Modeling walking behavior of pedestrian groups with floor field cellular automaton approach*

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Walking in groups is very common in a realistic walking environment. An extended floor field cellular automaton (CA) model is therefore proposed to describe the walking behavior of pedestrian groups. This model represents the motion of pedestrian groups in a realistic way. The simulation results reveal that the walking behavior of groups has an important but negative influence on pedestrian flow dynamics, especially when the density is at a high level. The presence of pedestrian groups retards the emergence of lane formation and increases the instability of operation of pedestrian flow. Moreover, the average velocity and volume of pedestrian flow are significantly reduced due to the group motion. Meanwhile, the parameter-sensitive analysis suggests that pedestrian groups should make a compromise between efficient movement and staying coherent with a certain spatial structure when walking in a dense crowd.

Keywords: pedestrian groups, floor field CA model, leader–follower pattern, simulation

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1. Introduction

Pedestrian simulation models play an important role in the planning of pedestrian facilities, crowd evacuations, and so on. Therefore, various kinds of simulation model have been developed in recent decades, such as the magnetic force model,[1,2] social force model,[3] centrifugal force model,[4] CA model,[5–9] lattice gas model,[10,11] multi-agent model,[12–15] etc. These models show a good capability to predict the dynamics of pedestrian flow and crowd motions. However, most of these existing models treated the crowd as a collection of isolated individuals, which does not coincide with reality. Actually, according to empirical observations, the majority of pedestrians walk in groups rather than as individuals. Generally, two or three pedestrians walking together are the most frequent, and groups composed of more than four members are rare. Moreover, it has been found that the group sizes are distributed according to a Poisson distribution.[16]

Empirically, the walking behavior of pedestrian groups has different characteristics from those who walk alone, since the members in groups interact with each other in the walking process. From field observations, pedestrian groups tend to move together with a certain spatial structure. For instance, groups composed of two always keep walking side by side, forming a line perpendicular to the walking direction, and groups of size three or four may tend to maintain a V-like or U-like pattern. Additionally, it has been proven that these walking patterns have significant effects on pedestrian flow dynamics. Hence, characteristics of pedestrian group walking behavior should be taken into consideration when developing a more reliable prediction model for the design of pedestrian facilities, management of crowd evacuation.

At present, many research efforts emphasize modeling the walking behavior of pedestrian groups. Moussaïd *et al*. extended the typical social force model by formulating interaction forces among the group members.[16] The new model achieved a large success in the depiction of pedestrian group motions at different pedestrian density levels. Qiu and Hu proposed a framework for pedestrian group motion in crowds.[17] Köster *et al*. found two principles of pedestrian group walking behavior: that the group members stick together when they thread their way through the crowds and walk abreast for easy communication.[18] Manzoni *et al*.[19] and Vizzari *et al*.[20] developed a multi-agent model to predict pedestrian group movements by designing a mechanism to preserve the cohesion of pedestrian groups in different situations. Fewer studies have been conducted to model pedestrian group behavior with the CA approach. Pu built a CA model to study the groups in pedestrian traffic dynamics.[21] However, this model was based on the assumption that the spatial structures of pedestrian groups are fixed while walking, which is inconsistent with reality. Yang *et al*. studied the effects of behaviors of pedestrian groups on crowd evacuation by simulating a two-dimensional (2D) CA model.[22] However, this study focuses more on the descriptive analysis of the psychology and lacks a direct mathematical formula for simulation. To our knowl-

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edge, as one of the most widely used and acceptable model for pedestrian flow simulation, the floor field CA model has not included the pedestrian group behavior. Therefore, there is a necessity to improve this model by considering the behavior of pedestrian groups, as this is expected to be important for its application in engineering practice.

