0	3
G	458.5	3	547.5	3	490.8	3	470.0	3	510.7	3	473.6	3
H	408.1	3	494.9	3	438.9	3	419.0	3	466.0	3	421.7	3
I	531.6	3	621.1	2	561.5	3	543.0	3	586.3	3	546.1	3
J	639.6	2	729.8	2	670.8	2	651.3	2	690.9	2	655.4	2
K	670.2	2	761.4	2	701.9	2	682.2	2	719.2	2	686.3	2
L	614.0	2	700.7	2	643.6	2	624.6	2	671.2	2	629.0	2
M	491.3	3	583.1	3	522.4	3	503.3	3	539.5	3	508.2	3
N	521.0	3	610.7	2	550.5	3	532.2	3	574.7	3	537.0	3
O	518.7	3	608.4	2	549.3	3	530.1	3	571.1	3	534.4	3
P	495.3	3	585.8	3	529.1	3	507.3	3	542.5	3	511.7	3

For this purpose, the factors affecting the subway station evacuation operation (evacuation factors) as well as the catastrophic events that lead to the station's evacuation were identified. The evacuation factors include management factors, station characteristics, station facilities, emergency facilities, and human factors, and the catastrophic events include fire, earthquake, flood, chemical and biological terrorist attacks, and other terrorist attacks. Then the evacuation factors were weighted according to the type of events using the eigenvector method based on the positive pairwise comparison matrix. In the next stage, possible ranges for valuing the evacuation factors were defined. Due to the difference in the catastrophic event probability at each station, the risk of the catastrophic events was evaluated. Then the station score was calculated according to the value and weight of the evacuation factors and wighted influence of the catastrophic events. Finally, according to the score, the station was graded. Accordingly, the proposed model was implemented in 16 stations of the Tehran subway.
Based on the results obtained, the following can be concluded:

- Using the proposed model to evaluate the station's evacuation capability is an appropriate method for identifying the stations that have a poor evacuation capability and can be used to prioritize stations in order to take appropriate measures.
- Uncrowded stations, even though served by a small number of passengers, may also have a low evacuation capacity and lead to casualties in an emergency situation. This is due to the lack of emergency management and safety facilities and equipment. In fact, when a catastrophic event occurs, at first sight, it is expected that the highest casualty rate will be at crowded stations, while the uncrowded stations may have the highest casualties. Therefore, considering the factor of population density is not enough to prioritize the stations to equip and other factors described in this paper should be considered.
- Risk of catastrophic events is one of the important factors in station's evacuation capability score. In fact, it can be said that by assessing the risk of catastrophic events at stations and equipping stations on its basis, the degree of safety and evacuation capability can be improved more effectively, and it is better to assess the risk of catastrophic events before taking any steps to equip the stations with safety facilities.
- Sensitivity analysis of the evacuation factors showed that the most effective way to increase the station evacuation capability is to improve its status in management factors. It should be noted that improving the status of management factors at a station, in addition to being more efficient, is the most convenient and least costly way to increase the station's evacuation capability.

The proposed model can be used to investigate the status of subway stations in evacuation capability and identify high-risk stations and prioritization in order to increase the station's evacuation capability. Also using the proposed model, it is possible to evaluate the most effective way to improve the evacuation capability of a specific station, and based on this, modify or equip that station.
The model proposed in this paper has some limitations. For example, in order to assess the risk of castastrophic events at subway stations more accurately, the factors that affect the risk evaluation criteria should also be considered. For example, installation of smoke detectors at subway stations is a factor that affects finding ability (Z2) of fire or establishing police team and installation of closed circuit camera (CCTV) at station are factors that affect the probability of occurrence (Z2) of terrorist attacks. The proposed model also does not predict the evacuation capability of stations during crowded and routine situations. The reason for this is the factors affecting evacuation in emergencies and crowded or routine times are different. For example, emergency exits, emergency guiding signs, emergency lights, and evacuation plans are the factors that do not affect evacuation in crowded or routine times. Comparing the evacuation capability of the stations during emergency and crowded situation will provide useful results. Future developments will concern this limitation.

