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Modified Social Force Model Based on Predictive Collision Avoidance Considering Degree of Competitiveness

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Abstract. Modeling building evacuation during fire emergencies is an important issue. The social force model is a well-regarded evacuation modeling technique, and it has been integrated into the Fire Dynamics Simulator with Evacuation (FDS + Evac) of NIST to simulate building fire evacuation. However, these models still have limitations to be improved. First, occupants' movement can be unrealistically prevented. For example, the corner of doors exerts unrealistic repulsive forces on occupants, so the simulated flow at narrow doors is much smaller than experimental data. Second, the degree of occupants' competitiveness is not considered. Finally, current models are rarely validated by data form real-life emergencies, in which occupants may behave differently from normal situations. In this paper, new social forces are used to replace old ones to modify occupants' collision avoidance: both time headway and time-to-collision are viewed as indicators of potential collisions, and social forces are active if time headway or time-to-collision reaches thresholds. A parameter is used to represent how the degree of occupants' competitiveness affects their collision avoidance. The modified model is validated by both lab experiments and real emergency evacuation. First, the relation between simulated flow and door width in non-competitive situation is used for validation. In the simulation, 94 occupants, initially distributed in a 9 m - by - 4 m area, evacuate from a door. The simulated flow rates through doors of width ranging from 0.6 m to 1.2 m are consistent with the experimental data. Second, effects of competitiveness are studied. Simulation results show that whether competitiveness speeds up or slow down the evacuation through a door is affected by the initial number of occupants, door width, and other occupants outside the door. Finally, simulation results in competitive situation are consistent with data from a real-life emergency evacuation. The data used is extracted from a video recording occupants evacuating from an airport through a security gate in an earthquake. Simulation results are consistent with the real-life data in both the total evacuation time and the time when congestion occurred.

Keywords: Building evacuation, Social force model, Collision avoidance, Competitiveness

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1. Introduction

Modeling building evacuation during fire emergencies is an important issue. Occupants behave differently between normal situations and emergencies. For example, occupants in normal situations tend to keep certain distance to others/obstructions. However, in emergencies, such tendency may diminish [6], so body compression and congestion occur more easily than normal. It is noted that in high-density situation, occupants of low competitiveness still try to keep distance to others, although their desire to maintain personal space may not be achieved. Many evacuation models have been developed, e.g., network-flow models [2], fluid dynamics models [8], velocity models (first-order models, compared with second-order models like social force models) [24], cellular automata models [13], social force models [5–7], etc. One of the well-regarded models is the social force model developed by Helbing et al. [7]. The model simulates occupants as Newtonian-like particles driven by desired force, social force, and physical force [22]. For the desired force, a concept of desired velocity is introduced to represent the velocity an occupant wants to achieve. The desired force is caused by the difference between an occupant's desired and actual velocities, and its effect is to reduce such difference. The social force is a repulsive force, indicating that occupants tend to keep distance to others/obstructions. The physical forces are caused by body compression. The social force model reproduces many collective phenomena of crowds. Many modifications and extensions have been made [4, 10, 11, 16, 19, 20, 22, 26]. To reduce unrealistic collision avoidance behavior and/or oscillations of collisions in the model, predictive models were developed [11, 20, 26]. The social force exerted on an occupant is modified based on the time when the distance to others is minimum in [26], and the time-to-collision (TTC) in [11]. The TTC is the time before occupants collide if they maintain their current velocity. Desired speed is modified for occupants to keep the time headway with others/obstacles in [20]. Pedestrians' movements in natural environments [10, 26] or lab experiments [19] are extracted from videos, and models are calibrated or modified accordingly. Yet there are still limitations of the models.

First, occupants in the models avoid collisions under the action of distance-dependent social repulsive forces, which may lead to unrealistic simulation results. One typical example is that when occupants get through a narrow door, much smaller simulated flow than experimental data are reported, e.g., zero flow rate is reported if the door width is less than 0.7 m [14, 16]. Second, the degree of occupants' competitiveness is not considered. In emergencies, the increase of occupants' competitiveness may significantly affect the evacuation time [13]. It is noted that the degree of competitiveness may be affected by many factors, e.g., culture background. In countries like the UK, it is reported that people show low degree of competitiveness during evacuations [30]. However, in countries like China, people may be competitive during evacuations. For example, participants complete for elevators during building evacuation experiments [31]. In the social force models, occupants will push others when congested to adapt their actual velocities to desired velocities, i.e., they are all competitive in the models [22]. Finally, current evacuation models, including social force models, are validated mainly by experiments and/or drills [13, 14, 17, 20, 22], in which people may behave differently from real emergencies. Validating models using real-life emergency data is rare [29].

The contribution of this paper is summarized as follows.

First, a new predictive avoidance based on experimental analyses on occupants' movements [9] is used. The time headway and TTC are both considered. Social forces are added if the time headway or TTC is smaller than specified thresholds. With this simple modification, simulated flow rates through doors of different width in non-competitive situations are consistent with the experimental data from the literature [15]. The modified model also has fewer parameters than the original model.

Second, the degree of occupants' competitiveness is considered in the modified model. Occupants' movements in two extreme situations, i.e., non-competitive and fully competitive situations are first analyzed. In non-competitive situations, occupants keep certain distance to others/obstructions to avoid possible collisions. In fully competitive situations, occupants are not affected by social repulsive forces, i.e., they will push others to adapt their actual velocities to desired velocities. Between these two extreme situations, a continuous parameter is introduced to capture the degree of competitiveness. Two scenes are studied by simulation.

The first scene simulates occupants evacuating from a room through a door. High competitiveness is seen to be beneficial to evacuation flow through wide doors, but harmful for evacuation through narrow doors. This effect is consistent with observations and experimental data in the literature [6, 21]. Simulation results of the modified model also show that the shape of the crowd in the simulation at bottleneck changes with competitiveness values: in low competitive situations, people tend to wait in line; while in high competitive situations, people tend to form an arc at a bottleneck.