The concept of floor field was introduced into the pedestrian CA model to depict the self-organization phenomena emerging in pedestrian dynamics such as lane formation in bi-directional pedestrian flow, oscillations around a bottleneck etc.[23,24] In this model, there are two kinds of floor field, i.e. static and dynamic ones. The static one is proposed to model the attractiveness of the destination to pedestrians and does not evolve with time, while the dynamic one translates a long-ranged spatial interaction into an attractive local interaction among pedestrians. From this basic model, many extensions with consideration of social and psychological factors are proposed to replicate various pedestrian dynamic phenomena. In order to represent pedestrian behavior near corners and bottlenecks in a realistic way, Nishinari *et al*. extended the floor field CA model by taking into account the wall potential and contraction effect at a wide exit.[25] Zheng *et al*. introduced the fire floor field into the typical model and simulated pedestrian crowd evacuation with a fire spreading.[26] Li and Dong extended a CA model based on the floor field to consider the effects of other pedestrians from different directions within the field of view of a walker.[27] Additionally, the floor field approach was expanded to model bicycle flow by Yang *et al*.[28]

In this paper, we propose a method to involve the walking behavior of pedestrian groups in the floor field CA model and investigate their influence on pedestrian flow dynamics. The remainder of this paper is organized as follows. The improved model for modeling the walking behavior of pedestrian groups is described in detail in Section 2. The numerical simulation experiments are conducted to study the dynamics of pedestrian flow with groups in Section 3. Finally, some conclusions are drawn and the benefits and utility of the proposed model are discussed in Section 4.

2. Model development

2.1. Introduction of floor field model

The CA model is discrete in both space and time, where pedestrian movements are modeled at a microscopic level. Pedestrians are allowed to move to one of their neighboring cells at each time step with a certain probability determined by specific rules set in the model. The traditional floor field model is a kind of CA model inspired by the phenomenon of chemotaxis in biology.[23] By introducing the static floor field $S_{i,j}$ and dynamic floor field $D_{i,j}$, the pedestrian behavior of finding a shortest path to egresses and tending to follow other individuals in the evacuation process is successfully modeled. More specifically, the static version describes the attractiveness of exits to the pedestrian and is set to be inversely proportional to the distance from the exits, that is, a cell closer to an exit owning a relatively large value. On the other hand, the dynamic version represents the virtual trace of pedestrians. The dynamic floor field $D_{i,j}$ is time dependent and modified according to diffusion and decay rules determined by parameters α and δ. In each time step, the dynamic floor field at the origin cell of each moving pedestrian is increased by one as well as decaying with probability δ and diffuses with probability α to one of its neighboring cells. Since pedestrians seldom walk back in reality, the walkers in our model are without back steps. The neighborhood adopted in this model is shown in Fig. 1. Each pedestrian occupies a cell and moves forward, left or right according to the transition probability at each time step. Based on the two fields, the transition probability can be calculated from the following equation:

$$
\begin{aligned}
&P_{i,j} = N \exp(k_{\mathrm{s}} S_{i,j}) \exp(k_{\mathrm{D}} D_{i,j})(1-\eta_{i,j})\varepsilon_{ij},\\
&\eta_{i,j} = \begin{cases} 0, & \text{if the cell}(i,j) \text{ is empty,} \\ 1, & \text{if the cell}(i,j) \text{ is occupied by a boundary,} \end{cases}\\
&\varepsilon_{i,j} = \begin{cases} 0, & \text{if the cell}(i,j) \text{ is occupied by a pedestrian,} \\ 1, & \text{if the cell}(i,j) \text{ is empty.} \end{cases}
\end{aligned} \tag{1}
$$

With the normalization,

$$
N = \left[\sum \exp(k_{\mathrm{s}} S_{i,j}) \exp(k_{\mathrm{D}} D_{i,j})(1-\eta_{i,j})\varepsilon_{i,j}\right]^{-1},
$$

where k_{s} and k_{D} are the sensitive parameters determining the weight of S_{ij} and D_{ij}.

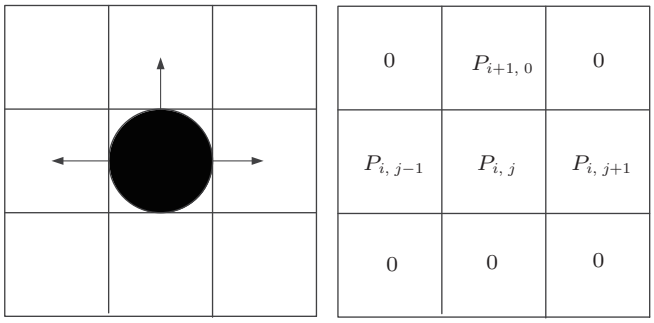


Fig. 1. Schematic illustration of the neighborhood.

