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Cellular automaton modeling of pedestrian movement behavior on an escalator*

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Cellular automaton modeling of pedestrian movement behavior on an escalator*

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As a convenient passenger transit facility between floors with different heights, escalators have been extensively used in shopping malls, metro stations, airport terminals, *etc*. Compared with other vertical transit facilities including stairs and elevators, escalators usually have large transit capacity. It is expected to reduce pedestrian traveling time and thus improve the quality of pedestrian's experiences especially in jamming conditions. However, it is noticed that pedestrians may present different movement patterns, *e.g.*, queuing on each step of the escalator, walking on the left-side and meanwhile standing on the right-side of the escalator. These different patterns affect the actual escalator traffic volume and finally the passenger spatiotemporal distribution in different built environments. Thus, in the present study, a microscopic cellular automaton (CA) simulation model considering pedestrian movement behavior on escalators is built. Simulations are performed considering different pedestrian movement speeds, queuing modes, and segregation on escalators with different escalator speeds. The actual escalator capacities under different pedestrian movement patterns are investigated. It is found that walking on escalators will not always benefit escalator transit volume improvement, especially in jamming conditions.

Keywords: cellular automaton, pedestrian movement, escalator capacity

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1. Introduction

Recently, pedestrian behaviors in public place have attracted attention from researchers of different disciplines. One of the most important ways to study pedestrian is to establish a model and perform numerical simulations. Dozens of models including leader-follower model,[1] kinetic theory model,[2] self-organizing model,[3] optimization-based overtaking model[4] have been built in the past decades.

Of all these models, the cellular automaton (CA) model is the simplest but most efficient one. Nagel and Schreckenberg built a cellular automaton model in which each pedestrian is treated as a particle.[5] Similarly, Burstedde built a two-dimensional cellular automaton model to simulate the pedestrian dynamics.[6] In order to simulate evacuation processes, Kirchner and Schadschneider built a bionics-inspired cellular automaton model.[7] For realizing the characteristics of co-habitation of younger and elderly people, Shimura *et al.* formulized a cellular automaton model which can well capture the experimental findings.[8] The particle in the model can move more than one cell at onetime step, in this way different people can have varying speeds. Similarly, by taking into account other different behaviors, cellular automaton models have also been used to explore pedestrians walking through corners,[9] the evacuation problem in rooms,[10,11] bidirectional pedestrian flow,[12] and some other typical pedestrian flow patterns.[13,14]

Except for cellular automaton models, continuum models such as the so called "social force" model have also been proposed. The social force model can reproduce almost all daily observed collective pedestrian self-organization phenomena.[15] It has also been used to study pedestrian behaviors, such as waiting behaviors,[16] detour behaviors,[17] *etc*. More recently, Lu *et al.* studied the effect of group size and crowd density on pedestrian evacuation efficiency.[18] Summarizing the relevant simulation results we can easily find that different pedestrian behaviors can bring in different effects on evacuation efficiency and movement characteristics.

It is noticed that the appearance of escalator, an important transit tool, has greatly improved people's quality in our daily life and changed the way people move in public places. However, the studies on pedestrian features on escalators are somehow rare. It is only recently that researchers started to pay attention to pedestrian behaviors when using vertical pedestrian facilities including elevators[19] and escalators. Li *et al.* estab-

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lished a state shifting model to describe pedestrian behaviors during escalator operation.[20] They investigated group trampling risks, analyzed the effect of multiple factors on group stampede, and finally obtained some numerical results which can benefit the development of trampling disaster countermeasures. Xing *et al.* analyzed the escalator related injuries in metro stations[21] and also used the cellular automaton model to simulate the selection of escalators and stairs in a subway station.[22] Their results can also provide prevention strategies for high risk groups of passengers in escalator related injuries. For daily escalator usage, it can be usually observed that many pedestrians prefer to move forward on a relatively uncongested escalator. This behavior induced at least the following phenomena: (i) some people are more willing to keep a step or two steps between others on the escalator, (ii) some people prefer standing on the right side of the escalator while some others prefer walking on the left side of the escalator. Considering the fact that the space of the escalator is very limited, pedestrian movement features in this narrow space may present notable influence on the escalator capacity. To deepen our understanding of how escalator capacity can be influenced, a cellular automaton model taking into account the behavior of people in this paper will be established in this study.

