Physica A 605 (2022) 128032

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

Observation and cellular-automaton based modeling of pedestrian behavior on an escalator

Chuan-Zhi Xie [a], Tie-Qiao Tang [a,*], Peng-Cheng Hu [a], Liang Chen [b]

[a] School of Transportation Science and Engineering, Beijing Key Laboratory for Cooperative Vehicle Infrastructure Systems and Safety Control, Beihang University, Beijing 100191, China
[b] Beijing Key Laboratory of Traffic Engineering, Beijing University of Technology, Beijing 100124, China

ARTICLE INFO

Article history:
Received 25 March 2022
Received in revised form 1 August 2022
Available online 13 August 2022

Keywords:
Escalator
Cellular automaton
Pedestrian guidance strategy
Simulation

ABSTRACT

In-depth analysis of pedestrian movement behavior on staircases and escalators can significantly improve their operation efficiency and safety. However, compared with stairs, researchers have generally given little attention to pedestrian movement on escalators. In this paper, we conduct a case study to extract the physical attributes of the escalator, the pedestrians' microscopic movement characteristics, and the macro-level pedestrian flow dynamics on the escalator of Beihang University's canteen. Using the data, we establish a step-length-based CA model to represent the pedestrian movement across the escalator. The CA model can effectively render the pedestrian's grouping formation and walking characteristics at the micro-level and describe the pedestrian flow at the macro-level. Through simulations, we quantitatively analyze some widely used pedestrian guidance strategies on escalators (e.g., the "walk left, stand right" rule, changing the grouping formation). The results may have bearing on real-life escalator management.

1. Introduction

Crowd-related emergencies have become increasingly frequent in recent years, making pedestrian dynamics an increasingly urgent topic of research [1]. Thus, it is meaningful to study pedestrian dynamics in various typical crowded scenarios. Engineered structures are growing continually higher and deeper alongside rapid and widespread urbanization; vertical pedestrian facilities (e.g., stairs, escalators) are necessary to make these buildings function (e.g., commuting, evacuation, etc.) properly [2]. Pedestrian density across these facilities may surge at certain times, creating crowd-related safety risks [3]. Even in the normal operation of these facilities, pedestrian's microscopic behavior may still cause safety accidents. For example, on February 9, 2014, a crash occurred in a train station in Australia when pedestrians were taking a downward escalator; the incident was caused by passengers pausing at the bottom of the escalator but not moving down the platform; the people following them fell and piled on top of each other, resulting in more than a dozen injuries [4]. Considering accidents similar to the accident in Australia caused by pedestrian's microscopic behavior, comprehensive evaluations of the complex pedestrian behavior on vertical pedestrian facilities may help administrators formulate effective pedestrian behavior guidelines and crowd management strategies. In fact, in recent years, researchers in the field of traffic and safety have conducted extensive studies to create more detailed descriptions of micro-level pedestrian behavior on these facilities and review accidents [5].

* Corresponding author.
E-mail address: tieqiaotang@buaa.edu.cn (T.Q. Tang).

https://doi.org/10.1016/j.physa.2022.128032
0378-4371/

Both simulation-based and experiment-based studies are both widely adopted for exploring pedestrian micro-behavior under various scenarios. Considering pedestrian flow on vertical walking facilities, simulations based on cellular automaton (CA) models [6–8], social force models [9,10], and commercial software (e.g., building EXODUS [11]) have been done. As for cellular automaton models, for example, Yue et al. proposed a CA model to simulate pedestrian behavior on escalators, including pedestrian movement speeds, queuing modes, and segregation by different escalator speeds and found that walking on escalators does not always improve transit volumes (especially when vertical facilities are jammed) [8]. As for social force models, for example, Wu et al. revised the social force model for stairs by introducing the effects of gravity and simplified the model for the direction of the psychological force between pedestrians considering the narrow space of the stair, which dramatically improves the computational efficiency [9]. As for simulations based on commercial software, for example, Kinsey et al. refined the building EXODUS escalator model by considering human factors to demonstrate the impact of escalators on evacuation performance, and revealed some interesting conclusions [11]; for example, they found out that under evacuation conditions, allowing the escalator to function as normal can provide significant benefit to pedestrians by reducing overall evacuation times even in situations where all the pedestrians choose to ride up the escalator.

Besides simulations, experiments are helpful in collecting real movement data on vertical pedestrian facilities and gathering inputs for model calibration purposes. Likewise, many controlled experiments and in-field studies have been conducted on this subject. For example, Ding et al. held a fire drill in a high-rise building to validate the results of their CA model, which incorporates the evacuees' physical and psychological statuses in their movements across staircases [12]. By focusing on in-filed methods, Fu et al. collected data considering pedestrians' ascending and descending behavior on stairs in a university campus [13,14]; their research serves as solid empirical support for group walking modeling on stairs and pedestrians facility design.

The above researches (including models and experiments) mainly explored the pedestrian behavior on some vertical walking facilities from microscopic perspectives, but the specific research scenarios and research priorities are somewhat different. In general, we can summarize the above researches into the following three categories: (1) the overall evacuation performance inside multi-floor buildings (e.g., Ref. [6]); (2) the pedestrian movement on a single stair (e.g., Ref. [12]); (3) the pedestrian movement on/around escalators (e.g., Ref. [11]). Intuitively, although escalators and stairs are both crucial vertical walking facilities, researchers paid more attention to the latter. If we search this topic from WOS database, the above conclusions can also be confirmed: in the WOS database, 78 papers can be found by searching with the keywords of pedestrian flow and stair, but only 27 papers can be found by searching with the keywords of pedestrian flow and escalator. Although there are some similarities in the pedestrian movements on stair and escalator, there are still many differences. Therefore, the simulation or experiment researches of the pedestrian movement on stair are difficult to be directly used to the pedestrian movement on escalator. Specifically, the simulation-based researches on stair are not suitable for simulating the pedestrian flow on escalator, where the main reasons are as follows:

(1) The willingness and choice of the pedestrian movement on stair and escalator are different. Hence, it is difficult to reproduce some unique pedestrian microscopic behaviors (e.g., lateral avoidance phenomenon) on escalator by using the pedestrian flow models for stair.

(2) Some macroscopic phenomena that are caused by the pedestrian microscopic behaviors (e.g., walk left, stand right, etc.) on escalator (e.g., the capacity difference between the left side and the right side of escalator) cannot exactly be reproduced by the pedestrian flow models for stair.

Similarly, experimental works on stairs mainly focus on the emergency evacuation efficiency and safety of pedestrian flow on stairs and mostly consider the human factor's influence. However, escalators are usually used as commuting tools under non-emergency situations, and escalators have their speeds. Hence, when exploring how to enhance the pedestrian's non-emergency usage (or evacuation) on escalators (i.e., including two aspects: safety and efficiency), both factors of escalators' movement and pedestrians' spontaneous movement should be considered simultaneously.

Thus, an in-depth understanding of pedestrian movement behavior and mechanisms on the escalator is necessary. It should be pointed out that by collecting in-situ data in different countries and carrying out a series of simulations considering different human factors, Kinsey and his co-workers have made remarkable contributions to deepen the understanding of the pedestrian flow around the escalator area inside subway stations (e.g., Ref. [11]). Inspired by the above-mentioned studies, which reveal that exploring the microscopic behavior of pedestrians on vertical walking facilities has practical significance, this paper supplements and refines the research on pedestrian's microscopic behavior on escalators. Specifically, we focus on exploring escalators with more grouping behavior and pedestrian behavior's impact (e.g., walking behavior, etc.) on the escalator system under a higher grouping proportion. The proposed model in this study can be feasible for most escalator scenarios; strategies raised and tested in this paper can assist escalators' management.

Through a case study, modeling, simulation and other means, this paper makes an in-depth study of microscopic behavior of pedestrians on an escalator, and quantitatively assesses the effectiveness of some guidance and management strategies in different situations. To be specific, in Section 2, we introduce the pedestrian behavior we observed on the escalator in the canteen of Beihang University; we propose a step-length-based CA model to depict the pedestrian movement based on the observations. Section 3 presents numerical tests based on the proposed model and the effectiveness of some guidance and management strategies that may improve the escalator's operational performance. Finally, Section 4 gives conclusions and future research prospects concerning pedestrian flows on escalators.

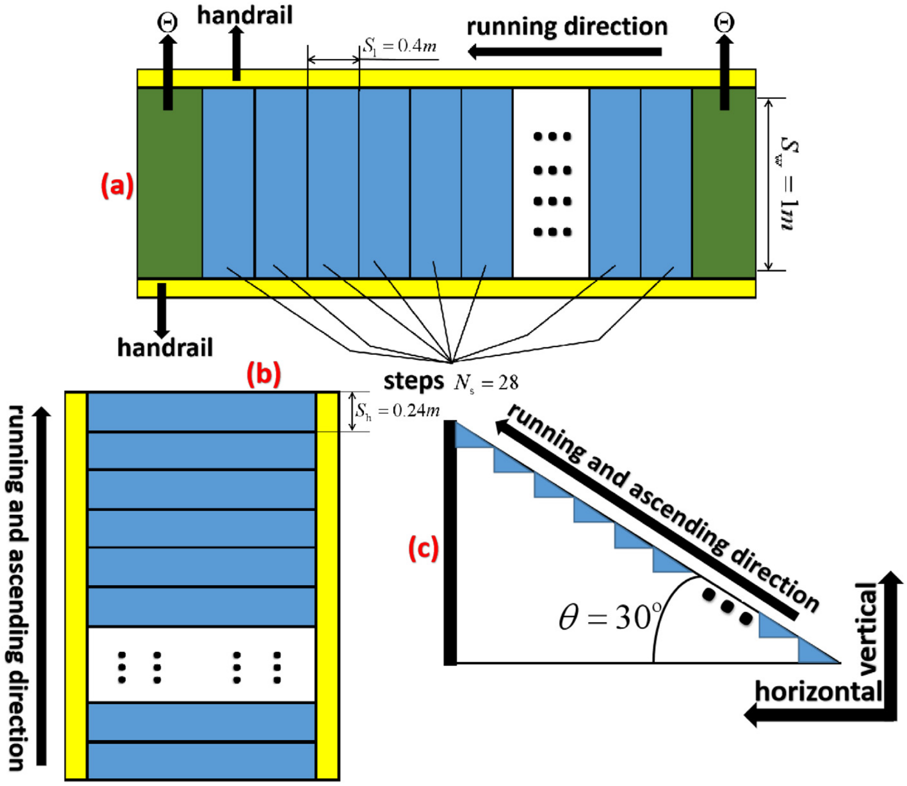

Fig. 1. The three-view drawing of case study escalator, where (a) top view, (b) front view and (c) side view.