The static floor field $S(i,j)$ of cell (i,j) is calculated from the following formulas:

$$
\begin{aligned}
&D_{\max} = \max_{(i_l,j_l)} \left\{ \min_{(i_{\mathrm{Ts}},j_{\mathrm{Ts}})} \left(\sqrt{(i_{\mathrm{Ts}}-i_l)^2 + (j_{\mathrm{Ts}}-j_l)^2} \right) \right\},\\
&d_{i,j} = \min_{(i_{\mathrm{Ts}},j_{\mathrm{Ts}})} \left(\sqrt{(i_{\mathrm{Ts}}-i)^2 + (j_{\mathrm{Ts}}-j)^2} \right),\\
&S_{i,j} = d_{i,j}/D_{\max},
\end{aligned} \tag{2}
$$

where (i_l, j_l) runs over all the cells in the system and $(i_{\mathrm{Ts}}, j_{\mathrm{Ts}})$ runs over all the destinations for a certain kind of pedestrian. Therefore, $D_{\max}$ is the maximum among the shortest distance from each cell in the system to the destination and $d_{i,j}$ is the minimum distance from cell (i, j) to the destination.

2.2. Modeling of pedestrian groups

When modeling the walking behavior of pedestrian groups, the interactions among group members should be considered. Therefore, the transition probability of pedestrian in groups differs from that in the original floor field model.

Based on the proxemics behavior theory, pedestrian groups tend to sustain a certain spatial arrangement or pattern for easy communication and spatial cohesion among members while walking.[29] Moreover, it is assumed that there exists a leader effect in pedestrian groups, which means that the leader plays a decisive role in the motion of the whole group and other members in the group make their movement decision depending on the leader. In addition, the group members try to keep close to each other when they are separated. Based on these factors, the pedestrians in groups are attributed identities of the leader and followers. As the size of pedestrian groups is not large, we postulate that there is only one leader in the group, and the behavior of the leader is considered the same as that of an isolated individual, whose motion is determined by the two floor fields. Namely, the leader makes motion decisions based on the shortest path to the destination and interactions with other groups and other pedestrians. On the other hand, the followers' walking behavior is determined partly by the static floor field and partly by the motion of the leader. This reflects that the followers are likely to walk to the destination but are affected by the behavior of the leader in the group. A new formula is proposed to characterize the walking behavior of the group members:

$$P_{i,j} = \begin{cases} N \exp(k_{\mathrm{s}} S_{i,j}) \exp(k_{\mathrm{D}} D_{i,j})(1-\eta_{i,j})\varepsilon_{i,j}, & \text{leader}, \\ N \exp(k'_{\mathrm{s}} \cdot k_{\mathrm{s}} \cdot S_{i,j}) \exp(-k_{\mathrm{D}} d_{lm}) P_I(i,j)(1-\eta_{i,j})\varepsilon_{i,j}, & \text{follower}, \end{cases} \tag{3}$$

where k'_{s} is the degree of dependence on static floor field, varying from 0 to 1. When $k'_{\mathrm{s}} = 0$, it means that the motion of follower does not depend on the static floor field but totally depends on the leader. $d_{l,m}(i,j) = \sqrt{(i_l - i)^2 + (j_l - j)^2}$ is the distance between each of the member's neighboring cells and the leader's position; k_{d} is the sensitive parameter, which is positive. $p_{\mathrm{I}} = \exp(k_{\mathrm{I}})$ for the direction of the leader's motion, and $p_{\mathrm{I}}(i,j) = 1$ for other cells, where k_{I} is the sensitive parameter, representing the follower's intention of walking in the same direction as the leader. More specifically, if the leader walks forward, the probability of the follower choosing the front cell to move is $\exp(k_{\mathrm{I}})$ times those of the right and left ones. With the formulation above, the followers adjust their walking behavior to sustain the group formation while walking (see Fig. 2).

