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Simulation and analysis of individual trampling risk during escalator transfers

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HIGHLIGHTS

- A five-stage trampling model for individual pedestrians was proposed.
- Several scenarios were simulated to study the impacts of 4 key factors.
- The pedestrian traffic is the main factor that influences the trampling risks.
- A decrease in the picking-up duration decreases the trampling risks.
- The trampling risk is higher than the average risk if the pedestrian velocity is low.

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ABSTRACT

A type of trampling process that is caused by picking-up activities during escalator transfers was studied in this paper. A five-stage trampling model for individual pedestrians was proposed, and the social force model was modified considering the transfer features. Several scenarios were simulated to study the impacts of 4 factors, namely, pedestrian traffic, escalator velocity, picking-up duration and pedestrian velocity, on trampling probability. The results show that pedestrian traffic strongly affects the trampling probability, with a positive correlation throughout all scenarios; the picking-up duration affects the trampling probability, with a negative correlation throughout all scenarios; lower pedestrian velocities can result in higher trampling probabilities if the picking-up duration is short; and the escalator velocity may also affect the trampling probability, but there are no general rules for all scenarios. Thus, the impacts of these 4 factors can be queued in descending order as follows: pedestrian traffic > picking-up duration > pedestrian velocity > escalator velocity. Countermeasures can be employed according to the results to reduce trampling risks.

1. Introduction

Escalators are common in large buildings, where they facilitate the transfer of pedestrians from one floor to another. Escalators are composed of several individual segments, each of which links two floors. A typical transfer between escalator

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segments proceeds as follows: "escalator" → "transfer aisle" → "escalator". Chaotic transfers can cause trampling accidents. In China, there were 33 accidents during escalator transfers in 2007, 38 accidents in 2008, and 44 accidents in 2010.[1] A recent trampling accident occurred on April 18, 2013, when a group of students were taking an escalator during their visit at a children's playground in Shenzhen, Guangdong. The trigger was that a student stopped suddenly to bend down to tie his shoes after his stepping down from the escalator. Ten students were injured in the accident.[2] Therefore, it is important to study trampling risks during escalator transfers for the safety of pedestrians and for the normal operation of large buildings.

2. Related studies

Previous studies on trampling accidents can be generally classified into 3 types:

(1) Empirical studies. In these studies, researchers analyzed the data recorded in real trampling accidents and attempted to find the triggers as well as the patterns of their evolution. Krausz and Bauckhage [1] analyzed the video data recorded in a trampling accident at Loveparade in Germany. They proposed an automatic, video-based method that was based on histograms of the flow vector magnitude and direction. Motion patterns, such as congestion and crowd turbulence, could be detected automatically to allow for early warnings. Helbing and Mukerji [2] analyzed videos that were recorded in the LoveParade stampede accidents from a systemic perspective. Geo-coded videos and a detailed timeline of the crowd's motions were employed to identify the key factors that caused the accident. The analysts argued that the accident was a systemic failure that included a failure of flow control and a lack of overview from the participants. They also proposed proactive measures that assess the criticality levels of crowd situations to avoid or mitigate such accidents. Wang, Liu, and Zhao [3] analyzed a trampling disaster that occurred at the Mihong Bridge in China. A poor estimation of the tourist population, a dereliction of duties, deficient communication, and a design fault in the bridge were believed to be the key factors that led to the disaster.

(2) Experimental studies. Because of ethical issues and the danger of trampling accidents, non-human organisms have always been employed as a proxy to discover the rules of group behavior in panic situations. Altshuler et al. [4] conducted experiments on Cuban leaf-cutting ants. Their results agreed with symmetry breaking (the ineffective use of exits) by panicked crowds. Shiwakoti et al. [5] performed experiments with panicking ants to study the effect of with and without a partial obstruction near the exit. The "partial obstruction effect" was reproduced. Soria et al. [6] found experimental evidence of the "faster is slower effect" in a system of escaping ants that were stressed with increasing levels of citronella. Lemercier et al. [7] designed an experimental study on human group-following behaviors. A total of 28 participants were employed to observe how humans adapt their motion to follow someone. Based on the results of that experiment, they designed a microscopic model to simulate the emergence of stop-and-go waves at both macroscopic and microscopic levels.