2. Model

2.1. Research scenario

Tang et al. analyzed the data of pedestrian flow in one canteen in Beihang University during the peak period, and found that some pedestrians in canteen have grouping, but this scenario has no escalator [15]. In this paper, we also use one canteen with escalator in Beihang University as the research scenario. Escalator is a 3-D scenario; however, when considering the computing efficiency and the accuracy of depicting pedestrians' behavior, the typical solution is to abstract 3-D scenarios (e.g., staircase, escalator) into 2-D maps (e.g., Ref. [16]). This study's scenario is an ascending escalator and the escalator-floor connecting area. It is abstracted from the top view: escalator steps' length and width are considered, but height is ignored with the condition that the pedestrian can ascend at most one step of the escalator for each movement. The physical properties can be measured as follows (see Fig. 1):

(1) The width of each step of the escalator is 1 m (S_w = 1 m), which allows up to two typical pedestrians to stand side-by-side.
(2) The length of each step of the escalator is 0.4 m (S_l = 0.4 m).
(3) The height of each step of the escalator is 0.24 m (S_h = 0.24 m).
(4) The inclination angle of the escalator is 30 degrees ($\theta = 30°$).
(5) The escalator has a total of 28 steps (N_s = 28).
(6) The connection areas between the escalator and the floor (denoted as Θ) are limited to the space that can accommodate two pedestrians standing side-by-side, i.e., approximately 1 m in width and 0.5 m in length.

2.2. Case study and results

In this study, two 4 K high-definition digital cameras (their types are Sony FDR-AX100E) were used to record the pedestrian movement on the escalator, and professional photography tripods were used to fix cameras. One camera was responsible for recording the pedestrian movement at the entrance and the first half of the escalator, and the other one was responsible for recording the pedestrian movement at the exit and the second half of the escalator. The video data (e.g., the pedestrian entrance time, the amount of pedestrians, the pedestrian grouping formation, the pedestrian walking

Fig. 2. An example of how to infer the state of grouping from visual observations.

choice, etc.) was manually observed, counted, and analyzed. Also, the project was approved and examined by the head director of School of Transportation Science and Engineering, Beihang University.

To data, the operating speed of the escalator is 1/0.75 step/s (i.e., 8/15 m/s in the horizontal direction) and remained unchanged, so a new step is created every 0.75 s from the bottom. The observation time is from 10:50 a.m. to 11:58 a.m. (i.e., 4080s) on a working day. This period covers the peak pedestrian inflow time, i.e., the students' lunch hour, during which a total of 2,816 pedestrians flow into the observational area. According to our observations, the maximum number of pedestrians on the escalator steps is 56 (which means 2 pedestrians per step). Taking every 10 s as the observation period, the maximum number of pedestrians crossing the escalator entrance section is 26.

The social relationships and physical interactions between pedestrians are also observed to determine whether the objects are in certain states of grouping (see Fig. 2). Specifically, for pedestrians moving around the escalator area (i.e., from the entrance to exit), if there exists physical contact (e.g., hand-holding, shoulder-hanging) or verbal communicating behavior between pedestrians, then these pedestrians are considered to be in the state of grouping (Note: (1) Pedestrians who are actually in the state of grouping but have not been observed to have physical contact or verbal communicating behavior are judged as single pedestrians; (2) Pedestrians who are actually in a group with larger size but are not accurately identified in the video according to practical reasons are judged in several groups with smaller size based on grouping judging rules). Among the 2,816 pedestrians, there are 1,370 in grouping states, including 494 two-size groups (or dyads), 82 three-size groups (or triads), 21 four-size groups, 8 five-size groups, and 2 six-size groups. A total of 35 pedestrians choose to walk on the escalator, among whom 33 are walking singly and 2 are in grouping states. The judgment rules of pedestrian's walking behavior are set as follows: (1) if pedestrians (or pedestrian groups) keep walking after getting on the escalator until they meet other pedestrians in their moving direction and stop walking (or choose to bypass), they are regarded with walking behavior; (2) if pedestrians (or pedestrian groups) only choose to walk 1–2 steps (or not) during the beginning process that they get on the escalator to occupy the intended position and decide to stay in their intended position, they are regarded without walking behavior; (3) for pedestrians (or pedestrian groups) on the middle part of the escalator, if they only make minor adjustments of their position (i.e., they do not have a consistent walking tendency), these adjustments are not regarded as walking. Among the 35 pedestrians, the minimum number of pedestrians on the escalator is 5 and the maximum is 21 at the exact time when they step on the escalator. For the walking pedestrians, we can extract their movement speed from the video. For the ith pedestrian with walking behavior, his/her movement speed is composed of two parts: the escalator speed (i.e., v_e) and his/her spontaneous speed (i.e., v_p^i is the speed with the escalator as the reference frame). During this study, v_e is a constant while v_p^i is calculated by $v_p^i = WS_p^i/(TW_e^i - TW_s^i)$, where WS_p^i is the ith pedestrian spontaneous walking step parallel to the escalator running direction, and TW_s^i, TW_e^i are respectively the start time and end time of the ith pedestrian spontaneous walking. Note: the position adjustment of the ith pedestrian vertical to the escalator running direction is not taking into consideration when calculating v_p^i.

Kinsey and Liu et al. made a statistics analysis of the proportions of the pedestrian walking and grouping in the scenarios with escalator (e.g., subway station) [17,18]. Applying our statistics data, we can conclude that compared with the data [17,18], the proportion of the pedestrian walking is lower while the proportion of the pedestrian grouping is higher (see Tables 1 and 2). The differences in the proportion of the pedestrian walking may be caused by the reason that the pedestrians have different movement purposes, i.e., the pedestrians in canteen aim to have lunch during their

Table 1
The proportion of pedestrian walking in different scenarios.

		Proportion (%)	
		Upward	Downward
Research scenario	Spanish subway station	27	21
	English subway station	25.2	25.1
	Chinese university's canteen (the current research)	1.3	

Table 2
The proportion of pedestrian grouping in different scenarios.

		Proportion (%)
Research scenario	Chinese subway station	<5
	Chinese university's canteen (the current research)	48.7

Fig. 3. Pedestrian organization patterns under various grouping formations, where (a) reflects front–back two-size group, (b) left–right two-size group, (c) diagonal two-size group, (d) three-size group, (e) four-size group, (f) five-size group, and (g) six-size group.

rest time while the pedestrians in subway station are more likely to save time; the higher grouping proportion may be because the pedestrians in university canteen are more likely to have social relationships and interact more closely in groups.

Based on the above primary data and further in-depth observation and analysis of the objects' behavior, we establish the following characteristics:

(1) The proportion of pedestrians choosing to walk is relatively low ($\approx$1.3%), and pedestrians in groups generally choose not to walk on the escalator. Similar to Ref. [19], we apply a Chi-square test (Note: the test was run on SPSS20.0) to determine whether there is a statistically significant difference between the walking choices of pedestrians in groups and those of pedestrians walking singly (see Tables 3 and 4). A significant difference does exist ($p < 0.05$).

(2) When pedestrians walking singly enter the escalator, if there is a physically separable space with the pedestrian in front (i.e., the input flow is not saturated), more than 90% of them choose to wait and maintain a "comfort" distance ($\geq$ 1 step) from the pedestrian in front of them in their moving direction rather than directly following them. Additionally, 91% of these pedestrians follow the "stand right" rule if the right position is available.

Additionally, as mentioned above, approximately 49% of them are in groups, which further affect their moving choices. The physical formations among pedestrians in states of grouping differ and may influence the movement of other pedestrians [20,21]. The pedestrian formations and proportions are shown as follows (see Figs. 3 and 4): (1) 3.4% of total

Table 3
Crosstabulation of "pedestrian type" × "walking choice".

			Walking choice		Total
			Not walking	Walking	
Pedestrian type	Single	Count(%)	1411(97.6%)	35(2.4%)	1446(100%)
	In group	Count(%)	1368(99.9%)	2(0.1%)	1370(100%)
Total		Count(%)	2779(98.7%)	37(1.3%)	2816(100%)

Table 4
Chi-square test based on Table 3.

	Value	Degree of freedom	*p*-value
Pearson chi-square	28.067	1	.000

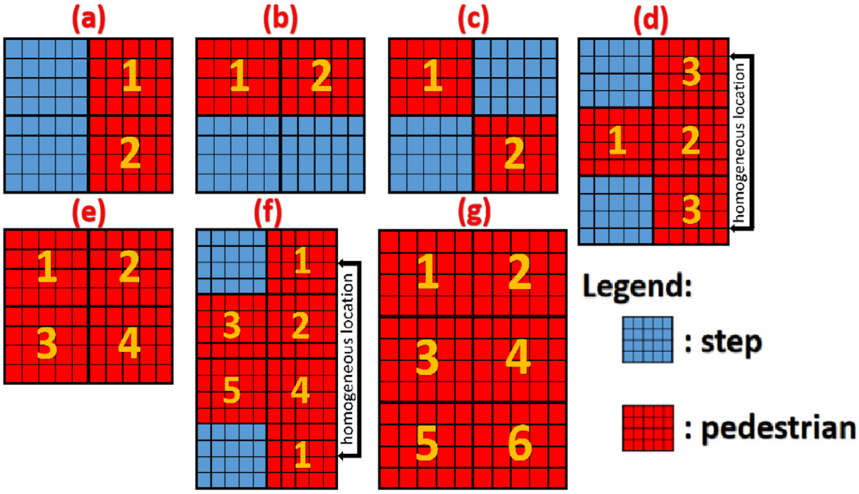

Fig. 4. Simplified and abstract graph based on Fig. 3, where (a)–(g) respectively correspond to Fig. 3(a)–(g).

pedestrians belong to front–back two-size group; (2) 26.7% of total pedestrians belong to left–right two-size group; (3) 4.9% of total pedestrians belong to diagonal two-size group; (4) 8.7% of total pedestrians belong to three-size group; (5) 2.9% of total pedestrians belong to four-size group; (6) 1.4% of total pedestrians belong to five-size group; (7) 0.4% of total pedestrians belong to six-size group.

2.3. Model for pedestrian motion

Mechanics-based continuous models have previously been used to investigate high-density pedestrian flows (e.g., Refs. [22,23]). However, for the pedestrian flow on an escalator, the movement characteristics are unique and markedly differ from the pedestrian flow across a floor. Each pedestrian can only cross one step at most during one movement and cannot move to a position between two steps. It is necessary to consider this movement as discrete rather than continuous in space. To study this effect, we establish a step-length-based CA model to describe pedestrians' discrete movement on the escalator.

2.3.1. Space discretization

To support our CA model, we should also discretize the actual observation scene. It should be pointed out that in each CA-based pedestrian model, the spatial discretization level is determined by the physical properties of pedestrians and space (i.e., walkable areas and obstacles), and an appropriate level of spatial discretization can benefit a CA-based pedestrian model. We discretize the escalator area as follows (see Fig. 5):

(1) The three-dimensional escalator area is transformed into a two-dimensional area. The composition of the two-dimensional area is based on the top view structure of the escalator (see Fig. 1(a)).
(2) The size of each cell is 0.1 m × 0.1 m.
(3) Each step (blue area in Fig. 5(b)) is discretized into two areas that a pedestrian can traverse. The size of each walkable area is 0.5 m × 0.4 m (i.e., 5 × 4 cells).

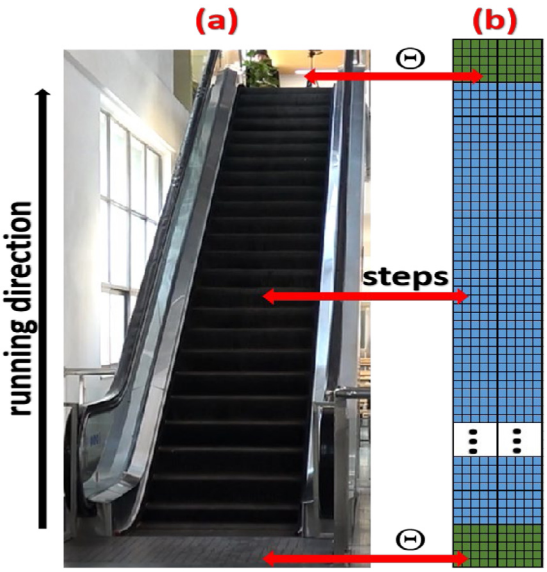

Fig. 5. Escalator area, where (a) real-world graph of the escalator structure and (b) the abstract graph of (a).

