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Pedestrian Evacuation Modeling and Simulation on Metro Platforms Considering Panic Impacts

Fang Li, Shaokuan Chen*, Xiudan Wang, Fu Feng

MOE Key Laboratory for Urban Transportation Complex Systems Theory and Technology, Beijing Jiaotong University, No.3 Shangyuancun, Haidian District, Beijing 100044, P.R. China

Abstract

A pedestrian evacuation model is presented, in which the social force model and a mathematical model are incorporated. The social force model is capable of describing the pedestrian behavior realistically under the non-panic evacuation situations. However, a series of catastrophes make us reasonably think about crowd dynamics under stress and panic. In order to forecast the catastrophe point of pedestrian mood changes in a real emergency situation, a mathematical model is proposed by considering residence time, crowd density and exit distance. This paper follows the implementation of the system simulation modeling environment written in Java program language on AnyLogic simulation software to facilitate studying the panic spread mechanisms of passengers. Furthermore, different simulation scenarios on passenger evacuation from the platform of the Xizhimen Metro station in Beijing are carried out to validate the feasibility of the proposed method and to further evaluate the influence of evacuees' number and pedestrian distribution on evacuation efficiency when passenger panic is spreading.

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Keywords: Metro station; Passenger evacuation time; Panic evacuation model; Panic spread time; Panic rate

1. Introduction

Pedestrians are generally confined to the limited space due to its airtight, independence and other characteristics during the evacuation processes from metro stations. Trapped people are the largest uncertainties because their motives and actions are dynamic and the panic behavior which may occur is basically maladaptive. In short, panic is

* Corresponding author. Tel.: +86-(0)10-5168-8695.
E-mail address: shkchen@bjtu.edu.cn

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a focus of attention because it is thought to be a major potential human problem in most situations of sudden extreme stress. Therefore, it is an urgent issue for crisis management to study the characteristics of panic spreading in unconventional emergencies of metro stations.

The layouts of metro station and their impacts on evacuation considering the change of human behavior incurred by panic should be paid attention to when an emergency event occurs. The existing studies on simulation technology of emergency evacuation mainly incorporated with accident investigation (Yang et al., 2010), controllable experiments (Ge et al., 2011), mathematical-physical modeling (Helbing et al., 2006; Chen et al., 2008 & 2012) and animal-based crowed experiments (Nirajan et al., 2011) to recur evacuation processes. Moreover, some literatures have been given on the study of the impacts of inner emotional on evacuation behavior (Fruin, 1971; Helbing et al., 2005; Zhang et al., 2005; Tetsuya et al., 2012; Wang et al., 2012).

Fruin (1971) introduced the concept of the panic parameter to study the panic evacuation and found that occupant density has a great impact on the evacuation speed when the panic parameter is low and congestion is more prone to occur at the bottleneck while the panic parameter is high. Helbing et al. (2005) established a mathematical function which implied that desired speed changes with the panic degree and verified the effects of "faster-is-slower" and "freezing-by-heating" under the panic state. Zhang et al. (2005) analyzed pedestrian's velocity while the road condition is changing under time pressure and proposed the concept of partial decreasing coefficient of speed on curvilinear road and downstairs. Tetsuya et al. (2012) established an aircraft emergency evacuation model to reflect the resulting selfish behavior of those panic passengers and to further evaluate the performance of the proposed model by comparing the simulation results and an actual aircraft accident. Wang et al. (2012) established a qualitative simulation model of a large-scale evacuation system based on the qualitative knowledge to study the influence of some factors on panic spreading. This model confirmed that the severity of disaster exponentially positively correlates with the panic spreading and the effectiveness of rescue guidance is influenced by the leading emotion in the crowds as a whole.