In building evacuation, occupants often use stairs to evacuate, so there are many occupants in the staircase during evacuation. Occupants entering the staircase (or landing) may merge with others already on the staircase, and congestion may occur at the bottleneck from the floor to the staircase (or landing). It is important to study the flow through doors from each floor to staircase considering merging with other occupants on the staircase. In the second scene, effects of competitiveness on the flow considering merging are studied by simulation. Due to effects of other occupants in the staircase, the flow is seen to be smaller than the first scene, but the trend that high competitiveness is beneficial to evacuation flow through wide doors, but harmful for evacuation through narrow doors, is similar.

Finally, data extracted from a video of a real-life emergency evacuation through a security gate [25] are used to partially validate the modified model. Evacuees in the video were in danger and show high competitiveness. Simulation results agree with the real-life emergency data on both total evacuation time and occurrence of observed congestions. It should be noted that only one real-life emergency case is used here for validation, because such data are difficult to obtain. More data sets are needed for validation in the future.

2. Literature Review

Two major methods have been used to study pedestrian dynamics in building evacuation, i.e., experiment/drill, and modeling.

Experiments on occupants reveal macroscopic and microscopic characteristics of crowds and individuals. Interactions among individuals lead to self-organized behaviors and have become key issues to understand pedestrian dynamics [19]. Many experiments and analyses were conducted on such interactions of individuals, e.g., direction change versus distance to others [18], time headway of pedestrian streams [9], etc. Noticeably, the time headway is found approximately constant after analyzing different data sets of pedestrian streams in normal situations [9]. It is recently found that TTC also plays an important role in pedestrian dynamics [12]: a power-law relationship is found between interaction energy and TTC by analyzing pedestrian dataset.

To study occupants' behavior during evacuation, interviews and videos from real-life emergencies have also been analyzed [3, 25, 27]. It was found that occupants behave differently in emergencies from normal situations. For example, they move significantly faster than normal after they are aware of danger, and occupants' tendency to keep certain distance to others diminish, and they may even start pushing [6]. This may lead to congestion, which has significant impact upon the evacuation time, if the convergence of the population overloads the component being used [13]. It is important to know when congestion occurs during evacuation.

Parallel to experiment/drill, many evacuation models have been developed, including network-flow models [2], fluid dynamics models [8], velocity models [24], cellular automata models [13], social force models [4–7, 22], etc. One well-regarded model is the social force model developed by Helbing et al. [7]. Each occupant in the model is described as a Newtonian-like particle driven by physical and non-physical forces. The model can describe occupants' desire to move and tendency to keep certain distance to others. Many collective phenomena of crowd evacuation, including lane formation, and the faster-is-slower effect (high motivation may slow down the evacuation), can be reproduced by the model. Despite the advantages above, the original model has several limitations. For example, unnatural oscillations of collisions are found in the simulation; the model parameters were not calibrated by experimental data; the degree of occupants' competitiveness is not captured. As discussed in Sect. 1, many modifications have been made on the social force model [4, 10, 11, 16, 19, 20, 22, 26]. By revising terms of social forces, unrealistic collision avoidance behavior and/or oscillations of collisions is reduced [4, 11, 20, 26]. Occupants' movements in natural environments [10, 26] or lab experiments [19] are extracted from videos, and models are calibrated or modified accordingly [10, 19, 26]. A self-stopping mechanism was introduced to consider occupants' movements in normal situations [22]. However, the degree of competitiveness is not mentioned, and the effect of competitiveness on evacuation is not discussed in detail.

Validation is of fundamental importance for evacuation models. Recent developed evacuation models are often validated by experiments/drills [13, 14, 17, 20, 22]. The flow through doors of different width, and the relation between cumulative number of evacuees and time are both well-accepted benchmarks for pedestrian (evacuation) models. To the authors' knowledge, data from real-life emergencies are rarely used for validation [29]. The reason may be that relevant data are difficult to obtain.

3. Modeling

This section briefly reviews the original social force model in Sect. 3.1, and provides a modified model in Sect. 3.2. A new predictive collision avoidance is used in the modified model based on experimental analyses on occupants' movements. The degree of occupants' competitiveness is also considered.

3.1. Original Social Force Model

As mentioned in Sect. 2, in the original social force model by Helbing et al. [5–7], each occupant i is a Newtonian-like particle driven by three kinds of forces: the desired force, $\boldsymbol{F}_{Di}$, the social force, $\boldsymbol{F}_{Si}$, and the physical force, $\boldsymbol{F}_{Gi}$, i.e.,

$$m_i \frac{d\boldsymbol{v}_i}{dt} = \boldsymbol{F}_{Di} + \boldsymbol{F}_{Si} + \boldsymbol{F}_{Gi}, \tag{1}$$

where m_i and $\boldsymbol{v}_i$ are occupant i's mass and velocity, respectively. The desired force, $\boldsymbol{F}_{Di}$, representing the inner desire of occupant i to move to his targets, is caused by the difference between occupant i's actually velocity, $\boldsymbol{v}_i$, and his desired velocity, $\boldsymbol{v}_i^d$. Occupant i wants to accelerate/decelerate to achieve his desired velocity within a relaxation time, τ, i.e.,

$$\boldsymbol{F}_{Di} = m_i \frac{\boldsymbol{v}_i^d - \boldsymbol{v}_i}{\tau}. \tag{2}$$

The social force, $\boldsymbol{F}_{Si}$, indicates occupant i's tendency to keep certain distance to others/obstructions. It is a sum of distance-dependent repulsive forces exerted by others/obstructions, e.g., the social force exerted by occupant j is

$$\boldsymbol{F}_{Sij} = Ae^{\varepsilon_{ij}/B}\left[\lambda + (1-\lambda)\frac{1+\cos\theta_{ij}}{2}\right]\boldsymbol{n}_{ij}. \tag{3}$$

Here A and B are constants that determine the strength and range of the social force. The direction of the social force is denoted by $\boldsymbol{n}_{ij}$, a unit vector pointing from occupant j to i, and

$$\varepsilon_{ij} = R_i + R_j - d_{ij}, \tag{4}$$

where R_i and R_j are the radii of occupants i and j, respectively; and d_{ij} is the distance between occupants i and j. The parameter λ shows the anisotropic character of pedestrian interaction, i.e., other occupants in front of occupant i have a larger influence on occupant i than those behind. The angle θ_{ij} denotes the angle between the direction of $\boldsymbol{v}_i$ and $-\boldsymbol{n}_{ij}$. The forms of the social forces by obstructions are similar.

