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Fault tree analysis for subway fire evacuation with agent-based modeling

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Abstract

In the process of the continuous development of subway construction, the safe evacuation of subway passengers has been paid much attention to. As the subway itself has the characteristics of limited space and high passenger density, once a fire emergency occurs, it can cause huge losses only by passive rescue. Therefore, it is important to actively plan for evacuation to reduce life and property losses due to fires in subways. This study aims to develop a fault tree analysis method for identifying scenarios that lead to evacuation failure in subways due to impassability incurred by fires. First, a virtual evacuation model is established using an agent modeling technique, with collected passenger characteristics to calibrate local evacuation behaviors. Then, fire impassability scenarios (e.g. fire(s) in the escalator(s), in emergency stairs, or the combination) are evaluated using the established agent model. Eventually, a fault tree analysis is constructed to identify scenarios that lead to evacuation failures. The research results show that the passability of escalator(s) is critical for subway fire resilience. It is important to use stationary escalator(s) as evacuation pathways for more evacuation capacity. Fire risk management around escalator(s) should be stricter. Passengers and staff are advised to learn how to stop a running escalator to avoid evacuation failures.

Keywords Subway, Evacuation, Fire, Risk, Emergency, Resilience

Introduction

With the development of urbanization, the pressure of urban transportation is becoming an increasingly acute problem. The emergence of urban subways has greatly alleviated this problem. However, subways have complex internal structures. The combination of fires at critical locations and a high number of passengers will lead to catastrophic consequences. Therefore, evacuation inside subway stations continues to be a high priority for transportation and security agencies [1], and it is important to scientifically plan for fire evacuation to prevent and control fire risks in subway stations.

Many researchers have adopted different methods to study evacuation under different conditions. Porzycki et al. [2] conducted real evacuation experiments from the perspective of group behaviors and the interactions among evacuees. They found that the moving speed in the smoke was affected not only by the visibility but also by the mental status of evacuees and their familiarity with the environment and evacuation procedures. Compared to evacuation experiments with high costs and difficulty, simulation-based modeling provides an alternative method [3]. Many evacuation models are proposed to describe crowd dynamics, which are mainly divided into two types, namely microscopic and macroscopic models [4]. The microscopic models including the social force (SF) model [5], cellular automaton (CA) model [6], and agent-based model [7] can describe individual behavior more accurately and are closer to reality. Therefore, they are more widely used.

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Among these models, the agent-based model has advanced significantly in recent years as the processing speed of computers greatly improved. Agent-based models can simulate a crowd of "agents" which can have elementary artificial intelligence to make decisions. Each agent can have a unique set of behavioral rules that allow modeling heterogeneity in the population [8]. For instance, Shi et al. [9] used an agent-based model to simulate the evacuation process under different fire conditions, so as to study the evacuation behavior of passengers, evacuation time, flow rate, and the strategy of using escalators as evacuation passages.

Besides evacuees' behaviors and evacuation models, some scholars have also studied key factors influencing an evacuation. Zhang et al. [10] proposed four key performance indicators, namely pedestrian density, evacuation length, evacuation time, and evacuation capacity, to evaluate evacuation performance under different route planning strategies. The research was applied to a subway station in Wuhan, China, to verify the usability of improving the efficiency of evacuation performance. Yang et al. [11] introduced passenger distribution modeling based on the ant colony optimization algorithm and further analyzed the impact of passenger distribution on evacuation dynamics under fire. It is concluded that when the fire reaches a certain scale, evacuation will be significantly affected by passenger distribution.

Previous studies about the fire evacuation of subway stations were primarily focused on passengers' moving behaviors, evacuation modeling, and evacuation optimization. There is a gap in the knowledge to utilize the information gained from agent-based modeling in decision-making that improves safety.

To address this gap, this study aims at adopting agent-based modeling and further develops a fault tree analysis method for identifying scenarios that lead to evacuation failure in subways due to impassability incurred by fires. We used a case study in a subway station in Xuzhou, Jiangsu Province, China as an example to demonstrate the method. This method can be used for any subway station to identify critical locations to prevent evacuation failure due to fire. The developed fault tree provides a basis for transport officials to formulate emergency evacuation plans to prevent the catastrophic consequences of fires in subway stations.

Method

The method flowchart of the study is shown in Fig. 1. The method starts with collecting the basic evacuation characteristics of passengers in subway stations using a questionnaire investigation (see later in section 3). This is to obtain first-hand data on passengers' characteristics for modeling local evacuation behavior, hence providing a basis for establishing a reliable agent-based simulation model later in the study.

Next, agent-based modeling is adopted to simulate individual movement during evacuation. Although there are various options in choosing an agent-based model, Pathfinder software is used in this study as it receives wide application in past studies [12, 13]. It can determine the escape path and evacuation time of the simulation process by setting up an evacuation environment with defined personal characteristics. The internal environment of the subway station is defined in a Building Information Model (BIM), which is used as a basis to construct the evacuation model in Pathfinder. Then, in order to explore the relationship between the use of evacuation facilities (stairs and escalators) and evacuation results further, this study takes the successful evacuation standard in China which is whether all passengers in the station can evacuate within 6 minutes [14].