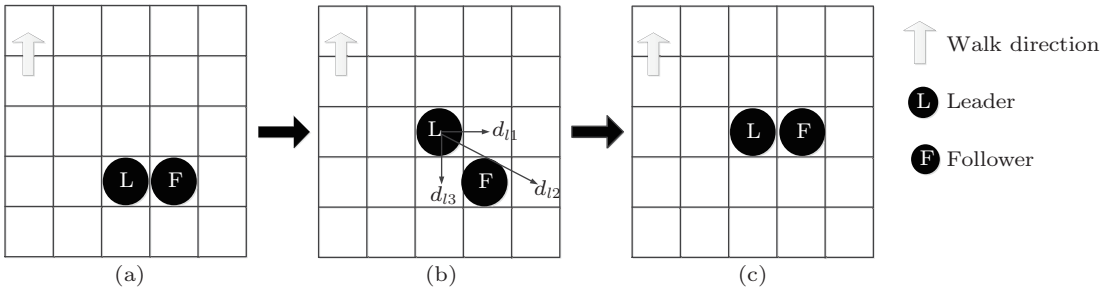


Fig. 2. Modeling the process of the walking behavior of the pedestrian group.

2.3. Basic rules

(I) Generate pedestrians.

Individuals and groups are generated in the system with random positions. Every pedestrian owns a unique ID to identify whether the pedestrian is isolated or in groups. What is more, pedestrians in a group are distributed together in a certain spatial structure. The leader in the group is randomly appointed. For the paired pedestrians each pair is in a line, and the pedestrian groups of three are in U-like, V-like or L-like shapes, etc.

(II) Calculate the static floor field.

The static floor field of each cell is determined by its shortest distance from opposite boundary of the system, which is unchangeable during the simulation.

(III) Calculate transition probability and update position.

The transition probability between an isolated individual and the group leader is based on the value of floor fields. For other group members, the transition probability is calculated in another way, which is partly dependent on the leader's motion. According to the transition probability, each pedestrian randomly chooses the target cell.

(IV) Update the dynamic floor field.

The dynamic floor field is time dependent. At initial time, the dynamic floor field is set to be zero. From time step t to time step $t+1$, the dynamic floor field of each original cell with a moving particle is increased by one and reduced by one with probability μ and diffuses to one of its neighboring cell with probability δ, which leads to broadening dilution and finally vanishing of the trace.

(V) Then, for each pedestrian, repeat III and IV until each pedestrian arrives at the destination.

3. Simulation

3.1. Simulation scenario

The developed floor field model is defined in a channel with size LW, where L and W are the length and width of the channel, respectively. The layout of the channel is shown in Fig. 3. There are two kinds of pedestrian in the channel, i.e. right walker and left walker. The system is discretized into cells each with a size of 0.4 m $\times$0.4 m. Its upper and lower boundaries are closed, which means that the pedestrians are not allowed to walk through them. However, the left and right boundaries are periodic; i.e., when the pedestrian arrives at the left (right) one he or she can reenter into the system from the right (left) one. In this way, the number of pedestrians in the channel is fixed. This is a common condition for boundaries, which has been adopted by many studies and has no influence on the simulation results.[30–32]

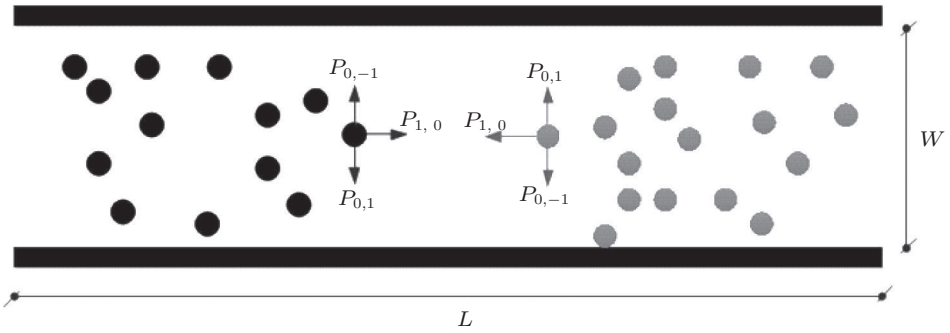


Fig. 3. Schematic illustration of the pedestrian simulation system.