The rest of the paper is organized as follows. In Section 2, the method of establishing the model is detailed. In Section 3, simulation results are presented and discussion is made. Finally, some conclusions are drawn from the present study in Section 4.

2. Modeling pedestrian movement on the escalator

The space is divided into equally sized cells while time is divided into equal length time steps. Each cell can be either vacant or occupied. The cells in the model can be occupied by people, obstacle, or walls. Pedestrian movement is realized according to prescribed rules.

2.1. Escalator space representation

Considering that each escalator step is running with a speed of v_{E} along the fixed rail tracks as shown in Fig. 1(a), its tread depth and rise height on the top and at the bottom of the escalator are different from those in the middle of the escalator. In the middle section, the tread depth value and rise height value can be denoted as T and R as shown in Fig. 1(b) respectively. As a result, it is difficult to describe the step features in traditional CA models. Thus, in the present paper, we use finer cells to discretize escalator space as shown in Fig. 1(c). In this way, each escalator step can be represented by a series of cells along the horizontal plane. In Fig. 1(c), the pale pink boundaries are the escalator handrails. The length and width of the escalator are denoted as L and W, respectively. Finally, the escalator geometry can be described. It is noticed that in multi-grid models such as the model given in Ref. [23] , space is also discretized in the same way. Simulation of staircase evacuation indicated that this treatment performs well in reproducing pedestrian movement on stairs.

Due to the using of a finer space representation method, in our model, each pedestrian thus occupies more than one cell. When we use a cell size of 0.1 m by 0.1 m, each pedestrian occupies 8 cells as indicated by the blue ellipses in Fig. 1(c). As an illustrative example of the escalator in metro station, we set $L = 20$ m and $W = 1$ m, which means that 200×10 cells are used to represent the pedestrian movement area in Fig. 1(c).

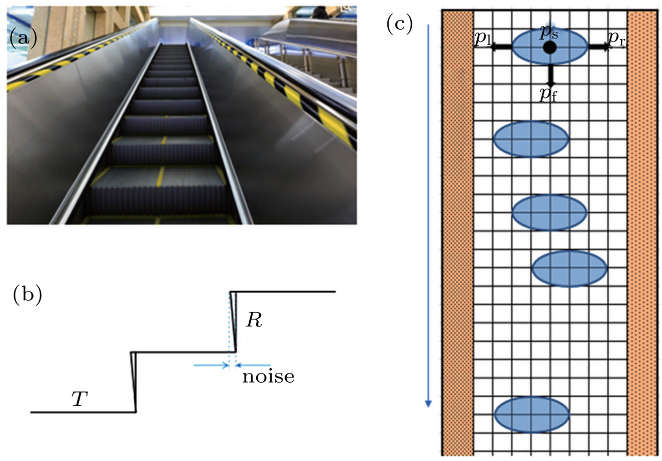

Fig. 1. (color online) Escalator step features. (a) and (b) Step differences at bottom section and geometrical feature in middle section of typical escalator, and (c) escalator step space discretization in the model. Each cell has a size of 0.1 m.×0.1 m. Blue parts denote pedestrians, and pale pink boundaries represent escalator handrails.

2.2. Pedestrian movement rules

To explore the influence of pedestrian movement pattern on the capacity of escalator, it is important to model these pedestrian behaviors. In the present paper, we define queuing mode as means of lining up along the escalator movement direction. When taking escalator in our life, people tend to keep a certain distance from others which could make them feel comfortable. In this paper, we consider three kinds of queuing modes, *i.e.*, the number of steps between two successive pedestrians is n_{s} = zero, one (4 cells) and two (8 cells). By adopting the multi-cell assumption, the relative position differences and the speed differences can be reproduced in the model.

In our model, the pedestrians are always generated from the top cells of the escalator and move from the top to the bottom of the escalator. The speed at which pedestrian walks to the escalator is denoted as v_{H} while the escalator speed is denoted as v_{E}. Each time step is set to be 1 s in the present study.

We further assume that when escalator moving on, pedestrians can only have four next position choices due to the limited space. These four locations are denoted as the forward direction, the right direction, left direction and still, the word "still" refers to staying in the pedestrian's original position. They are presented respectively in the Fig. 1(c).

