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# Fuzzy-theory-based social force model for simulating pedestrian choice of ticket gates in subway stations

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Ticket gates are vital equipment within subway stations, which have also caused bottlenecks in pedestrian flow. The effective utilization of ticket gates can enhance the pedestrian traffic efficiency. Nevertheless, pedestrian choice of ticket gates has the characteristics of uncertainty and fuzziness. In this regard, we build a fuzzy-theory-based pedestrian choice model of ticket gates: the distance, queuing pedestrians and luggage are adopted as three input variables in the fuzzy logic method, and the probability of selecting each ticket gate is set as the output variable. On this basic, we employ social force model (SFM) to simulate the ticket gates selection process in subway stations. Simulation results demonstrate that the choice model based on fuzzy logic can capture pedestrian choice behavior of ticket gates well. In comparison to traditional choice strategies (choosing the nearest ticket gate or choosing the ticket gate with the fewest queuing pedestrians), the proposed choice model of ticket gates based on fuzzy logic has the higher passing efficiency and the utilization of ticket gates is more balanced. The outcomes of this research can provide substantial support for the humanized design and operation management of subway stations.

**Keywords:** pedestrian dynamic, pedestrian simulation, ticket gates, fuzzy logic, social force model

**PACS:** 89.40.–a, 02.50.Cw, 05.65.+b

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## 1. Introduction

### 1.1. Background

With the rapid advancement of urbanization in China, urban rail transit has made significant progress. Many cities, particularly megacities such as Beijing and Shanghai, China, have gradually established and expanded subway networks. Subways are characterized by their large transportation capacity, high speed, low energy consumption, and minimal pollution, making them pivotal in urban transportation. Subway stations usually have a large number of passengers gathering and distributing, especially during peak hours, which can easily lead to overcrowding and stampede accidents. The scientific management and effective organization of pedestrian flow within subway stations are of paramount importance to alleviate congestion and ensure the safety and comfort of pedestrian traffic.[1,2]

Ticket gates are vital equipment within subway stations, employed for the monitoring, control and management of passengers' entering and exiting.[3] These ticket gates play a pivotal role in contemporary urban transportation systems, with the primary objective of ensuring the safety, orderliness, and compliance with ticketing regulations within subway stations. Moreover, it can record the number of passengers entering and exiting the station, aid station management personnel in monitoring peak and off-peak periods of passenger flow, enhance platform safety, and reduce instances of fare evasion. It provides data for the analysis of travel patterns and the study of passenger behavior, which in turn contributes to the enhancement of subway system planning, management and optimization.[4]

The bottlenecks of pedestrian flow caused by ticket gates often lead to congestion and low efficiency. When pedestrians arrive at the ticket gates, they need to select a target ticket gate, and swipe card or scan code to pass through. Ticket gate selection behavior constitutes a significant subject of study in pedestrian flow within subway stations. As well known, strategy I (choosing the nearest ticket gate) and strategy II (choosing the ticket gate with the fewest queuing pedestrians) are two traditional ticket gate choice methods in pedestrian simulation.[5] Nevertheless, in actual situations, the selection process is not so straightforward but involves significant ambiguity and uncertainty. Pedestrian's individual attributes, queue conditions, and surrounding environment are all potential influencing factors. Understanding the queuing mechanism of pedestrians at the ticket gates and the characteristics of ticket gate selection has great significance. How to build a scientific and reasonable ticket gates selection model and simulate

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pedestrian movement patterns worth further research.

### 1.2. Related studies

(i) Pedestrian choice of ticket gates

In the urban rail transit system, passengers need to swipe card or scan code in front of ticket gates to entry and exit stations. It is easy to gather pedestrians in front of ticket gates and cause crowd phenomenon.[6,7] Pedestrians form queues in front of ticket gates and choose the target ticket gate to pass through. Zheng *et al*. developed a novel queuing line concept and analyzed the pedestrian queuing process in front of ticket gates.[8] Analyzing the queuing characteristics of ticket gates based on actual data, Mx/G/1 model is used to describe it.[9,10] Mo *et al*. analyzed passenger behavior in choosing the ticket gates of subway, defined the pedestrians' preference of proximal gate machine, and built a mathematical model through field research,[11] which also reflected the heterogeneity of pedestrians. Li *et al*. proposed a ticket gate choice model considering the minimum estimated travel time,[5] however, this model is idealized and deviated significantly from the actual situation. In an emergency evacuation, all ticket gates are open, but the balanced utilization of ticket gates will affect the evacuation efficiency. Passenger volume, space layout and pedestrian heterogeneity are the factors affecting the balanced utilization of ticket gates.[12] Fu *et al*. analyzed the effect of ticket gate layout on mixed-flow movement including luggage-laden pedestrians based on the exercise experiments.[13] The efficiency of pedestrian ticket checking directly affects the operational efficiency of the high-speed rail station. Liu *et al*. built an enhanced social force model for simulating the check-in process, and subsequently validated its performance.[14] In short, the existing studies ignore the uncertainty and ambiguity in the selection process of ticket gates, and the impact of widening ticket gates (only equipped in some subway stations) is often overlooked.