(4) Each escalator-floor connecting area (green area in Fig. 5(b)) is discretized into two areas where pedestrians can walk to enter or leave the escalator. The research objects are adults (mainly college students or teachers). Thus, considering their body size and walking characteristics, the size of each walkable area is 0.5 m $\times$ 0.5 m (i.e., 5 $\times$ 5 cells).

In fact, how to discretize the space occupied by pedestrians in CA model is an important and always concerned issue. In 1971, Fruin pointed out that when describing pedestrian movement, a pedestrian's body size should be set as an ellipse with 0.6 m in width and 0.45 m in depth [24]. Later, researchers put forward some different opinions on the Fruin body ellipse. For example, Ref. [25] pointed out that the Fruin body ellipse was derived for a large 95th percentile male with respect to maximum body breadth and depth, but the 95th percentile weight was in the 1950s about 90 kg. Besides, different from Fruit's study, when adopting the CA model to depict pedestrian movement, Ref. [26] simplified the space occupied by each pedestrian as a square with the pedestrian's body width as the side length. Researches have widely adopted the body shape hypothesis (i.e., square) proposed by Ref. [26] for depicting pedestrian movement. Furthermore, some Asian researchers set the body size of an Asian pedestrian as a 0.5 m $\times$ 0.5 m or 0.4 m $\times$ 0.4 m square when adopting CA models to reproduce pedestrian movement extracted from controlled experiments or observations (e.g. Refs. [12,27]). In particular, Ref. [12] used CA model to explore Chinese university students' movement on stairs and obtained some results which are accordant with the experiment data, where the spaces occupied by a pedestrian on landings and stairs were set as 0.5 m $\times$ 0.5 m (i.e., body width $\times$ body width) and 0.5 m $\times$ 0.3 m (i.e., body width $\times$ trend depth), respectively. Although stairs and escalators have some different characteristics, they all belong to vertical walking facilities. The space occupied by pedestrians on such facilities is jointly determined by the size of pedestrian body and the size of facilities, while the space on floors around such facilities is only determined by the size of pedestrian body. Indeed, setting 0.5 m $\times$ 0.4 m as the minimum cell size for steps on the escalator and 0.5 m $\times$ 0.5 m as the minimum cell size for the escalator-floor connecting area can meet the modeling needs for the current scenario. Still, considering the proposed model's extensibility to other escalator scenarios, especially: (1) the escalator with slope but not step, in which pedestrians' movements are more discrete; (2) the escalator with different designed width for each step; (3) the pedestrian crowd is with more complicated composition (e.g., adult-child pair), resulting in the heterogeneity of pedestrian's body sizes, the current cell size setting can have some benefits.

Our observation data show that two pedestrians stay in a row on one step of escalator and in the escalator-floor connecting area, which shows that each step of escalator and the escalator-floor connecting area should be discretized into two areas, where the sizes of each area are respectively 0.5 m $\times$ 0.4 m. Based on the above space discretization, we should take the minimum common divisors of body width and S_l as the space minimum discretization size (that is here set as 0.1 m), where the discretization has the following advantages:

(1) It can ensure the continuity of the model in space.

(2) It can ensure the model extensibility for other escalator scenarios (e.g., the size of each step of other escalators is larger than the sum of two pedestrians' body size, but less than that of three pedestrians' body size).

(3) It can ensure the model extensibility for describing some special behaviors of pedestrians (e.g., the behavior that some pedestrians stay in the middle area of each step of escalator).

2.3.2. Movement rules of pedestrians

The movement rules of pedestrians are evaluated after the space discretization. The direction of the escalator's movement is from bottom to top (from the first to the second floor) and the escalator's "inverse speed" (denoted by v_e' and "inverse speed" is the reciprocal of speed, where the speed is denoted as v) is constant. Therefore, each pedestrian is generated at the bottom escalator-floor connecting area, and his/her spontaneous "inverse speed" (relative to the escalator) on the escalator is $v_p^{i\,\prime}(i = 1, 2, \ldots, 2816)$ (Note: $v_e' = 1/v_e$, $v_p^{i\,\prime} = 1/v_p^i$). For each pedestrian moving on the escalator steps, there are two possible moving choices: (1) when the pedestrian chooses to walk spontaneously, he will always choose to walk with the same speed as long as there is possible walkable space which is determined by Eqs. (2)–(11); (2) when the pedestrian chooses not to walk (i.e., ride), he will always keep stationary relative to the escalator. In this model, before each pedestrian enters the escalator, his/her walk-ride (not to walk) attribute (i.e., binary attribute) and his/her spontaneous walking speed are pre-allocated. When a pedestrian moves to the top escalator-floor connecting area, he/she is removed from the system at the next global update time step.

We choose the "inverse speed" as a measurement of speed to make the movement more intuitive. The escalator's own "inverse speed" v_e' means that a new step is generated every $\left|v_e'\right|$s; for the ith pedestrian's spontaneous movement relative "inverse speed" $v_p^{i\,\prime}$ denotes the time required for him or her to cross a certain step spontaneously is $\left|v_p^{i\,\prime}\right|$s.

Each pedestrian's comprehensive movement on the escalator is composed of their own spontaneous movement and the escalator's movement. The escalator may operate at a different speed than the pedestrian's spontaneous movement. We adopt an asynchronous update to reflect the disparity between them. In an asynchronous update, the minimum time step (i.e., TS_m) should be equal to the minimum common divisor of the escalator movement "inverse speed" and each pedestrian's spontaneous movement relative "inverse speed" (i.e., $TS_m = 0.01$ s). TS represents the total time step of system cumulative update, and when $TS/\left|v_e'\right| = N+$ (i.e., $N+$ denotes a set of positive integers), the positions of the escalator steps are updated at TS; when $TS/\left|v_p^{i\,\prime}\right| = N+$, the corresponding pedestrian's position change caused by his or her spontaneous movement is updated at TS.

In this model, at each TS, the change in each pedestrian's position caused by the escalator's movement is calculated first; the change in position caused by his or her spontaneous movement is calculated second. The results of position change caused by the former are the initial condition of the latter. There are two possible changes in each pedestrian's position caused by the escalator's movement (see Fig. 6(a)): (1) the position remains unchanged or (2) the position advances 4 cells (i.e., one step) in the running direction. This position change can be expressed by Eq. (1):

$$P_{TS}^i = \begin{cases} P_a^i, \text{ if}(TS/\left|v_e'\right|) = N+ \\ P_s^i, \text{ if}(TS/\left|v_e'\right|) \neq N+ \end{cases}, \tag{1}$$

where P_{TS}^i represents the position choice for ith pedestrian caused by the escalator's movement; P_a^i and P_s^i respectively represent the corresponding positions where pedestrian ith advances either 4 cells or does not move (see Fig. 6(a)).

There are three possible changes in each pedestrian's position caused by his/her spontaneous movement (see Fig. 6(b)): (1) the position remains unchanged; (2) the position advances 4 cells (one step) in the escalator's running direction; (3) the position advances four cells in the escalator's running direction while changing five cells in the transverse direction to the escalator's movement. When making calculations, we consider pedestrians walking singly and pedestrians walking in any type of group separately. The position change of a pedestrian walking singly can be expressed as Eqs. (2)–(6):

$$PP_a^i = \alpha_1 \cdot \alpha_2 \cdot \alpha_{TS}, \tag{2}$$

$$PP_{ar}^i = \begin{cases} \alpha_1 \cdot (1 - PP_a^i) \cdot \alpha_3 \cdot \alpha_4 \cdot \alpha_{TS}, & \text{if } i\text{th pedestrian is on the left lane} \\ 0, & \text{otherwise} \end{cases}, \tag{3}$$

$$PP_{al}^i = \begin{cases} \alpha_1 \cdot (1 - PP_a^i) \cdot \alpha_3 \cdot \alpha_5 \cdot \alpha_{TS}, & \text{if } i\text{th pedestrian is on the right lane} \\ 0, & \text{otherwise} \end{cases}, \tag{4}$$

$$PP_s^i = 1 - PP_a^i - PP_{ar}^i - PP_{al}^i, \tag{5}$$

$$P_{TS}^i = \begin{cases} P_a^i, & \text{if} \quad PP_a^i = 1 \\ P_{ar}^i, & \text{if} \quad PP_{ar}^i = 1 \\ P_{al}^i, & \text{if} \quad PP_{al}^i = 1 \\ P_s^i, & \text{if} \quad PP_s^i = 1 \end{cases}, \tag{6}$$

where P_{TS}^i, P_a^i, and P_s^i have the same meanings as in Eq. (1) except for caused by ith pedestrian's spontaneous movement; P_{ar}^i and P_{al}^i represent the corresponding positions where ith pedestrian moves front right or front left (see Fig. 6(b)). α_1, α_2, α_3, α_4, α_5, α_{TS} are six binary variables satisfying the following conditions: (1) if the ith pedestrian intends to walk, $\alpha_1 \equiv 1$, otherwise, $\alpha_1 \equiv 0$; (2) if P_a^i is empty, $\alpha_2 = 1$, otherwise, $\alpha_2 = 0$; (3) if the ith pedestrian intends to bypass, $\alpha_3 \equiv 1$, otherwise, $\alpha_3 \equiv 0$; (4) if P_{ar}^i is empty, $\alpha_4 = 1$, otherwise, $\alpha_4 = 0$; (5) if P_{al}^i is empty, $\alpha_5 = 1$, otherwise, $\alpha_5 = 0$; (6) if

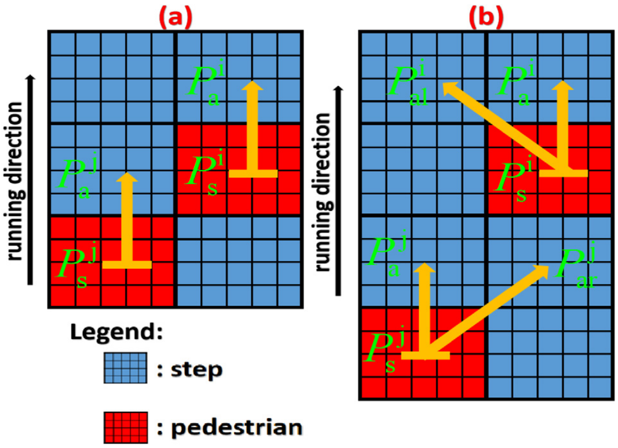

Fig. 6. Sketch of pedestrian position changes, where (a) the one caused by escalator's movement and (b) the spontaneous one.

$(TS/\left|v_p^{i\,\prime}\right|) = N+$, $\alpha_{TS} = 1$, otherwise, $\alpha_{TS} = 0$; (7) PP_a^i, PP_{ar}^i, PP_{al}^i, PP_s^i represent possibilities of positions (i.e., P_a^i, P_{ar}^i, P_{al}^i, P_s^i) to be chosen respectively.