To investigate the influence of pedestrian behavior on escalator capacity, we adopt the following algorithm to perform the simulation studies. Without considering the different speed distributions, we assume that everyone in the escalator has the same speed, and in each simulation, we first set the value of v_{H} and v_{E}. Since each update, a person can only move forward a lattice. The simulation of people's speed is relatively large and can be completed by increasing the number of updates at one time step.

In Eqs. (1)–(4), we assume that the movement probability p_i is related to the speed of the escalator. The p_{f} represents the probability of people's moving to the bottom of the escalator, and the higher the escalator speed, the smaller the value of p_{f} will be, p_{s} represents the probability of people's staying at the original position and called stay probability below, p_{l} and p_{r} are the probability of moving to the left and right of the escalator respectively. We set p_{l} and p_{r} to be equal. The parameters D_{f} and λ_{E} represent respectively the strength of the person's going forward and the effect of the escalator speed on the movement. In Eq. (2), the value of p_{s} is determined by a combination of D_{f} and λ_{E}. When people stand on escalators with high speeds, due to the influence of rapid operation on people, we think that people will reduce the tendency to move forward, and when the escalator speed is 0, the stay probability is 0, in the experiment, as a hypothesis, people have a strong will to move forward, therefore the parameters D_{f} and λ_{E} are set to be 0.8 and 0.05 respectively.

i) Check whether there are pedestrians or barriers in a pedestrian's four neighboring directions, and then calculate the pedestrian movement direction probability p_i according to the following formulas:

$$p_{\mathrm{f}} = D_{\mathrm{f}} * (1 - \lambda_{\mathrm{E}} * v_{\mathrm{E}}), \tag{1}$$

$$p_{\mathrm{s}} = \lambda_{\mathrm{E}} * v_{\mathrm{E}}, \tag{2}$$

$$p_{\mathrm{l}} = \frac{1 - D_{\mathrm{f}}}{2} * (1 - \lambda_{\mathrm{E}} \cdot v_{\mathrm{E}}), \tag{3}$$

$$p_{\mathrm{r}} = p_{\mathrm{l}}. \tag{4}$$

If one expected that the location is occupied by another pedestrian, then the corresponding p_i is set to be zero. Finally, the p_i values of the four positions are all normalized.

ii) Generate a random value p between 0 and 1. The value will be compared with the p_i values of the four positions to update the pedestrian location.

It should be noticed that these pedestrians would always keep their queuing rule when they are on the escalator. The algorithm described above can be summarized as a flow chart shown in Fig. 2.

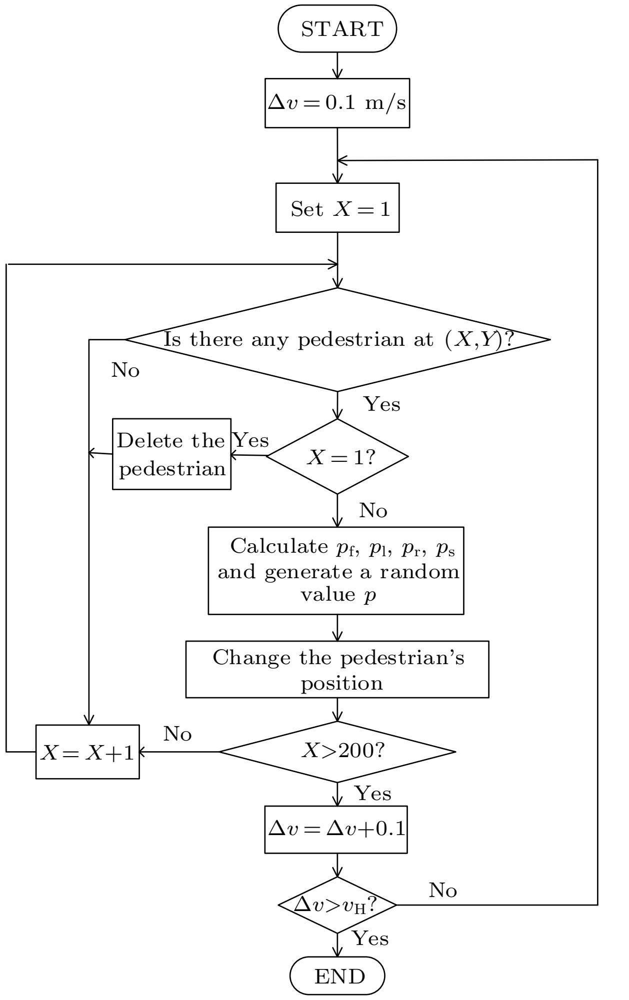

Fig. 2. Flow chart of people moving their location only relying on their speed. (X,Y) represent the location coordinate of the pedestrian.