(ii) Application of fuzzy logic in the field of pedestrian flow

Fuzzy logic theory has a powerful ability to process fuzzy information and can be used to solve many uncertainty problems. In recent years, fuzzy logic theory has found widespread application in the domain of pedestrian flow. Liu *et al*. established a cellular automata model based on fuzzy theory to simulate pedestrian evacuation from multi-exit rooms.[15] Yang *et al*. employed fuzzy logic theory to investigate issues related to follower guide selection and guide exit selection.[16] Zhou *et al*. introduced a fuzzy logic-based approach for modeling and simulating pedestrian dynamics, incorporating human experiential knowledge and perceptual information derived from the surrounding environment.[17] Yang *et al*. proposed a fuzzy-theory-based pedestrian dynamics models to study the waiting passenger distribution at the subway platform.[18] Xue *et al*. proposed an innovative pedestrian model that integrates fuzzy logic theory into a multi-agent system, introducing elements of uncertainty and imprecision into the decision-making process.[19] Fu *et al*. built a discrete evacuation model based on fuzzy theory, incorporating imprecise and subjective information.[20] Cao *et al*. combined fuzzy logic into original social force model to imitate the pedestrian evacuation process.[21] Fuzzy logic theory can well solve some uncertainty and fuzziness problems in transportation-related matters, which may be a good way to solve the problem of ticket gate selection.

(iii) Pedestrian flow simulation model

Pedestrian flow simulation models can be categorized into three primary types: macroscopic model,[22] mesoscopic model,[23] and microscopic model.[24] In macroscopic model, pedestrians in free state are analyzed by the method for investigating the movement of gas molecules, and pedestrians in congested state are modelled by the method for simulating the movement of liquid molecules. The mesoscopic model ignores the differences between individuals and focuses on describing the overall nature of pedestrian movement. While the macroscopic model and mesoscopic model ignore the individual behavior, they cannot describe the details of pedestrian movement. Social force model (SFM)[25–27] and cellular automata model (CAM)[28–30] are the two most widely used microscopic models in capturing the movement behaviors of pedestrians. Wu *et al*. proposed a behavioral heterogeneity-based social force model to elucidate the inherent heterogeneity characteristics within pedestrian dynamics.[31] Zhai *et al*. proposed an improved CAM by incorporating microscopic features.[32] SFM and CAM all have the strong combination ability with pedestrian micro-movement behavior. For instance, Peng *et al*. proposed a torsional social force model (T-SFM) to simulate rotation behavior of pedestrians under multiple scenarios.[33] Yue *et al*. used the cellular automaton model to simulate the pedestrian movement behavior on an escalator.[34] SFM is a continuous model, while CAM is a discrete model.[33,35] Consequently, the SFM is more flexible in terms of pedestrian speed changes, which leads to a more accurate description of pedestrian movement behavior. In this paper, SFM is used to simulate pedestrian dynamics.

### 1.3. Contribution and organization

From a review of previous work, pedestrian choice of ticket gates exhibit inherent characteristics of uncertainty and fuzziness. The fuzzy logic methodology, renowned for its capacity to handle qualitative knowledge and experiential data with indistinct boundaries, is employed in this study to investigate pedestrian choice behavior of ticket gates in subway stations. The specific contributions of this paper are as follows.

(I) Considering the distance, queuing pedestrians and luggage, choice model of ticket gates based on fuzzy logic is built in subway stations, which fully takes into account the fuzziness and uncertainty in pedestrians' ticket gates selection process, fusing the impact of widening ticket gates.

(II) The choice model of ticket gates is fused into SFM to simulate pedestrian choice process of ticket gates, and the ensuing simulation results (simulation process, utilization of ticket gates and passing efficiency) are subjected to a detailed analysis.

The subsequent sections of this article are organized as follows. Section 2 builds a pedestrian choice model of ticket gates based on fuzzy logic. Subsequently, in Section 3, the pedestrian choice model for ticket gates is incorporated into SFM to simulate pedestrian choice behavior. Section 4 conducts a case study at the Gong-nong-guang-chang station in Changchun city, China, examining aspects such as ticket gates utilization and passage efficiency based on the simulation results. Finally, Section 5 provides a comprehensive conclusion by summarizing our work.

## 2. Choice model of ticket gates based on fuzzy logic

According to our multiple field observations, pedestrians will quickly select the target ticket gate listening to the information they get, and the selection process is fast fuzzy and uncertain, and random sometimes. Consequently, we establish choice model of ticket gates based on fuzzy logic (marked as strategy III), which is proficient in handling qualitative knowledge and experience with unclear boundaries. Fuzzy logic is an adept approach for handling qualitative knowledge and experiences characterized by ambiguous boundaries, as it emulates the human brain's capacity for making judgments and reasoning in the face of uncertainty, a task that is challenging for conventional methodologies.[36] The fuzzy logic method includes five parts: variable, fuzzification, fuzzy rules, fuzzy inference system and defuzzification.[37,38]

In selecting ticket gates, pedestrians will consider the distance between the current location and target ticket gate, queuing pedestrians and luggage condition according to field investigations. The ticket gate with the closer distance, fewer pedestrians in line and fewer people with luggage may be the best choice in general. However, different influencing factors are mutually influenced. Therefore, we set the three factors (the distance between the current location and target ticket gate, queuing pedestrians and luggage condition) as input variables, and they are marked as *dis*, *que*, and *lug*, respectively. Probability of selecting ticket gates (*pro*) is set as the output variable. Moreover, combining the field investigation and relevant studies [29,39] to quantify carried luggage, we classify the luggage: L1 (without luggage or a little amount), L2 (a moderate amount of luggage), L3 (a large amount of luggage), and L4 (an oversized luggage). The pedestrian with an oversized luggage could not pass through a regular width ticket gate, and the widened ticket gate can meet his/her needs. The widened ticket gate is also specifically designed for pedestrians with the oversized luggage in subway stations. In other words, the probability of pedestrians with the oversized luggage for selecting the widened ticket gate is 100%. For this type people, there is no need to consider it in the choice model of ticket gates based on fuzzy logic.