Based on the simulation results of various evacuation scenarios, a fault tree of subway passenger evacuation failure can be constructed. Fault tree analysis (FTA) is used to identify scenarios that cause evacuation failures. FTA is a tree decision-making structure based on a graphical method to show the logical causation of failure [15]. The fault tree generally aims at risk control, that is, the most undesirable accident is taken as the top event, and then various faults that may lead to the top event are determined layer by layer from the top to the bottom through logical analysis. These fault events are expanded layer by layer in the form of a tree structure. Among them, the bottom events refer to the fault events that cannot be further subdivided, and the intermediate events refer to all other fault events in the middle of the bottom events and the top event. Combined with the mathematical analysis of the fault tree, the criticality of the evacuation facilities can be ranked. Such analysis can provide a reference for the efficient dynamic management of the station evacuation system.

Questionnaire investigation

Questionnaire design and data collection

The questionnaire consisted of four parts: a) demographic characteristics; b) knowledge of subway stations; c) emergency response and measures during evacuation; d) questionnaire validity (See Table 1 for details). We chose an electronic platform named "Wenjuanxing" to distribute questionnaires around the investigated subway station and collect results via smartphones [16]. The questionnaires were collected from 246 participants, among which 6 questionnaires included invalid data and were excluded. The questionnaire obtained 240 valid data for analysis (97.56% response rate).

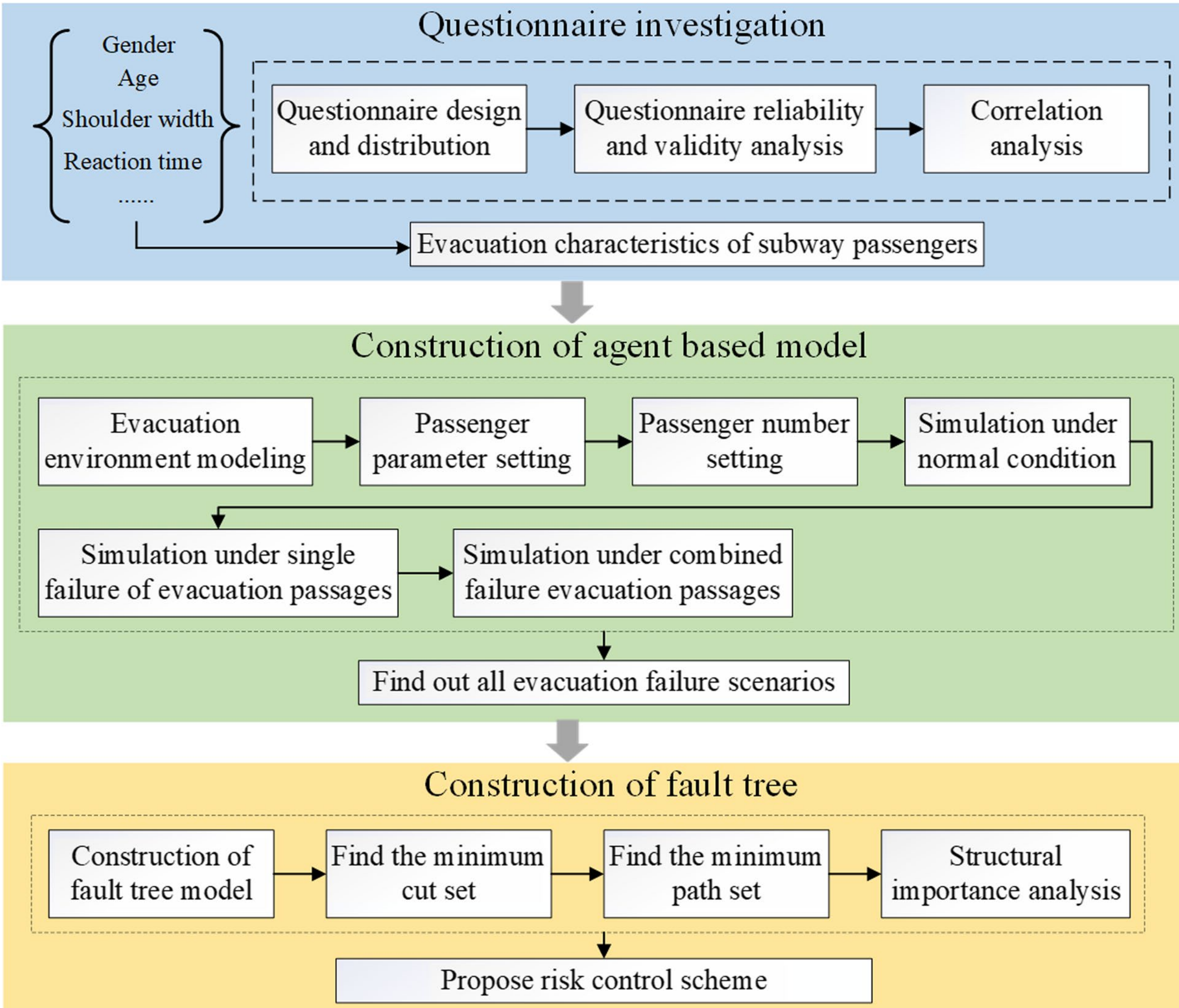


Fig. 1 Method flowchart of the study

The following demographic information was collected from the participants including gender, age, education level, frequency of taking the subway, evacuation training experience, and outwear size (see Table 2). Most of the participants were between 19 and 60 years old (90%), had received at least undergraduate education (77%), and took the subway less than 10 times a month (77%). Many of the participants (64%) had received evacuation training from families, schools, and fire agencies. And the majority of participants wore clothes in medium, large, and extra-large sizes.