The physical force, $\boldsymbol{F}_{Gi}$, is activated when occupant i touches others or obstructions. It is also a sum of physical forces exerted by others/obstructions, e.g., the physical force on occupant i caused by occupant j is

$$\boldsymbol{F}_{Gij} = kg(\varepsilon_{ij})\boldsymbol{n}_{ij} + \kappa g(\varepsilon_{ij})(-\boldsymbol{v}_{ij} \cdot \boldsymbol{t}_{ij})\boldsymbol{t}_{ij}. \tag{5}$$

This physical force includes a repulsive spring force as the first term, and a friction force caused by the relative tangential motion as the second term. In (5), k and κ are constants determining the strength of the spring force and the friction force; $\boldsymbol{v}_{ij} = \boldsymbol{v}_i - \boldsymbol{v}_j$, is the relative velocity between occupants i and j; and $\boldsymbol{t}_{ij}$ is a unit vector perpendicular to $\boldsymbol{n}_{ij}$, indicating the direction of the friction force. The function $g(\varepsilon_{ij})$ is the larger value of ε_{ij} and 0, indicating that the physical force is activated only if occupants i and j touch each other. The physical forces by obstructions are similar.

3.2. Modified Model

This subsection provides a modified model based on experimental study on how occupants react with others/obstructions. The degree of occupants' competitiveness is also considered.

Analysis on pedestrian streams in normal situations shows that the time headway is approximately constant (denoted as H^T in this paper) across different data sets [9], indicating that occupants may adjust their motions to avoid possible collisions based on the time headway. The TTC is another important indicator of collisions. As stated in Sect. 1, the TTC is the time before occupants collide if they maintain their current velocity. It is found that TTC plays an important role in pedestrian dynamics [12]. The TTC is not mentioned as an important factor in [9] because in the data sets analyzed, the difference between occupants' speeds is often so small that the TTC is too large to be considered. The TTC has large impact on occupants' movements if the velocity difference from others/obstructions is large, e.g., when occupants with a high speed reach congested area.

The modified model introduces a new and simple avoidance mechanism based on the time headway and TTC.

If the smallest time headway from occupant i to any others/obstructions is no larger than H^T, occupant i modifies his motion to avoid potential collisions. The modified model uses a social force to replace the distance-dependent social force in (3), i.e.,

$$\boldsymbol{F}_{Si}^{H} = -m_i \frac{\boldsymbol{v}_i^d}{\tau}. \tag{6}$$

The social force is selected so that the superposition of the desired force, $m_i \frac{\boldsymbol{v}_i^d - \boldsymbol{v}_i}{\tau}$ and $\boldsymbol{F}_{Si}^H$ is $-m_i \frac{\boldsymbol{v}_i}{\tau}$. The effect of this superposition is equal to that of a desired force with a desired velocity of 0, representing occupants' desired to slow down and keep the time headway larger than the threshold, H^T. It is noted that occupants' moving direction is not affected by the superposition of the desired force, and $\boldsymbol{F}_{Si}^H$.

Similarly, if the TTC from occupant i to others/obstructions, e.g., occupant j, is smaller than a threshold denoted by C^T, an imminent collision is detected. Occupants need to slow down and/or adjust moving direction to avoid it. An extra social force, $\boldsymbol{F}_{Sij}^C$, is added to avoid the imminent collision. This social force shows occupant i's desire to make the relative speed zero in the normal direction between the predicted positions of himself and occupant j when the collision occurs. The direction of $\boldsymbol{F}_{Sij}^C$ is denoted by $\boldsymbol{d}_{i'j'}$, the vector from occupant j' to i' as shown in Figure 1. Here the primes on the indices i and j indicate the future positions of occupants i and j when they collide. The social force, $\boldsymbol{F}_{Sij}^C$, is then

$$\boldsymbol{F}_{Sij}^C = -m_i \frac{\boldsymbol{v}_{ij} \cdot \boldsymbol{n}_{i'j'}}{\tau} \boldsymbol{n}_{i'j'}, \tag{7}$$

where $\boldsymbol{n}_{i'j'}$ is the unit vector in the direction of $\boldsymbol{d}_{i'j'}$. The calculation of the time headway and TTC is shown below. As shown in Figure 2, $\boldsymbol{d}_{ij}$ is the vector from occupant j to i; and θ_{ij} is the angle between $\boldsymbol{v}_i$ and $-\boldsymbol{d}_{ij}$, as mentioned in Sect. 3.1. The time headway is meaningful only if occupant i will collide with current position of occupant j if he maintains his velocity, i.e., $|\boldsymbol{d}_{ij}| \sin\theta_{ij} \leq R_i + R_j$, and $\boldsymbol{d}_{ij} \cdot \boldsymbol{v}_i < 0$. The time headway, H_{ij}, is then

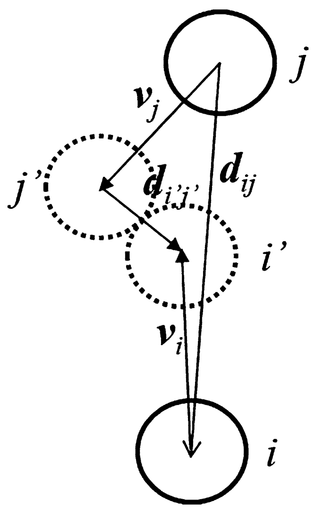


Figure 1. Calculation of the TTC.