To facilitate input, we normalized the input variables. The normalized distance to the ticket gates, normalized number of queuing pedestrians and normalized luggage condition are defined by $dis_t \in [0,\ 1]$, $que_t \in [0,\ 1]$, and $lug_t \in [0,\ 1]$, respectively.

$$dis_t = \frac{dis}{d_{\mathrm{t,\ max}}}, \tag{1}$$

$$que_t = \frac{que}{n_{\mathrm{t,\ max}}}, \tag{2}$$

$$lug_t = \frac{n_1 + 2n_2 + 3n_3}{3que}. \tag{3}$$

Here, $d_{\mathrm{t,\ max}}$ is the maximum distance between pedestrian and ticket gates. $n_{\mathrm{t,\ max}}$ is the maximum value of queuing pedestrians. $n_1$, $n_2$, and $n_3$ represent the number of pedestrians who carry a little amount luggage (including no luggage), a moderate amount of luggage, and a large amount of luggage, respectively.

Fuzzification is the procedure by which the membership degree of a fuzzy set is derived from a particular input, following the application of the membership function. In the fuzzy logic system, the variable *dis* is mapped to the fuzzy set $\{short,\ medium,\ long\}$, the variable *que* is mapped to the set $\{small,\ medium,\ big\}$, and the variable *lug* is mapped to the set $\{small,\ medium,\ big\}$. We take the set $\{short,\ medium,\ long\}$ as an example to explain in detail. "*short*", "*medium*" and "*long*" denote that the distance to the ticket gates is short, medium, and long, respectively. Others sets can give similar explanations. The variable *pro* is mapped to the set $\{VLp,\ Lp,\ Mp,\ Sp,\ VSp\}$. In this context, the terms "*VLp*", "*Lp*", "*Mp*", "*Sp*", and "*VSp*" denote the likelihood of selecting a ticket gate with a very large probability, a large probability, a medium probability, a small probability, and a very small probability, respectively. In our work, Bell membership function $\mu = 1/\left[1+\left((D_{\mathrm{g}}-c)/a\right)^{2b}\right]$ [40] and Gaussian membership function $\mu = \exp\left(-(S_\rho - \eta)^2/2\sigma^2\right)$ [41] are used to describe the membership degrees of $\mu\,(dis)$, $\mu\,(que)$, $\mu\,(lug)$, and $\mu\,(pro)$.

The membership functions for *dis*, *que*, and *lug* are shown in Figs. 1–3.

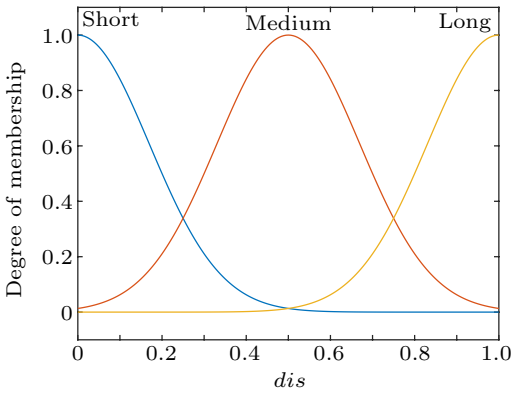



**Fig. 1.** The membership functions for *dis*.

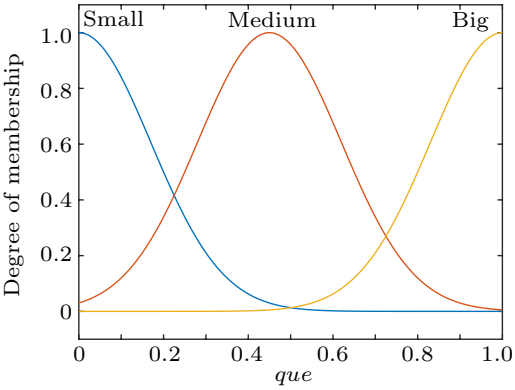



**Fig. 2.** The membership functions for *que*.

Fuzzy rules serve as a mean to articulate the fuzzy relationship between input and output through linguistic expressions. This paper chooses most people's options to develop the rule base of the fuzzy logic system for selecting ticket gates as shown in Table 1 to fully leverage the advantages of fuzzy logic theory in handling fuzzy information.

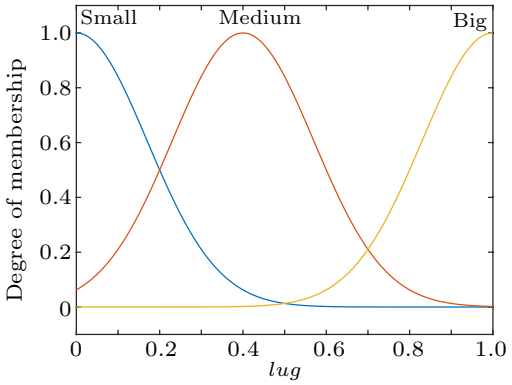



**Fig. 3.** The membership functions for *lug*.

The membership functions for *pro* is shown in Fig. 4.

