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Cellular automaton simulation of pedestrian flow considering vision and multi-velocity

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HIGHLIGHTS

- Introduce multithreading mechanism into the update rules of CA model.
- Vision area function being the basis for pedestrians' decision making.
- Compare the effects of visual area function on different types of pedestrian.
- Analyze the effects of velocity on pedestrian dynamics under different densities.

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ABSTRACT

A cellular automaton (CA) model with an asynchronous update has been used to identify the pedestrians walking at the different speeds. The multithreading mechanism is introduced into the simulation update rules where the pedestrians are allowed to move with the different walking velocities independently. The vision area is provided to describe the environment during the movement. The pedestrians who are overtaking, blocking, forming lanes and conducting other interactive phenomena are represented well in this model. In the study, several simulations are held using the different pedestrian velocity compositions using the model. The relationships between velocity–density and pedestrian types are analyzed. The pedestrian flow shows the different relationships between velocity–density and flow-density at the various pedestrian compositions. The lowest velocity pedestrian type has a significant influence on the average pedestrian flow velocity.

1. Introduction

As the pedestrians can move freely, there is no limit in the use of "lanes". They are easily affected by the other pedestrians and their surrounding environment [1]. The pedestrian characteristics such as their walking facilities, trip activities, and environmental conditions have a considerable impact on the pedestrian dynamics. These factors are useful in understanding the pedestrian flow performance and establishing the microscopic simulation model. In the experimental and field studies, the impacts of the facilities, personal and trip activities, and environmental conditions on the walking speed and the fundamental diagram of the pedestrians have been analyzed [2,3]. The relationship between the walking speed at capacity and the directional distribution of the pedestrian flow (or flow ratio) are investigated in the field research [4]. The comparison

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of the survey results from the different countries showed that both habit and custom have an effect on the personal space of the pedestrians. Also, the methods of physics and modern computer science such as cellular automata (CA) [5–11] and social force models [12] have been successfully used to identify the pedestrian flow problems [13–15]. As a result of non-repeatability and safety factors in the experiments and field studies, the simulation methods seem to be more acceptable [16,17]. Based on the simulation models, researchers can study the effects of the different characteristics and facilities of the pedestrians on the pedestrian flow and evacuation dynamics such as pedestrian's moving habit [7], right-moving preference [18], exit width and layout [19–21]. Many of the collective effects and self-organization phenomena of the pedestrian flow have been represented by these models such as jamming and clogging, lane formation and flow oscillations at doors, and collective patterns in counterflow [22,23].

However, most studies have not paid enough attention to the influences of the pedestrian flow composition (particularly on free walking speed) on average flow speed and facility capacity. Also, among the given pedestrian simulation models, especially the CA models, the pedestrians have the same desired speed. It has been assumed that the pedestrian particles are updated in parallel [1,5,16]. This stresses that many researchers have ignored the effects of the speed diversity of pedestrian dynamics in the simulation models. The synchronous (parallel) updating scheme has some shortcomings. First, two or more people try to enter the same space in the similar time step [24]. In solving the conflicts and avoid the overlapping in the simulations, a friction parameter μ is introduced into the cellular automata models. This parameter has both qualitative and quantitative effects on the pedestrian evacuation [13]. Regarding the differences in stride frequency and reaction time, the walking space involves those who come first, where the conflicts and overlapping rarely occur in daily life. Second, many parallel update simulations adopt the same maximum velocity for the pedestrians. The desired velocity for the pedestrians is quite different with the discrepancies in their physiological function. Also, the pedestrians can change their walking directions quickly and flexibly. Therefore, a multi-velocity simulation model is more realistic than a single-velocity simulation [17].

In the walking process, the environmental stimuli through a visual perception are an essential factor that affects the pedestrian movement behaviors [25]. The pedestrians have the capacity to choose a route based on their environment and overtake easily other pedestrians if they want to. Thus, the visual field and the different walk velocities are special while the common characteristics of the pedestrian movement are underestimated and not well represented in the simulation of the pedestrian dynamics. The pedestrian movement simulation model should fully consider these differences to analyze the special phenomena in the pedestrian dynamics [26].

Recently, some researchers have linked the visual information with the pedestrian movement. Ma et al. [27] introduced the view radius on a simplified social force model to describe the range that the pedestrians perceive. The view radius model is derived from the Vicsek's model [28], where the direction and velocity of the pedestrians is the average value of the neighborhood in their random perturbation vision (η). However, this model is more suitable for a crowded evacuation in low visibility or typical self-driven biological system. Asano et al. [29] proposed a fan-shaped vision field based on the game theory to deal with the pedestrian collision. Park et al. [30] noted the collision avoidance behavior models by calculating the distance and the angle in the area called information process space (IPS) between the agents. The collision can be predicted and avoided by this model. The cited models are all continuous-space models.

In discrete-space models like CA models, the pedestrians can select a cell with a shorter distance to the exit [31], and so as the floor field cellular automaton [16,17]. Many studies focus on the effects of the facilities and the bidirectional pedestrian flow on the pedestrian dynamics. However, in a crowded environment, the pedestrians always avoid the collision or overtake the others. Upon identifying the direction of their destination, the pedestrians will analyze their surrounding environment and then decide their walking process where the faster ones would not choose the straight line but rather walk along the zigzag line in a crowd to maintain their desired velocities. With this process, the overtaking and lateral movements always occur. On the contrary, there is also a lane formation effect on the pedestrian flows. The mechanism is that if there are pedestrians coming in the opposite direction or having a gap that is too small to overtake, the collision avoidance and the following behaviors will be the choice [32]. When the desired directions of the pedestrians are given, they can choose the optimal walking direction for the next step according to the feedback on the visual area. To study the pedestrian flows with the different compositions of the velocity, Weng et al. [26] simulated the pedestrian counterflow with two different velocities through an update at the different time-step intervals. However, pedestrians with the same velocity have a parallel update, and so as Yuan's and Tan's models [31].