(3) Simulation studies. In simulation studies, trampling processes are simulated and studied in a virtual world by modeling the interactive behaviors among pedestrians. Lee and Hughes [8] proposed a strategy that was based on a continuum theory to minimize the risk of trampling in a very dense crowd. The study demonstrated that effective crowd control can be achieved by adjusting either the size of the crowd or the complexity of the environment, which effectively influences the crowd speed. Yu and Johansson [9] modified the social force model by adding a factor that reflects the strong interactions between pedestrians in extremely crowded areas based on which stop-and-go and crowd turbulence could be reproduced. Kuang et al. [10] proposed an extended optimal velocity model to simulate single-file pedestrian movement at a high density by considering the differences in the interaction forces between pedestrians. Their numerical simulations showed that the model could reproduce the space–time evolution of headway during pedestrian movement.

Among the above 3 approaches, one obstacle for empirical studies is that it is difficult to collect all the data for every trampling accident; the problem posed by experimental studies using non-human organisms is that different species have different sizes, behaviors, and cognitive abilities compared with humans. Thus, a simulation approach was employed in this paper. Moreover, most previous studies focused mainly on panicking crowd assembly. However, some escalator accidents happen in normal conditions (rather than in panic conditions) [11], and the most frequent causes of escalator injury include slips, trips, or falls [12]. Activities that someone stops suddenly to pick up something (see Section 1) or to tie their shoes [11] are typical triggers of some stampede accidents during escalator transfers. Such situations differ from previously studied scenarios. Moreover, the movement of pedestrians in escalator transfers is unique. As shown in Table 1, when transferring in escalators, pedestrians must shift their motion states during a transfer on and off the escalators: they typically stand still and are carried along by the escalator; however, at some point, they must step off the escalator and walk by themselves.

The Helbing social force model [13–17] is regarded as one of the bases for microscopic crowd simulation and has been successfully employed for many applications [18–23]. Rational crowd patterns, such as "faster-is-slower" and "stop-and-go", can be reproduced [18]. Therefore, in this paper, the social force model is employed to model trampling accidents caused

[1] The trample accident in Xi'an and it is urgent to guarantee the safety in escalator transfer activities. Available from: http://news.21csp.com.cn/c34/201303/56641.html (Accessed 2 November 2013).

[2] A trample accident happened in the escalator. Available from: http://news.163.com/13/0418/08/8SNTC9RR00014AED.html (Accessed 2 November 2013).

Table 1
Stages in escalator transfer.

Stages	States			
	Locations	Motion states	Motion controller	Underlying surfaces
Stage 1	At the entrance	Walking	Pedestrians	Horizontal
Stage 2	On an escalator	Standing	Escalator	Slope
Stage 3	In the transfer aisle	Walking	Pedestrians	Horizontal
Stage 4	On another escalator	Standing	Escalator	Slope
Stage 5	At the exit	Walking	Pedestrians	Horizontal

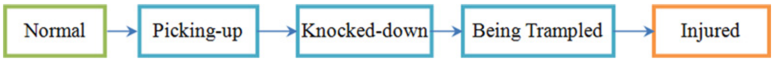


Fig. 1. A five-stage trampling model.

by picking-up activities during escalator transfers and to identify the impacts of key factors on trampling risks. This paper is organized as follows: in Section 3, a five-stage trampling model for individual pedestrians is proposed. In Section 4, a simulated environment for a trampling accident is developed, and a series of scenarios with different parameters based on that environment is studied in Section 5 to test their impact on the trampling probability. In Section 6, conclusions and countermeasures are provided.

3. A trampling model that is caused by picking-up activity

3.1. A five-stage trampling model for individual pedestrians

Here, we propose a five-stage model to describe the state evolution of a pedestrian in a trampling accident caused by picking-up activities. The model divides the behaviors of the pedestrian into 5 states, including normal walking, slowing or stopping to pick up something, being knocked down by someone, being trampled, and being injured. The stages are correspondingly named the normal stage, the picking-up stage, the knocked-down stage, the being-trampled stage and the injured stage (Fig. 1).