For pedestrians walking in groups, their positional changes can be expressed by Eqs. (7)–(11), i.e.,

$$PP_a^i = \alpha_1 \cdot \alpha_2' \cdot \alpha_{TS}, \tag{7}$$

$$PP_{ar}^i = \begin{cases} \alpha_1 \cdot (1 - PP_a^i) \cdot \alpha_3 \cdot \alpha_4' \cdot \alpha_{TS}, & \text{if } i\text{th pedestrian is on the left lane} \\ 0, & \text{otherwise} \end{cases}, \tag{8}$$

$$PP_{al}^i = \begin{cases} \alpha_1 \cdot (1 - PP_a^i) \cdot \alpha_3 \cdot \alpha_5' \cdot \alpha_{TS}, & \text{if } i\text{th pedestrian is on the right lane} \\ 0, & \text{otherwise} \end{cases}, \tag{9}$$

$$PP_s^i = 1 - PP_a^i - PP_{ar}^i - PP_{al}^i, \tag{10}$$

$$P_{TS}^i = \begin{cases} P_a^i, & \text{if} \quad PP_a^i = 1 \\ P_{ar}^i, & \text{if} \quad PP_{ar}^i = 1 \\ P_{al}^i, & \text{if} \quad PP_{al}^i = 1 \\ P_s^i, & \text{if} \quad PP_s^i = 1 \end{cases}, \tag{11}$$

where α_2', α_4' and α_5' are three 0–1 variables satisfying the following conditions: (1) if P_a^i is occupied by pedestrians who are not in the same group as the ith pedestrian, $\alpha_2' = 0$, otherwise, $\alpha_2' = 1$; (2) if P_{ar}^i is occupied by pedestrians who are not in the same group as the ith pedestrian, $\alpha_4' = 0$, otherwise, $\alpha_4' = 1$; (3) if P_{al}^i is occupied by pedestrians who are not in the same group as the ith pedestrian, $\alpha_5' = 0$, otherwise, $\alpha_5' = 1$; (4) PP_a^i, PP_{ar}^i, PP_{al}^i, PP_s^i represent possibilities of positions (i.e., P_a^i, P_{ar}^i, P_{al}^i, P_s^i) to be chosen respectively.

Actually, Eqs. (1)–(11) are formulaic expressions of pedestrian behavior rules. If comparing pedestrian flow on the escalator with those on the staircase, pedestrian behavior on the escalator is more coherent and with less complexity: some human factors may not exist (e.g., fatigue, body rotation) for the escalator scenario but are often considered for the staircase scenario (i.e., those factors do have effect for pedestrian flow on the staircase). In this section, the grouping factor is regarded within the basic rule-based CA model; the other factors (e.g., the "walk left, stand right" rule) can be extracted as rules and added to Eqs. (1)–(11) to simulate the pedestrian flow under such circumstances. Also, from Fig. 7 and Eqs. (1)–(11), it can be seen that only single and 2-size group pedestrians are considered to have the potential walking intention. The assumption is made based on the following evidence: (1) pedestrian's spontaneous movement on the escalator is not necessary (compared to the staircase), and if pedestrians are in a large size grouping state, walking behavior may result in the hardness of maintaining the original grouping intention of those pedestrians; (2) from the case study in this paper (i.e., high grouping proportion case), pedestrians within more than two-size group tend to stand on the escalator but not walk. Nevertheless, suppose future researchers want to apply the basic model in this section to some particular scenarios where pedestrians within a large-scale group need to walk spontaneously. In that case, the model can be extended by adding the realistic rules describing such a condition.

To sum up, the schematic diagram of the pedestrian flow around escalator area based on model in Section 2.3 is shown in Fig. 7. In this study, the walking step length of each pedestrian around the escalator area is considered, and the physical size of each part of the escalator area and the characteristics of pedestrian walking space are integrated; an asynchronous

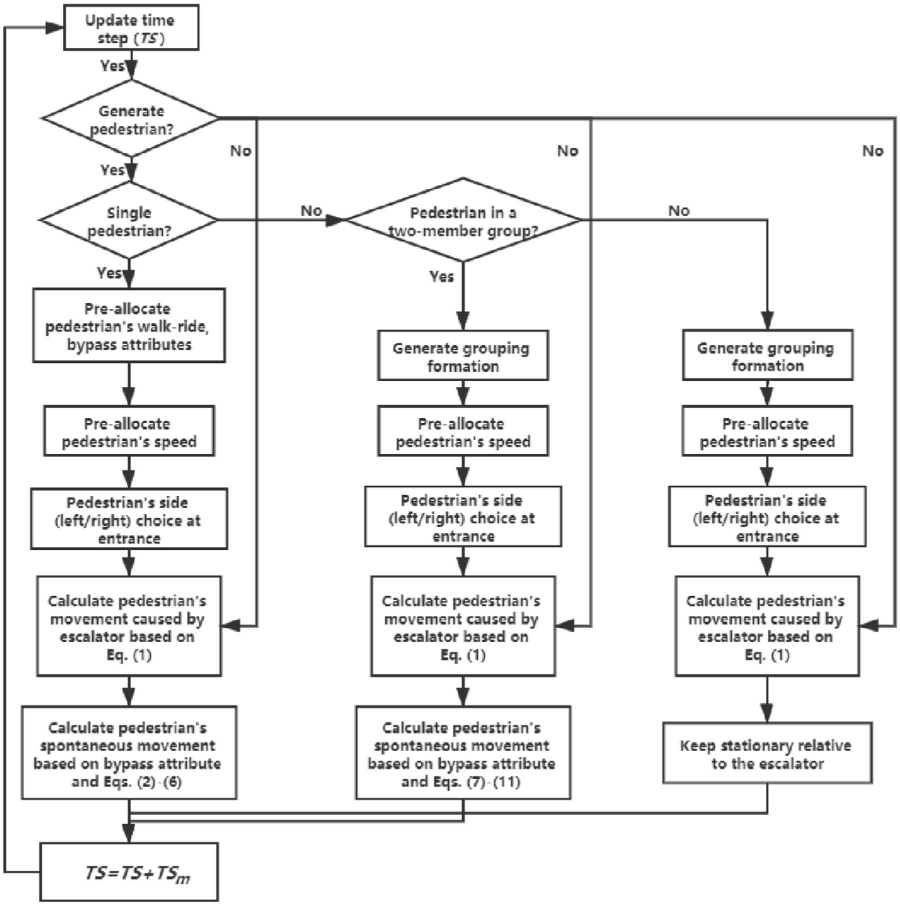

Fig. 7. Schematic diagram of the pedestrian flow around escalator area.

updating step-length based CA model is established which can better simulate the pedestrian flow on the escalator than the traditional CA model or mechanics-based continuous model.

Besides, our model is also capable of visualization, which can clearly show pedestrians' movement state, including several grouping states; managers of the escalator can adopt the basic model in this section to simulate the pedestrian flow on their escalator and find the step-by-step position change of pedestrians. Similar to Refs. [16,28] which apply CA model to vertical walking facility (i.e., the staircase), we also screenshot examples of the proposed model's visualized results (see Fig. 8).

3. Numerical test

In this section, we firstly reproduce pedestrian movements based on the case study scenario using the CA model presented in Section 2 (i.e., Simulation I). We then modify the proportion of pedestrians walking to determine the how it affect the capacity of the escalator (i.e., Simulation II). After that, we formulate some pedestrian guidance and management strategies and explore how they affect the operational efficiency and safety of the escalator area (i.e., Simulations III, IV).

3.1. Simulation I

We reproduce the pedestrian movements in the case study area first (i.e., Simulation I). Indeed, the walking proportion of pedestrian in the case study is relatively low, which lead to the pedestrian's position change being more likely affected by the escalator's physical attributes but not the pedestrian's spontaneous behavior. However, for the case study, the input flow and the grouping state within the flow are counted by every 10 s. Thus, if considering every 10 s as the input time section, in each section, the detailed pedestrian attributes are not totally given by the case study (e.g., the sequence of each group), which may cause some uncertainty for simulation. Simulation I is not intended to serve as the complete verification of the proposed model (which is also not qualified enough considering only one reproduced condition) but is

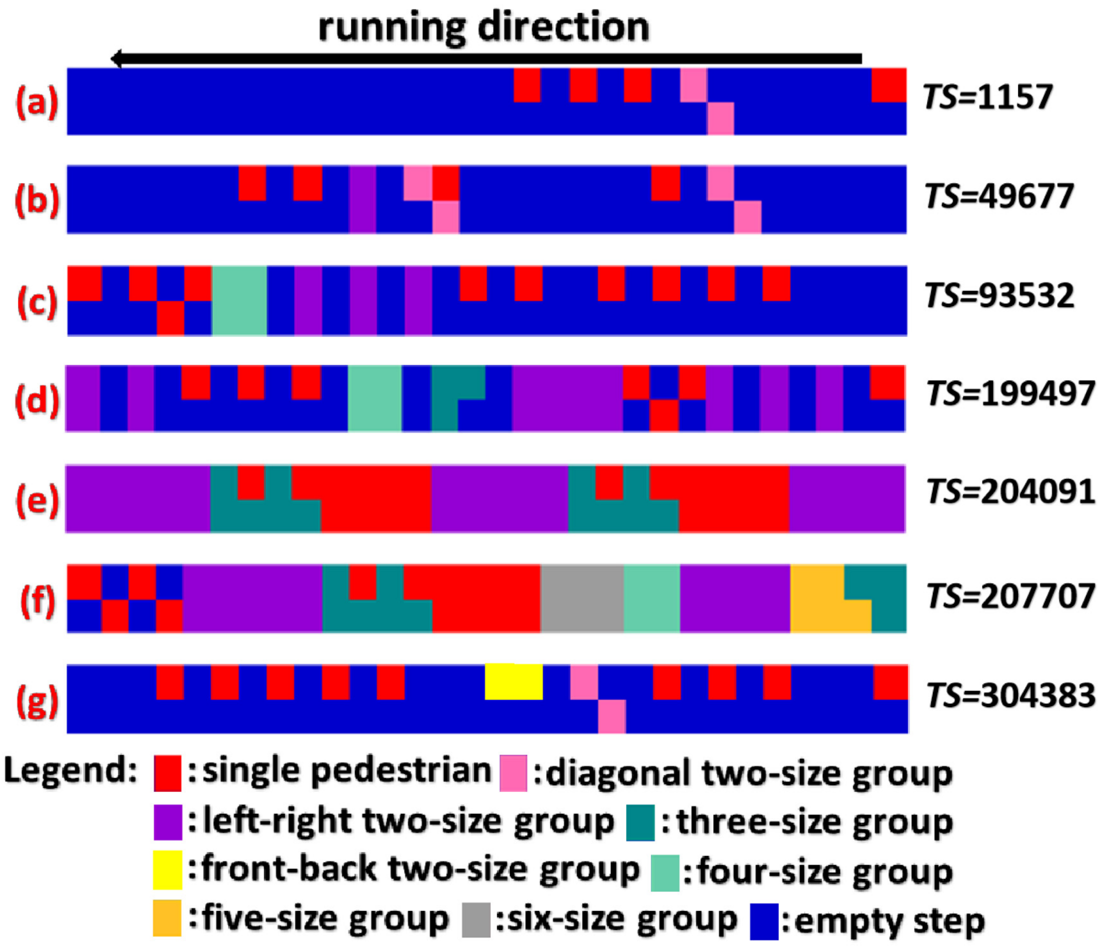

Fig. 8. Pedestrian movement on escalator at different time steps (denoted by *TS*).