3.2. Simulation result

The simulation experiments are implemented on the platform of MATLAB. The channel is 6 m $\times$ 24 m. At the initial time, pedestrians are distributed randomly in the system. If a pedestrian chooses to move to the forward cell, his or her walking speed is 1. However, when the pedestrian moves to the right (left) neighboring cell or stays in the original cell, his or her speed is 0. Then, the overall average speed of pedestrian flow is the percentage of pedestrians moving forward in the crowd. Since the simulation is under the periodic conditions, the density of pedestrian flow is unchangeable. The pedestrian flow is the product of the average speed and density.

The first step is to validate the availability of this approach on modeling the walking behavior of pedestrian groups. Figure 3 shows the distribution of pedestrian crowds composed of pairs at different density levels with the evolution of time. It can be seen that pedestrians in groups stay together with a certain spatial structure at the beginning of time. In the walking process, some groups have to split up temporarily in order to evade the oncoming pedestrians. However, with the followers' attempt to keep pace with the group leader, the groups will reform after a few time steps. Therefore, when the time step is 1000, a majority of the groups still keep close to each other. This phenomenon is consistent with empirical observations. However, it should be noted that, with the increase of pedestrian density, the number of separate groups increases (see Fig. 4). The reason may be that in a dense crowd pedestrian groups will conflict with other people frequently, which makes it more difficult for followers to catch up with the leader.

Similarly, figure 5 reveals that pedestrian groups of size 3 can also hold group formation in the simulation. However, compared with the above case, the triples are more easily separated. It may be concluded that a larger cohesion is needed to ensure that all people in groups stay together. This can be verified by observing the fact that large groups always split into small subgroups when walking. In conclusion, the simulated groups exhibit coherent behavior and form walking patterns similar to the ones observed in real crowds. Moreover, our model successfully describes the group behavior of resolving imminent collisions.

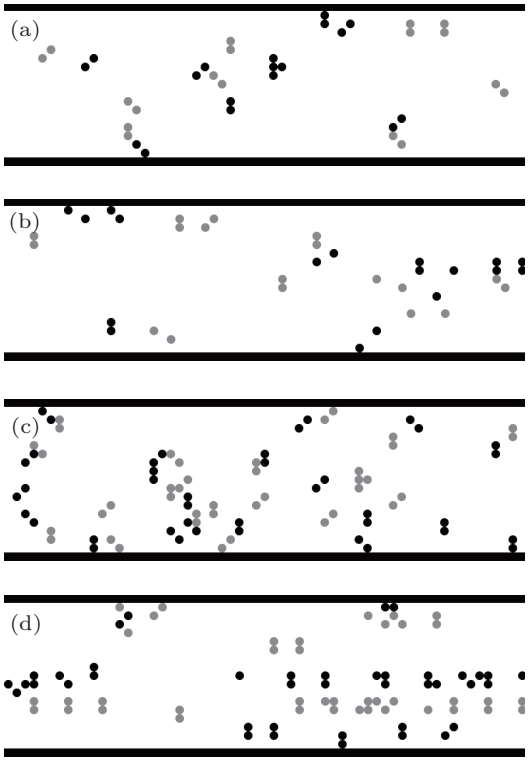


Fig. 4. Simulated pedestrian flow composed of pairs, where $\mu = 0.1$, $\delta = 0.2$, $k_s = -2.0$; $k_D = 1.0$; $k'_s = 0.5$; $k_D = 0.6$; $k_I = 4$. (a) Number of pairs = 18, time step = 0; (b) number of pairs = 18, time step = 1000; (c) number of pairs = 40, time step = 0; (d) number of pairs = 40, time step = 1000.