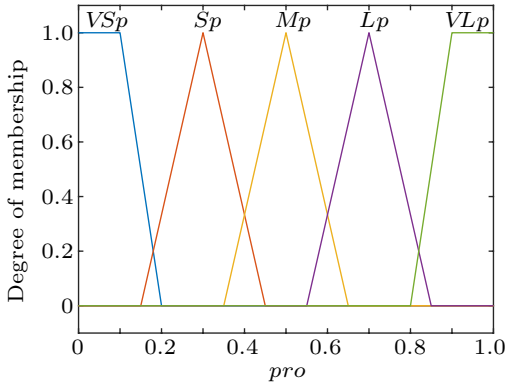



**Fig. 4.** The membership functions for *pro*.

**Table 1.** The inference rules of the probability of choosing ticket gates.

| Input | | | Output | Input | | | Output | Input | | | Output |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *dis* | *que* | *lug* | *pro* | *dis* | *que* | *lug* | *pro* | *dis* | *que* | *lug* | *pro* |
| Short | Small | Small | *VLp* | Medium | Small | Small | *VLp* | Long | Small | Small | *Lp* |
| Short | Small | Medium | *VLp* | Medium | Small | Medium | Lp | Long | Small | Medium | *Lp* |
| Short | Small | Big | *Lp* | Medium | Small | Big | *Lp* | Long | Small | Big | *Mp* |
| Short | Medium | Small | *Lp* | Medium | Medium | Small | *Mp* | Long | Medium | Small | *Mp* |
| Short | Medium | Medium | *Lp* | Medium | Medium | Medium | *Mp* | Long | Medium | Medium | *Sp* |
| Short | Medium | Big | *Mp* | Medium | Medium | Big | *Mp* | Long | Medium | Big | *Sp* |
| Short | Big | Small | *Mp* | Medium | Big | Small | *Sp* | Long | Big | Small | *Sp* |
| Short | Big | Medium | *Sp* | Medium | Big | Medium | *Sp* | Long | Big | Medium | *VSp* |
| Short | Big | Big | *Sp* | Medium | Big | Big | *VSp* | Long | Big | Big | *VSp* |

To enhance the precision of fuzzy output, defuzzification is a necessary step. Defuzzification is the process of converting the fuzzy outcome, represented by *pro*, into a precise, unambiguous numerical value $p'$. Center of gravity defuzzification method

$$p' = \int_X x\mu(x)\,\mathrm{d}x \int_X \mu(x)\,\mathrm{d}x$$

is used referring to related research.[25]

## 3. Simulation model

### 3.1. Ellipse body model

In the simulation of pedestrian flow, most scholars use the circles to represent pedestrians.[42,43] In pedestrian micro simulation, circular models may overlook some behavioral details. Actually, it is closer to the ellipse in the top view of real human body. Kinds of the ellipse models are proposed to describe pedestrians.[44,45] In order to more realistically reflect the human body situation, we also use the ellipse to describe

human body. Figure 5 shows the schematic of ellipse body model. $2a$ and $2b$ represent the thickness and shoulder width of the pedestrian. In this paper, we use the survey results of the thickness and shoulder width shown in the article of Peng *et al.*[33]

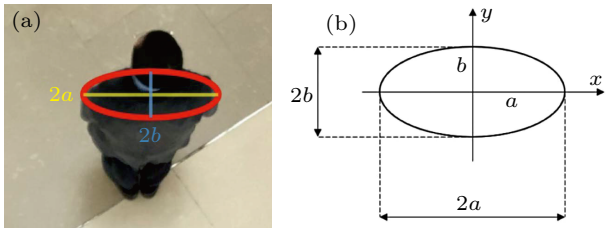



**Fig. 5.** The schematic diagram of the ellipse body model: (a) three-dimensional body model and (b) ellipse model.

### 3.2. Social force model

Social force model (SFM) is a pedestrian dynamics model proposed based on Newton's second law.[46] Diagram of social force model is shown in Fig. 6. In the SFM, the movement dynamics of pedestrians is driven by the driving force $F_{i,\text{driving}}$, interaction force $F_{ij}$ with other pedestrian and repulsive force $F_{iw}$ from the wall. The specific calculation equation is shown as follows:

$$\begin{cases} m_{i,l}\frac{\mathrm{d}v_i}{\mathrm{d}t} = F_{i,\text{driving}} + \sum\limits_{j=1,j\neq i}^{J} F_{ij} + \sum\limits_{w=1}^{W} F_{iw}, \\ F_{i,\text{driving}} = m_{i,l}\frac{v_i^0(t)e_i^0(t)-v_i(t)}{\tau}, \\ F_{ij} = A_i \exp\left(\frac{r_{ij}-d_{ij}}{B_i}\right) n_{ij} + k_n g\left(r_{ij}-d_{ij}\right) n_{ij} \\ \qquad + k_t g\left(r_{ij}-d_{ij}\right)\left[\left(v_j-v_i\right)^T t_{ij}\right] t_{ij}, \\ F_{iw} = A_i \exp\left(\frac{r_{ij}-d_{iw}}{B_i}\right) n_{iw} + k_n g\left(r_i-d_{iw}\right) n_{ij} \\ \qquad + k_t g\left(r_i-d_{iw}\right)\left[\left(v_i\right)^T t_{iw}\right] t_{iw}, \\ m_{i,l} = m_i + \varphi\xi_i, \end{cases} \tag{4}$$