In this paper, simulating the pedestrian flow with multi-velocities and representing the overtaking phenomena in this movement, a self-update mechanism, and vision radius function is introduced into the CA model. In this model, each pedestrian updates independently and the update time interval is based on every walking speed. The pedestrians make decisions based on their visual judgment in each time interval. This model can improve the description of the pedestrian movement characteristics, decision-making behaviors, overtaking patterns and interactive phenomena. The effect of the velocity composition on the pedestrian flow is also analyzed.

The rest of this study is organized as follows. Section 2 describes the update mechanism of the simulation models, the vision area function and the pedestrian movement behaviors. In the following section, the simulation results are interpreted and discussed. Finally, the conclusion is provided in Section 4.

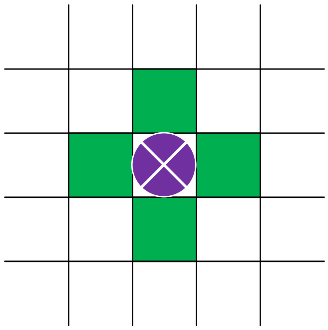


Fig. 1. Von Neumann neighbor setup in a two-dimensional rectangular grid.

2. CA model

2.1. Basic model

The CA model is defined on a discrete W × L cell grid in a two-dimensional system. The cell size is $0.4\times0.4\ m^2$ as Refs. [1,5] proposed. Each cell is either occupied or empty and pedestrian overlapping is forbidden.

In order to realize the real display in walking process and avoid overlapping problems caused by parallel update, this CA simulation model depends on the multithreading mechanism. As each pedestrian is an independent thread in this simulation system, they can update independently. The faster speed the pedestrian is traveling at, the shorter sleep time for the thread has after each step. The sleeping time refers to the time required for the system to update the pedestrian position calculation. All hose threads will share the common coordinate system. Thus, pedestrians can check their surrounding pedestrians and obstacles dynamically and then make choice for the next step. The state of coordinate system is synchronized when a pedestrian is checking the surrounding environment. As the walking velocity of pedestrians is different, the sleep time is different. All thread priorities are the same. Thus, if there are two or more people completing for the same position, the criterion is first come first serve, and other pedestrians stay in place until they can move to target. If several pedestrians arrive at a same cell in the same time step, the pedestrian with faster walking velocity will move first.

This simulation method can make a more realistic prediction about the flow movement pattern and a decision making process of pedestrians than parallel update mechanism. However, the multithreading mechanism we use here has some fundamental flaws. Firstly, the multithreading mechanism consumes lots of computer memory if pedestrians spend too much time in calculation in a time interval. Secondly, there is not a global simulation clock such that pedestrians are scheduled to be updated based on their rest period, and the rest time of pedestrians is based on the computer clock. Thus, the accuracy of simulation will greatly depend on the hardware conditions. Therefore, the simpler the pedestrian movement rule is, the higher the simulation accuracy is.

In normal and free flow situations, there are two fundamental elements which decide the walking velocity of pedestrian, including stride length and stride frequency. In this model, the stride length is fixed by the cell size. i.e., in every time step, one pedestrian can move only one cell and thus the update interval is equal to the stride frequency. To simulate the movement of pedestrians with different walk velocities, we change the stride frequency to decide walking velocity, and the update interval of each pedestrian (thread) is calculated by Eq. (1).

The cell length is 0.4 m, which means the maximal stride length is the same for everyone. In order to reflect the multi-velocity, the stride frequencies of pedestrians are various. In this model, the update interval of pedestrians is determined by

$$t_i = \frac{\varDelta L}{v_i}, \tag{1}$$

Where t_i is the sleep time for pedestrian i, $\varDelta L$ refers to the length of pedestrians taking a step and v_i means the walking velocity of pedestrian i.

In order to ensure that every step is the same distance in the horizontal and vertical axis, a Von Neumann neighbor is used. In every time step, pedestrians can choose to wait or move to the four neighboring cells according to the surrounding environment. The green cells are the neighbors (see Fig. 1).

In a pedestrian system, whether it is a one-way pedestrian flow or bi-directional pedestrian flow, pedestrians with higher velocity will overtake those with slow velocity. Pedestrians will have frequent and strong interactions. As shown in Fig. 2, if one pedestrian is walking in a crowd (going to the right), he or she may face those situations.

In Fig. 2, we take core cell pedestrian, the one with white cross on it as an example. The green circle around the pedestrian is the pedestrian with slower velocity than the core cell pedestrian. The arrow in the figure indicates the pedestrian in the core cell will select after analyzing the surrounding environment.

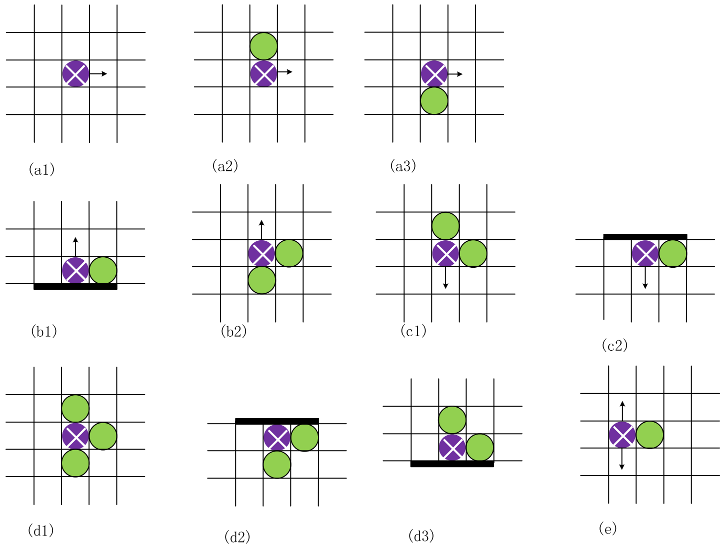


Fig. 2. Illustration of possible situations a pedestrian may face when overtaking others.