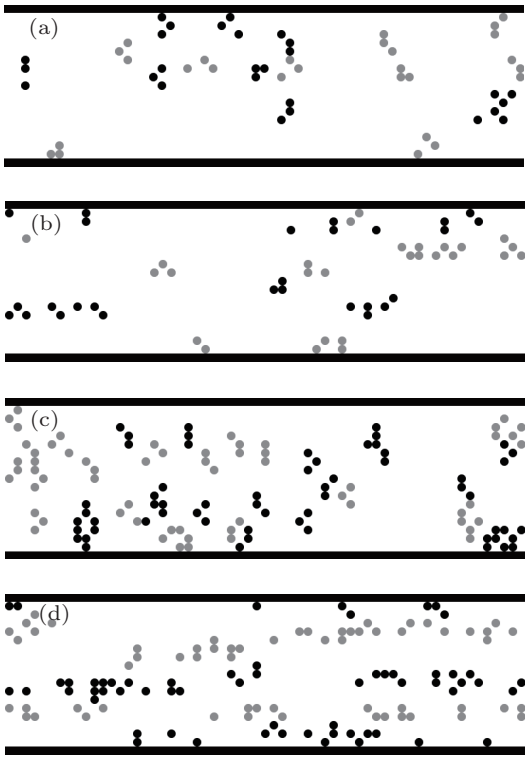


Fig. 5. Simulated pedestrian flow composed of triples where $\mu = 0.1$, $\delta = 0.2$, $k_s = -2.0$; $k_D = 1.0$; $k'_s = 0.5$; $k_d = 0.6$; $k_I = 4$. (a) Number of triples = 18, time step = 0; (b) number of triples = 18, time step = 1000; (c) number of triples = 40, time step = 0; (d) number of triples = 40, time step = 1000.

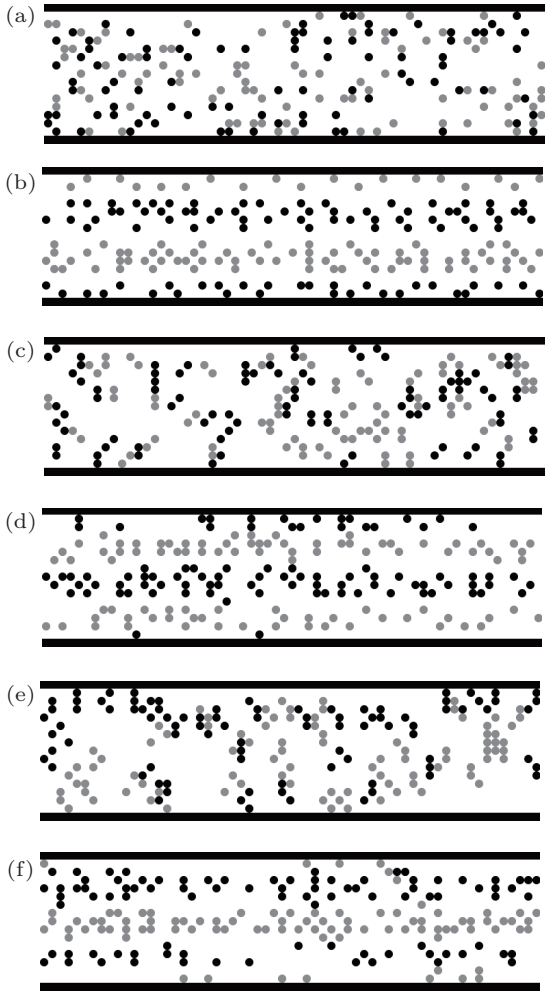


Fig. 6. Simulated pedestrian flow at density = 0.2, where $\mu = 0.1$, $\delta = 0.2$, $k_s = -2.0$; $k_D = 1.0$; $k'_s = 0.5$; $k_D = 0.6$; $k_I = 4$. (a) Pedestrian flow composed of individuals, time step = 0; (b) pedestrian flow composed of individuals, time step = 250; (c) pedestrian flow composed of pairs, time step = 0; (d) pedestrian flow composed of pairs, time step = 450; (e) pedestrian flow composed of triples, time step = 0; (f) pedestrian flow composed of triples, time step = 600.

Then, effects of groups on pedestrian flow dynamics are investigated. For the purpose of observing their effects in a discernible way, comparative simulation experiments are performed. We vary the composition of pedestrian crowds but restrain other conditions such as the system size, the density, etc. Figure 6 shows that the emergence of lane formation in pedestrian flow in total consists of isolated individuals, pairs, and triples, respectively. It can be found that for pedestrian flow in isolated individuals four lanes are formed at the 250th time step and the pedestrian flow attains its stable state after that. However, in Figs. 6(c) and 6(d), the lanes emerge after 450 time steps. Moreover, the interface of the lane is not smooth, and there exists a disturbance between the adjacent lanes. The analogous phenomenon can be observed in pedestrian flow with groups of size three. However, its lane formation occurs at the 600th time step and the pedestrians in different lanes interact with each other in a more frequent way. Ad-