where $m_i$ is the mass of pedestrian $i$. $\xi_i$ is the mass of luggage carried by pedestrian $i$. If the luggage is carried entirely on the person's back or held by hand (luggage is completely off the ground), $\varphi = 0$; When the luggage is wheeled, the pedestrian pushes the suitcase, $\varphi > 0$. $v_i$ is the actual velocity, $v_i^0(t)$ is the desired speed at time $t$, $e_i^0(t)$ is the unit vector pointing to the target at time $t$, $\tau$ is certain characteristic time, $A_i$ and $B_i$ are constants which represent the strength and range of social interaction forces, respectively. $r_{ij}$ and $d_{ij}$ are the sum of their radius and the distance between their centers of mass, respectively. $n_{ij}$ and $n_{iw}$ are the normalized vector pointing from pedestrian $j$ and wall $w$ to pedestrian $i$, respectively. $k_n$ and $k_t$ are the coefficient of body compression and sliding friction, respectively. $t_{ij}$ and $t_{iw}$ are the tangential direction. $J$ and $W$ denote the number of pedestrians and walls. $g(x) = \max(x, 0)$ indicates pedestrians touch each other/touch the walls or not. Note all the parameters of Eq. (4) are specific defined in the research.[46]

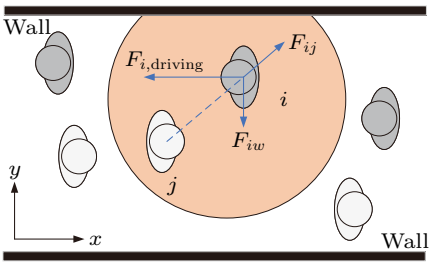



**Fig. 6.** Diagram of social force model.

### 3.3. Model implementation

(i) Model applicability and assumption condition

Pedestrian selection in low-density situation has randomness, while pedestrian selection in high-density situation has spatial limitations. The low-density and high-density situations may not be suitable for the built model in our work. The model is only applicable to pedestrian flow under medium density conditions.

In the simulation process of ticket gate selection behavior, five assumptions are posited.

**Assumption A** The ticket gate selection behaviors of all pedestrians follow the established choice model. The pedestrian's decision-making process is completed instantaneously, without considering their hesitant behavior.

**Assumption B** When one pedestrian sees the ticket gates or the guidance sign above, he/she makes decision to choose the target ticket gate. According to relevant studies,[47,48] pedestrian sight distance is set to 6 m in the simulation. According to the actual situation, the closer the distance to the gate, the lower the probability of pedestrians changing their choices. The vast majority of pedestrians make their choice when they are 4 m–6 m away from the ticket gates, and rarely change it afterwards.

**Assumption C** In the simulation process, there is no image and spatial representation of the size of the luggage, and we set luggage attributes for pedestrians.

**Assumption D** The widened ticket gate will prioritize serving pedestrians with the oversized luggage. The widened ticket gate is set for the pedestrians with the oversized luggage. However, when the widening gate is idle, other pedestrians can also use it.

**Assumption E** When the ticket gates and security equipment are located close to each other, it can affect pedestrians' choice of ticket gates. This issue is not taken into account in our modeling process, and according to our field investigation in Gong-nong-guang-chang station, the location of security equipment has no effect on the choice of ticket gates.

(ii) Model implementation

To simulate pedestrian choice behavior concerning ticket gates, the ticket gate choice model based on fuzzy logic is integrated into the SFM. The workflow of the simulation for pedestrian choice behavior of ticket gates is depicted in Fig. 7.

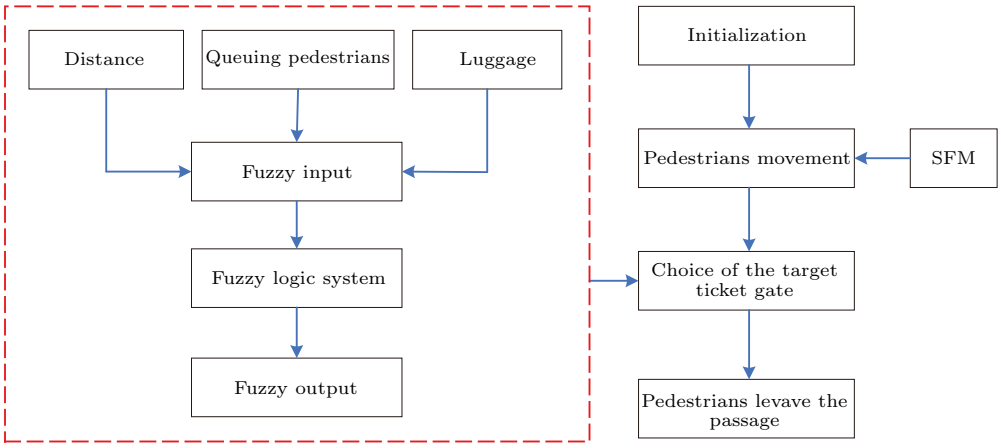



**Fig. 7.** The workflow of the simulation for pedestrian choice of ticket gates.

**Step 1** Initialization of the simulation scenario and parameters, including the positions of the ticket gates, the pedestrian attributes, and the inflow rates at the passage origin.