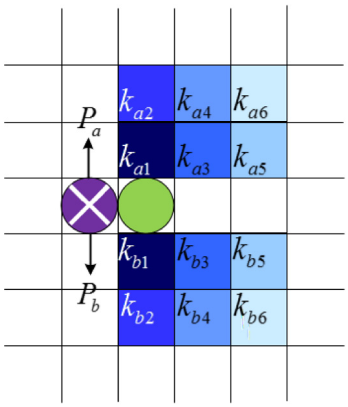


Fig. 3. Definition of the visual field of pedestrian.

Fig. 2 shows all the possible situations that a pedestrian may face during walking (going to the right). In Fig. 2(a1)–(a3), a pedestrian will move right if the right cell is unoccupied, no matter whether the above and below adjacent cells are occupied or not. However, if the right cell is occupied, the core cell pedestrian will walk above or below in order to outstrip the one in front of him. Fig. 2(b1–b2) shows that if the below cell is occupied or wall is below the core pedestrian, he will move up. Fig. 2(c1–c2) is the same situation with Fig. 2(b1–b2) yet the direction is opposite. In Fig. 2(d1–d3), the cells above, below and right are either occupied or against the wall. Thus, the pedestrian will stay in the same place in this step. In Fig. 2(e), the right cell is occupied, yet both of the upper and below cells are empty. When facing two choices, in Refs. [7,18,26,33], people prefer to walk on the right-hand side and exceed from the left-hand side, which has been used in the CA models. However, the data collected from one way walkway shows that pedestrians do not always exceed from the left-hand side and most pedestrians exceed from the side with fewer people in front of him. Therefore, it is more reasonable to consider the situation in front of the above and below cells. Thus, a vision area is defined for configuration (e) in Fig. 2 to represent the front situation of pedestrians when they decide to overtake, as is shown in Fig. 3.

2.2. Vision area function

Fig. 3 shows the visual field of pedestrians. The shaded square cell is the visual field composed of six cells on both sides. Similarly, the concept of space grade is introduced for cells. P_a is the above cell space grade, P_b refers to the below cell space grade, and P_a and P_b are determined by the six square cell in front of them. In this paper, it is assumed that the pedestrian will move to the cell with higher space grade during the walking process. If $P_a = P_b$, pedestrians will choose the right hand

Table 1
Rule set of CA pedestrian simulation: below is a cycle of a pedestrian per time step.

Step 1:
(1) synchronize the coordinate system state
(2) Analyze the surrounding environment.
Identify the pedestrian around and then make judgments according to Fig. 2; if in Fig. 2(e), call the vision area function.
(3) Enter the target cell.
Step 2:
(1) Rest t_i according to the walking speed in Eq. (1).
This time step is completed.

cell. Thus, the blank grade is given by

$$P_i = \sum_{r=1}^{N} \varepsilon_{ir} k_{ir} v_{ir} \tag{2}$$

Where k_{ir} $(i = a, b. r = 1, 2, \ldots, 6)$ is a scalar constant indicating the importance of cell in visual field and ε_{ir} is the occupied coefficient of cell (i, r). If the cell (i, r) is unoccupied, $\varepsilon_{ir} = 1$; if the cell is occupied by a pedestrian with the same walking direction, $\varepsilon_{ir} = 0.5$; if the cell is occupied by a pedestrian with the opposite walking direction, $\varepsilon_{ir} = -0.5$. The reason for that is in this simulation, all the pedestrians are in the same walking direction. Thus, $\varepsilon_{ir} = 1$ or $0.5.v_{ir}$ is the pedestrian velocity which occupies cell (i, r). It means that pedestrians are more willing to follow the faster pedestrian group.

Generally, in the visual field, the shorter distance from the cell to the pedestrian, the higher influence there will be. Therefore, the importance level of cell (i, r) to pedestrians and the relationship can be defined as:

$$k_{ar} = k_{br} \tag{3}$$

$$k_{ir} > \sum_{r'=r+1}^{n} k_{ir'} \tag{4}$$

Where $r = 1, 2, \ldots, 5$ and $r' = r + 1 = 2, \ldots, 6$.

Eqs. (2) and (4) show that in the overtaking process, pedestrians compare not only the number of the blank cell but also the position of the occupied cells.

2.3. Simulation formulation

As stated in Table 1, the rule set of CA simulation consists of two procedures. It can be applied in every time step for everyone as following.

① synchronize the coordinate system state.
② analyze the surrounding environment.
③ move to the cell wanted. Secondly, rest t_i. Subsequently, start the next time step.

3. Simulation results and discussions

The simulations are conducted in a one-way corridor with 6 m × 50 m such as 15 cells × 125 cells with each cell of 0.4 m × 0.4 m and all the pedestrians go to the right. The upper and bottom boundaries are closed and no one is allowed to cross. The left boundary is the entrance to the pedestrian and the right boundary is the exit. When a pedestrian reaches the right boundary, it means that this simulation process has been completed, and then the thread representing the pedestrian is eliminated from the system. Considering this simulation is a one-way corridor, the step back problems of pedestrians are not considered in this model. All pedestrians move from the left to the right boundary. The simulation assumes that the desired speed of the pedestrians is the uniform distribution of 1.0 m/s to 1.6 m/s and the distribution interval is 0.1 m/s. The corridor is relatively and uniformly populated at the start of the simulation.