We use the sequential update method to search from the bottom of the escalator and update. The rules of pedestrian movement are shown in Fig. 4, the update is repeated multitimes in one time step to achieve faster movements. Δv is a variable that determines the number of updates in one time step. For example, for the person whose speed is 0.8 m/s, his initial Δv will be 0.1, the value will increase 0.1 until it increases to 0.8 m/s. That means that a total of eight position updates need to be completed in one time step.

2.3. Simulation scheme

In this model, we assume the maximum simulation time step to be t_{span}. At the beginning, we set $t = 1$. At each time step, there will be at most two people added on the top of the escalator. For those pedestrians on the escalator, each of them will accomplish his/her own movement which includes the human movement and the movement with the escalator to realize the speed superposition. When a pedestrian arrives at the bottom of the escalator, he/she will be deleted from the simulation system. If the simulation time reaches maximum simulation time step t_{span}, the simulation ends and the results are recorded.

The complete simulation scheme for pedestrian movement on the escalator can be found in Fig. 3.

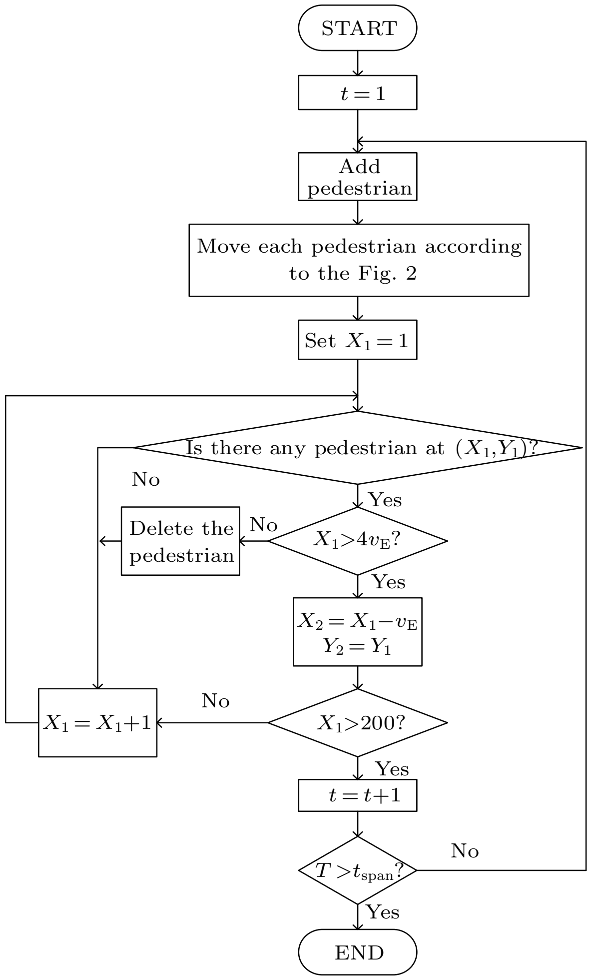

Fig. 3. Complete flow chart, people moving with their own speed and escalator speed. (X_1, Y_1) and (X_2, Y_2) represent the location coordinate of the pedestrian after updating.

3. Simulation results and discussion

Numerical simulations are performed for a metro station escalator to investigate escalator capacity considering the influence of different pedestrian movement features. The escalator has a horizontal length of $L = 20$ m and width of $W = 1$ m. The riser height of the escalator is $R = 0.2$ m while the tread depth is $T = 0.42$ m with a noise of 0.02 m. The maximum simulation time step is $t_{\text{span}} = 500$ s. In this section, we introduce the main results and discuss the influential factors.

3.1. Escalator capacity

In previous studies, most of scholars studied the efficiency of evacuation for built environment based on the relationship between density and flow rate. Flow rate represents the level of evacuation efficiency, which is similar to the flow rate in this paper; we use the capacity to explore the efficiency of escalator transportation.