Questionnaire reliability and validity analysis

The collected questionnaires were statistically analyzed by Statistical Package for the Social Sciences (SPSS) 24.0. Before data analysis, this study adopted a 5-point Likert scale to quantify the results with options to preprocess the collected data. The questionnaire options A, B, C, and D were translated to scores 1, 2, 3, and 4.

Cronbach's α [17] was used to evaluate the internal consistency reliability of the questionnaire, i.e. the homogeneity between the measured variables. The higher the value of Cronbach's α, the higher the internal consistency reliability of the questionnaire. The coefficient of each variable in this questionnaire was greater than the threshold of 0.7, with an overall reliability of 0.731. This indicated that the questionnaire had good internal consistency to meet data reliability requirements. The Kaiser-Meyer-Olkin (KMO) and Bartlett's sphericity tests were used to check the validity of the questionnaire [18]. The KMO of the questionnaire was greater than 0.7, and Bartlett spherical test was significant ($p < 0.05$), which

Table 1 Design of questionnaire variables

Variables	Code	Content
Demographic characteristics (DC)	DC1	Gender
	DC2	Age
	DC3	Education level
	DC4	Frequency of taking the subway
	DC5	Evacuation training experience
	DC6	Outwear size (to find shoulder width)
Knowledge of subway station (KSS)	KSS1	Number and location of subway exits
	KSS2	Emergency evacuation sign literacy
	KSS3	Location of train emergency stop button
	KSS4	Location of emergency stop button of the escalator(s)
Emergency responses and measures during an evacuation (ERMDE)	ERMDE1	Fully aware that fire accident occurred
	ERMDE2	The reaction time required to confirm the accident and start an evacuation state
	ERMDE3	Selection of evacuation route
	ERMDE4	Reaction to congestion at the exit
	ERMDE5	Reaction in case of a large amount of smoke during evacuation
	ERMDE6	Reaction after losing personal belongings
Questionnaire validity	–	Have you ever taken the Xuzhou subway?

Table 2 Summary of demographic information of passengers ($n = 240$)

Category	Description	Percentage (%)
Gender	Male	58
	Female	42
Age (years)	≤18	5
	19–35	63
	36–60	27
	>60	5
Education level	High school and below	11
	Junior college education	12
	Undergraduate	70
	Master or above	7
Frequency of taking the subway	Less than 5 times a month	57
	About 10 times a month	20
	About 5 times a week	17
	At least 10 times a week	6
Evacuation training experience	No experience	36
	School education	35
	Home education	19
	Firefighting organization training	10
Outwear size	S	13
	M	28
	L	18
	XL	25
	XXL	13
	XXXL	3

meant that the questionnaire had a good level of validity, and the variables of the questionnaire can effectively represent the real states of passengers.

Correlation analysis

Demographic characteristics (DC1–6, see Tables 1 and 2) were taken as independent variables. Knowledge of subway station (KSS1–4, see Table 1) and emergency responses and measures during evacuation (ERMDE1–6, see Table 1) were used as dependent variables. The *p*-values obtained by SPSS software will be given later in Table 3. When the *p*-value is over 0.05, it means that the null hypothesis is accepted, i.e. there is an independent relationship between the two variables, otherwise, there is a correlation between the two variables. A total of 17 groups of data were correlated. In particular, there were 7 groups with *p*-values less than 0.01, indicating they were significantly correlated.

Taking passenger response time as an example, it is significantly correlated with age, education level, and evacuation experience. In terms of reaction time and age, young and middle-aged people who accounted for the largest proportion of participants had shorter reaction time and can quickly enter the evacuation state; Between reaction time and education level, the reaction time decreased with the improvement of educational level; Compared with participants without evacuation safety education, the reaction time of participants who received evacuation safety education would be greatly shortened. Thus, in the subsequent simulation, the reaction time of passengers should be diverse.

Construction of agent-based evacuation model

Evacuation environment

The studied subway station has three floors above the ground, of which the first floor is the station hall and the second floor is the platform. The station covers approximately 7025m^2, and the area of each platform is 120 m × 7.7 m. The station hall is centrally symmetrical, with two 3.6 m wide entrances on each side. The ticket gates consist of 8 one-way gates (each 0.5 m wide), 1 two-way gate (0.5 m wide), and 1 wide channel gate (0.9 m wide). These gates are supposed to remain open all the time during an emergency evacuation, so the modeling is simplified to 9 doors with a width of 0.5 m and 1 door with a width of 0.9 m. In addition, the ticket hall beside the ticket gates is equipped with a 1.5 m double door for evacuation.