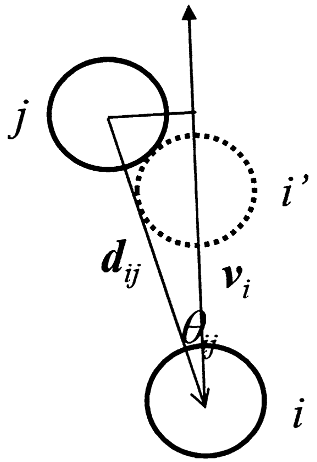


Figure 2. Calculation of the time headway.

$$H_{ij} = \max\left\{0, \frac{|\boldsymbol{d}_{ij}|\cos\theta_{ij} - \sqrt{(R_i + R_j)^2 - (|\boldsymbol{d}_{ij}|\sin\theta_{ij})^2}}{|\boldsymbol{v}_i|}\right\} \quad (8)$$

The TTC between occupants i and j, is the time before colliding if occupants i and j maintain their current velocities. As in Figure 1, through the difference of the definition between the time headway and the TTC, The only thing needed to calculate the TTC is to replace $\boldsymbol{v}_i$ in (8) with $\boldsymbol{v}_{ij}$. Similar to the time headway, the TTC is meaningful only if occupant i will collide with occupant j if they both maintain their current velocities, i.e., $|\boldsymbol{d}_{ij}|\sin\psi_{ij} \leq R_i + R_j$, and $\boldsymbol{d}_{ij} \cdot \boldsymbol{v}_{ij} < 0$. Here ψ_{ij} is denoted as the angle between $\boldsymbol{v}_{ij}$ and $-\boldsymbol{d}_{ij}$. The TTC from occupant i to j, denoted by C_{ij}, is then

$$C_{ij} = \max\left\{0, \frac{|\boldsymbol{d}_{ij}|\cos\psi_{ij} - \sqrt{(R_i + R_j)^2 - (|\boldsymbol{d}_{ij}|\sin\psi_{ij})^2}}{|\boldsymbol{v}_{ij}|}\right\} \quad (9)$$

It is noted that since the social forces jump when the time headway or TTC reaches thresholds, they are discontinuous in the modified model, compared with the continuous social forces as (3) in the original model. The desired force and physical force remain the same with the original model as in (2) and (5).

The Eqs. (6) and (7) apply in non-competitive situations, in which occupants are not pushy, and they try to keep certain distance to others. To capture the degree of occupants' competitiveness, two extreme situations, i.e., non-competitive and fully competitive situations are first analyzed. The non-competitive situations case has been shown as in (6) and (7). In fully competitive situations, occupants push their way to adapt their actual velocities to desired velocities, they are assumed not affected by possible collisions with others, i.e., they are not affected by any repulsive social forces. Between two extreme situations, a continuous parameter $\alpha \in [0,1]$ is introduced to reflect the degree of competitiveness. Equations (6) and (7) are then replaced by

$$\boldsymbol{F}_{Si}^{H} = -m_i(1-\alpha)\frac{\boldsymbol{v}_i^d}{\tau}, \tag{10}$$

$$\boldsymbol{F}_{Sij}^{C} = -m_i(1-\alpha)\frac{\boldsymbol{v}_{ij}\cdot\boldsymbol{n}_{i'j'}}{\tau}\boldsymbol{n}_{i'j'}. \tag{11}$$

Here the parameter $\alpha = 0$, and $\alpha = 1$ indicate that occupants are non-competitive and fully competitive, respectively. The value of α may be affected by many factors, e.g., culture background, knowledge, experience, social relationships, density of occupants, etc. This paper only discusses effects of competitiveness and assumes that the competitiveness is constant during evacuation. How to determine or estimate α will be future work.

To summarize, the modified model revises the original social force based on experimental analyses on occupants' movements. Occupants predict and avoid collisions based on the time headway and TTC. The degree of the competitiveness is also considered so that the model can address occupants with different competitiveness, comparing with the original model. Social forces in the original model, as shown in (3), are replaced by forces in (10) and (11). It should be mentioned that in this modified model, the parameters A, B, and λ in the original social force model are no longer needed. The modified model has few parameters than the original model.

4. Simulation Results and Validation

The modified model is validated by three examples in this section. The first example is in non-competitive situations. The modified model is validated by experimental data on occupant flow through doors of different width. The second example investigates effects of occupants' competitiveness on evacuation in the modified model, and compares them with the literature. The last example employs data from a real-life emergency, in which occupants are of high competitiveness, to partially validate the modified model. In the simulation, adaptive time step is used, similar to [5]. The default time step of the simulation is 0.002 s, and it updates during the simulation to avoid too large velocity change in one time step. At every time step, occupants are updated synchronously. Occupants who are closest to exits are assumed fully competitive, i.e., they are driven only by desired and physical forces, but not affected by social forces.

Example 1 The relation between flow rates through doors of different width are compared between simulation results of the modified model and experimental data in this example. The experimental data are from a widely-cited paper by Kretz et al. [15]. In the experiments, 94 non-competitive occupants are initially in a 9 m - by - 4 m area with a door of 0.4 m depth, as shown in Figure 3. The relation between the flow rate and the door width in non-competitive situations is investigated. The value of the door width in the experiment is varied from 0.4 m to 1.6 m. The authors in [15] stated that the flow saturates when the door width reaches 1.2 m because *the participants did not leave the area behind the bottleneck fast enough,* so this paper uses the experimental data with the door up to 1.2 m width for validation.

The geometrical layout and the initial number of occupants may affect evacuation flow. To reduce such effects, the geometrical layout and the number of occupants in the simulation are the same with the experimental settings by Kretz et al. [15]. Every occupant in the simulation is estimated as a circular disk with a radius of 0.21 m. The parameter k / m and κ/m are $1500s^{-2}$ and $3000m^{-1}s^{-1}$, respectively, and the relaxation time τ is 0.5 s, the same to [5]; the threshold H^T is 0.5 s, according to [9]; and C^T is equal to H^T. Desired speed is normally distributed with a mean value of 1.34 m/s and a standard deviation of 0.37 m/s, according to [28].