The scenario can be described as follows. For a moment, a pedestrian is walking normally to perform escalator transfers (in the normal stage). Suddenly, he stops and bends down to pick up something (moving into the picking-up stage). If there is insufficient time for the trailing pedestrians to dodge him, then the pedestrian will be knocked down onto the ground (into the knocked-down stage) and be trampled for a certain period of time (moving into the being-trampled stage), resulting in injury to the pedestrian (moving into the injured stage). In this process, some of the stages are simple to identify. For example, the picking-up stage can be identified by a sudden reduction in the pedestrian's speed, and the being-trampled stage occurs when the pedestrian is trampled while lying on the ground. However, the other stages are relatively complex and require detailed algorithms for identification.

(1) Algorithm for determining the knocked-down stage.

Let the duration to finish the picking-up activity be t_k. Let the moment when a pedestrian P stops walking be T_s, and let the moment when he is collided with for the first time be T_c. If $(T_c - T_s) > t_k$, or, in other words, there is no collision during $(T_c - T_s)$, the pedestrian will achieve the picking-up activity. However, if $(T_c - T_s) \leq t_k$, then the pedestrian is collided with by the other pedestrians. Let the collision duration be $\mathrm{d}t$, let the immediate velocity of P at T_c be v_t, and let the total forces from other pedestrians be F_p; then, the distance during $\mathrm{d}t$ can be obtained by using Eq. (1).

$$S = v_t \cdot \mathrm{d}t + \frac{F_p}{2 \cdot m} \cdot \mathrm{d}t^2 \tag{1}$$

where m is the mass of P, and v_t can be obtained using the social force model (Eqs. (2)–(4)).

$$m_i \frac{\mathrm{d}\mathbf{v}_i}{\mathrm{d}t} = m_i \frac{v_i^0(t)\mathbf{e}_i^0(t) - \mathbf{v}_i(t)}{\boldsymbol{\tau}_i} + \sum_{j(\neq i)} \mathbf{f}_{ij} + \sum_{w} \mathbf{f}_{iw} \tag{2}$$

$$\mathbf{f}_{ij} = \left\{A_i \exp[(r_{ij} - d_{ij})/B_i] + kg(r_{ij} - d_{ij})\right\} \mathbf{n}_{ij} + \kappa g(r_{ij} - d_{ij}) \boldsymbol{\Delta} v_{ji}^t \mathbf{t}_{ij} \tag{3}$$

$$\mathbf{f}_{iw} = \{A_i \exp[(r_i - d_{iw})/B_i] + kg(r_i - d_{iw})\} \mathbf{n}_{iw} - \kappa g(r_i - d_{iw})(\mathbf{v}_i \cdot \mathbf{t}_{iw})\mathbf{t}_{iw}. \tag{4}$$

The definitions of the parameters in Eqs. (2)–(4) can be found in Helbing et al. [13]. Let the maximum velocity of P be v_m. Then, the maximum distance (S_m) for P during d_t can be computed using Eq. (5):

$$S_m = v_m \cdot \mathrm{d}t. \tag{5}$$

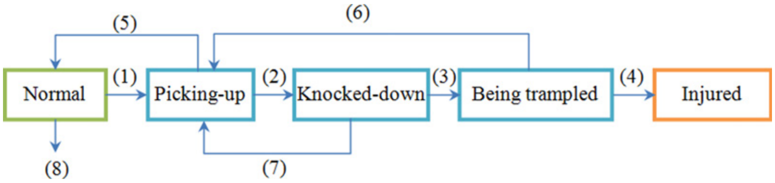


Fig. 2. A shift model between 5 stages.

Table 2
State shifting and the determinative algorithms.