Each platform on the second floor is connected to the station hall through two sets of upper and lower escalators (1.2 m wide) and an evacuation stair (1.8 m wide). When the subway is set on fire at critical locations (see Fig. 2b), the escalators can be stopped and treated as ordinary stairs. Consequently, in order to simplify the simulation process, the escalators are modeled based on the specifications of ordinary stairs, and the original gradient of the stairs is fixed. The train passengers on the two sides of the platform are not connected and the passenger flow is separated. The simplified diagrams of the platform and station hall are shown in Fig. 2.

Table 3 Correlation between questionnaire variables (*P* value)

Code	DC1	DC2	DC3	DC4	DC5	DC6
KSS1	0.291	0.065	<u>0.013</u>	<u>0.026</u>	**0.001**	0.329
KSS2	0.262	**0.000**	<u>0.012</u>	<u>0.030</u>	**0.005**	0.976
KSS3	<u>0.015</u>	0.159	0.192	**0.004**	0.051	0.453
KSS4	0.053	<u>0.038</u>	<u>0.027</u>	0.529	0.200	0.172
ERMDE1	0.198	0.524	0.575	0.252	0.403	0.104
ERMDE2	0.294	**0.001**	**0.000**	0.733	**0.000**	0.176
ERMDE3	<u>0.042</u>	0.296	0.246	0.985	0.059	0.191
ERMDE4	0.812	<u>0.038</u>	0.253	0.947	0.585	0.217
ERMDE5	0.189	0.235	0.560	0.593	0.453	0.073
ERMDE6	0.689	0.383	0.448	<u>0.047</u>	0.122	0.179

Data underlined indicates correlation (i.e., $p < 0.05$); data with darker background indicate a significant correlation (i.e., $p < 0.01$). DC1–6 are the specific contents of Demographic Characteristics variable, KSS1–4 are the specific contents of Knowledge of Subway Station variable, and ERMDE1–6 are the specific contents of Emergency Responses and Measures During an Evacuation variable (See Table 1 for more details).