The capacity of an escalator refers to the maximum number of people that can be passed in a unit of time.[24] We use the simulation to calculate escalator capacity. When the speed of escalator equals zeros, *i.e.*, $v_{\text{E}} = 0$, pedestrian movement on the escalator is relative and this case is similar to the stair movement scenario. In this case, pedestrian position change features are only determined by the pedestrian's own speed features. So, we first fix $v_{\text{E}} = 0$ to explore the influence of pedestrian movement speed. Simulations of human speeds ranging from 0.1 m/s to 1.2 m/s are conducted. Results for the pedestrian's speeds of 0.1, 0.3, 0.5, 0.7, 0.9, and 1.1 can be found in Fig. 4, respectively.

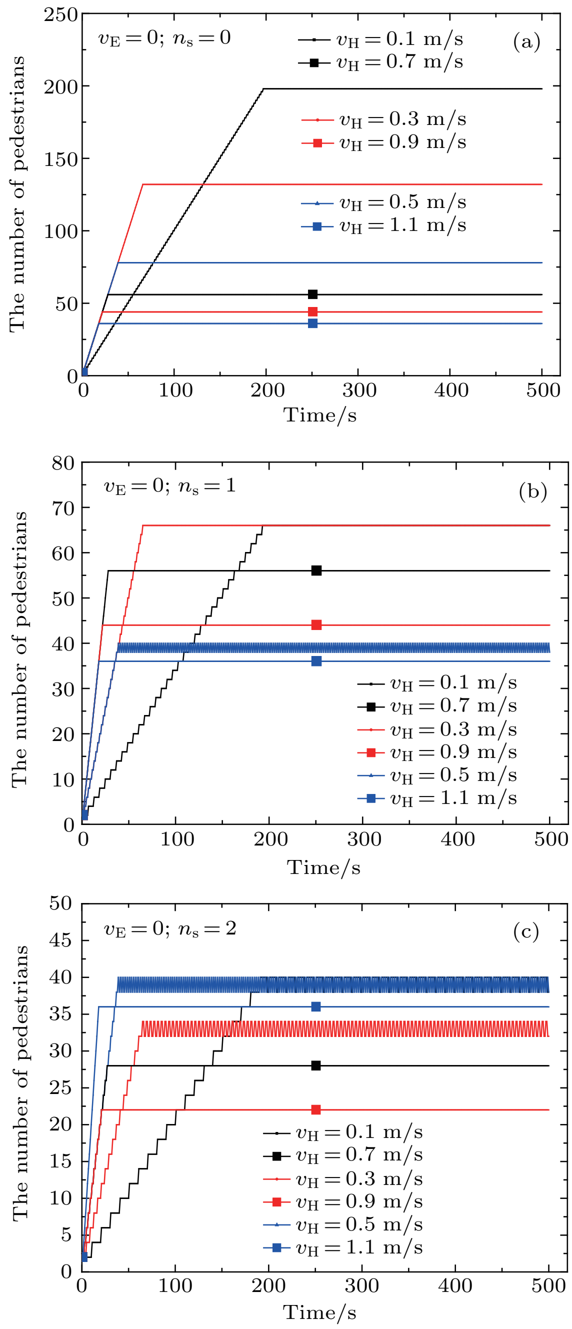

Fig. 4. (color online) Number of pedestrians on the escalator when its speed is 0 and pedestrian speed v_{H} varies from 0.1 m/s to 1.2 m/s, with number of escalator steps n_{s} being (a) 0, (b) 1, and (c) 2.

A total of three different queuing forms, *i.e.*, $n_{\text{s}} = 0$, 1, and 2, are simulated. As shown in Fig. 4, the curve trends for the number of pedestrians on the escalator in Figs. 4(a)–4(c) show good agreement with each other. At the beginning of the simulation, pedestrians step onto the escalator, and go downward. The number of pedestrians on the escalator increases. After a while, the number of pedestrians keeps almost constant. That is because the number of pedestrians stepping onto the escalator becomes equal to the number of pedestrians get off the escalator at the bottom. As a consequence, the initial phase is a transitional phase while the later one is relatively stable. According to the definition of escalator capacity, the initial stage of the simulation should be omitted while the steady state can be used to calculate escalator capacity.

Further making a comparison among Figs. 4(a), 4(b), and 4(c), we can see that the number of pedestrian rises slowly but the number is relatively large when pedestrians' speed is relatively low. When pedestrians' speed becomes higher, the number of pedestrians on the escalator becomes less with increasing n_s. That means that the pedestrian movement features do have an important influence on escalator capacity.