Route number	Description of the state shifting	Determinative algorithm
(1)	A pedestrian slowed down (or stopped) for picking-up activities. The speed (V_p) was significantly slower than the normal speed (V_{normal}).	$V_p \ll V_{\text{normal}}$
(2)	A pedestrian was knocked down during the picking-up activities.	Eq. (6)
(3)	A pedestrian was trampled after having been knocked down, and the total number of trampling times (m) had not reached the predetermined threshold (n) yet.	$\begin{cases} m < n \\ T_{fi} - T_{gi} < t_p \quad (i = 1, \ldots, m) \end{cases}$
(4)	The threshold of the trampling times was reached, and the pedestrian was injured.	Eq. (7)
(5)	A pedestrian achieved the picking-up activity and continued performing normal transfers.	$(T_c - T_s) > t_k$ or there were no forces during t_k
(6)	A pedestrian stood up after having been trampled several times.	$\begin{cases} m < n \\ T_{fi} - T_{gi} > t_p \quad (i = 1, \ldots, m) \end{cases}$
(7)	A pedestrian stood up after having been knocked down.	$T_f - T_g > t_p$
(8)	A pedestrian continued walking normally for subsequent transfers.	–

If $S > S_m$, then the pedestrian moves farther than he is able to move, and P will be knocked down at that moment $(T_c + \mathrm{d}t)$. The conditions that determine the knocked-down stage can be summarized as in Eq. (6):

$$\begin{cases} T_c - T_s \le t_k \\ S_m < S. \end{cases} \tag{6}$$

(2) Algorithm for determining the injured stage.

It is still possible for a pedestrian to stand up and continue walking after he has been knocked down if no more stampedes occur. Let the moment when P is knocked down be T_g, let the reaction duration to stand up be t_p, and let the moment when P is trampled for the first time after he was knocked down be T_f. If $(T_f - T_g) > t_p$, or, in other words, there are no additional tramplings during t_p, then P has sufficient time to stand up. However, if $(T_f - T_g) \le t_p$, then P is trampled before he can stand up, and P will continue lying on the ground. If such situations are repeated for a predetermined number of times (n), then the pedestrian can be considered injured. Suppose that the total number of trampling times is m; then, the conditions that determine the injured stage can be summarized as in Eq. (7).

$$\begin{cases} m \ge n \\ T_{fi} - T_{gi} < t_p \quad (i = 1, \ldots, m). \end{cases} \tag{7}$$

3.2. Stage shifting model

As mentioned in Section 3.1, the evolution route does not always transition forward linearly from stage 1 to stage 5. The evolution may also be backward. For example, a pedestrian can continue walking normally if there is no collision during his picking-up activity, and a knocked-down pedestrian can stand up if there are no more collisions, even after having been stampeded several times. The possible shift route between the five stages can be graphed as in Fig. 2, and the algorithms used to determine each route are listed in Table 2 based on the algorithms that were proposed in Section 3.1.

3.3. Modifications to the social forces after a pedestrian has been knocked down

Here, it is assumed that a pedestrian has no influence on the other pedestrians after he was knocked down and when he is lying on the ground. In terms of social forces, the pedestrian will not produce physical forces and psychological forces in those stages, including the knocked-down stage, the being-trampled stage, and the injured stage. The trailing pedestrians will regard the pedestrian as part of the ground and step (or even trample) across him for subsequent transfers; however, the pedestrian will continue bearing physical forces from others, and because the pedestrian cannot see the others while lying on the ground, the psychological forces from other pedestrians can be ignored. The social forces from any other pedestrian j in Helbing's social force model can be modified to Eq. (8).

$$\mathbf{f}_{ij} = \begin{cases} kg(r_{ij} - d_{ij})\mathbf{n}_{ij} + \kappa g(r_{ij} - d_{ij})\Delta v_{ji}^t \mathbf{t}_{ij} & \text{(When lying on the ground)} \\ \left\{A_i \exp[(r_{ij} - d_{ij})/B_i] + kg(r_{ij} - d_{ij})\right\} \mathbf{n}_{ij} + \kappa g(r_{ij} - d_{ij})\Delta v_{ji}^t \mathbf{t}_{ij} & \text{(Otherwise)} \end{cases} \tag{8}$$

where i is the pedestrian. The definitions of the parameters in Eq. (8) can be found in Helbing et al. [13].