**Step 2** Pedestrian movements are driven by the SFM.

**Step 3** Target ticket gate selection for passengers to pass through is determined using fuzzy logic theory. This paper considers three primary influential factors in the decision-making process: the distance between the current location and the target ticket gate, queuing pedestrians, and luggage conditions. In addition, the probability of pedestrians with the oversized luggage for selecting the widened ticket gate is set as 1.

**Step 4** Pedestrians pass through the target ticket gate and leave the passage.

## 4. Case study

### 4.1. Scenario description

The case study focuses on the ticket gates of Gong-nong-guang-chang station in Changchun city, China. Screenshot of the ticket gates in Gong-nong-guang-chang subway station is shown in Fig. 8. A simplified scenario based on actual measurements is illustrated in Fig. 9. Length ($L_{\text{length}}$) and width ($L_{\text{width}}$) of the passage are 24 m and 5.2 m, respectively. There are six ticket gates include five regular width ticket gates and one widened ticket gate. For the convenience of description, the regular width ticket gates are marked as GA1, GA2, GA3, GA4, and GA5, and the widened ticket gate is marked as WGA6. The width of the regular ticket gates is 0.55 m and the width of widened ticket gate is 0.95 m. Distance between ticket gates and left entrance $L_{\text{l}}$ is 14.4 m, and the distance between ticket gates and right exit $L_{\text{r}}$ is 8 m. The gray rectangle symbolizes the ticket gate equipment.

Furthermore, due to the heterogeneity of pedestrians, the service time at the ticket gates varies for different individuals. According to our on-site observations, we believe that the service time for pedestrians at a ticket gate and the service time for pedestrians with oversized luggage at the widened ticket gates are all following the normal distribution. Therefore, we conducted fitting analysis on them respectively based on the collected video data, shown in Fig. 10. For the service time for pedestrians at a ticket gate, the mean value is 2.895 s and the standard deviation is 0.419. For the service time for pedestrians with oversized luggage at the widened ticket gates, the mean value is 3.257 s and the standard deviation is 0.399. This also indicates that the presence of oversized luggage can impact the service time, resulting in longer processing times for the widened ticket gates.



**Fig. 8.** Screenshot of the ticket gates in Gong-nong-guang-chang subway station.

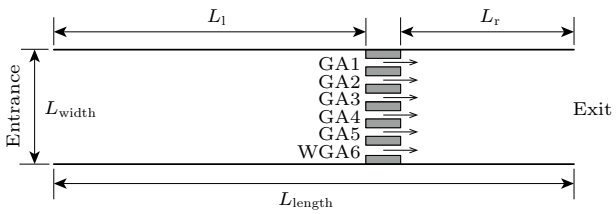



**Fig. 9.** Simplified scenario.

In addition, we set the expected speed of pedestrians as 1.2 m/s according to relevant studies and field observation. However, pedestrians carrying luggage typically exhibit an expected walking speed in the range of 0.8 m/s–1.2 m/s, depending on factors such as environment, luggage type, and individual characteristics. As the amount of luggage carried by a pedestrian increases, their expected walking speed decreases. Accordingly, we set an expected walking speed of 0.8 m/s for

pedestrians carrying oversized luggage. Based on actual investigation, we use Poisson distribution to generate pedestrians at the left origin of the channel.

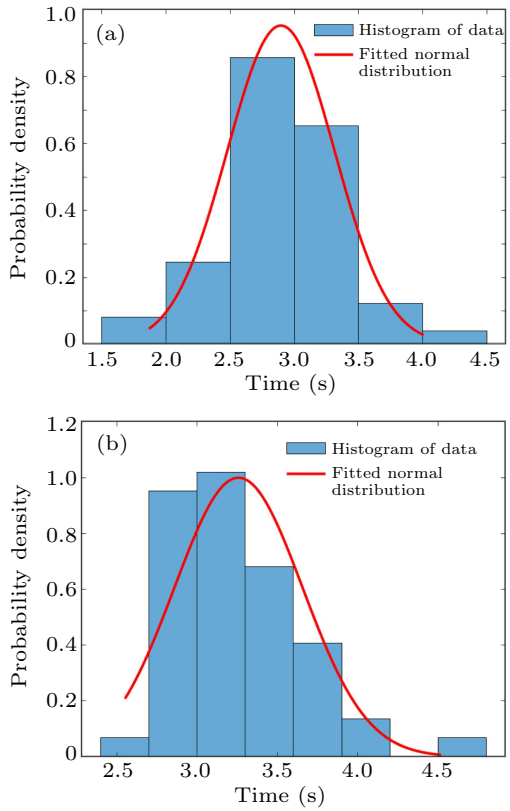



**Fig. 10.** Fitting of service time probability distribution: (a) regular width ticket gates, (b) the widened ticket gates.

### 4.2. Simulation process

In the platform of AnyLogic8.7.0, pedestrian choice behavior of ticket gates is simulated. The whole process including the pedestrian generation, see the ticket gates and making choice, passing through the ticket gates, and leaving the passage are all detailed reproduced. The screenshot of two-dimensional simulation process is depicted in Fig. 11. Blue, green, pink and red ellipses represent pedestrians with L1, L2, L3, and L4, respectively. The screenshot of three-dimensional simulation process is shown in Fig. 12.