Insufficient research has focused on modeling the characteristics of panic spreading. In this study, a model is proposed to further describe panic spread phenomena and its influence on evacuation efficiency. Its unique features and advantages over the existing models are twofold: (1) Passengers' critical psychical characteristics, e.g. residence time, crowd density and exit distance, are taken into account to distinguish whether the passenger is panic or not. (2) Improvements are made to enhance the accuracy of the simulation model from two aspects. First, the proposed model together with the agent-based approach is utilized to simulate movements of individual passengers in an emergency evacuation process. Second, for normal (non-panic) conditions, each individual passenger is able to change his/her desired speed according to the density within a circle with one-meter radius from the current position in a real-time manner. For panic conditions, each individual passenger changes his/her desired speed with the critical level. The proposed model in this paper is used to simulate panic evacuation processes based on the AnyLogic software.

2. Model formulation

2.1 Evacuation model for non-panic situation

Non-panic behavior rules strictly obey the social force model (Helbing et al., 2005), which is defined by the following equation of motion.

$$f_i = m_i \frac{d\vec{v_i}(t)}{dt} + \sum_{(i \neq j)} f_{ij} + \sum_w f_{iw} + \varepsilon_i(t), \quad (1)$$

where f_i is the sum of the social forces influencing pedestrian i.

$m_i \frac{d\vec{v_i}(t)}{dt}$ is the driving force when pedestrians keep desired speeds.

$\sum_{(i \neq j)} f_{ij}$ and $\sum_w f_{iw}$ are the repulsive forces describing attempts to keep a certain safety distance to other pedestrians j and obstacles w, respectively.

$\varepsilon_i(t)$ is the individual fluctuations force reflecting unsystematic behavioral variations.

In the situation of non-panic, the value of the desired speed V_i changes with the density ρ. This study utilizes the correction fitting functions (Chen et al., 2008 & 2012) for pedestrians in the Xizhimen station described as in Eq. (2) and Eq. (3), which express the relations between desired speed (m/s) and density (people/m^2) of pedestrians on the platform and upstairs of Line 2 in the Xizhimen station respectively.

$$V_i = 0.0011\rho^4 - 0.0273\rho^3 + 0.2448\rho^2 - 1.0359\rho + 1.7079, \quad (2)$$

$$V_i = -0.0025\rho^3 + 0.0441\rho^2 - 0.2723\rho + 0.8634. \quad (3)$$

2.2 Evacuation model for panic situation

The panic behavior of pedestrians is affected not only by emergency situation but also by the characteristics of agents, environmental condition and the response of pedestrians to emergency. The proposed model shows various levels of emotion depending on the mental condition of a pedestrian by considering three crisis factors: residence time t, crowd density ρ and exit distance d. The corresponding effects on evacuation are defined as $f(t)$, $g(\rho)$, $h(d)$, which are all non-decreasing functions since the oppressive feeling of pedestrian does not decrease in emergency.

There is an assumption given here that a critical point of residence time t^L exists in the model and $f(t^L)$ is the corresponding critical degree. If t is lower than t^L, the residence time is not enough to compel agents to exhibit panic behavior. Otherwise, if t is higher than t^L, the panic behavior of pedestrians will occur. To furthermore determine the time when panic behavior occurs, the panic threshold level L_0 is defined as follows.

$$\begin{cases} L_0 = \min(f(t^L), g(\rho^L), h(d^L)) \\ f(t) = (1 + e^{-(\frac{10.6t}{t^*} - 5.3)})^{-1} \\ g(\rho) = (1 + e^{-(\frac{10.6\rho}{\rho^*} - 5.3)})^{-1} \\ h(d) = (1 + e^{-(\frac{10.6d}{d^*} - 5.3)})^{-1} \end{cases}, \quad (4)$$

where t^L is the critical point of residence time and its value is 60 seconds, which denotes the respond time of pedestrians.

ρ^L is the critical point of density which is set to 3.33(p/m^2) (Fruin, 1971).

d^L is the critical point of exit distance, which is the farthest distance towards the exit of non-wandering area.

t^* is the maximum tolerable value of residence time, which is the average evacuation time obtained by the non-panic evacuation model in Section *2.1*.