With the introduction of the new pedestrian at the entrance similar to the pedestrian exit, the corridor will be maintained at a steady state by keeping the total number of pedestrians in the system for each simulation. If a pedestrian is removed from the system and the total number of pedestrians is smaller than what is set for the simulation, a new pedestrian will be generated at the entrance. The new pedestrian type and position are randomly created with a uniform distribution. The speed range is from 1.0 m/s to 1.6 m/s, the position range on the vertical axis is from 0 m to 6 m, the distribution interval is 0.4 m, and all the positions of the new pedestrians on the horizontal axis are 0. If a newly generated pedestrian position has been occupied by a pedestrian already, the system will find an empty cell at the entrance to the new pedestrian. If all the cells at the entrance have been occupied, this new pedestrian will be canceled.

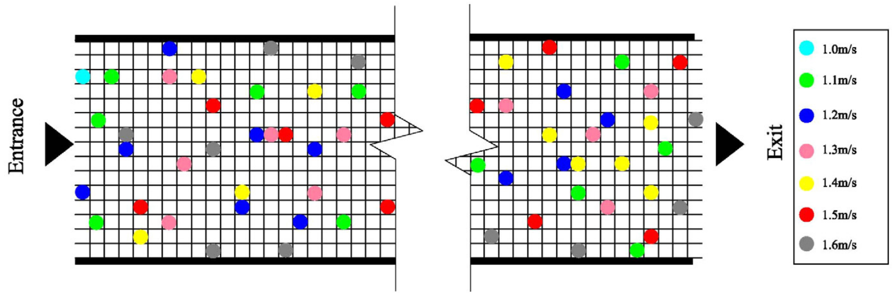


Fig. 4. System's initial state. Colored circles represent the people with the different walking velocities. Pedestrians enter the simulation system from the left side and leave from the right side. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The density k is defined as Eq. (5):

$$k = \frac{N}{W * L} \tag{5}$$

Where N = total number of the pedestrians in the system and $W * L$ = corridor size.

The average velocity (v_i) of pedestrian (i) over a distance is defined as the distance that the pedestrian covers on the horizontal axis by dividing the exclusive elapsed time step. The mean velocity of the pedestrian flow is the arithmetic average value of all the pedestrians in the system. The mean flow rate is measured at the exit during the time period from t_1 to t_2, which can be defined as:

$$q = \frac{P(t_2) - P(t_1)}{t_2 - t_1} \tag{6}$$

Where $P(t)$ = total pedestrian number passed the exit at time (t).

For each simulation, when $P(t_2) = 10{,}000$, this simulation is stopped while the k, q and v are computed according to the statistics of the pedestrians between $P(t_2) = 8800$ and $P(t_1) = 6000$, and the corresponding sample size for pedestrians between 1.0 m/s and 1.6 m/s is 400 (see Fig. 4).

Unidirectional flows are simulated and analyzed with the total number of pedestrians from 100 to 1200. The increment is 100 for each simulation. In the simulation, the maximum capacity of the system is 1244 pedestrians. When the maximum capacity is achieved, the entrance will have no place for any new pedestrian for a short period as the first half of the corridor is so crowded that the pedestrians move very slowly. Until the total number of pedestrians is lower than 1244, there will have a place at the entrance.

3.1. Simulation accuracy

In this simulation, there is no global simulation clock and the rest time in each thread is based on the computer clock. If the CPU cannot respond to this thread in time, the sleep time will be extended. To ensure the reliability and veracity of the simulations, the system will return the time consumed and the number of steps from the entrance to the exit from every pedestrian. Based on the data, the accuracy of the simulation is analyzed. The deviations from the simulation are given as:

$$\Delta T_i = (T_i^{exit} - T_i^{entrance}) - S_i \times t_i \tag{7}$$

Where $T_i^{entrance}$ and T_i^{exit} = enter and leave system time respectively, S_i = total steps taken from the entrance to exit, t_i = update interval, ΔT_i = deviation from actual time consumed ($T_i^{exit} - T_i^{entrance}$) and theoretical time ($S_i \times t_i$) consumed of pedestrian (i).

Fig. 5 depicts the deviation from the total and the actual time consumed, showing the deviation range and size. Although the deviation occurs to most pedestrians, the maximum deviation is 0.251 s. This is small for the walking process, which means that in the simulations conducted the thread starts on time. Thus, the simulation largely reflects the practical situation.

3.2. Fundamental diagram of the simulation model

Based on the simulation data, the mean flow rates and the mean velocity of the different velocity types of the total density are calculated (Fig. 6). R^2 is the ratio of the sum of squares of the regressions and the sum of the squared sums of the total deviations. The larger the ratio, the greater the proportion that can be explained by the regression sum of squares in the sum of squared sums of the total deviations. The more accurate the model, the more significant the regression effect. Numerically speaking, R^2 is between 0 and 1, and the closer to 1, the better the regression fitting effect. The value of R^2 in Fig. 6(a) is close to 1, which means he fitting is very accurate. The flow rates increase in the pedestrian density growth. However, there are