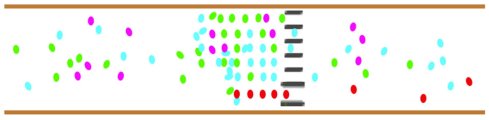


**Fig. 11.** Screenshot of two-dimensional simulation process.

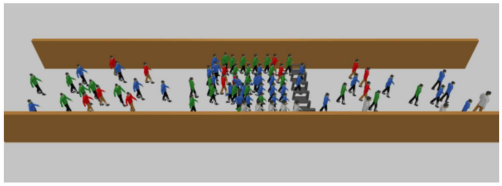


**Fig. 12.** Screenshot of three-dimensional simulation process.

It is obviously that pedestrians formed the queuing phenomenon in front of the ticket gates. In addition, the pedestrians with an oversized luggage (red ellipses) all select the WGA6, which is in line with the actual situation.

### 4.3. Analysis of the utilization of ticket gates

In order to analyze the utilization of ticket gates, we simulate the choice process of ticket gates with 1/6 people carrying the oversized luggage and count the number of queuing pedestrians in front of ticket gates in three strategies (shown in Fig. 13). The number of service pedestrians of each ticket gate with three strategies are shown in Fig. 14. The number of queuing pedestrians in front of WGA6 is larger than other ticket gates, resulting in longer evacuation time. This is because the probability of pedestrians carrying oversized luggage choosing the widened ticket gate is 1. When the widening gate is idle, people carrying L1, L2 or L3 can also choose the widened ticket gate. This phenomenon is consistent with the actual situation. This is also the reason why the number of service pedestrians of the widened ticket gate exceeds one sixth of the total number of people.

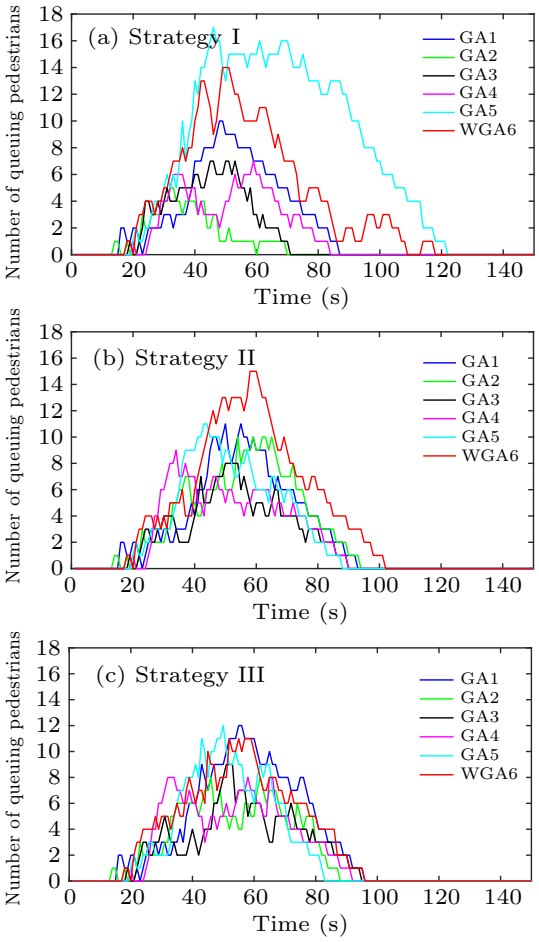



**Fig. 13.** Number of queuing pedestrians in front of ticket gates with three strategies.

In addition, it is noted that the number of queuing pedestrians is more balanced with strategy III. Standard deviations

of the number of service pedestrians with three strategies are 5.89, 3.00 and 2.94, respectively. It indicates that compared with strategy I and strategy II, the utilization of ticket gates is more balanced with strategy III.