ρ^* is the maximum tolerable value of density which is set to 5.0(p/m^2) (Fruin, 1971).

d^* is the maximum tolerable value of exit distance, which is the farthest distance towards the exit of wandering area.

$0 \le f(t) \le 1$, $0 \le g(\rho) \le 1$, $0 \le h(d) \le 1$.

For a certain pedestrian, the crisis level L_{p0} of his/her real time is given by

$$\begin{cases} L_{p0} = a \times f(t) + b \times g(\rho) + c \times h(d) \\ a + b + c = 1 \end{cases}, \quad (5)$$

where a, b and c are weighting factors.

The influence degree of the residence time ε_{pt} is defined as follow.

$$\varepsilon_{pt} = (|T_{pt} - T|/T) \times 100\%, \quad (6)$$

where the evacuation time merely influenced by the residence time T_{pt} is able to be obtained when a equals 1. The non-panic evacuation time T is obtained by the model in Section *2.1*. The influence degree of density $\varepsilon_{p\rho}$ and exit distance ε_{pd} on evacuation are obtained as similar as Eq. (6).

The weighting factor of the residence time a is given by

$$a = \varepsilon_{pt}/(\varepsilon_{pt} + \varepsilon_{p\rho} + \varepsilon_{pd}). \quad (7)$$

The weighting coefficients b and c of density and of exit distance are obtained as similar as Eq. (7).

The crisis level L_{p0} of a certain pedestrian in the AnyLogic software is calculated once per second. Agents exhibit panic behavior when L_{p0} is higher than L_0 and their desired speeds are described as Eq. (8).

$$V_i = (1 - L_{p0}) \times V_0 + L_{p0} \times V_{max}, \quad (8)$$

where V_0 is the initial desired speed under the non-panic situation.
V_{max} is the maximum desired speed under the non-panic situation.

3. Simulation validation

Conducting a real metro evacuation trial is oftentimes unaffordable as it is extremely expensive and may cause severe injury to participants. Simulation models as an alternative have been used to overcome the aforementioned issues in recent years. Based on the proposed model, a simulation program is developed in our study.

3.1 Simulation background

AnyLogic is a dynamic simulation tool which provides the pedestrian library for simulating pedestrian flows in a certain environment and allows embedded models to simulate pedestrian psychology by further development. In the proposed model, pedestrian evacuation is considered as a process of perception, decision-making and action which are described as below.

Perception: An agent can not only perceive the interaction with others and obstacles, but also collect information to judge whether the agent is panic or not.

Decision-making: Agents make decisions according to the perception, such as choosing the shortest evacuation route, changing desired speeds, directions and surpassing others.

Action: Specific behavior rules are consistent with the pedestrian library of AnyLogic based on the social force model.

The flowchart of the evacuation simulation model is shown in Fig. 1.

Evacuation complies with the following rules.

- At the beginning of evacuation, pedestrians are randomly distributed on the platform.
- Since the beginning of evacuation, stairs on both sides of the platform turn into up-going operation.
- In the simulation process, the behaviors that evacuees surpass others, rotate, lateral walk and step backward slightly are allowed.

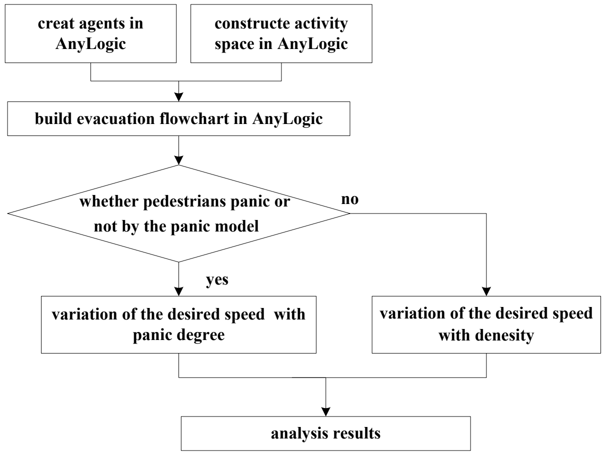

Fig. 1. Flowchart of agent-based evacuation simulation

3.2 Simulation settings

Taking the platform of Metro Line 2 in the Xizhimen station for example, the platform is divided into wandering area and non-wandering area. Wandering area means the middle zone of the platform where pedestrians are more far away from the both exits than those in the non-wandering area. The layout of platform in the Xizhimen station along Metro Line 2 is illustrated in Fig. 2.