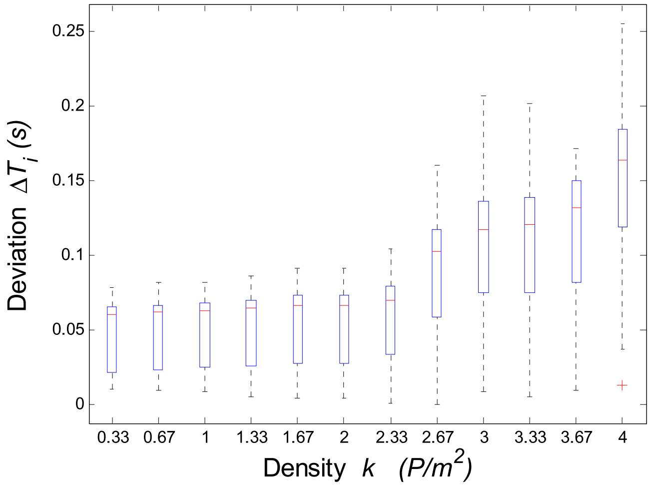
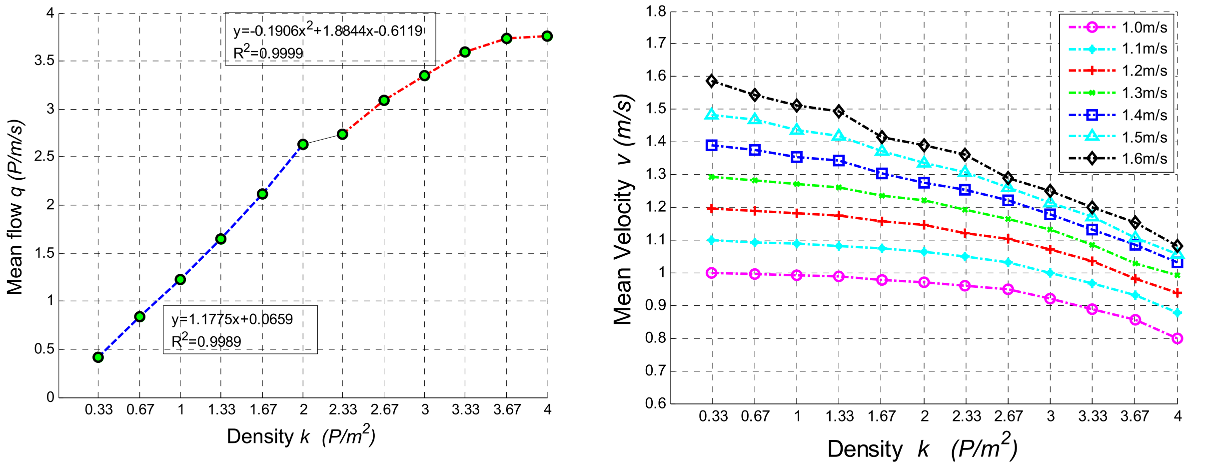


Fig. 5. The boxplot of ΔT_i, the sample size of each density is the same, 2800 pedestrians with uniform velocity distribution from 1.0 m/s to 1.6 m/s.



(a) Curve of the flow density

(b) Curves of velocity-density for different pedestrian

Fig. 6. Flow rate and mean velocity of the different pedestrians vs densities.

two obvious stages at the flow curve, and the fitting formulas for the two stages are shown in Fig. 6a. This is similar to the road traffic flow. During the first period, the relation between the flow and density is almost linear. There is space for the faster pedestrians to overtake the others in the corridor. When the density $k > 2$ P/m^2, the hindrance effects of the mutual interactions on pedestrians will become apparent, there will be insufficient space for the pedestrians to overtake the others, and the velocity will be reduced at relatively fast speed with the increase in density. Using the simulation data, the velocity–density curves of the different pedestrian types are given in Fig. 6b. Under the desired speed distribution set with the density growth, all types of the pedestrian velocity decline. The faster the pedestrians are, the faster the velocity decreases. However, the sequence of mean velocity has not changed and the faster ones always maintain the competitive advantage on the velocity. Different densities have different effects on the various velocities of the pedestrians.

3.3. Effect of the vision area function

This study focuses on the relationship between the average velocity of pedestrian flow and the composition of pedestrian velocity type. For example, the different pedestrian velocity types will affect each other, thus affecting the average velocity of pedestrian flow in the corridor. In this simulation process, vision area function is known when the pedestrians are faced with the situation as shown in Fig. 2e and when the pedestrians will be overtaking others in front of them. To observe the role of vision area function in pedestrian walking, another simulation is undertaken. However, as observed in the simulation, the vision area function is canceled while the other parameters are the same as the previous simulations. Having no vision area function seen, the walking direction is randomly decided on Fig. 2e.

Fig. 7 shows the comparison of two simulation curves with mean velocity against the total density. Fig. 7a highlights the mean velocity of all the pedestrians in two simulations. When the total density $k < 1.33$ or $k > 3$, the two curves almost overlap, which means that in low density there is enough space for them to walk as pedestrians can walk freely with rare interference with each other. If the density is greater than 3 ($k > 3$) the pedestrian flow becomes crowded and the free walking space drops sharply. Thus, the overtaking opportunity is reduced.

Based on the simulation data, the influence of vision area function on the different velocities of pedestrians is compared (Fig. 7b to h). The vision area function has different influences on the various velocities of the pedestrian. For the pedestrian type of $v_i = 1.0$ m/s, the vision area function has minimal influence on them. They are the slowest in the pedestrian flow with a little chance to overtake the others. The two curves of the mean velocity are overlapped to some extent (Fig. 7b). If the density is greater than 3 ($k > 3$), the mean velocity of the pedestrian with vision area function is slower than that without it. Vision area function can help the pedestrians overtake the others. Thus, the slowest pedestrian would be affected in the crowded environment.