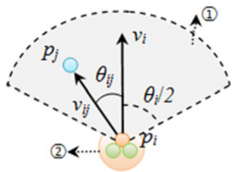


Fig. 3. The modified definition of a pedestrian force range.

3.4. Modifications to the definition of the pedestrian force range

The forces between the pedestrians are critical drivers of trampling behaviors. Some researchers have argued that a pedestrian will be affected by those individuals who are in a visual view region [22]. However, when transferring on escalators, a pedestrian can be affected not only by pedestrians who are in the view region (Fig. 3 ①) but also by those who are outside the view region but have physical contact with the source pedestrian (Fig. 3 ②), especially when the trampling accident occurs.

The algorithms to define a pedestrian's neighbors are as follows:

(1) Definition of the neighbors in the view region.

As shown in Fig. 3, let the source pedestrian be p_i, let the location of p_i be L_i, let the radius of p_i be r_i, let the view field angle be θ_i ($\theta_i \leq 180°$), let the view field radius be d_i, and let the velocity vector of p_i be v_i. Let the set of all pedestrians in the scene at moment t be S_t, let p_j be any other pedestrian in S_t, let the radius of p_j be r_j, let the location of p_j be L_j, let the relative velocity vector between p_i and p_j be v_{ij} pointing from p_i to p_j, and let the angle between v_{ij} and v_i be θ_{ij}. Let the set of the pedestrian who located in θ_i and d_i be S_{t1}; then, S_{t1} must meet the following conditions (Eq. (9)):

$$S_{t1} = \begin{cases} d_{ij} = |L_i, L_j| \leq d_i \\ \cos\theta_{ji} = \dfrac{v_i \cdot v_{ij}}{|v_i|\ |v_{ij}|} \geq \cos(\theta_i/2) \end{cases} \quad (i, j \in S_t) \tag{9}$$

where d_{ij} is the distance between p_i and p_j. If $d_{ij} \leq d_i$ and $\cos\theta_{ij} \geq \cos(\theta_i/2)$, then p_j is in the view region of p_i and can be seen by p_i. Those pedestrians in S_{t1} will exert psychological and physical forces on p_i.

(2) Definition of the neighbors outside the view region.

In addition to the pedestrians who are in the view region, those who are outside the view region but have physical contact will also exert forces on the source pedestrian. Let the set of these pedestrians be S_{t2}. Then, S_{t2} must meet the following conditions (Eq. (10)):

$$S_{t2} = \begin{cases} d_{ij} = |L_i, L_j| \leq (r_i + r_j) \\ \cos\theta_{ji} = \dfrac{v_i \cdot v_{ij}}{|v_i|\ |v_{ij}|} < \cos(\theta_i/2) \end{cases} \quad (i, j \in S_t) \tag{10}$$

where $d_{ij} \leq (r_i + r_j)$ means that p_j has physical contact with p_i. Let the set of all the pedestrians who will exert forces on the source pedestrian be S. Then, S is (Eq. (11)):

$$S = S_{t1} \cup S_{t2}. \tag{11}$$

The pedestrian force on p_i can then be determined using Eq. (12) by summing the force (f_{ij}) from every pedestrian in set S.

$$f_i = \sum f_{ij} \quad (j \in S; j \neq i) \tag{12}$$

where the force (f_{ij}) can be computed using Eq. (8).

4. Simulated scenarios

(1) Description of the scenario.

The scenario is a transfer between ramp escalators (rather than stair escalators) in a super-market. A two-dimensional scenario map projected to the $\langle X\text{–}Y \rangle$ plane is shown in Fig. 4. The colors represent different regions. R0 is the entrance to escalator R1. R1 and R3 are the escalators, R2 is the transfer aisle linking escalators R1 and R3, and R4 is the exit of escalator R3. The number labels are the (X, Y) coordinate pairs in units of meters. The arrows represent the travel directions. Here, it is assumed that the pedestrians are in a single flow. In other words, there are no pedestrians leaving and no pedestrians joining the flow during the transfer.

(2) Description of the random trampling process.