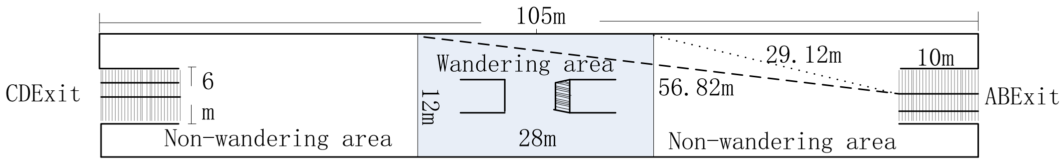

Fig. 2. Layout of platform in the Xizhimen station along Metro Line 2

The evacuation simulation is first implemented for the scenarios without any train stopping when an emergency occurs. Seven evacuation simulations are performed using the proposed model by incorporating panic impacts to study the impact of evacuees' number on evacuation processes. The numbers of seven scenarios are 356, 656, 956, 1800, 2156, 2456 and 2756, respectively. For comparison, simulations without consideration of panic impacts are also performed. Furthermore, in order to analyze the influence of pedestrian distribution on evacuation efficiency when panic is spreading, the evacuation simulation is also carried out for two groups of scenario where they both have the same number of evacuees but the different initial position. One group with train consists of the scenario 8, 9 and 10, which not only includes 1800 pedestrians on the train, but also includes 356, 656 and 956 pedestrians on the platform, respectively. As a comparative study, the other group without train consists of the scenario 5, 6 and 7, which includes 2156, 2456 and 2756 pedestrians on the platform, respectively.

To calibrate the panic evacuation model, the parameter values of t^L, ρ^L and ρ^* are obtained from the corresponding results in literatures, d^L and d^* are able to be directly measured, t^* is estimated from simulation trials because of the difficulty in direct measurements. The weighting factors of residence time, crowd density and exit distance for each scenario are shown in Table 1.

Table 1. Calibration on weighting factors in simulation

Scenario index	Total number of pedestrians	Pedestrian distribution		L_0	*a*	*b*	*c*
		platform	train				
1	356	356	0	0.71	0.40	0.20	0.40
2	656	656	0	0.71	0.294	0.588	0.118
3	956	956	0	0.71	0.196	0.549	0.225
4	1800	1800	0	0.59	0.327	0.635	0.038
5	2156	2156	0	0.37	0.597	0.226	0.177
6	2456	2456	0	0.25	0.706	0.088	0.206
7	2756	2756	0	0.20	0.4	0.519	0.081
8	2156	356	1800	0.296	0.500	0.409	0.091
9	2456	656	1800	0.237	0.278	0.470	0.252
10	2756	956	1800	0.177	0.228	0.475	0.297

4. Simulation analysis

Pedestrians may exert stressful actions when panic is spreading. Therefore, it is very necessary to understand the transmission mechanism of panic by analyzing the panic spread time and panic rate. Besides, an important characteristic of evacuation is the evacuation time which is an essential property in the representation of human survivability in evacuation models.

4.1 Panic spread time (PST)

The panic spread time means the duration between the starting moment when the first pedestrian shows panic and the ending moment when there are not any more panic pedestrians. Under this definition, it is obvious that the panic spread time varies with the number of evacuees and pedestrian distribution as shown in Figure 3 and Figure 4. From these figures, it is able to conclude that the panic spread time ranges from 32 seconds to 74 seconds, which means that the panic spread time varies with different scenarios.