Since occupants in the experiments are non-competitive, the competitiveness value in the simulation is 0. The width of the door is varied to investigate its relation to the flow rate. The initial positions, and the desired speeds of occupants are stochastic in simulations. For each value of the door width, the simulation is repeated for 30 times, large enough so that the samples can be considered normally distributed in a statistical manner [1]. The statistical results of the simulation is shown in Table 1. Confidence intervals of the average simulated flow rates are then estimated. Results of the modified model are compared with the experimental data by Kretz et al. [15] and Seyfried et al. [23], the simulation results of the social force model by Helbing et al. [5], and of FDS + Evac [14]. The same parameters set with [5] is used for the social force

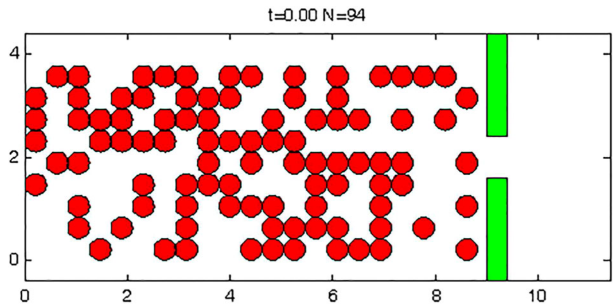


Figure 3. Geometrical layout and initial number of occupants in the experiment conducted by Kretz et al. [15] and in the simulation of the modified model of example 1. *Green rectangles* indicate walls, and *red circles* indicate occupants, who initially are randomly distributed in the $9m \times 4m$ area before the evacuation. Here *t* is the time; and *N* is the number of occupants who are not yet evacuated (Color figure online).

Table 1
Mean Value and Standard Deviation (SD) of Simulated Flow for Different Door Width, Compared with Experimental Data by Kretz et al. [15] and Seyfried et al. [23]

Door width (m)	Simulation: mean (SD) person/s (person/s)	Kretz: mean person/s	Seyfried: mean person/s
0.6	1.06 (0.04)	1.12	
0.7	1.21 (0.03)	1.23	
0.8	1.35 (0.02)	1.42	1.29
0.9	1.59 (0.06)	1.57	1.67
1.0	1.89 (0.06)	1.84	1.90
1.1	2.07 (0.08)		2.12
1.2	2.13 (0.11)	2.13	2.36
1.3	2.23 (0.08)		
1.4	2.40 (0.11)		

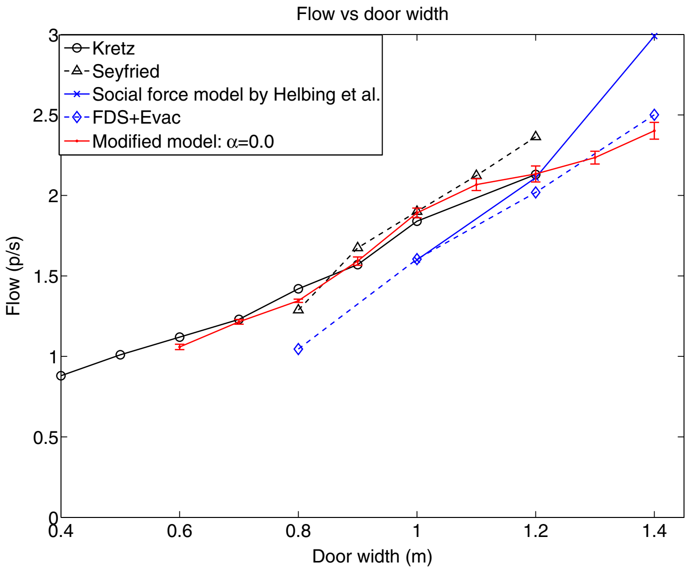


Figure 4. **The relation between the flow rate and door width. *Black circles* and *triangles* indicate experimental data in [15] and [23], respectively. *Blue crosses* and *diamonds* indicate simulation results of the social force model by Helbing et al. [5], and FDS + Evac [14], respectively. *Red bars* indicate 99% confidence intervals of the average flow rates of the modified model (Color figure online).**

model by Helbing et al.; and the default parameter set labeled Adults 2 in [14] is used for FDS + Evac. Results are shown in Figure 4. It can be seen that the flows of the social force model by Helbing et al, and FDS + Evac are much smaller than the experimental data for doors no wider than 1 m. With the modified model, flow rates through doors no narrower than 0.6 m are consistent with experimental data [15, 23], compared with the simulation results of [5, 14].

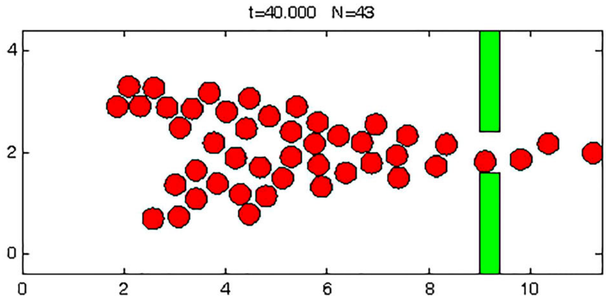
Example 2 This example investigates effects of occupants' competitiveness on occupants in the simulation. Two scenes are studied. The first scene simulates occupants evacuating from a room through a door. The geometrical layout are the same to those in Example 1. The competitiveness values considered are $\alpha = 0$, 0.2, and 0.5. Two different initial number of occupants is simulated, i.e., $N = 94$, and $N = 47$. Simulation results show that occupants behave differently under different degree of competitiveness. Screenshots of typical simulation results are shown in Figure 5, in which the initial number of occupants is 94, and the door width is 0.8 m. It can be seen from Figure 5 that occupants of low competitiveness tend to form lines. It is similar to the experiment in [23], in which occupants are in non-competitive situations. The reason is that the social forces are large, and occupants tend to keep certain distance to others. Occupants of high competitiveness tend to form arcs at the bottleneck, because the social forces are small, and their tendency to keep certain distance to others diminishes. The arch shape is similar to the figure in [6]. The trial of the occupants are shown in Figure 6.