Table 5
The Pearson tests results.

Number of data pair	p-value	Pearson correlation
408	.000	>0.99

used as a "case study" for simulation and comparison regarding the collected case study data in reality. For Simulation I, the conditions and assumptions are listed as follows:

(1) The pedestrian's input parameters (e.g., input time, the number of pedestrians, grouping status and walking attribute) with ten seconds as a section and the fundamental attribute of escalator (e.g., speed, size) are determined by the observation data in the case study.

(2) $v_p^{i\,\prime} \sim N(0.53, 0.33^2)$, where the upper bound is 0.75 s/step and the lower bound is 0.40 s/step; the walking speeds of the two pedestrians in a group are considered to be equal.

(3) Based on the data that pedestrians have bypassing behavior, only four among the 2,816 pedestrians choose to bypass, so we can neglect the bypassing behavior for Simulation I.

The number of pedestrian inflows (which is the same for Simulation I and the case study), the number of pedestrian outflows counted in the case study, and the number of pedestrian outflows counted in Simulation I are collected every 10 s, as shown in Fig. 9. Based on the cumulative pedestrian's outflow data (similar to Ref. [29]) of the observation study and simulation in Fig. 9, we quantitatively compare whether there is one statistical correlation between the cumulative pedestrian's outflow data of the observational study and simulation under the same pedestrian's inflow condition.

First, we conduct the Pearson test (see Table 5), and can conclude that the two kinds of data are statistically correlated (i.e., $p < 0.05$) and have a strong positive correlation (i.e., Pearson Correlation $\approx$1). Next, we study the trend of data by

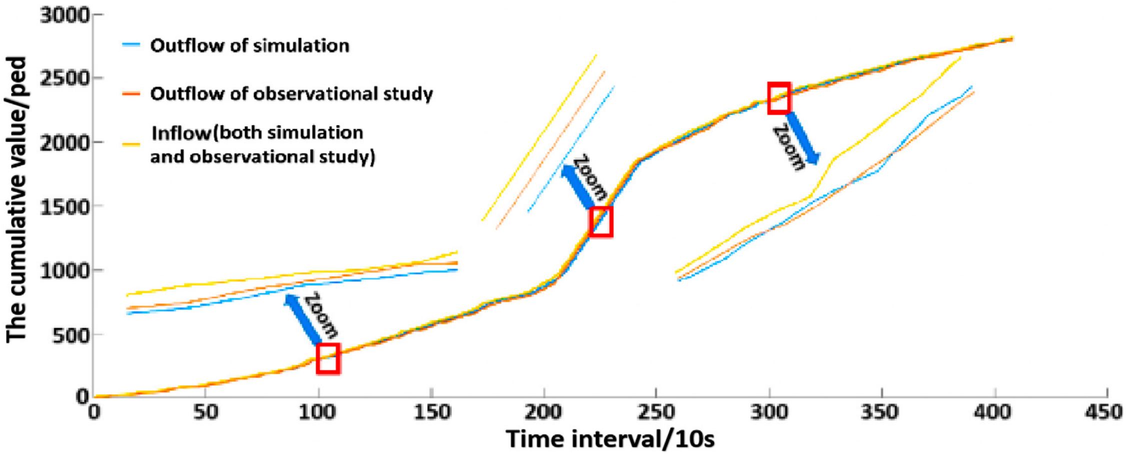

Fig. 9. Comparison of cumulative inflows and cumulative outflows in Simulation I and case study.

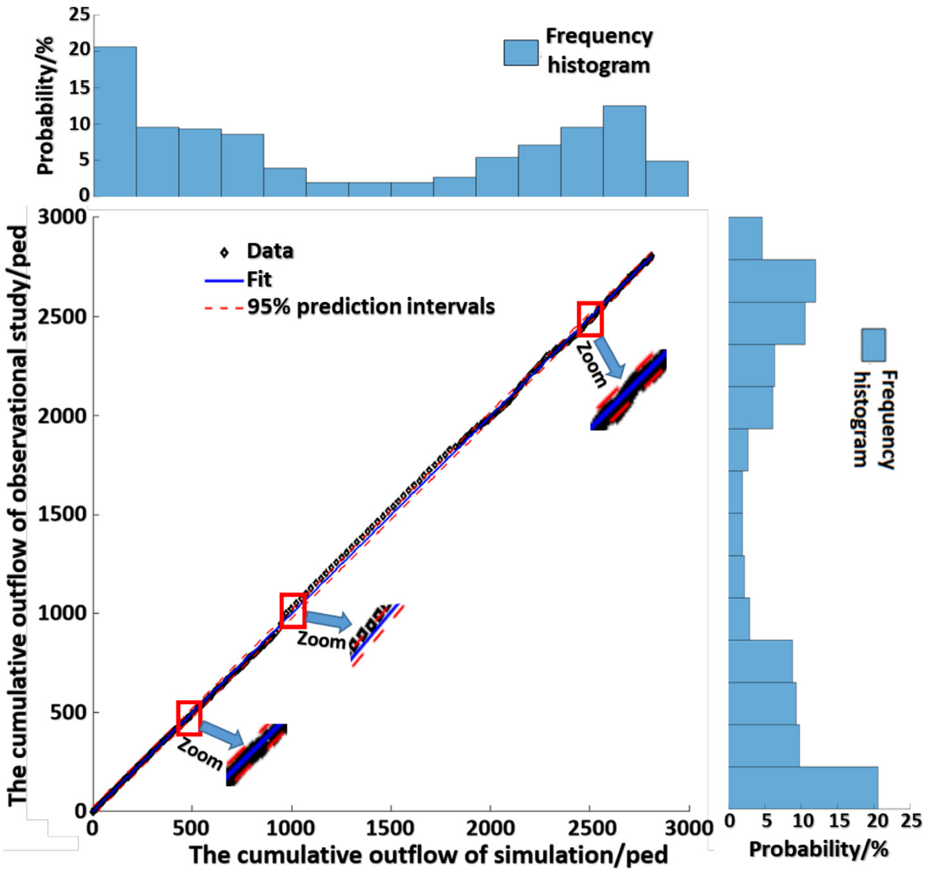

Fig. 10. The linear regression of the cumulative outflow of simulation versus observational study.

using a linear regression, where the resulting equation can be formulated as:

$$y = 0.9981x - 0.5734, \tag{12}$$

where the intuitive results are shown in Fig. 10. From Fig. 10, we can find that the growth trends of each kind of data are approximately equal. Judging from Simulation I and the case study, under the case study input conditions, the model can have a relatively good matching.

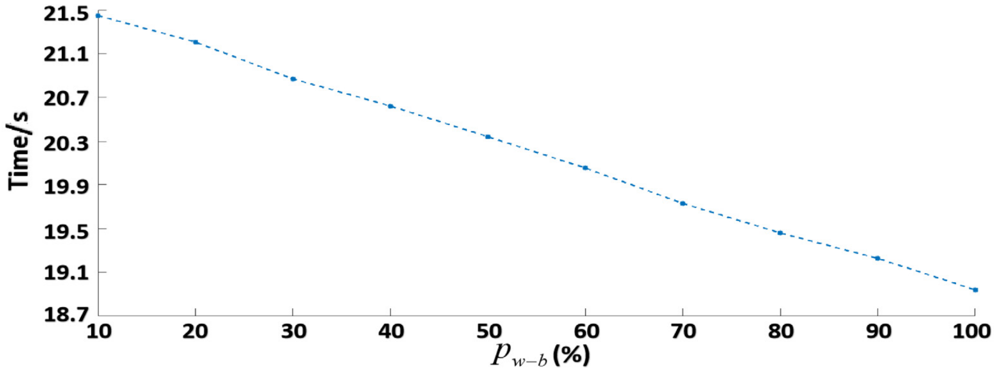

Fig. 11. Average time spent by pedestrians on the escalator considering p_{w-b} = 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 100%, respectively.

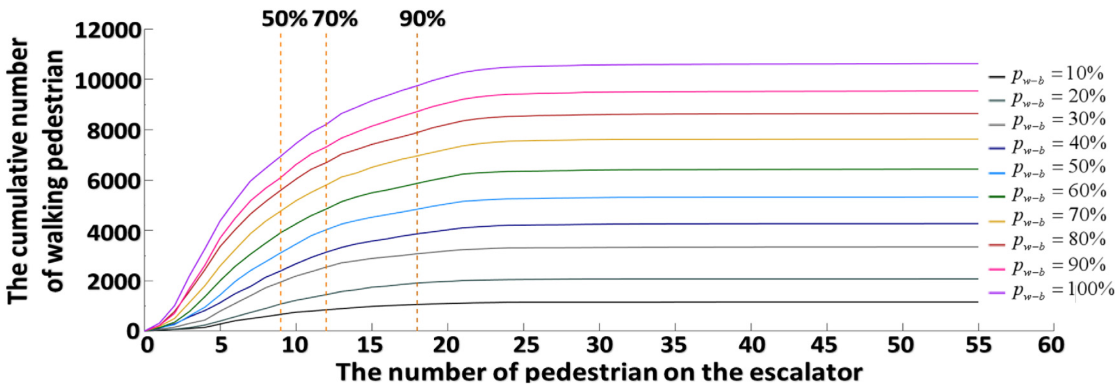

Fig. 12. Relationship between cumulative number of walking pedestrians and number of pedestrians on the escalator.

3.2. Simulation II

The proportion of pedestrians walking and bypassing is low in the case study. However, in actuality, pedestrians are fairly likely to choose to walk or bypass the escalator on specific occasions such as in subway stations [30]. Accordingly, we change the proportion of pedestrians who intend to walk and bypass to explore the influence of individual pedestrian walking and bypassing behavior (i.e., Simulation II). In simulation II, we give an assumption that pedestrians with walking intention will always find the available and empty walkable area on the escalator (i.e., pedestrians will maintain their walking if possible). In some cases, the assumption will lead to the bypassing behavior to other pedestrians (e.g., one pedestrian may change his lane on the escalator to keep walking when facing other pedestrians as obstacles). For Simulation II, the conditions and assumptions are listed as follows:

(1) The simulated pedestrian input, v_e and $v_p^{i\,\prime}$ are consistent with the case study.

(2) The proportion of pedestrians who intend to walk and bypass (i.e., p_{w-b}) can be changed.

Fig. 11 shows the average time spent by pedestrians on the escalator considering different p_{w-b}. Fig. 12 shows the relationship between the cumulative number of pedestrians walking on the escalator at *TS* and the number of pedestrians on the escalator at *TS*. Fig. 13 shows the speed-density relationship diagram of the pedestrian flow considering different p_{w-b}.