The panic spread time in the scenarios with different number of evacuees are shown in Fig. 3. In Scenario 1, none of the pedestrians exhibits panic behavior as there are only 356 pedestrians on the platform and the flow is unimpeded. From scenario 2 to 7, panic spread time increases gradually. However, it appears a downward trend when the number of pedestrians exceeds a certain value (2156), because crowded pedestrians accelerate the panic spreading in addition to emergency situation.

The panic spread time in the situations with different pedestrian distribution are shown in Fig. 4. It can be seen that the spreading of panic is more quickly in the scenarios without train stopping (scenario 5, 6 and 7) than that in the scenarios with train stopping (scenario 8, 9 and 10). In former situations, an initial high density of pedestrians on the platform accelerates the spreading speed of panic significantly. This may occur because passengers may scramble to reach egress exits as soon as possible in a real emergency situation. This will result in more frequent interactions while all of the pedestrians are gathering at egress exits than those situations that most of the pedestrians gather in trains.

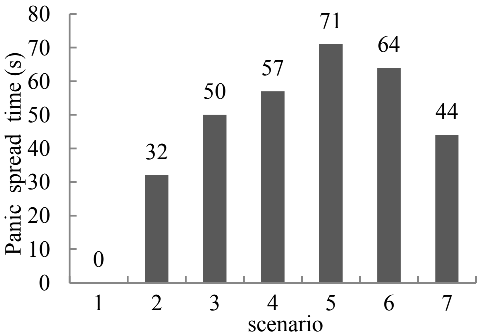

Fig. 3. Influence of evacuees' number on the PST

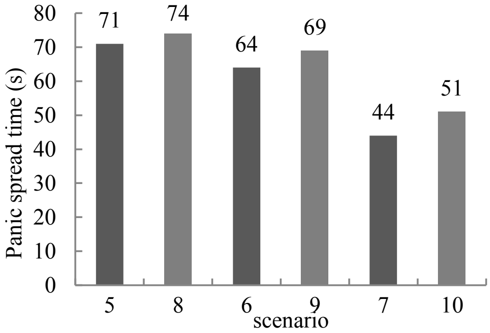

Fig. 4. Influence of pedestrian distribution on the PST

4.2 Panic rate (PR)

The panic rate is calculated by the ratio of the number of panic pedestrians to residual pedestrians, which are both dynamically changing in the process of evacuation.

The comparison of panic rate for different number of evacuees is shown in Fig. 5. In Scenario 1, pedestrians escape so quickly that panic does not occur in an unimpeded flow. Scenario 2 and 3 show the variation of panic rate which are divided into three stages. In the first stage, danger is not strong enough to threaten pedestrians' psychology so that the panic rate is zero in the whole process of evacuation. In the second stage, pedestrians begin to feel threatened, which results in the increasing of the panic rate. In the last stage, pedestrians have a higher expectation of escape speeds with less pedestrians remaining. Meanwhile, panic passengers are more inclined to escape immediately than non-panic passengers, which lead to the panic rate lowered. In the scenario 4, 5, 6 and 7, the panic rate presents the same increasing trend. The reason is that apart from the emergency itself, the congestion at the bottleneck of entrance to stairs makes more pedestrians in panic when the amount of evacuees reaches a high level. According to aforementioned analysis, the variation of panic rate in the evacuation process is influenced by the initial number of evacuees.