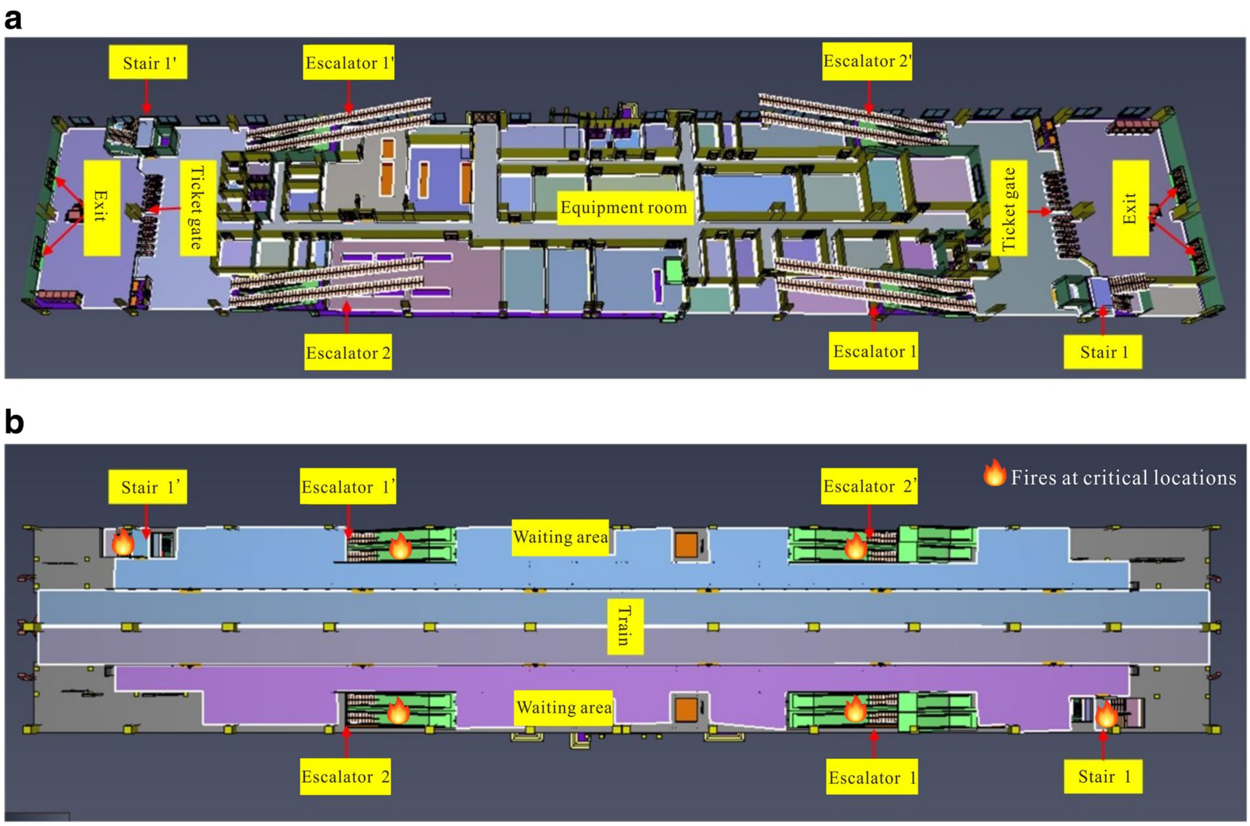


Fig. 2 The simplified diagram of (**b**) the platform and (**a**) station hall

Passenger parameter setting

The evacuation process can be affected by passengers' characteristics, thus, based on the age and gender information collected through questionnaires, passengers were divided into 6 categories. By collecting passengers' clothing sizes through questionnaires and comparing them with the standard size chart, we obtained the actual interval of shoulder width and thoracic thickness data of Xuzhou Metro passengers, and assumed that the data were evenly distributed within the interval. Then, referring to the Human Dimensions of Chinese Adults [19], we finalized the shoulder width and thoracic thickness of different types of passengers.

In an emergency, passengers naturally move faster out of fear, typically about 1.21 times faster than normal [20]. Therefore, we combined the statistical average speed data [21, 22], the results of station field investigation, and the speed correction coefficient (1.21) to set the speed interval of different categories of passengers, and assumed that the speed conforms to uniform distribution within the interval [23]. The characteristics of various categories are shown in Table 4.

Table 4 Characteristics of passengers

Age	Category	Shoulder width (cm)	Thoracic thickness (cm)	Evacuation speed (m/s)	Proportion (%)
≤18	Teenager	[32.5, 40.1]	[16.8, 23.3]	[1.33, 1.44]	5%
19–35	Young male	[37.5, 45.5]	[19.4, 25.6]	[1.60, 1.72]	32%
	Young female	[35.2, 42.7]	[18.3, 24.3]	[1.54, 1.65]	31%
36–60	Middle-aged male	[37.3, 45.3]	[20.7, 25.6]	[1.51, 1.63]	14%
	Middle-aged female	[34.6, 43.2]	[19.5, 24.8]	[1.45, 1.56]	13%
>60	Elderly	[34.3, 42.3]	[19.1, 25.3]	[1.32, 1.42]	5%

Code for design of metro in China stipulates a response time of 60s for passengers to evacuate. And in some literature [24, 25], the reaction time is usually set as a fixed value. However, the results of the correlation analysis showed that evacuation reaction time would be affected by the age, education level, and evacuation experience of passengers. Therefore, the reaction time of passengers should be different, and it is good to set the reaction time within an interval. According to the actual emergency response of subway passengers in Xuzhou reflected in the previous questionnaire survey, we reduced the fastest reaction time of passengers by 30s, i.e. the reaction time of passengers varied within the interval range [30s, 60s] and was subject to the uniform distribution.

Passenger number setting

The specification of a subway train is 120 m × 2.88 m. There are 24 doors opened to allow passengers to exit trains to one side of the platforms. The width of each exit is 1.3 m. When the subway train seats are full and the number of people standing on the effective free floor area per square meter is 6, the rated passenger capacity of one train (6 B-type carriages) is 1380 [26]. Based on the design data of Xuzhou Metro Line 1 to predict the morning peak passenger flow of the station, the number of passengers on the platform and station hall is estimated to be 300 and 90 respectively. Considering one of the most dangerous situations, i.e. the trains filled with passengers in both directions enter the station simultaneously during the morning peak, the total number of evacuees can be determined to be 3150. The distribution of passengers in the station is shown in the following Table 5.

Table 5 The distribution of passengers in the station

Location	train	platform	station hall
Number of passengers	2760	300	90
Total number	3150		

Simulation and analysis

Simulation under normal condition

Before the evacuation simulation in the fault scenarios, the evacuation of station passengers under normal condition was conducted first, and the results were set as the control group. The passengers evacuate from the subway trains to the platform first and then move to the exits. Only when all passengers in the station evacuate safely within 6 min, the simulated evacuation is deemed to be successful. As the platform is symmetric, only half of the platform is analyzed and discussed.

The total evacuation time under normal condition was 278.2 s, which was less than 6 min required by the standard. Hence, it can be considered that the station was able to complete the passenger evacuation under normal condition successfully. As can be observed in Fig. 3, the number of passengers remaining at the station (i.e. curve Remaining (total) in Fig. 3) decreased at around 41.5 s, which meant that the first passenger successfully exited the station at 41.5 s. And the number of passengers on the right side of the train remained unchanged at 1380 for 31 s (i.e. curve Train_Right in Fig. 3, train in one direction), due to the need for the determined reaction time of passengers before evacuation. While the number of passengers on the right side of the platform (i.e. curve Platform_Right in Fig. 3, half side of the platform in Fig. 2b) reached a peak of 934 around 90s, and then began to decline slowly. Since a