ditionally, pedestrians in different lanes may enter the adjacent lane. The most plausible explanation for these differences described above is the tendency of pedestrians in groups to hold configuration by following the group leader. They will make inefficient decisions on walking resulting in a baffling effect of the instability of pedestrian flow operation. As is well known, the organization of lanes is beneficial for the pedestrian flow since it reduces the frequency and strength of avoidance maneuvers. In this sense, the presence of pedestrian groups has a negative effect on pedestrian flow. What is more, as the pedestrian groups are likely to keep walking side by side, they get in the way of other people's motion, retarding the occurrence of lane formation as well as increasing the instability of flow.

Further, we explore the effects of walking behavior of pedestrian groups on pedestrian flow in a quantitative way by comparing the fundamental diagrams. Considering the fact that the sizes of pedestrian groups obey the Poisson distribution in reality, we assume that the percentage of pedestrian individual, pairs, and triples is 60%, 26%, and 14% respectively. Another three kinds of pedestrian flow consisting of individuals, pairs, and triples are simulated. Each simulation lasts 10^4 time steps and repeats 10 times. For each time, the first 10^3 time steps are discarded to prevent the randomness. Then the fundamental diagrams are obtained by averaging the simulation results.

Figures 7(a) and (b) depict the relationship between average velocity and density, and that between volume and density respectively. The four kinds of pedestrian flow follow the same tendency that the velocity of pedestrian flow decreases with increasing density, but shares a sharp decrease when the density exceeds the critical point. In contrast, the volume experiences an increasing trend when the density increases. Then, after the critical density, it begins to decrease. However, some significant differences exist among these curves. Pedestrian flow of individuals performs with the highest operating efficiency while the flow with triples is the worst. Moreover, in the range of low density, the differences among these curves are negligible. Then, when the density reaches a moderate level, the gaps among them become large. In particular, when the density exceeds the critical one, the differences are more significant. The characteristics of these curves show that the effects of groups on pedestrian flow dynamics are related to the density level. This conclusion accords with that of Ref. [14]. The explanation for this is that, when pedestrian density is low in the channel, there is enough space for groups to maintain their formation as well as to move together with a desired speed and direction. Yet, at a high density level, groups need to adapt the configuration or split in order to avoid other people around. For the purpose of getting back to the group formation, the walking behavior of people in a group will be insensible and deviate from their desired direction. Further, in the dense crowd, pedestrians staying coherent turn into obstacles of other pedestrians who are trying to walk in a desired path. These two main factors may result in the low efficiency of pedestrian flow of groups at high density.

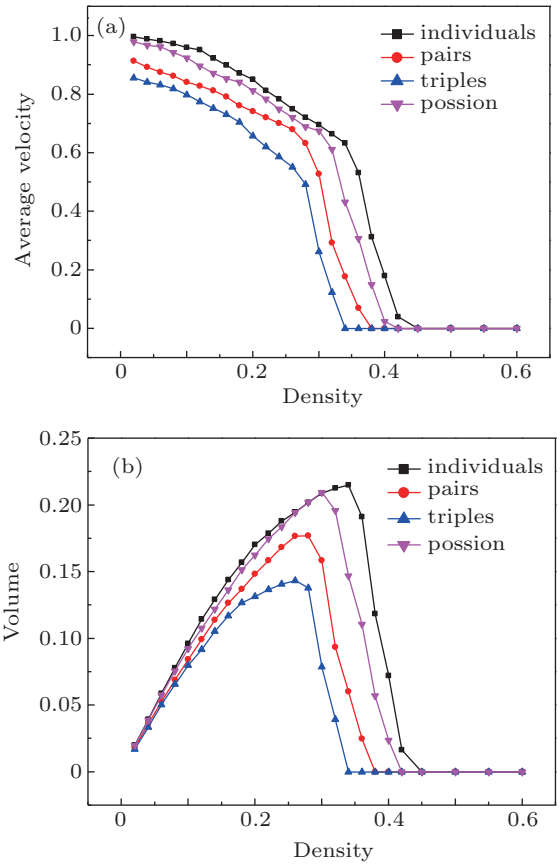


Fig. 7. (color online) Fundamental diagrams of four kinds of pedestrian flow: (a) density against average velocity, and (b) density against volume.