Because most picking-up activities occur after a pedestrian steps down from an escalator, the transfer aisle, R2, was chosen as the study area where a trample accident happened and evolved between the five stages. The process is as follows:

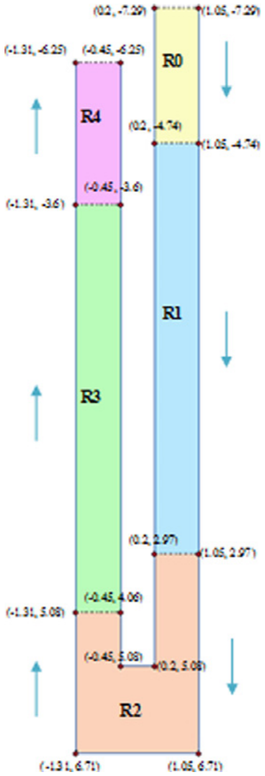


Fig. 4. An illustration of the scenario.

after a given interval, a pedestrian out of those who stepped down from escalator R1 was selected randomly to conduct the picking-up activity. After a period of time, the number of all pedestrians (N_t) who conducted the picking-up activity and the number of the pedestrians (N_p) who were injured were counted. The trampling probability (P_t) can then be obtained using Eq. (13).

$$P_t = \frac{N_t}{N_p} \times 100\%. \tag{13}$$

(3) Impact factors delineation.

The factors that lead to trampling accident are many [3]. The pedestrian traffic [2,3] and the pedestrian velocity [9] have been indicated as some of these factors in non-escalator scenarios. However, how these 2 factors influence the trampling risks of individuals during escalator transfers still needs further study. Additionally, a pedestrian's response time to the trampling incident, as well as the velocity of an escalator may also influence the severity of a trampling accident. So, we choose these 4 factors to identify their influences on a trampling accident.

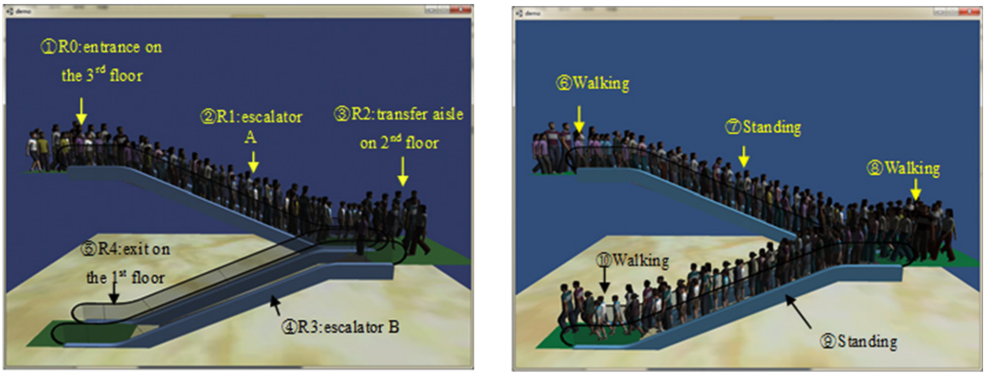
(4) Parameter settings.

In the simulation, parameters in Helbing's social force model were set as follows: m was 80 kg, K was 120 000, and κ was 240 000, which were referenced from those values in Helbing [12]; A was set to be 3.0, and B was set to be 0.2, which were referenced from those values in Helbing et al. [14]. The radius of a pedestrian was 0.2 m. The radius in a pedestrian's visual region was 1.0 m.