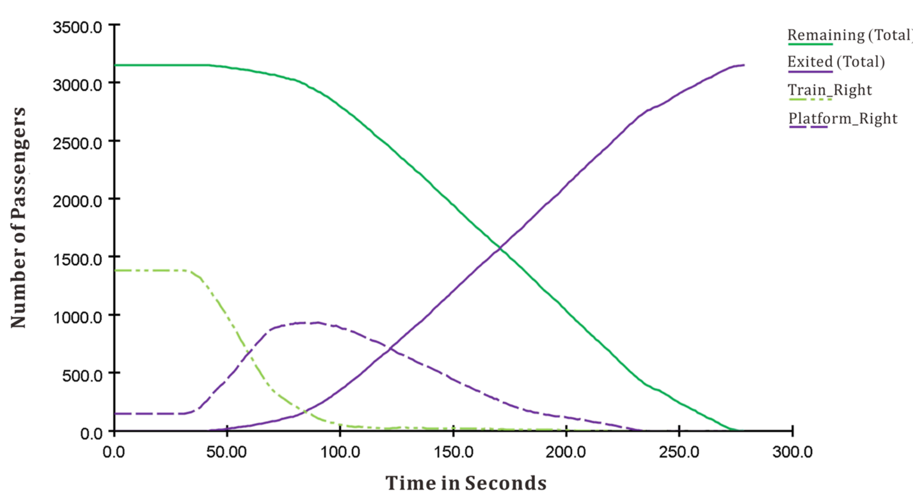


Fig. 3 Changes in passenger numbers during the evacuation

large number of passengers in the train poured into the platform at beginning of the evacuation, the platform's evacuation capacity was limited, leading to temporary crowds. However, with the continuous evacuation of the crowd in the later stage, congestion gradually disappeared, and the passengers who remained in the station showed a steady downward trend.

Passenger flow rate at critical locations is analyzed in Fig. 4. As can be seen from Fig. 4(a), the first passenger successfully evacuated in Stair 1, and the evacuation speed reached a peak of 2.18 person/s at 52 s. At about 90s, all evacuation passages reached the maximum load, and congestion began to emerge. The maximum evacuation efficiency of these three passages was almost the same, and the average flow rate was about 2 person/s. When the evacuation was carried out around 186 s, the evacuations of Stair 1 and Escalator 1 were completed, whereas Escalator 2 was still crowded, and its evacuation state of the full load was maintained until the end of the evacuation. Each escalator (Escalator 1, 2, see Fig. 4) has left and right parts, meaning the ascending and descending directions under normal operation.

It showed that passengers tended to choose the closest exit in the process of the evacuation, which often led to significant congestion of a certain evacuation passage, resulting in a great increase in evacuation time. The cumulative number of passengers versus time is plotted in Fig. 4(b), which intuitively reflects that Escalator 2 bore a heavier evacuation load (i.e. more passes). Figure 5 shows the heat maps of the simulated agents at different times during the evacuation. It can be seen that a number of passengers were still gathered at the entrance of Escalator 2 on the platform at 186 s.

In summary, in terms of maximum evacuation efficiency: a) The rate of all three passages was about 2 person/s; b) Working time: Escalator 2 > Stair 1 > Escalator 1; c) Flow rate of evacuated passengers: Escalator 2 > Escalator 1 > Stair 1.

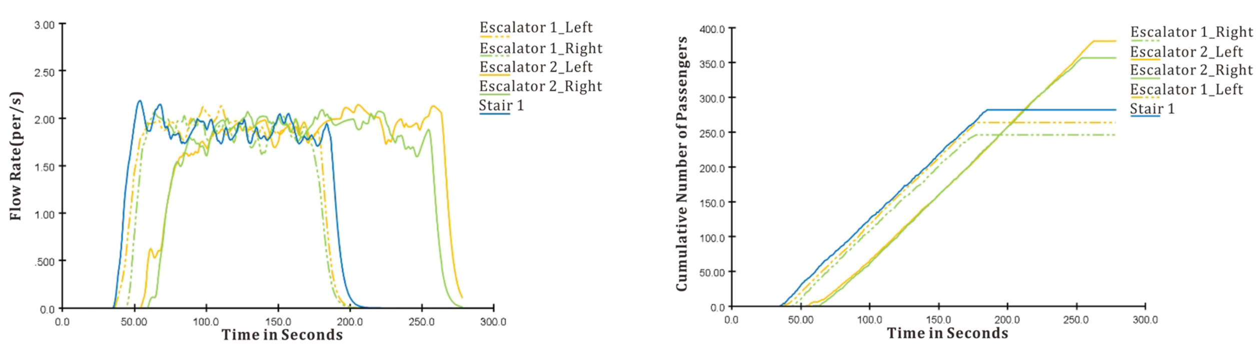
Fire scenario setting

In case of fire, the stairs can have two states: unusable and normal; the escalators can have three states: normal, brake failure, and unusable. An "Unusable" stair or escalator means that a fire occurs in the stair or escalator, resulting in the loss of passability. The term "brake failure" means that passengers fail to stop the escalator due to their ignorance of the stop button or the failure of the stop button itself, and only half of the escalator (i.e. descending direction) can be used for evacuation.