The relation between flow rate and door width for different competitiveness values at different initial number (or density) of occupants is shown in Figure 7. Figure 7a, b show results when the initial number of occupants is 94, and 47, respectively. From simulation results, competition is seen to be beneficial to evacuation flow for wide exits but harmful for narrow exits. This trend is the same to observations and experiments from the literature [6, 21]. One possible reason is as follows. The competitiveness has two opposite effects on evacuation flow: Effect 1 is that occupants in competition keep less distance than normal, indicating a higher efficiency of utilizing space, which is beneficial to evacuation flow; and Effect 2 is that occupants in competition are pushier than normal, more easily leading to congestion. In this example, for a wide door, Effect 1 dominates; for a narrow door, Effect 2 is more significant.

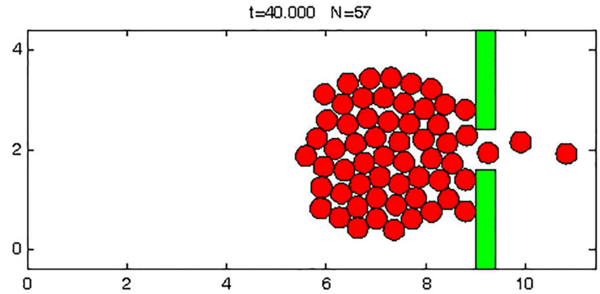
For Figure 7a ($N = 94$), the competitiveness begins to speed up evacuation flow for the door wider than about 1.6 m; while for Figure 7b ($N = 47$), the critical width is much smaller, i.e., about 1.2 m. The reason is that larger initial number of occupants leads to more significant Effect 2.

It should be mentioned that the flow may saturate at wide doors, e.g., the flow for $\alpha = 0.5$, and doors wider than 2.5 m in Figure 7a, because the number of occupants is limited.

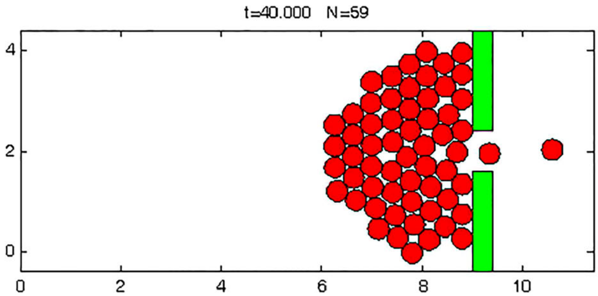
In building evacuation, occupants at each floor often use stairs to evacuate, so there are many occupants in the staircase during evacuation. Occupants entering the staircase (or landing) merge with others already on the staircase. Congestion may occur at the bottleneck from each floor to the staircase (or landing). It is important to study the flow through doors from each floor to staircase considering merging with other occupants on the staircase. The second scene studies effects of competitiveness on the flow considering merging. As shown in Figure 8, the left area represents the floor; and the right area represents the landing. The door opens directly onto the landing. It should be noted that the geometrical layout of the floor and the landing is simplified. On the top and at the bot-



(a) $\alpha = 0$



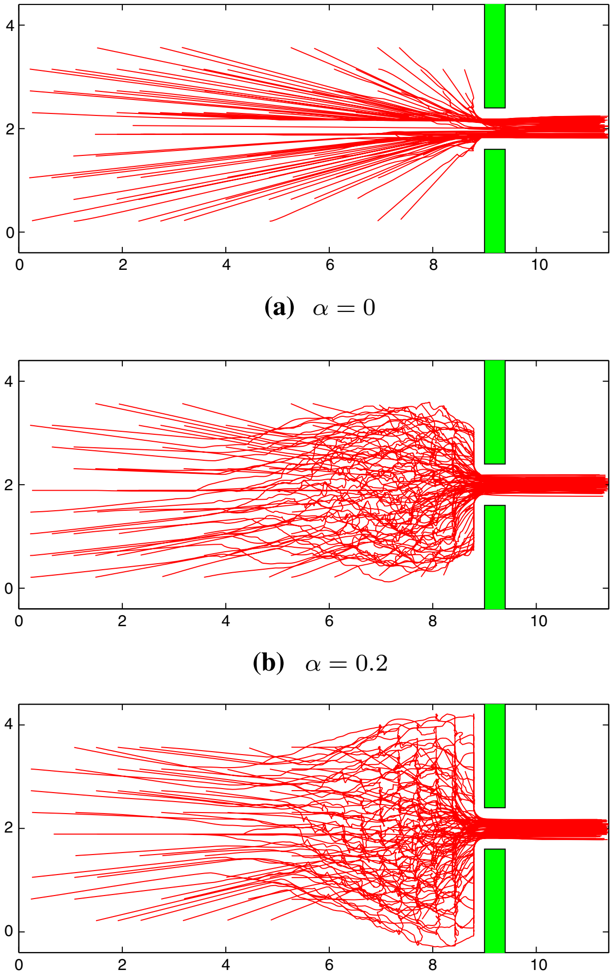
(b) $\alpha = 0.2$



(c) $\alpha = 0.5$

Figure 5. Screenshots of the simulation at the time $t = 40.0s$ with different degree of competitiveness, a $\alpha = 0.0$, b $\alpha = 0.2$, and c $\alpha = 0.5$. The initial number of occupants in the simulation is 94, and the door width is 0.8 m. *N* is the number of occupants who are not yet evacuated.

tom of the figure, there is staircase connecting the landing, although the staircase is not shown in the figure. Occupants evacuate through the door to the landing. The moving directions of occupants on the floor are to the landing through the door; and the moving directions of occupants on the landing and staircase are to the top of the figure. In the simulation, the initial number of occupants on the floor is 47. The initial density of occu-