For the other pedestrian types from $v_i = 1.1$ m/s to 1.4 m/s (Fig. 5b to f). The features of two curves are almost the same as Fig. 7a. Vision area function would not influence the mean velocity when the density is $k < 1$ or $k > 3$, for the pedestrians $v_i = 1.5$ m/s and 1.6 m/s (Fig. 5g to h), their velocity is the fastest in the pedestrian flow. They could continue overtaking the slower pedestrians when walking, so the vision area function has the more obvious impact on improving the mean velocity. If the density is greater than 3 ($k > 3$), the pedestrian flows into the congested state, the opportunity to overtake becomes less while the vision area function has little effect on the mean velocity.

From the comparison of the two curves, when $k = 2$ it is viewed that vision area function have an influence on the mean velocity, which means that when $k = 2$, pedestrians cannot be blocked or walk freely. Those with high-velocity pedestrians must transverse their walk or temporary stay if they want to surpass the pedestrians with low speed. The mutual interference in the different velocity pedestrians is the most significant.

3.4. Effect of the different composition of pedestrian velocity

In many simulations, the desired speed for all the pedestrians is the same. For instance, the average value of free walking is treated as the desired speed for all the pedestrians in the system. Thus, four simulation experiments have been conducted while the average value of the desired speed for all the pedestrians in the system is the same. However, the pedestrian composition is different. The velocity composition is as follows: (a) simulation 1, all free walking speed of pedestrians is 1.3 m/s; (b) in simulation 2, the pedestrian composition are 1.0 m/s vs. 1.6 m/s; (c) in simulation 3, the pedestrian composition is 1.1 m/s vs. 1.5 m/s; (d) in simulation 4, the pedestrian composition is 1.2 m/s vs. 1.4 m/s. For simulations 2, 3 and 4, the proportions of the two types of pedestrians in a total number of pedestrians are 50% and 50% respectively. Thus, the average value of the desired speed is the same, which is 1.3 m/s for these four simulations.

Fig. 8 shows the mean velocity and mean flow vs. the total density with the different pedestrian desired velocity compositions.

In simulation 1, the mean velocity curves are the same as the parallel update models in [1,14]. In those studies, the desired velocities for all the pedestrians are the same. However, for simulations 2,3, and 4, it can be observed that the pedestrian composition has a great influence on the pedestrian flow, and the average velocity of the pedestrian flow decreases with the increase in density. From the curves, it can be observed that the highest average velocity is the set between 1.2 m/s and 1.4 m/s. The lowest is a set between 1 m/s and 1.6 m/s and the mid-average velocity is a set between 1.1 m/s and 1.5 m/s despite the weighted average velocity of the desired speed is the same as 1.3 m/s. This case study highlights that the pedestrian flow velocity is illustrated by the slowest pedestrians while the average velocity of the pedestrian flow shows a strong correlation among the smaller pedestrian velocity group. When the density is greater than 2 ($k > 2$), the difference of mean flow and mean velocity is greater. Thus, during the evacuation, if the exit layout is reasonable and the width is sufficient, the pedestrian velocity will have a great influence on the evacuation time.

To discuss this phenomenon, the set between 1 m/s and 1.6 m/s as an example was taken (Fig. 9). There are 600 pedestrians in the system during the simulation. The proportions of the two types of pedestrians are 50% and 50% respectively. From the red arrow that the pedestrians with 1 m/s have already formed a wall as seen, thus blocking the pedestrians with 1.6 m/s behind them whose velocity drops to 1 m/s. Fig. 9 shows the reason the pedestrian group with the lowest velocity has a great influence on the mean velocity of pedestrian flow. With the increase in density (k), the system becomes crowded, and the place for pedestrian overtaking becomes less and less. This phenomenon is very common in our daily life that if there is a row of pedestrians at a slower speed in front of the transfer channel, most of us would choose to reduce the speed and then look for opportunities to overtake. The blue arrow area is the lane formation of the faster pedestrians. In real life, the speed difference among the pedestrians will not be so huge.

The pedestrian flow will be affected by many factors while the result of the most external components will be reflected on the pedestrian speed. The different walking speeds contribute directly to the pedestrian flow. Therefore, there is a deviation between the single speed and multispeed curve in shape. The different facilities have various users. Thus, the future work in evacuation dynamics and facility capacity should fully consider the diversity and speed composition to simulate more accurately.