Fig. 11 indicates that the average time spent by pedestrians on the escalator decreases as p_{w-b} increases. On the whole, the movement of pedestrians does not degrade the operating efficiency of the escalator. Fig. 12 shows that under each p_{w-b} condition, the number of walking pedestrians on the escalator tends to increases and then decreases as there are more people on the escalator (i.e., as the escalator becomes crowded); up to 90% of pedestrian walking occurs when there are fewer than 20 pedestrians on the escalator. As the pedestrian density on the escalator increases, it becomes more difficult for them to walk; the pedestrians' average speed on the escalator then approaches the escalator's running speed (see Fig. 13). Comparing the results in Simulation II with Refs. [11,30], there are the following similarities and differences:

(1) For the similarities, Refs. [11,30] simulated the impacts of different walking proportions on the total evacuation time (i.e., TET) in subway station and found that TET would drop with the increase of the proportion that pedestrians walked on escalator, which showed that the escalator operation efficiency would be enhanced. This conclusion is in line with results shown in Fig. 11.

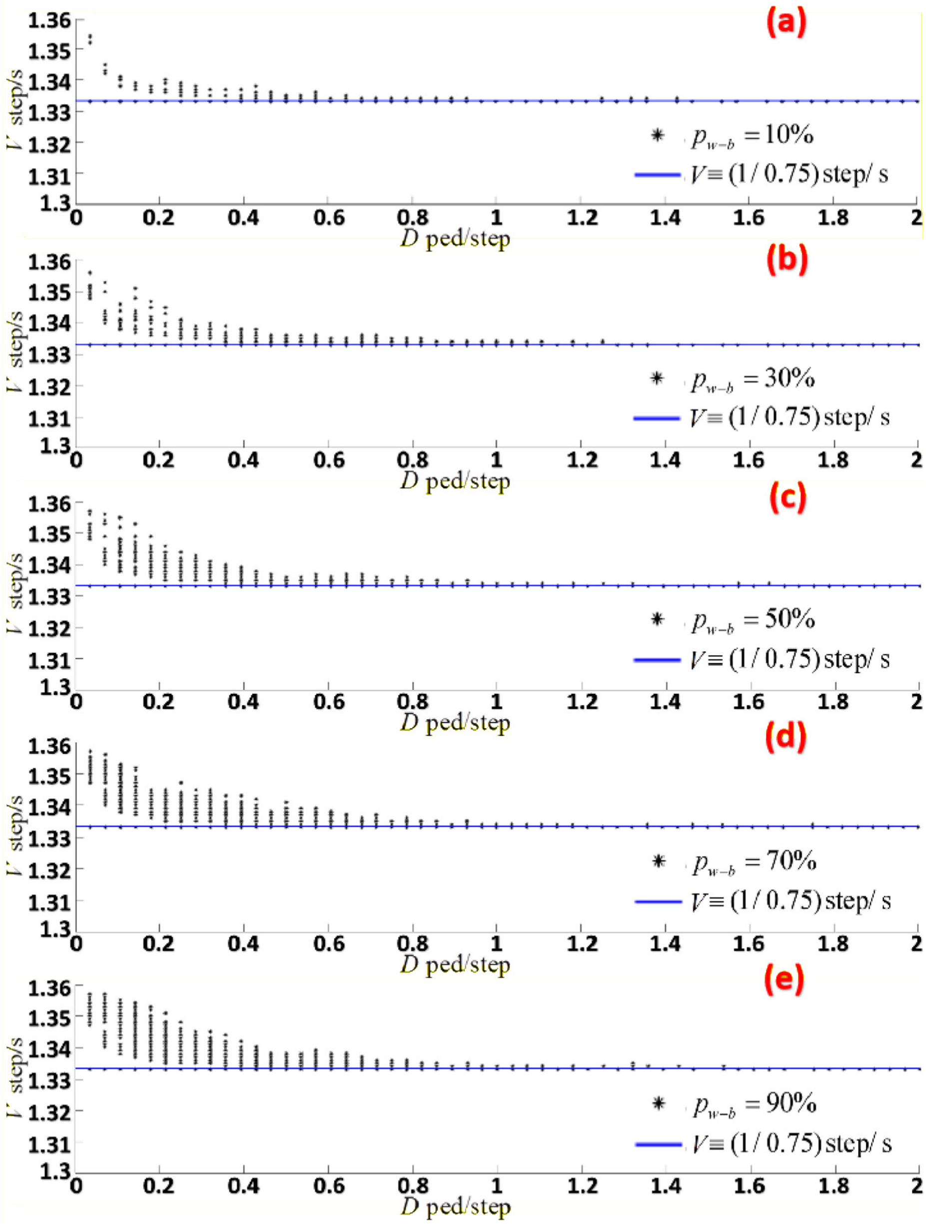

Fig. 13. Speed-density relationship diagram considering different p_{w-b} :(a)–(e) represent p_{w-b} = 10%, 30%, 50%, 70%, 90%, respectively.

(2) For the differences, Refs. [11,30] mainly studied the impacts of the walking proportion on some macro parameters (e.g., TET). However, Figs. 12 and 13 describe the pedestrian's walking process from more microscopic perspective by revealing the relationship between the number of walking times and density under different walking proportion. Even under different walking proportion, the effects of pedestrian density on the pedestrian walking willingness show uniformity.

What is more, the walkable area on the escalator can be basically extracted as a two-lane system, where pedestrians with coherent walking intention will always find a reachable and empty position as the result of the movement choice — which may occur as the bypassing; in the proposed CA model, such behavior is determined by rules. However, if only considering the walking and bypassing behavior in a broader scenario, Newton's law and fuzzy logic-based methods may perform better in depicting pedestrian behavior than rule-based methods [31]; that is, the choice of methods should suit the research scenarios.

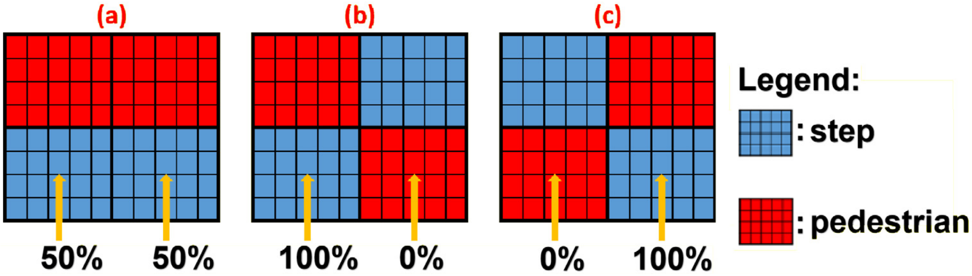

Fig. 14. Sketch of pedestrian position choices with the random rule.

3.3. Simulation III

As described in Section 2, most pedestrians follow the "stand right" rule under the scenario described here. When more pedestrians choose to walk on the escalator, this rule can be more universally understood as the "walk left, stand right" rule. Take Holborn station in London as an example. The Guardian once reported (2016) that most commuters regard this rule as a norm to be observed. When administrators tried to change this rule to "both sides can stand or walk" during peak traffic hours, controversy arose [32]. Indeed, the intention of asking pedestrian to walk on the left and stand on the right is to allow pedestrian a choice to walk or ride, and if a pedestrian choose to ride he will not block others behind them willing to walk. However, how this rule quantitatively affects the escalator's operating efficiency and safety is worth exploring. We design Simulation III accordingly. For Simulation III, the conditions and assumptions are listed as follows:

(1) The simulated pedestrian input, v_e and $v_p^{i\,\prime}$ are consistent with the case study.

(2) The proportion of pedestrians who intend to walk and bypass (i.e., p_{w-b}) can be changed.

(3) The "walk left, stand right" rule is carried out to test its effectiveness.

Under conditions of different p_{w-b} in Simulation III, for cases without the "walk left, stand right" rule, single pedestrians randomly choose the left or right position when entering the escalator (i.e., the random rule). To be specific, considering the moment when a pedestrian reaches the escalator and he/she needs to choose a side to step on the escalator, under the random rule regardless of the pedestrian's walking willingness, he/she may face two possible position choices: (1) if both the left and right positions of the escalator's first step are not occupied, the probability of the pedestrian occupying the left or right side is equal (i.e., 50% versus 50%) (see Fig. 14(a)); (2) If only one of the left and right positions of the escalator's first step is empty, the pedestrian will occupy the empty side with 100% probability (see Fig. 14(b) and (c)). It should be pointed out that the random rule is only applicable for the pedestrian's first step choice when entering the escalator (i.e., the random rule is an assumption for simulation III), after pedestrians entering the escalator, their movement are calculated by the proposed CA model.

For cases with the "walk left, stand right" rule, pedestrians all obey the rule if possible. We adopt the average time spent by pedestrians on the escalator to explore the influence of the rule on the whole escalator's operating efficiency and adopt the cumulative times of pedestrians' bypassing behavior to explore the rule's impact on escalator's operating safety (see Fig. 15). As shown in Fig. 15, under the same p_{w-b} condition, after adopting the "walk left, stand right" rule, pedestrians spend less time on the escalator on average than before. Under the condition of Simulation III's input flow, the "walk left, stand right" rule appears to enhance the escalator's operating efficiency.

Pedestrians are more likely to squeeze or collide with others when executing bypassing behavior, especially when the escalator runs from down to up, which creates safety hazards. Thus, we adopt the cumulative times of pedestrian bypassing to reflect the escalator's operating safety. The "walk left, stand right" rule is not always explicitly promoted. When p_{w-b} is small, adopting the rule can reduce bypassing behavior; however, when p_{w-b} is large (e.g., $p_{w-b} > 90\%$), the rule may actually increase pedestrian bypassing behavior. If a pedestrian bypasses another pedestrian in front of him/her, the cumulative time of pedestrian bypassing behavior increases by one.

In fact, when all single pedestrians choose to walk, both the left and right sides can be used as walking passages instead of only the left side, which can prevent unnecessary lane changes. When the rule is not adopted, an increase in p_{w-b} causes bypassing behavior to first increase and then decrease; the peak value appears at approximately $p_{w-b} = 64\%$. This is because an increase in p_{w-b} decreases the number of stand-still pedestrians, resulting in fewer obstacles that walking pedestrians need to circumvent. According to the Guardian, administrators claimed that the adoption of the "both sides can stand or walk" rule during peak traffic hours can improve the capacity of escalators; the possible reason for this phenomenon is that most pedestrians are set to be stand-still as precondition for calculation. In addition, based on the observation and simulation data of pedestrian flow around subway stations' escalator area in three countries, Ref. [14] found that the increasing pedestrian walking proportion on the escalator can reduce the average total evaluation time (TET). The findings of Ref. [14] are consistent with the phenomenon presented in Fig. 15(a). Nevertheless, although this study share the same conclusions with Ref. [14], considering the influence of pedestrian walking proportion on TET, there exist some differences: (1) this study only takes the pedestrian flow around a single escalator into consideration, while