3.2. Effect of pedestrian and escalator speed

In this section, we further explore pedestrian movement on running escalator and check the effect of pedestrian movement on escalator capacity. For escalator running speed v_E = 0, 0.4, and 0.8 m/s, three different pedestrian queuing methods are considered. Simulation results can be found in Fig. 5.

From Fig. 5 we can find the following points. Firstly, when pedestrians queue with different modes on the escalator, the actual escalator capacity differs. It should be noticed that the results of Fig. 5(a) hold true on condition that the escalator speed is 0. That is to say, the escalator at this time is equivalent to a stair movement scenario. Pedestrians on the escalator walk forward with their own speed. When $n_s = 0$, the pedestrians stand very closely and move forward on the escalator with almost no gaps in between. The number of peoples who flow out at each time step keeps constant. When there is a distance between people, *e.g.*, when $n_s = 1$, the capacity of the escalator decreases due to the increase of the interval between people for small pedestrian velocity, however when the maximum pedestrian speed increases, the escalator capacity increases. A reasonable explanation is that when pedestrians walk on a stair, the capacity of the escalator is determined by both pedestrian speed and inter-pedestrian distance. Once the distance that a pedestrian can travel with his maximum speed exceeds the preferred n_s value, the influence of the interval on the capacity can be reduced.

Secondly, it is also noticed that the escalator capability first increases with pedestrian speed increasing, however, the capacity finally reaches a maximum value and keeps constant when pedestrian speed keeps on increasing. As can be found in Fig. 5(b), when a pedestrian's speed is a small value and the distance between people is 0 m, the capacity of an escalator is already at a maximum, this is because the operation of the escalator can improve the capacity of escalator, and the capacity can reach the maximum even if the pedestrian's speed is small. In Fig. 5(c), when there is no distance between people or the distance is a step in length, the capacity of the escalator can reach the maximum quickly; the reason is similar to that indicated in Fig. 5(b). Comparing Fig. 5(b) with Fig. 5(c), it is found that escalators can indeed improve the efficiency of transport, especially during rush hour. However, moving on the escalator does not guarantee a higher escalator capacity if each pedestrian stands next to each other on the escalator.

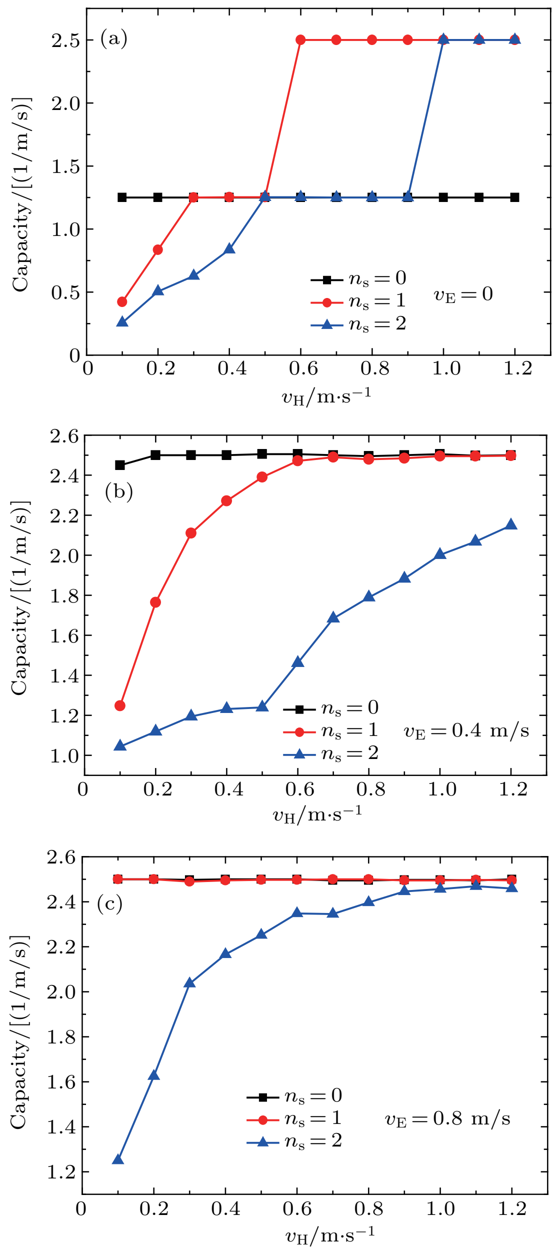

Fig. 5. (color online) Escalator capacity when pedestrian queuing in different modes, with escalator speeds being (a) 0 m/s, (b) 0.4 m/s, and (c) 0.8 m/s.