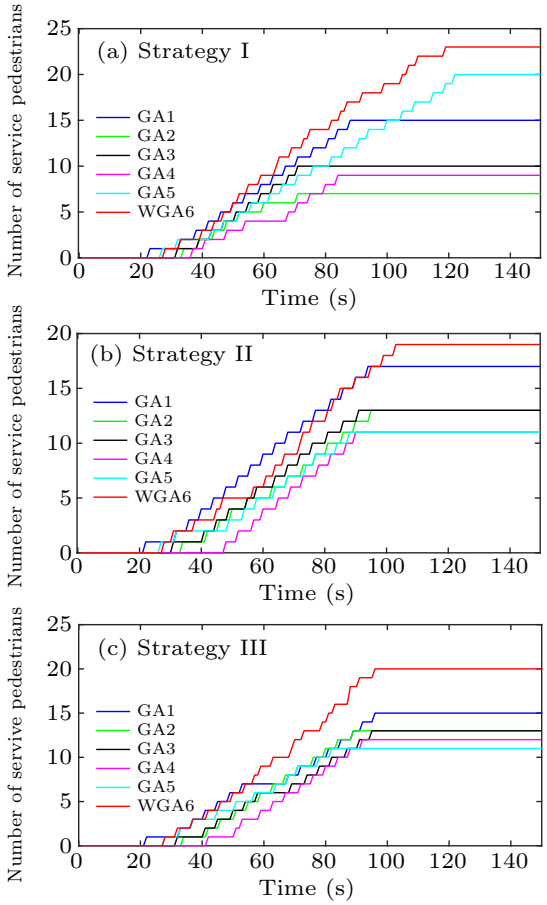



**Fig. 14.** Number of service pedestrians of each ticket gate with three strategies.

### 4.4. Analysis of passing efficiency

At the beginning of the simulation, 84 pedestrians are generated based on the Poisson distribution, and then the time of pedestrians to pass through the channel are counted for analyzing the passing efficiency. With the 30 independent simulation experiments, we count the time of pedestrians passing the passage with three strategies and make a box-plot (shown in Fig. 15). The average time it takes for pedestrians to pass through the passage using the three strategies is 124.87 s for strategy I, 107.77 s for strategy II, and 103.37 s for strategy III, respectively. Obviously, compared with strategy I and strategy II, the passing efficiency with strategy III is higher.

Meanwhile, to analyze the effect of oversized luggage on pedestrians passing efficiency, in the case of a fixed total number of pedestrians, the box-plot about the relationship between passing time and different ratios of pedestrians with oversized luggage is shown in Fig. 16. We count and calculate the mean value of passing time under different ratios of pedestrians with oversized luggage (shown in Table 2). As the ratio of pedestrians with oversized luggage increases, the passing efficiency decreases. When the ratio of pedestrians with oversized luggage is less than 0.2, the oversized luggage has little influence on pedestrians passing efficiency. In contrast, the effect of oversized luggage for pedestrians passing efficiency rapidly increases as the ratio of pedestrians with oversized luggage more than 0.2. In addition, when the ratio of pedestrians with oversized luggage more than 0.2, we can fit a straight line (blue line in Fig. 16) with a slope of 33.23 and an intercept of 9.35 with the passing time data. It also says that the effect of oversized luggage for pedestrians passing efficiency is increasing in a straight line in this case.

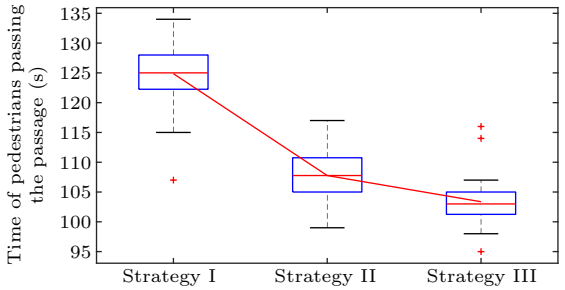



**Fig. 15.** Time of pedestrians passing the passage with three strategies.

The ratio of pedestrians with oversized luggage equal to 0 indicates that there are no people carrying oversized luggage. At this point, the passing efficiency is the highest (the minimum passing time 98.77 s). Similarly, the ratio of pedestrians with oversized luggage equal to 1.0 indicates that all people carry oversized luggage. The passing efficiency reaches to the minimum value (the maximum passing time 375.23 s).

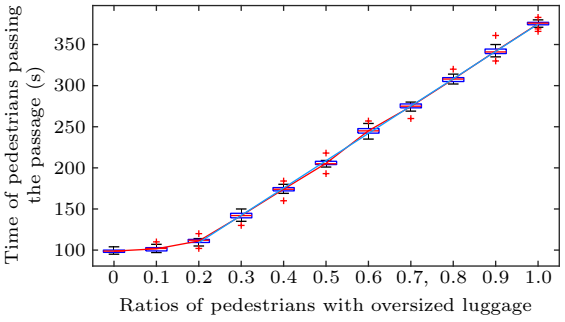



**Fig. 16.** Relationship between passing time and different ratios of pedestrians with oversized luggage.

**Table 2.** Mean value of passing time under different ratios of pedestrians with oversized luggage.

| Ratio of pedestrians with oversized luggage | 0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Mean value (s) | 98.77 | 101.53 | 111.10 | 141.87 | 174.10 | 205.50 | 245.10 | 274.60 | 307.80 | 342.03 | 375.23 |

## 5. Conclusion

This paper presents a fuzzy-theory-based social force model for analyzing pedestrian choice behavior concerning ticket gates in subway stations. We build a fuzzy-theory-based pedestrian choice model for ticket gate selection, with the distance, queuing pedestrians and luggage as three input variables in the fuzzy logic methodology, while the probability of selecting each ticket gate is designated as the output variable. This choice model effectively characterizes pedestrian choice behavior of ticket gates in subway stations, fusing the impact of widening ticket gates. The built choice model is integrated into SFM to simulate pedestrian choice behavior of ticket gates. The simulation process faithfully replicates real-world conditions. Results indicates that compared with the strategy I (choosing the nearest ticket gate) and strategy II (choosing the ticket gate with the fewest queuing pedestrians), the proposed choice model of ticket gates based on fuzzy logic exhibits the higher passing efficiency and a more balanced ticket gates utilization. As the ratio of pedestrians with oversized luggage increases, the passing efficiency decreases. Notably, when the ratio of pedestrians with oversized luggage is larger than 0.2, the impact of oversized luggage on passing efficiency increases in a straight line.

In this paper, we exclusively built the choice model of ticket gates in the case of scanning card, however, passengers can scan their phones' QR code for checking in and some subway stations offer facial recognition services. Scanning the phone's QR code or face swiping are different from the card. In addition, the location of security inspection equipment may also affect the choice of ticket gates, and we will analyze it in future research.

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