In this study, failure events "Stairs 1 unusable", "Escalator 1 brake failure", "Escalator 2 brake failure", "Escalator 1 unusable" and "Escalator 2 unusable" are denoted as failure events X_1, X_2, X_3, X_4 and X_5 respectively. Then, the failure states of the three evacuation passages are combined. The occurrence of each failure is regarded as a Boolean variable (0 for normal and 1 for failure). When all passages (i.e. Stair 1, Escalator 1, and Escalator 2) fail, the evacuation will inevitably fail. Such a "worst" scenario is excluded. In addition, X_2 and X_4, X_3 and X_5 are mutually exclusive. A total of 16 scenarios were identified as shown in Table 6.

Outcome of different failure scenarios

The simulation results of 16 failure scenarios are shown in Table 7. When considering a single failure event, there are two scenarios that can lead to the failure of station evacuation: X_4 or X_5; Any combined failure events (scenarios 6–16) are found to cause evacuation failure of the subway station.



(a) Passenger flow rate diagram of evacuation passage (b) Number of passengers in the evacuation passage

Fig. 4 Change diagram of passenger flow in evacuation passage

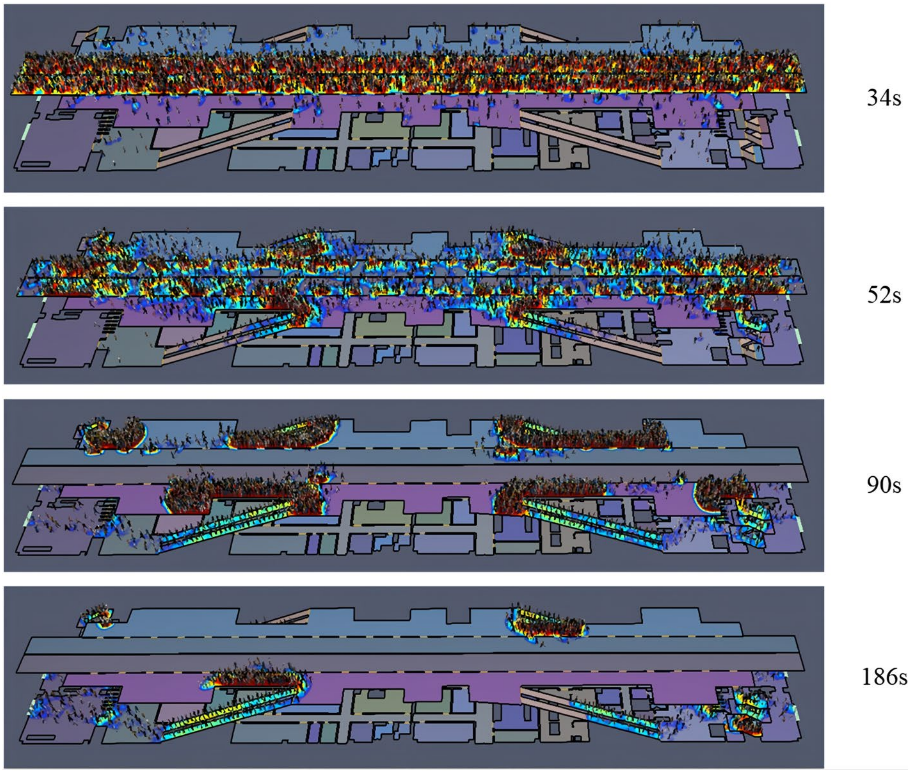


Fig. 5 Screenshots of passenger evacuation under normal condition

Table 6 Scenario setting

Test scenario	Stair 1 Unusable X_1	Escalator 1 Brake failure X_2	Escalator 2 Brake failure X_3	Escalator 1 Unusable X_4	Escalator 2 Unusable X_5
Scenario 1	1	0	0	0	0
Scenario 2	0	1	0	0	0
Scenario 3	0	0	1	0	0
Scenario 4	0	0	0	1	0
Scenario 5	0	0	0	0	1
Scenario 6	1	1	0	0	0
Scenario 7	1	0	1	0	0
Scenario 8	1	0	0	1	0
Scenario 9	1	0	0	0	1
Scenario 10	0	1	1	0	0
Scenario 11	0	1	0	0	1
Scenario 12	0	0	1	1	0
Scenario 13	0	0	0	1	1
Scenario 14	1	1	1	0	0
Scenario 15	1	1	0	0	1
Scenario 16	1	0	1	1	0

Table 7 Results of different failure scenarios

Scenario	Description	Evacuation time (s)	Evacuation outcome
Scenario 1	X_1	292.7	success
Scenario 2	X_2	329.5	success
Scenario 3	X_3	341.3	success
Scenario 4	X_4	416.5	failure
Scenario 5	X_5	410.0	failure
Scenario 6	X_1 and X_2	425.3	failure
Scenario 7	X_1 and X_3	383.7	failure
Scenario 8	X_1 and X_4	480.0	failure
Scenario 9	X_1 and X_5	486.8	failure
Scenario 10	X_2 and X_3	386.6	failure
Scenario 11	X_2 and X_5	564.5	failure
Scenario 12	X_3 and X_4	545.4	failure
Scenario 13	X_4 and X_5	1094.8	failure
Scenario 14	X_1, X_2 and X_3	487.4	failure
Scenario 15	X_1, X_2 and X_5	893.4	failure
Scenario 16	X_1, X_3 and X_4	865.7	failure