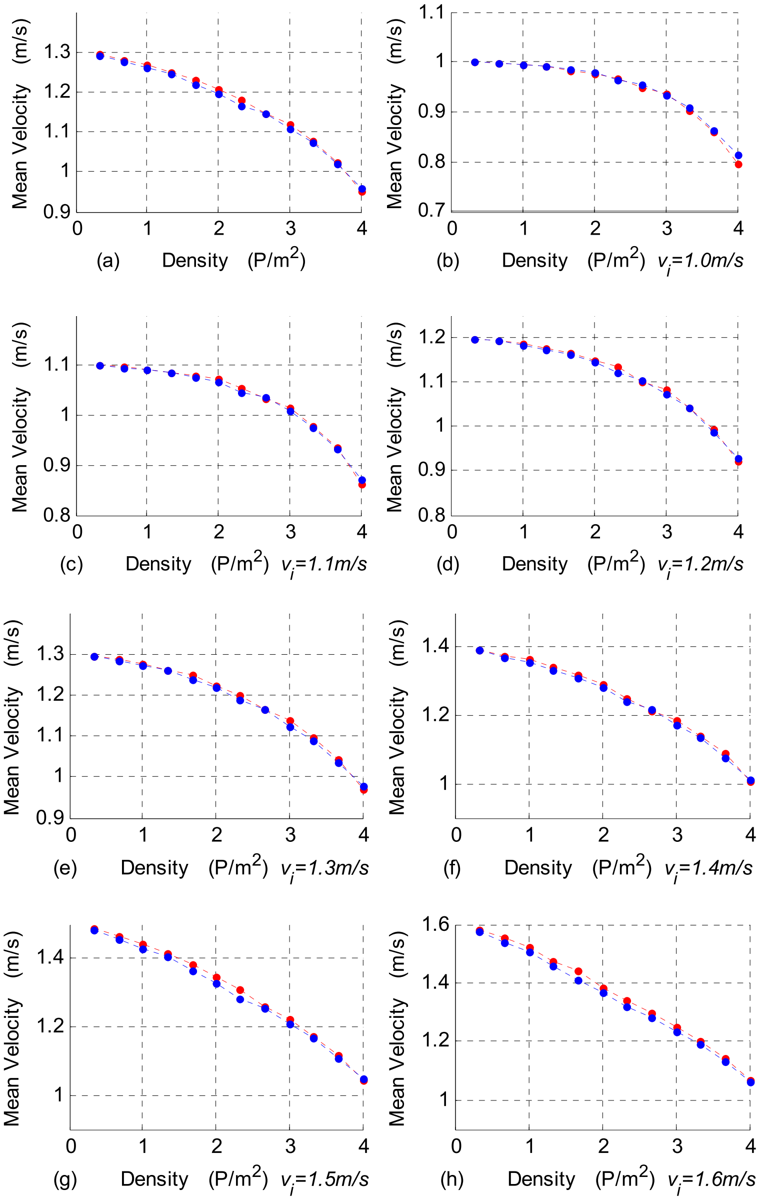


Fig. 7. These are the curves of velocity–density for pedestrian flow. The red curve indicates the simulation with the vision area function while the blue curve is the one without the vision area function. Fig. 7a is the curves of velocity–density, including all types of the pedestrians. Fig. 7b to h include the velocity–density curves of the different pedestrian types. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Conclusion

In this paper, an asynchronous update cellular automata model is presented to simulate the pedestrian movement with the different speeds. In this model, each pedestrian is updated at an exclusive time step. The simulation flow is analyzed from the pedestrian flow composition. The pedestrian density has different effects on the different pedestrian types. With an increase in the density, the faster pedestrians suffer from a greater impact. A set of rules for pedestrian walking and overtaking are established and the vision area function of the next step choice is presented to enable pedestrians to make optimal decisions in the case of a dual choice. The vision area function has a significant impact on the faster pedestrian, yet the little effect on the mean velocity of pedestrians. In the velocity–density study of the different pedestrian compositions, it is found that the lowest velocity pedestrian type has a greater impact on the average velocity of pedestrian flow due to the fact that it may form a wall, thereby blocking the faster pedestrian beyond them. The simulation results are very

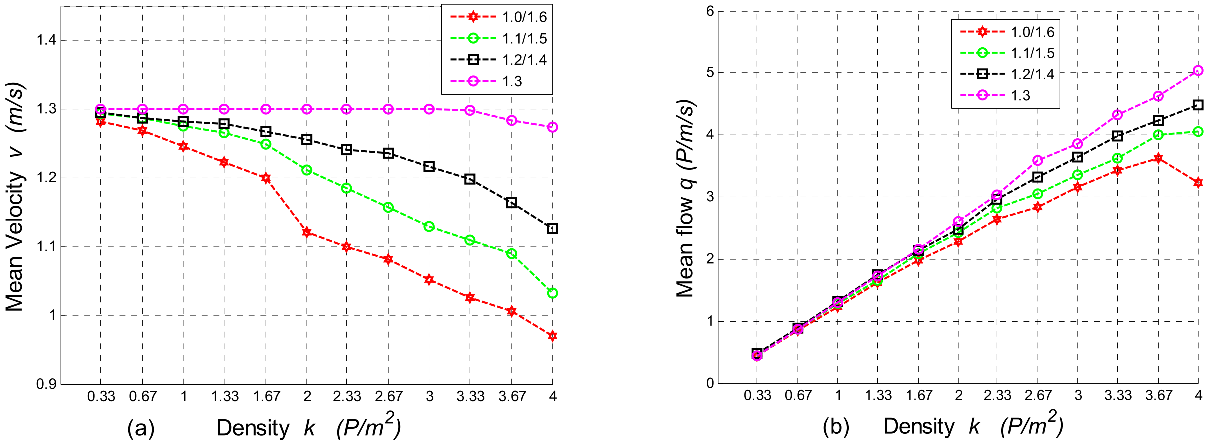


Fig. 8. This shows the curves of the velocity–density and flow-density for the different desired velocity compositions of the pedestrian flow.

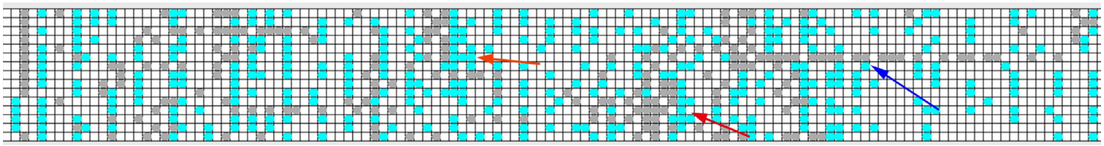


Fig. 9. The typical stages of the movement with density ($k = 2$).

useful in analyzing the pedestrian flow dynamics. The researcher hopes that this model can help understand the dynamics of pedestrian flow more clearly.