3.3. Effect of pedestrian segregation on the escalator

In the previous sections, it was assumed that pedestrians have no preference of using left/right sides of the escalator. In our daily life we can usually observe segregation phenomenon, where some pedestrians walk on the left-side and meanwhile some others stand on the right-side of the escalator. This means that people on the left have speeds and people on the right of the escalator do not have speed. Once the pedestrian walking on the left-side moves to the right-side of the escalator, the speed will be reduced to 0 and then follows the escalator to move forward. It is worth noting that all people always maintain an original set of exercise rules in the entire simulation process. In this subsection, we further simulate pedestrian segregation behavior and explore its influence on escalator capacity. In the revised model, the left-side of the escalator can only be used by those who walk on the escalator, while the right side of the escalator can be used by not only those who walk but also by those who stand still on the escalator. In other words, the standing still pedestrians rely completely on the speed of the escalator to reach their destination. The speeds of escalator is set to be 0.4 m/s and 0.8 m/s, respectively. The simulated escalator capacity is shown in Fig. 6.

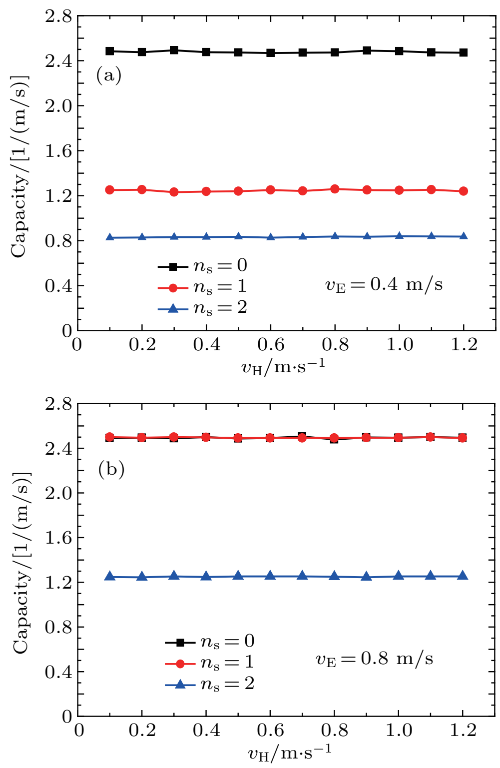

Fig. 6. (color online) Plots of escalator capacity versus pedestrian speed for escalator speed of (a) 0.4 m/s and (b) 0.8 m/s.

From Fig. 6 we can see that the following points. Firstly, when the number of steps between two successive pedestrians is $n_s = 0$, the capacity remains stable at about 2.5 no matter what escalator speed is. Meanwhile, it can also be found that the pedestrian speed v_H has little effect on the capacity of the escalator. Secondly, for other n_s, we can find that the pedestrian speed v_H has little effect on the capacity of the escalator. It is escalator running speed that plays an important role in determining the escalator capacity.

4. Conclusions

As a daily used pedestrian transit facility, escalators play an important role in pedestrian vertical movement. In order to provide in-depth understanding of how pedestrian behavior could affect escalator capacity, we propose a new cellular automaton model incorporated with pedestrian movement features on escalators. Based on the new model, plenty of simulations are performed. The influence of pedestrian speed on the escalator, escalator speed and finally queuing mode on escalator capacity are studied. It is found that the escalator capacity is determined by escalator speed and pedestrian queuing mode, as well as pedestrian movement speed. There is a complex relation among those influential factors. Comparing the capacities of escalator in different cases, we can sum up that although pedestrians' walking on the escalator would result in a high speed, it does not guarantee a higher escalator capacity if the escalator is crowded. For pedestrian segregation situations, it is also found that pedestrians' walking on stairs cannot improve the overall capacity. Therefore, during rush hours, pedestrians should not be encouraged to walk on the escalator.

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