(a) $\alpha = 0$

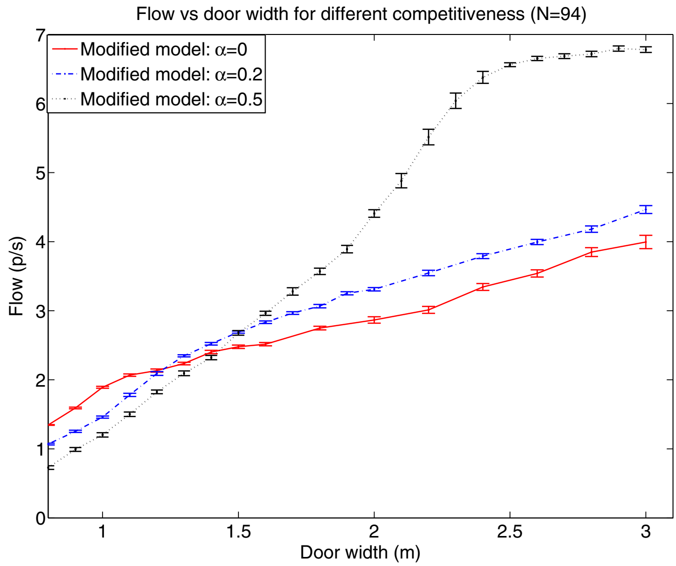
(b) $\alpha = 0.2$

(c) $\alpha = 0.5$

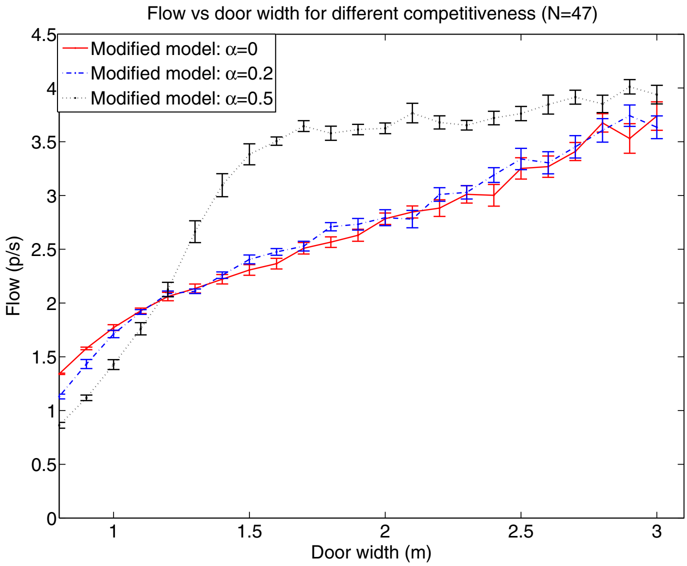
Figure 6. Trials of occupants with different degree of competitiveness, a $\alpha = 0.0$, b $\alpha = 0.2$, and c $\alpha = 0.5$. The initial number of occupants in the simulation is 94.

pants on the landing and staircase is 4 person/m^2. Occupants evacuating through the door merge with others on the landing in the simulation. The desired speeds of all occupants are all normally distributed with a mean value of 1.34 m/s and a standard deviation of 0.37 m/s, the same as in Example 1. For simplicity, competitiveness value of the occupants on the landing and staircase is fixed to be zero, and only competitiveness value of occupants on the floor is varied.

The relation between flow rate through the door and door width for different competitiveness values is shown in Figure 9. Compared with the first scene, the flow rate is much smaller due to effects of occupants on the landing. Similar with



(a) $N = 94$



(b) $N = 47$

Figure 7. Effects of competitiveness on evacuation flow. The initial number of occupants in the simulation is a $N = 94$, and b $N = 47$. *Red, blue,* and *black bars* show the 99% confidence intervals of flow rates for different door width under situations that α equals 0, 0.2, and 0.5, respectively (Color figure online).

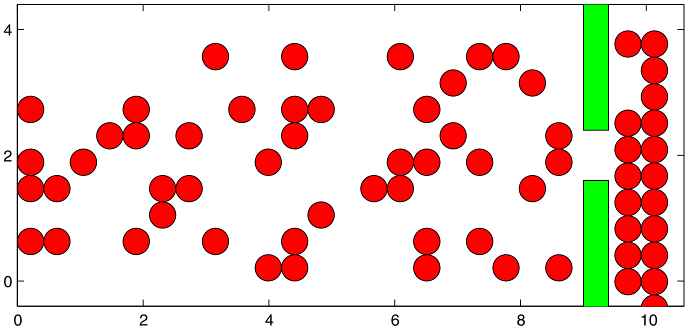


Figure 8. Geometrical layout and initial number of occupants in scene 2 of example 2. *Green rectangles* indicate walls, and *red circles* on the left of the figure indicate occupants, who initially are randomly distributed in the $9m \times 4m$ area. *Red circles* on the right of the figure indicate occupants, who initially are on the landing with the density 4 person/m^2 (Color figure online).

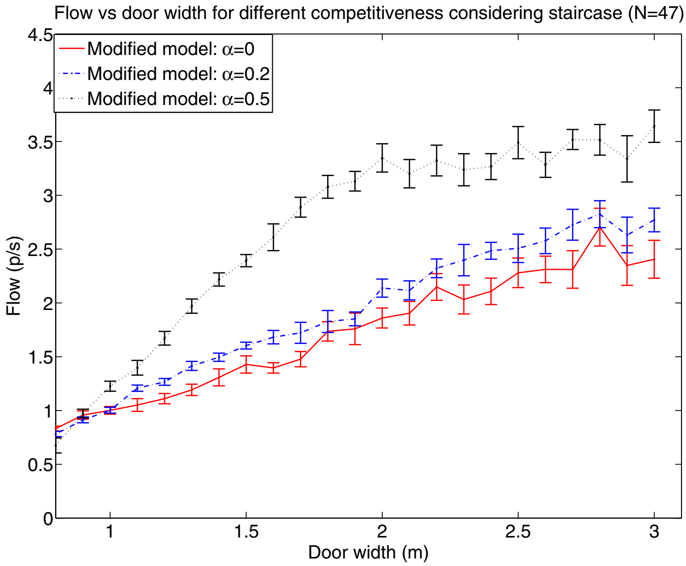


Figure 9. The relation between the flow rate and door width for scene 2 of example 2.