Finally, parameter sensitivity analysis is conducted to reveal the mechanism of group behavior, which will help gain an insight into the group behavior and thus guide groups in behaving in a reasonable manner. By varying parameter k_{d}, which reflects the strength of the followers' desire to stay coherent with the leader, the variations of average velocity of pedestrian flow for pairs and triples are obtained. From Fig. 8, the velocity declines significantly when k_{d} jumps from 0 to 0.1. Then, the curves share a moderate decrease with the increase of k_{d}. For the curve of density = 0.3, the decline is more significant than for the other two curves. These comparison results imply that for pedestrians in groups there is a trade-off between moving faster and staying coherent. Also, the results reveal that when pedestrian density is low, the behavior of groups sticking together to move generates little effect on pedestrian flow dynamics. While the crowd is dense, it is sensible for groups to make a compromise between staying together and finding their desired paths based on individual capability.

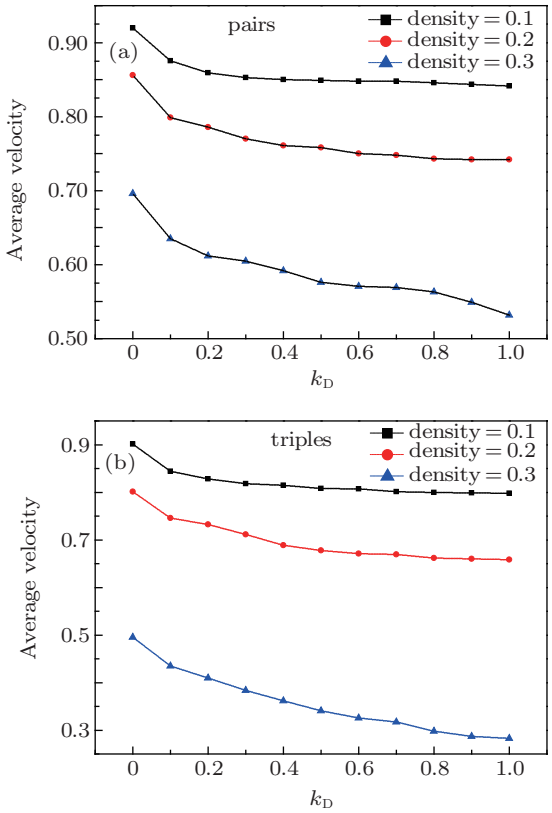


Fig. 8. (color online) (a) Variations of average velocities with k_D for pedestrian flow composed of pairs (a) and triples (b) when densities are 0.1, 0.2, and 0.3.

4. Conclusion and discussion

In this paper, an extended floor field CA model is proposed to incorporate into the walking behavior of pedestrian groups. By introducing the leader–follower walking pattern based on behavior theory, our model successfully captures the characteristics of walking behavior of pedestrian groups and predicts their walking process well. The effects of groups on pedestrian flow dynamics are analyzed in both qualitative and quantitative ways. It can be concluded that the presence of pedestrian groups retards the emergence of lane formation. Moreover, it makes a contribution to the instability of pedestrian flow operation. Meanwhile, this can be reflected from the fundamental diagrams which are obtained from the simulation of four kinds of pedestrian flows consisting of individuals, pairs, triples, and mixtures. The characteristics of these curves show that the effects of groups on pedestrian flow dynamics are related to the density level. When the density level is high, the pedestrian flow operation is considerably affected by the groups, which emphasizes the necessity to consider groups in studies of pedestrian dynamics. In addition, parameter sensitivity analysis is conducted to gain an insight into the behavior of groups. It is found that the strength of interactions among pedestrians in groups has a slight effect on average velocity of pedestrian flow for a low density level, but has a significant effect when the density level is high. This finding inspires the groups to make a sensible decision based on the trade-off between efficient movement and staying coherent. This model can be used to plan pedestrian facilities, manage crowds, guide pedestrians in walking behavior, etc.

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