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Appendix 1:

Designed questionnaire for calculating the weighted influence of each catastrophic events on subway stations.

With respect to **Risk evaluation criteria (criterion code)**
using the scale from 1 to 9 (where 9 is extreme and 1 is equally important,
please indicate the relative importance of options **A** (left column) to options **B** (right column) in station **(station name)**

A Options	**Extremely**		**Very strongly**		**Strongly**		**Moderately**		**Equally**		**Moderately**		**Strongly**		**Very strongly**		**Extremely**	**B Options**
Fire	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Earthquake
Fire	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Flood
Fire	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Terrorist attack
Fire	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Other terrorist attack
Earthquake	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Flood
Earthquake	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Terrorist attack
Earthquake	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Other terrorist attack
Flood	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Terrorist attack
Flood	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Other terrorist attack
Terrorist attack	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Other terrorist attack

ارائه یک روش کمی به منظور رتبه‌بندی ایستگاه‌های مترو بر اساس قابلیت تخلیه پذیری مسافران

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چکیده:

ایستگاه یکی از اجزای مهم سیستم‌های قطار مترو است که همواره در معرض حوادث طبیعی و غیر طبیعی قرار دارد. هنگام وقوع برخی حوادث مثل آتش‌سوزی، بمب‌گذاری، زلزله و غیره مسافران باید به بیرون از ایستگاه تخلیه شوند. در صورتی که هنگام وقوع حوادثی از این دست، تمامی مسافران در مدت زمان مشخص از ایستگاه تخلیه نشوند، وقوع فاجعه محتمل است. بنابراین قابلیت تخلیه‌پذیری ایستگاه، یکی از عوامل مهم در نجات جان مسافران است. هدف از انجام این تحقیق، ارائه مدلی برای بررسی قابلیت تخلیه‌پذیری ایستگاه‌های مترو به منظور شناخت وضعیت هر ایستگاه و شناسایی ایستگاه‌های پرخطر است. بدین منظور در ابتدا حوادث منجر به تخلیه ایستگاه و عوامل موثر بر آن تعیین شده است. از آنجایی که به دلیل شرایط جغرافیایی، محلی، طبیعی، توپوگرافی و غیره. احتمال وقوع حوادث مختلف در هر ایستگاه متفاوت است، در روش ارائه شده سطح ریسک هر حادثه در هر ایستگاه در ابتدا ارزیابی، سپس امتیاز هر ایستگاه با توجه به مقدار و وزن هر فاکتور تخلیه و سطح ریسک هر حادثه محاسبه می‌شود. در ادامه مدل ارائه شده در سیستم مترو شهر تهران پیاده‌سازی شده است. نتایج به دست آمده نشان دهنده آن است که ایستگاه‌های خلوت و کم جمعیت به دلیل نبود تجهیزات ایمنی و سیستم مدیریت بحران، قابلیت تخلیه‌پذیری کمی دارند و وقوع حادثه در این ایستگاه‌ها می‌تواند منجر به فاجعه شود. همچنین نتایج نشان می‌دهد که با بررسی ریسک حوادث مختلف در هر ایستگاه و تجهیز ایستگاه بر مبنای آن، سطح ایمنی و قابلیت تخلیه‌پذیری ایستگاه به طور چشم‌گیری افزایش می‌یابد. در نهایت تحلیل حساسیت عوامل تخلیه نشان داد که موثرترین راهکار به منظور افزایش قابلیت تخلیه‌پذیری در هر ایستگاه، بهبود وضعیت آن ایستگاه در عوامل مدیریت بحران است.

کلمات کلیدی: ایستگاه مترو، قابلیت تخلیه‌پذیری، حوادث فاجعه‌بار، ماتریس مقایسه زوجی، سیستم مترو تهران.