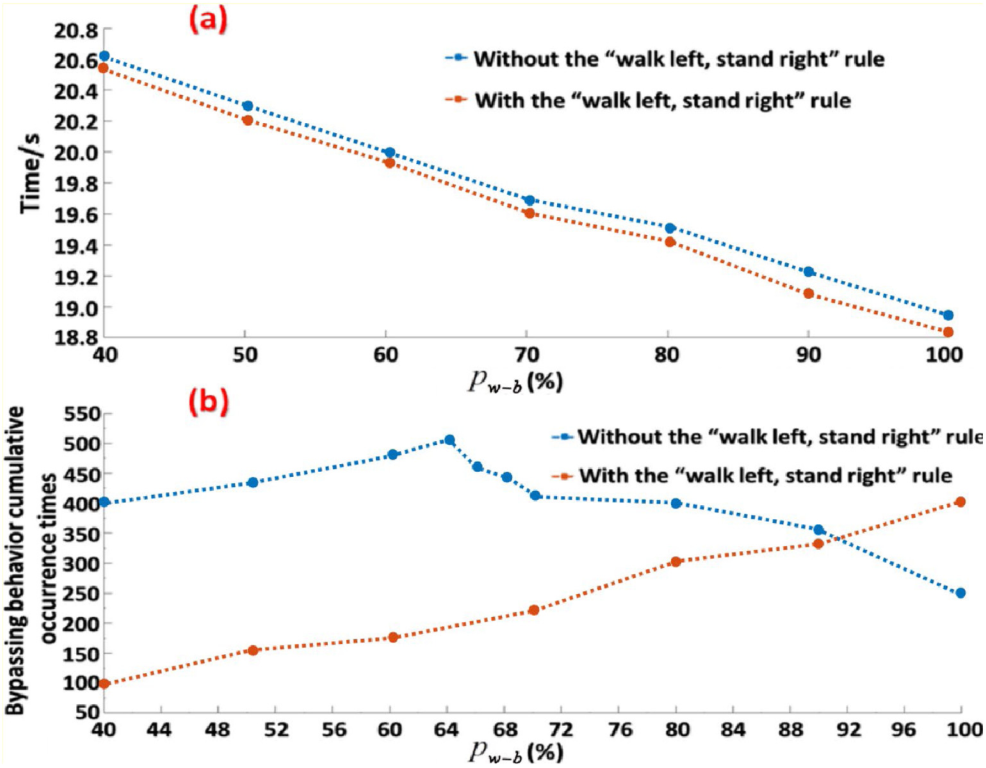

Fig. 15. (a) Average time spent by pedestrians, (b) cumulative time of pedestrian bypassing behavior on the escalator under different p_{w-b} conditions, with or without "walk left, stand right" rule.

Ref. [14] studies the comprehensive area consisting of several vertical walking facilities including escalators; (2) in this study, the influence of p_{w-b} is discussed in more detail (i.e., the change of p_{w-b} in different cases is finer). Judging by Fig. 15(a) and Guardian's report, the "walk left, stand right" rule can indeed improve the escalator capacity because it reduces the time that pedestrians stay on escalator. However, adopting the "walk left, stand right" rule cannot always enhance the escalator operation safety. If most of pedestrians choose to walk on the escalator, this rule may cause more competitions among pedestrians, where the competitions can cause safety hazards. Thus, the effectiveness of the "walk left, stand right" rule should be evaluated in combination with the actual situation. For example: (1) a London subway station found that encouraging all pedestrians to ride (i.e., $p_{w-b} = 0$) during peak hours would have a good effect (Ref. [25]); (2) in Simulation III, when p_{w-b} is relatively high, the "walk left, stand right" rule may actually increase pedestrian bypassing behavior; (3) the effectiveness of the "walk left, stand right" rule may be different in different scenarios (e.g., subway station, university's canteen, etc.) with different pedestrian flow characteristics (e.g., different peak arrival rate, etc.).

3.4. Simulation IV

In the case study and Section 3.1, the change of relative position of pedestrians inside a certain group can be considered as almost no effect on the operation of pedestrian flow on the escalator, which is due to the following reasons: (1) in such cases, compared to all pedestrians, the number of pedestrians who choose to walk and bypass is relatively small; (2) almost all pedestrians in grouping states choose not to walk. However, it can be seen that with the increase of p_{w-b}, pedestrians in grouping states are more and more likely to block pedestrians who choose to walk due to their physical formation. Thus, especially under scenarios where pedestrians have stronger intentions to walk, the impact of changing the grouping formation (i.e., Strategy I) on the escalator's operating safety and efficiency should be explored accordingly. To be specific, Strategy I can be described as follow: when space permits, the grouping formations in Figs. 4(b) and 4(c) are changed to Fig. 4(a) so that all pedestrians in two-size groups can stand on the same side of the escalator.

Simulation IV is carried out to measure the impact of the grouping formation change quantitatively. For Simulation IV, the conditions and assumptions are listed as follows:

(1) The simulated pedestrian input, v_e and $v_p^{i\,\prime}$ are consistent with the case study.
(2) The proportion of pedestrians who intend to walk and bypass (i.e., p_{w-b}) can be changed.

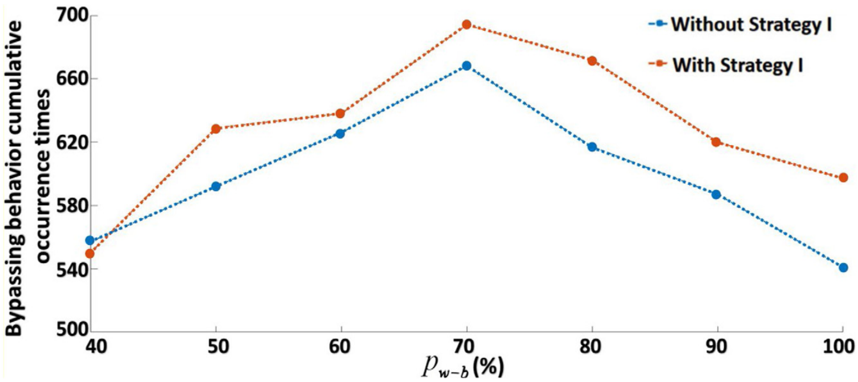

Fig. 16. Cumulative time of pedestrian bypassing behavior on the escalator under different p_{w-b} conditions, with or without Strategy I.

(3) Strategy I is carried out to test its effectiveness.

Under different p_{w-b} in Simulation IV, for cases without Strategy I, pedestrians in left–right two-size groups or diagonal two-size groups remain unchanged. For cases with Strategy I, pedestrians in left–right two-size groups or in diagonal two-size groups change their grouping formations into front–back two-size groups. For both cases, single pedestrians randomly choose the left or right position when entering the escalator. Similar to Simulation III: (1) the cumulative times of pedestrian bypassing are adopted to reflect the escalator's operating safety; (2) the average time pedestrians spent on the escalator and the cumulative times of pedestrians who intend to walk being blocked is adopted to explore the influence of the rule on the escalator's operating efficiency (Note: if a pedestrian intends to walk but is blocked by other pedestrians, the cumulative time of blocking increases by one). From Fig. 16, we can see that the bypassing behavior occurs more often in general if adopting Strategy I, which possibly means that Strategy I cannot enhance the operating safety. The reason is that, before adopting Strategy I, pedestrians in groups have more chance to occupy both sides of the escalator so that pedestrians with walking behavior could only wait (i.e., no chance to bypass) and be blocked by pedestrians in groups (see Fig. 17(b)). On the other hand, under the conditions of each p_{w-b}, the average time spent by pedestrians on the escalator and the cumulative times of blocking occurrence are reduced under Strategy I because pedestrians have more chance and space to bypass (see Fig. 17). For real-life escalator management, if the hazards of pedestrian's bypassing behavior can be controlled, Strategy I can be a feasible way to enhance the operating efficiency of escalators.

To sum up, the simulation results based on the proposed model and the case study match relatively well in the numerical test. Previous researches about pedestrian flow on escalators rarely consider scenarios with a high grouping proportion of pedestrians. Under such conditions, even varying the walking proportion of pedestrians, up to 90% of pedestrian walking still occurs when fewer than 20 pedestrians are on the escalator. Overall, the model proposed in this study has made a certain supplement and expansion to the research of escalator pedestrian flow, and some new phenomena are found based on simulation. In addition, the guiding rule and strategy which may improve the operating efficiency of escalators under scenarios with a high grouping proportion of pedestrians are analyzed. We find that both "walk left, stand right" rule and Strategy I can improve the operating efficiency of escalator. Still, they also have some adverse effects considering operating safety. Therefore, from the application points of view, for escalator operating management, under scenarios with a high grouping proportion of pedestrians, whether to adopt "walk left, stand right" rule or Strategy I needs to be combined with the manager's needs. On the one hand, if the manager has high requirements for operating efficiency of the escalator and can try to control the potential safety hazards to a certain extent, both "walk left, stand right" rule and Strategy I can be adopted. On the other hand, if the manager has high requirements for operating safety, Strategy I should not be adopted, while the adopting of "walk left, stand right" rule should be determined by the p_{w-b} (i.e., if $p_{w-b} < 90\%$, the rule should be adopted; otherwise, it should not). Results derived from the simulation may provide different options for escalator pedestrian flow management.

4. Conclusion

In daily life, pedestrians often use vertical walking facilities to traverse multi-story buildings. We focus on pedestrian behaviors on escalators in this study, which has received relatively little scholarly attention to date. We conduct a case study to extract the escalator's physical attributes, pedestrians' microscopic movement characteristics, and overall pedestrian flow dynamics. Using the pedestrian motion characteristics reflected in these data, we establish a step-length-based CA model to depict pedestrian movement across the escalator.

Based on the case study and compared with the results of subway stations in Spain, England, and China, we find that pedestrians' walking proportion is low in the university canteen scenario while the grouping proportion is high.

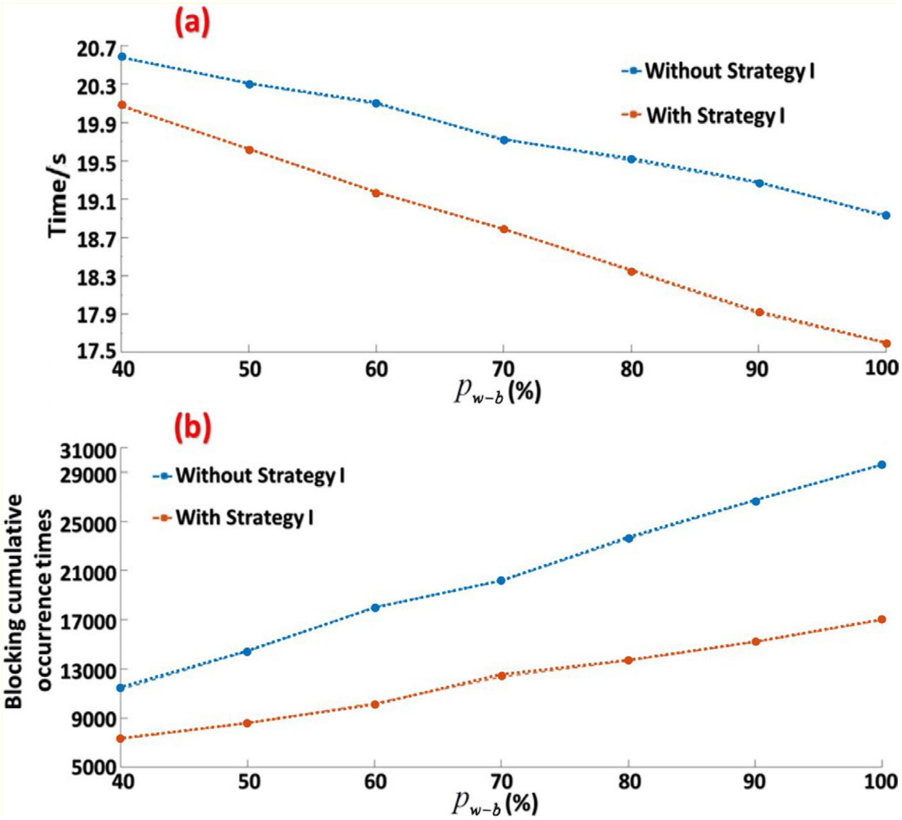

Fig. 17. (a) Average time spent by pedestrians, (b) cumulative time of blocking on the escalator under different p_{w-b} conditions, with or without Strategy I.