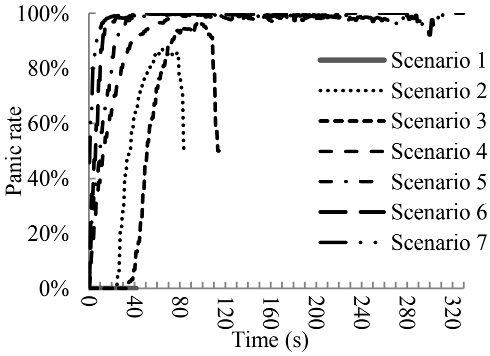

Fig. 5. Influence of evacuees' number on the PR

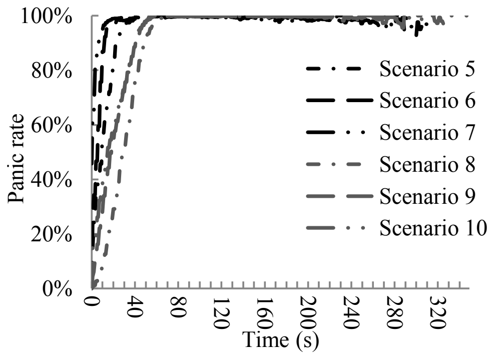

Fig. 6. Influence of pedestrian distribution on the PR

The curves of panic rates obtained from the simulation results for different scenarios with and without trains are illustrated in Fig. 6. Pedestrians in the scenario 5 are more prone to panic than that in the scenario 8 although both scenarios contain 2156 pedestrians. This may occur because all pedestrians are initially walking on the platform and the over-crowded pedestrians make the panic rate be increasing rapidly in the former scenario. However, the 1800 evacuees in trains have to go through train doors to the platform in the scenario 8. Meanwhile, the distribution of the rest 356 pedestrians on the platform is sparse, which makes the panic rate declined. The variation of panic rate in the evacuation process is also influenced by pedestrian distribution.

4.3 Evacuation Time

The evacuation time, which is a key factor to balance the probability of their survival, refers to the time that all pedestrians completely escape to safe zones. The evacuation times with or without taking panic into account are summarized in Table 2. Panic behavior sometimes may be helpful to the evacuation efficiency. In the former six scenarios, if there are more evacuees on the platform whose number is limited under a certain value (1800 persons), the evacuation time will be less and the evacuation efficiency will be more favorable; otherwise the increment of evacuation efficiency shifts into a declining trend and eventually has a negligible effect when the number of evacuees exceeds the certain value (1800 persons). Moreover, panic behavior may bring disastrous consequences. In scenarios 7 to 10, most evacuees quickly flock to stairs, which causes friction forces from multiple directions. If such strong local interactions delay people by a few seconds, even a fraction of one second, it may reduce the probability of their survival. In this way, the disorder state is not favorable to improve the evacuation efficiency in these scenarios.

Table2. Simulation results of evacuation time

Scenario index	Evacuation time	Pedestrian's distribution		Evacuation time without panic (s)	Evacuation time with panic (s)	Changes of evacuation time (s)	Changes of evacuation efficiency
		Platform	Train				
1	356	356	0	56.33	56.33	0	0
2	656	656	0	88.33	83.00	-5.33	6.03%
3	956	956	0	121.33	116.00	-5.33	4.39%
4	1800	1800	0	208.67	191.67	-17.00	8.51%
5	2156	2156	0	252.67	247.00	-5.67	2.24%
6	2456	2456	0	289.00	284.67	-4.33	1.50%
7	2756	2756	0	312.67	330.33	17.66	-5.65%
8	2156	356	1800	262.67	270.67	8.00	-3.05%
9	2456	656	1800	285.67	309.67	24.00	-8.40%
10	2756	956	1800	313.00	351.67	38.67	-12.35%

5. Summary and Conclusions

An emergency evacuation model on the platform of metro is proposed by considering residence time, crowd density and exit distance. This paper demonstrates the effectiveness of the proposed model through different simulation scenarios. The contributions of this study can be summarized as follows.

(a) The number of evacuees has an obvious impact on the spreading of panic. In the case studies of the Xizhimen station, the more evacuees there are, the longer panic spread time is needed. However, the panic spread time decreases when the number of evacuees exceeds a certain value (2156 persons).

(b) The panic spreading of pedestrians in the evacuation process is influenced by pedestrian distribution. Panic spreads faster and the pedestrians are more prone to bring panic behavior when all of the pedestrians are initially gathering on the platform of the Xizhimen station.

(c) It is demonstrated by the simulation results of the Xizhimen station that panic behavior affects the evacuation efficiency of whole pedestrian group.

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