4.1. The simulated virtual scenario

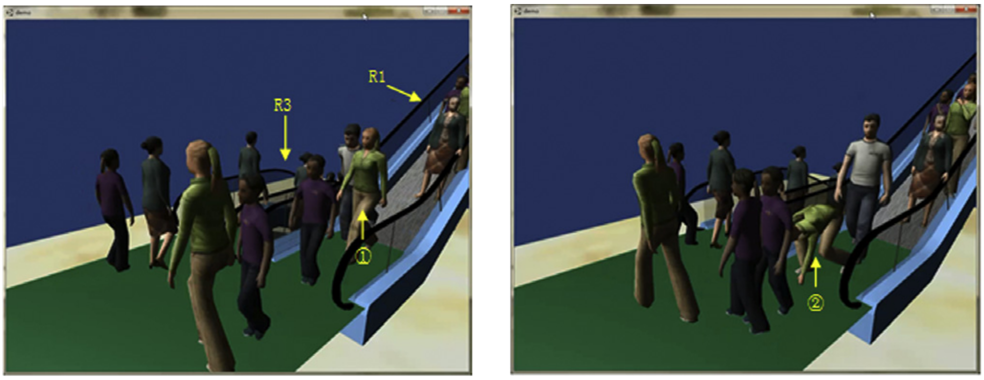
The transfer activities were simulated based on the above model. As shown in Fig. 5, pedestrians transferred from the third floor to the first floor on the escalators. To complete the transfer, the pedestrians must walk through a horizontal entrance R0 onto the downward escalator R1. Then, they stand on the escalator and are carried to transfer aisle R2 on the second floor. When they step down from escalator R1 onto the transfer aisle, they must walk until they step onto escalator R3, by which they are carried to the first floor.

A trampling accident caused by picking-up activities was successfully simulated in the virtual environment (Fig. 6). Fig. 6(a) shows the transfers of all pedestrians, including that of pedestrian P (Fig. 6 ①), who continued normally from escalator R1 to escalator R3 through the transfer aisle. Fig. 6(b) illustrates that P suddenly stopped and bent down to pick up something at a random moment after she stepped down from escalator R1 (Fig. 6 ②). Fig. 6(c) shows that the pedestrian was

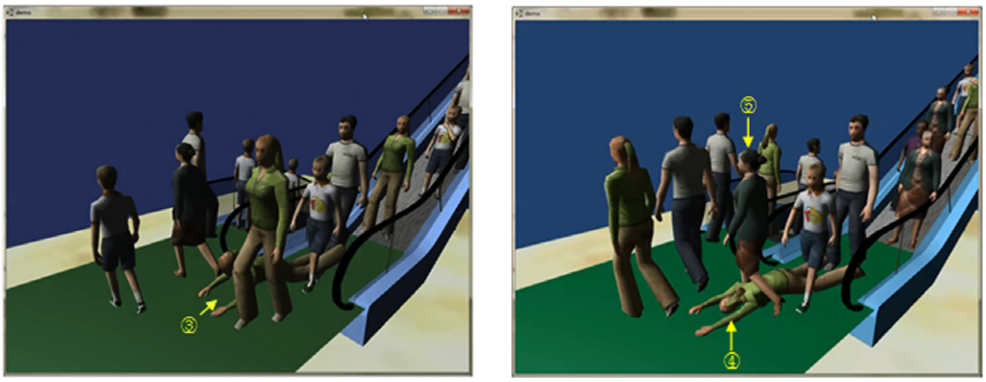


(a) Arriving at the aisle. (b) Arriving at the exit.

Fig. 5. A snapshot of the escalator transfers.



(a) Walking normally. (b) Stop to pick up.



(c) Be knocked down. (d) Be injured.

Fig. 6. A snapshot of the trampling process.

knocked down and lay on the ground (Fig. 6 ③). She was being trampled by the trailing pedestrians; however, the threshold of the trampling times had not been reached yet, and the pedestrian still attempted to stand up. Fig. 6(d) shows that the pedestrian was injured after the number of trampling times reached the predetermined threshold. The pedestrian could no longer stand up, and the trailing pedestrians could step over or trample across the pedestrian for their subsequent transfers (Fig. 6 ④).

5. Results

Based on the virtual environment in Section 4, several trampling scenarios were simulated, with different values for 4 factors including pedestrian traffic (L_p), escalator velocity (V_e), picking-up duration (T_k), and pedestrian velocity (V_p). The

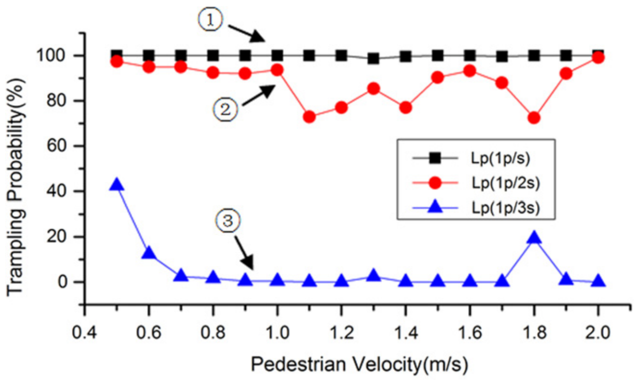


Fig. 7. The changes in P_t with pedestrian traffic ($V_e = 1.0$ m/s).