the first scene, high competitiveness is seen to be more beneficial to the flow through wide doors, but harmful to the flow through narrow door, but the critical width is smaller than the first scene (0.9 m vs. 1.2 m). One possible reason is that occupants evacuating through the door need to avoid collisions with others on the landing. Occupants of low competitiveness tend to wait for others who are outside on the landing, decreasing the flow through the door. The smaller critical width is due to this effect of others on the landing.

Figure 10. One frame of the video recording of the earthquake scene at the Chengdu Shuangliu International Airport. The video is available on the internet at http://v.youku.com/v_show/idX2NTY3ODg=.html.

Example 3 High-quality evacuation data from building fire evacuation are difficult to obtain, so this paper uses data extracted in an earthquake for validation. The real-life emergency data used are from Wenchuan 8.0-magnitute earthquake, which struck southwest China and caused major casualties on May 12, 2008. After the earthquake, some video recordings of the evacuation were available on the internet and have been analyzed [25], but many of them are difficult to be used to validate evacuation models, because of low quality of the video, or lack of knowledge of the environment (e.g., building layout). Fortunately, a video of the evacuation through a security gate to the outside at the Shuangliu Airport, Sichuan, China, can be used for validation. A snapshot of the evacuation is shown in Figure 10. The earthquake is life threatening, and occupants are highly motivated. In the video, occupants in the airport evacuated through a door, and this is similar to occupants evacuating through doors in building fire emergency. It is reasonable to use such data to validate building evacuation model. In the video, occupants came to the coverage area of the video camera from roughly the same direction and ran through a security gate, which is 0.7 m wide and 0.5 m deep. Congestion was observed at the gate during the evacuation. In the simulation, the geometrical layout is estimated as a 6 m - by- 2 m area, as shown in Figure 11. Occupants in the simulation are generated at a random place on the red line in Figure 11 when they appear in the video. After generated, evacuees evacuate to the exit with initial speeds and desired speeds of both 3 m/s, indicating the high motivation during evacuation. Evacuees' competitiveness is set 0.5, considering the life-threatening earthquake.

Simulation results of the modified model are compared with real-life emergency data when flows are decreased due to congestion (from 25 s to 55 s in the original video). Data extracted from the evacuation, and the simulation results by the

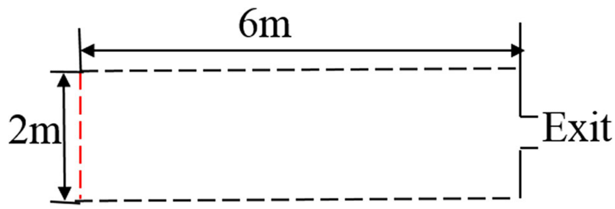


Figure 11. Geometrical layout of the simulation for Example 3.

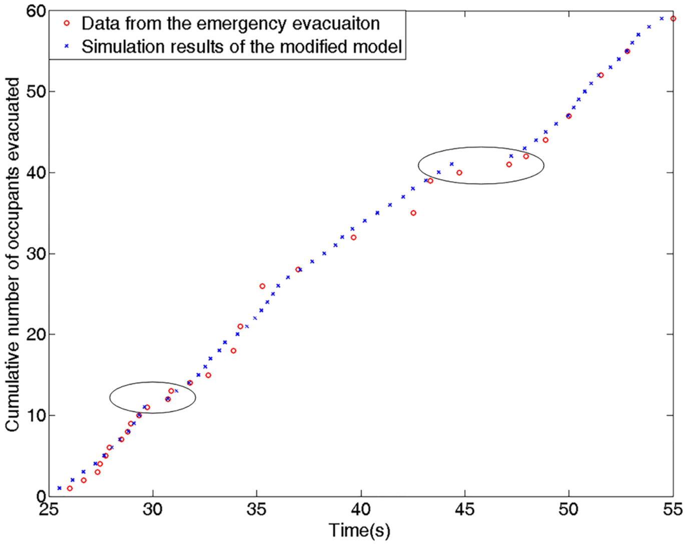


Figure 12. The relation between the cumulative number of evacuees and time during evacuation through a security gate at Shuangliu Airport, China on May 12, 2008. *Red dots* and *blue crosses* indicate the data extracted from the video, and simulated by the modified model, respectively. *Black circles* mark the time when congestion happened (Color figure online).

modified model are shown by red dots and blue crosses, respectively in Figure 12. The time when congestion occurred is marked by black circles. Simulation results are consistent with the real-life data in both the total evacuation time and time when congestion occurred.

Current evacuation model is rarely validated by real-life emergency data [29]. Since the available data are difficult to obtain and are not repeatable, the model is only partially validated by data from one real-life emergency. More data sets are needed for validation in the future.

5. Conclusion

Based on the experimental analyses on occupants' movements, this paper modifies the social force model to fix some imitations of the model. In the modified model, occupants predict collisions and adjust their motions based on the time headway and TTC. Competitiveness is also considered in the collision avoidance. The modified model is validated by both experiment and a real-life emergency evacuation. Compared with the original model, the modified model reproduces the experimental evacuation flow under door width between 0.6 m and 1.2 m when people are non-competitive. Effects of the competitiveness on occupants are studied in the simulation, and some simulation results are consistent with reported in the literature. A real-life emergency evacuation, during which occupants are highly competitive, is employed to partially validate the modified model. Future efforts may include quantitative validating the effects of competitiveness on evacuation, and employing more real-life emergency data set to validate the model.

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