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References

[1] L. Jian, Y. Lizhong, Z. Daoliang, Simulation of bi-direction pedestrian movement in corridor, Physica A 354 (2005) 619–628.
[2] W.H.K. Lam, C.Y. Cheung, Pedestrian speed/flow relationships for walking facilities in Hong Kong, J. Transp. Eng-Asce 126 (2000) 343–349.
[3] S.B. Young, Evaluation of pedestrian walking speeds in airport terminals, Transp. Res. Rec. (1999) 20–26.
[4] W.H.K. Lam, J.Y.S. Lee, C.Y. Cheung, A study of the bi-directional pedestrian flow characteristics at Hong Kong signalized crosswalk facilities, Transportation 29 (2002) 169–192.
[5] D. Helbing, P. Molnar, Social force model for pedestrian dynamics, Phys. Rev. E 51 (1995) 4282–4286.
[6] A. Kirchner, K. Nishinari, A. Schadschneider, Friction effects and clogging in a cellular automaton model for pedestrian dynamics, Phys. Rev. E 67 (2003) 056122.
[7] A. Kirchner, A. Schadschneider, Simulation of evacuation processes using a bionics-inspired cellular automaton model for pedestrian dynamics, Physica A 312 (2002) 260–276.
[8] 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.
[9] 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.
[10] X. Zhou, X. Ji, H. Huang, et al., Simulation of bidirectional pedestrian flow in transfer station corridor based on multi forces, J. Central South University 21 (6) (2014) 2520–2525.
[11] X. Ji, J. Zhang, Y. Hu, et al., Pedestrian movement analysis in transfer station corridor: Velocity-based and acceleration-based, Physica A 450 (2016) 416–434.
[12] M. Muramatsu, T. Irie, T. Nagatani, Jamming transition in pedestrian counter flow, Physica A 267 (1999) 487–498.
[13] C. Burstedde, K. Klauck, A. Schadschneider, J. Zittartz, Simulation of pedestrian dynamics using a two-dimensional cellular automaton, Physica A 295 (2001) 507–525.
[14] V.J. Blue, J.L. Adler, Cellular automata microsimulation for modeling bi-directional pedestrian walkways, Transp. Res. B 35 (2001) 293–312.
[15] H. Yue, H.Z. Guan, J. Zhang, C.F. Shao, Study on bi-direction pedestrian flow using cellular automata simulation, Physica A 389 (2010) 527–539.
[16] Z.J. Fu, L.Z. Yang, Y.Q. Chen, K.J. Zhu, S. Zhu, The effect of individual tendency on crowd evacuation efficiency under inhomogeneous exit attraction using a static field modified FFCA model, Physica A 392 (2013) 6090–6099.
[17] Z. Fu, X. Zhou, K. Zhu, Y. Chen, Y. Zhuang, Y. Hu, L. Yang, C. Chen, J. Li, A floor field cellular automaton for crowd evacuation considering different walking abilities, Physica A 420 (2015) 294–303.

[18] L. Yang, J. Li, S. Liu, Simulation of pedestrian counter-flow with right-moving preference, Physica A 387 (2008) 3281–3289.
[19] Z. Daoliang, Y. Lizhong, L. Jian, Exit dynamics of occupant evacuation in an emergency, Physica A 363 (2006) 501–511.
[20] A. Varas, M.D. Cornejo, D. Mainemer, B. Toledo, J. Rogan, V. Muñoz, J.A. Valdivia, Cellular automaton model for evacuation process with obstacles, Physica A 382 (2007) 631–642.
[21] H. Yue, H. Guan, C. Shao, X. Zhang, Simulation of pedestrian evacuation with asymmetrical exits layout, Physica A 390 (2011) 198–207.
[22] R. Nagai, M. Fukamachi, T. Nagatani, Experiment and simulation for counterflow of people going on all fours, Physica A 358 (2005) 516–528.
[23] A. Schadschneider, A. Kirchner, K. Nishinari, CA approach to collective phenomena in pedestrian dynamics, Lecture Notes in Comput. Sci. 2493 (2002) 239–248.
[24] A. Schadschneider, A. Seyfried, Validation of Ca models of pedestrian dynamics with fundamental diagrams, Cybern. Syst. 40 (2009) 367–389.
[25] W.L. Wang, S.M. Lo, S.B. Liu, H. Kuang, Microscopic modeling of pedestrian movement behavior: Interacting with visual attractors in the environment, Transp. Res. C 44 (2014) 21–33.
[26] W.G. Weng, T. Chen, H.Y. Yuan, W.C. Fan, Cellular automaton simulation of pedestrian counter flow with different walk velocities, Phys. Rev. E 74 (2006) 036102.
[27] P.J. Ma, B.H. Wang, The escape of pedestrians with view radius, Physica A 392 (2013) 215–220.
[28] T. Vicsek, A. Czirok, E. Ben-Jacob, I.I. Cohen, O. Shochet, Novel type of phase transition in a system of self-driven particles, Phys. Rev. Lett. 75 (1995) 1226–1229.
[29] M. Asano, T. Iryo, M. Kuwahara, Microscopic pedestrian simulation model combined with a tactical model for route choice behaviour, Transp. Res. C 18 (2010) 842–855.
[30] J.H. Park, F.A. Rojas, H.S. Yang, A collision avoidance behavior model for crowd simulation based on psychological findings, Comput. Animat. Virtual Worlds 24 (2013) 173–183.
[31] Y. Weifeng, T. Kang Hai, A novel algorithm of simulating multi-velocity evacuation based on cellular automata modeling and tenability condition, Physica A 379 (2007) 250–262.
[32] W. Guo, X.L. Wang, X.P. Zheng, Lane formation in pedestrian counterflows driven by a potential field considering following and avoidance behaviours, Physica A 432 (2015) 87–101.
[33] F. Weifeng, Y. Lizhong, F. Weicheng, Simulation of bi-direction pedestrian movement using a cellular automata model, Physica A 321 (2003) 633–640.