We also find that the walking choices of pedestrians in groups and those of pedestrians walking singly exist significant differences. Also, We use the data collected in the case study (e.g., input time, number of pedestrian input, grouping status, walking attributes) and the primary attributes of the escalator (e.g., speed, size) as the initial conditions of the simulation to reproduce the pedestrian flow on the escalator, and find that the proposed CA model is in close accordance with at least the case study. Although the case study is inside a university where pedestrians are with lower walking proportion and higher grouping proportion, other scenarios (e.g., escalators operate with faster speeds, etc.) can also be simulated by changing some conditions based on CA model proposed in this paper (see Simulations II–IV), and some findings are revealed. We also explore some widely used, generally feasible pedestrian flow guidance strategies (e.g., the "walk left, stand right" rule, changing the grouping formation) and evaluate their effectiveness via quantitative analysis. We focus on the effectiveness of these strategies in terms of operating efficiency, with the average time spent by pedestrians on the escalator as an index, and safety, i.e., the cumulative times of bypassing behavior. The results show that the both "walk left, stand right" rule and Strategy I have their advantages and disadvantages; for real-life managers, whether adopting "walk left, stand right" rule or Strategy I should be evaluated in combination with the actual situation.

Due to data availability, this paper adopted the pedestrian inflow peak period in a university canteen as the collection period. The crowd in the university canteen has its own characteristics: the grouping proportion is relatively high, while the walking proportion is relatively low compared to common scenarios. Indeed, if only considering the case study, by only adopting one university canteen as the observation site and adding the low walking proportion in the area, it is challenging to explore thoroughly the impact of a wide variety of pedestrian behavior on the escalator system. However, it is still a feasible way to take the case study data as the primary data input for research and depict other scenarios with high grouping proportion but with other more complicated features (e.g., the higher walking intention of pedestrians). To this end, this paper proposes a CA model aiming to depict pedestrian behavior around the escalator area; by adopting such a model, pedestrian behavior's impact (e.g., more walking behavior, etc.) on the escalator system can be explored, which can partly implement shortcomings of the relative lack of the case study verification.

However, this study still has some limitations. Firstly, this study only considers the escalator's movement from down to up, but not from up to down. Secondly, the proposed strategy is only verified by simulations but not empirically studies. Thirdly, when scenarios exist multiple vertical walking facilities (e.g., staircase and escalator), pedestrians' choices will be affected: Ref. [33] gives thorough research on such a topic. To this end, the effect of such a scenario setup is not considered.

Last but not least, the proposed model has deterministic nature (i.e., agents are considered fully obey the movement rules) but does not introduce randomness into depicting pedestrians' exceptional behavior when they implement their movement in reality. Given such limitation, for instance, the following behavior of pedestrians cannot be reproduced: (1) even if pedestrians are with strong walking tendency, they still may stop walking owing to their intrinsic reasons (i.e., fatigue effect, etc.) but not facing obstacles (i.e., other pedestrians on the escalator); (2) pedestrians may choose to break or change their original grouping formation states. Based on the solid empirical proof of pedestrian movement, especially under the high walking intention cases and considering the modeling part of the current study, one clear direction of extension is to introduce pedestrians' random behavior and further explore such its effect.

In the future, we plan to carry out further experiments, modeling, and simulations for more diverse pedestrian flow scenarios on escalators and with more complex escalator pedestrian flow components. To be specific, this work can be extended as follows: (1) pedestrian's behavior on the escalator with direction from up to down, and the compare of pedestrian's behavior on the escalator under different operating directions can be explored; (2) more empirically studies can be organized to verify the proposed strategy in this paper; (3) more complex pedestrian composition and the existing of the staircase's impact can be considered.

CRediT authorship contribution statement

Chuan-Zhi Xie: Conceptualization, Methodology, Software, Investigation, Writing – original draft. **Tie-Qiao Tang:** Conceptualization, Methodology, Supervision. **Peng-Cheng Hu:** Conceptualization, Experiment. **Liang Chen:** Conceptualization, Experiment, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgments

(1) This work is supported by the National Natural Science Foundation of China (71771005, 72171006 and 72001009).
(2) The authors wish to thank Dr. Alexandre Nicolas (Tenured Researcher with CNRS, France) for his science advice.
(3) The first author (Chuan-Zhi Xie) wishes to thank Mr. Can Dong for his warm support.

References

[1] D. Helbing, A. Johansson. Pedestrian, Crowd and evacuation dynamics, in: Encyclopedia of Complexity and Systems Science, Vol. 16, 2010, pp. 6476–6495.
[2] N. Okada, Y. Hasemi, S. Moriyama, Feasibility of upward evacuation by escalator-An experimental study, Fire Mater. 36 (5–6) (2012) 429–440.
[3] H. Jin, R.Y. Guo, Study of pedestrian flow on stairs with a cellular transmission model, Acta Phys. Sin. 68 (2) (2019) 20501.
[4] W. Li, J. Gong, P. Yu, S. Shen. Modeling, Simulation and analysis of group trampling risks during escalator transfers, Physica A 444 (2016) 970–984.
[5] S. Kadam, P.K. Bandyopadhyay, A case study of Elphinstone road foot-over-bridge stampede in Mumbai, Int. J. Crit. Infrastruct. 16 (1) (2020) 77–90.
[6] J. Ma, S.M. Lo, W.G. Song, Cellular automaton modeling approach for optimum ultra high-rise building evacuation design, Fire Saf. J. 54 (2012) 57–66.
[7] N. Ding, H. Zhang, T. Chen, P.B. Luh, Stair evacuation simulation based on cellular automata considering evacuees' walk preferences, Chin. Phys. B 24 (6) (2015) 068801.
[8] F.R. Yue, J. Chen, J. Ma, W.G. Song, S.M. Lo, Cellular automaton modeling of pedestrian movement behavior on an escalator, Chin. Phys. B 27 (12) (2018) 124501.
[9] H. Wu, J. Huang, Z.L. Guo, Y.G. Hu, Evacuation simulation in the narrow stair with revised social force model, Appl. Mech. Mater. 409 (2013) 1577–1582.
[10] Y.C. Qu, Z.Y. Gao, Y. Xiao, X.G. Li, Modeling the pedestrian's movement and simulating evacuation dynamics on stairs, Saf. Sci. 70 (2014) 189–201.
[11] M.J. Kinsey, E.R. Galea, P.J. Lawrence, Extended model of pedestrian escalator behaviour based on data collected within a Chinese underground station, in: Human Behaviour in Fire Conference, 2009, pp. 173–182.
[12] N. Ding, P.B. Luh, H. Zhang, T. Chen, Emergency evacuation simulation in staircases considering evacuees' physical and psychological status, in: IEEE International Conference on Automation Science and Engineering, CASE, 2013, pp. 741–746.
[13] L. Fu, Y. Liu, P. Yang, Y. Shi, Y. Zhao, J. Fang, Walking behavior of pedestrian social groups on stairs: a field study, Saf. Sci. 117 (2019) 447–457.
[14] L. Fu, Y. Liu, P. Yang, Y. Shi, Y. Zhao, J. Fang, Dynamic analysis of stepping behavior of pedestrian social groups on stairs, J. Stat. Mech. Theory Exp. 2020 (6) (2020) 063403.
[15] T.Q. Tang, B.T. Zhang, T. Wang, An improved optimization framework for evacuation planning in facilities considering pedestrian dynamics, J. Transp. Saf. Secur. 14 (4) (2022) 693–722.

[16] Z. Fu, X. Zhan, L. Luo, A. Schadschneider, J. Chen, Modeling fatigue of ascending stair evacuation with modified fine discrete floor field cellular automata, Phys. Lett. A 383 (16) 1897–1906.

[17] M.J. Kinsey, Vertical Transport Evacuation Modelling (PhD diss), University of Greenwich, 2011.

[18] Z.M. Liu, Y. Xie, H. Zhang, Simulation of passenger behavior and crowd stampede risk on escalator, J. Intell. Fuzzy Systems 37 (3) (2019) 3525–3533.

[19] H. Kataoka, K. Hashiguchi, K. Wago, Y. Ichikawa, H. Tezuka, S. Yamashita, Y. Kuhara, T. Akiyama, Dynamic guide signs system to control pedestrian flow, in: ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct, 2016, pp. 1572–1577.

[20] M. Moussaïd, N. Perozo, S. Garnier, D. Helbing, G. Theraulaz, The walking behaviour of pedestrian social groups and its impact on crowd dynamics, PLoS One 5 (4) (2010) e10047.

[21] C.V. Krüchten, A. Schadschneider, Empirical study on social groups in pedestrian evacuation dynamics, Physica A 475 (2017) 129–141.

[22] N.A.A. Bakar, M.A. Majid, K. Adam, M. Allegra, Social force as a microscopic simulation model for pedestrian behavior in crowd evacuation, Adv. Sci. Lett. 24 (10) (2018) 7611–7616.

[23] B.X. Liu, H. Liu, H. Zhang, X. Qin, A social force evacuation model driven by video data, Simul. Model. Pract. Theory 84 (2018) 190–203.

[24] J.J. Fruin, Pedestrian Planning and Design, 1971, p. 206.

[25] J. Sorsa, M. Ruokokoski, M.L. Siikonen, Human body size in lift traffic design, in: Symposium on Lift and Escalator Technologies, 2014, pp. 213–223.

[26] C. Burstedde, K. Klauck, A. Schadschneider, J. Zittartz, Simulation of pedestrian dynamics using a two-dimensional cellular automaton, Physica A 295 (3–4) (2001) 507–525.

[27] R.Y. Guo, H.J. Huang, S.C. Wong, Route choice in pedestrian evacuation under conditions of good and zero visibility: experimental and simulation results, Transp. Res. B 46 (6) (2012) 669–686.

[28] R. Liu, Z. Fu, A. Schadschneider, Q. Wen, J. Chen, S. Liu, Modeling the effect of visibility on upstairs crowd evacuation by a stochastic FFCA model with finer discretization, Physica A 531 (2019) 121723.

[29] Y. Zhu, T. Chen, N. Ding, W.C. Fan, Analyzing floor-stair merging flow based on experiments and simulation, Chin. Phys. B 29 (1) (2020) 010401.

[30] M.J. Kinsey, E.R. Galea, P.J. Lawrence, Modelling evacuation using escalators: A London underground dataset, in: Human Behaviour in Fire Conference 2012, 2014, pp. 385–399.

[31] X. Ji, X. Zhou, B. Ran, A cell-based study on pedestrian acceleration and overtaking in a transfer station corridor, Physica A 392 (8) (2013) 1828–1839.

[32] https://www.theguardian.com/uk-news/2016/jan/16/the-tube-at-a-standstill-why-tfl-stopped-people-walking-up-the-escalators.

[33] X. Ji, J. Zhang, B. Ran, A study on pedestrian choice between stairway and escalator in the transfer station based on floor field cellular automata, Physica A 392 (20) (2013) 5089–5100.