Evacuation evaluation model based on fault tree analysis

A fault tree is a tree type of logic to express different scenarios of events that can lead to the failure of a system. In this study, a fault tree is adopted to visualize the combinations of events that lead to evacuation failure in the subway station, based on the above scenario analysis. Basic events X_1, X_2, X_3, X_4 and X_5 are represented by the circles shown in Fig. 6. The evacuation failure caused by the combined failure events is simplified into three intermediate events (shown in the boxes in Fig. 6), namely M_1 (X_1 and X_2), M_2 (X_1 and X_3) and M_3 (X_2 and X_3). M_1, M_2, M_3, X_4 and X_5 are connected to the top event T (evacuation failure of the subway station).

The relationship of the events is connected by "AND" or "OR" logic gates. The "OR" logic gate means any failure event (M_1, M_2, M_3, X_4, or X_5) will lead to the failure of the whole system. The "AND" logic means when all the bottom events occur at the same time, the occurrence of intermediate events will be triggered. Through the above tree-like structure decomposition of the subway evacuation fault tree, the fault tree model of subway evacuation can be gained, as shown in Fig. 6. Such a fault tree reveals failure logic and can be applied to any other subway station. In addition, escalators (X_4, and X_5) are critical evacuation facilities and evacuation will fail once any of them fail.

Conclusions

This study first conducted a questionnaire survey to collect passenger characteristics of subway passengers. On this basis, agent-based modeling was used to simulate passenger evacuation under single or combined scenarios where fires cause impassability. A fault tree analysis is developed to express the logic of events that can lead to the failure of the studied subway station. The results show that:

(1) The passability of escalators is essential to a successful evacuation in case of fires. Escalators bear the most passenger flow during evacuation. Once a fire takes place and causes the impassability of escalators, the subway evacuation will be bound to fail. Therefore, the subway station should pay particular attention to the facility management of escalators.

(2) It is important to stop escalators in case of fires. If escalators fail to brake, only one direction can pro-

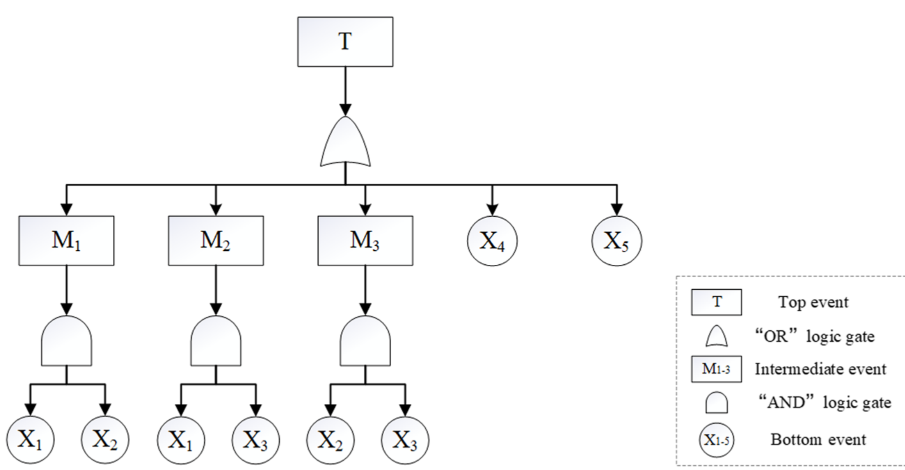


Fig. 6 A fault tree model of subway evacuation considering the failure of evacuation passage

vide passability and half of the capacity will lose. The subway station should popularize the knowledge of safe evacuation to the passengers and staff to better operate and brake the escalators.

(3) In the correlation analysis, gender, age, education level, frequency of taking the subway, and evacuation experience in the basic characteristics of passengers can impact emergency responses. The demographic characteristics of passengers should be analyzed by subway operators to better manage evacuation in case of fires.

The risk factors of subway evacuation are very complex. When constructing the fault tree, this study only considers the impact of the single factor of evacuation passages, which leads to a limited tree structure but with good scalability. In the future, more failure scenarios can be considered (e.g. the ticket gate) to construct a more generic fault tree for subways.

Abbreviations

DC	Demographic characteristics
KSS	Knowledge of subway station
ERMDE	Emergency responses and measures during an evacuation

Acknowledgments
Not applicable.

Authors' contributions
Y.Q. designed the research methods and was a major contributor in writing the manuscript. Y.W. established the fault tree based on the simulation results and was another contributor in writing the manuscript. X.S. contacted the management personnel of the subway station to provide BIM model. Z.Z. helped designed the research methods and edited the manuscript. C.L. conducted and analyzed agent-based simulation. X.Z. collected and analyzed the questionnaire data. J.L. provided feedback on the structural organization of the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
All data generated or analyzed during this study are included in this published article.

Declarations

Competing interests
The authors declare that they have no competing interests.

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