Table 3
Value ranges of 4 factors.

Factors	Abbreviations	Value ranges
Pedestrian traffic	L_p	One person per second (1 p/s) One person per 2 seconds (1 p/2 s) One person per 3 seconds (1 p/3 s)
Escalator velocity	V_e	1.0 m/s, 0.5 m/s, 0.3 m/s
Picking-up duration	T_k	2 s or 1 s
Pedestrian velocity	V_p	Between 0.5 m/s and 2.0 m/s, at an interval of 0.1 m/s

Table 4
The average P_t for each scenario.

L_p	1 p/s	1 p/2 s	1 p/3 s
Average P_t	99.87%	88.36%	5.16%

value range of each factor is listed in Table 3. Each simulation lasted for 500 s. The value of P_t was calculated using Eq. (13) to examine the impact of each factor on the trampling risk. To eliminate the influences of random processes in the simulations, each scenario was repeated 10 times, and the average value was assigned as the trampling probability of that scenario.

5.1. The impact of pedestrian traffic on the trampling probability

In this section, 9 scenarios were simulated to test the impact of pedestrian traffic on the trampling risks. In these scenarios, T_k was set to 1 s; V_e was set to 1.0 m/s, 0.5 m/s, and 0.3 m/s; and L_p was set to 1 p/s, 1 p/2 s, and 1 p/3 s.

(1) The impact of pedestrian traffic when V_e was 1.0 m/s.

The changes of P_t with V_p in each scenario are graphed in Fig. 7, and the average values of L_p are listed in Table 4.

A general rule, based on Table 3, is that the average value of P_t increases with an increase in L_p. When the pedestrian traffic increased from 1 p/3 s to 1 p/2 s and to 1 p/s, the average value of P_t increased from 5.16% to 88.36% and to 99.87%, respectively. Regarding the detailed changes (Fig. 7), when L_p was high (1 p/s), the values of P_t were high for all the pedestrian velocities (Fig. 7 ①). When L_p was 1 p/2 s, the curve of P_t could be divided into 2 segments at the pedestrian velocity of 1.0 m/s (Fig. 7 ②). When V_p was lower than 1.0 m/s, the fluctuations were slight, and the values of P_t were high, with an average value of 94.3% in this segment; however, when V_p was greater than 1.0 m/s, the fluctuations were relatively significant, and the values of P_t decreased, with an average value of 84.79% in this segment. When L_p was 1 p/3 s, an obvious trend could be found: P_t decreased significantly with the increase of V_p. When V_p was 0.5 m/s, the value of P_t was 42.5%, and when V_p was 0.6 m/s, the value of P_t was 12.5%; afterward, the P_t values were nearly 1%.

(2) The impact of pedestrian traffic when V_e was 0.5 m/s.

The changes of P_t with V_p in each L_p are graphed in Fig. 8, and the average values of L_p are listed in Table 5.

The same general rule that P_t increased with an increase in L_p can be found from Table 4. When the pedestrian traffic increased from 1 p/3 s to 1 p/2 s and to 1 p/s, the average value of P_t increased from 8.00% to 92.32% and to 99.89%, respectively. The detailed patterns can be found in Fig. 8. When L_p was high (1 p/s), all the values of P_t were high regardless of the changes in V_p. When L_p was 1 p/2 s, the curve of P_t could be divided into 2 segments at the pedestrian velocity of 1.0 m/s. In the segment where V_p was lower than 1.0 m/s, the values of P_t fluctuated more significantly than those in the other segment, and the average P_t in the former segment (85.67%) was lower than that in the latter segment (96.3%). When

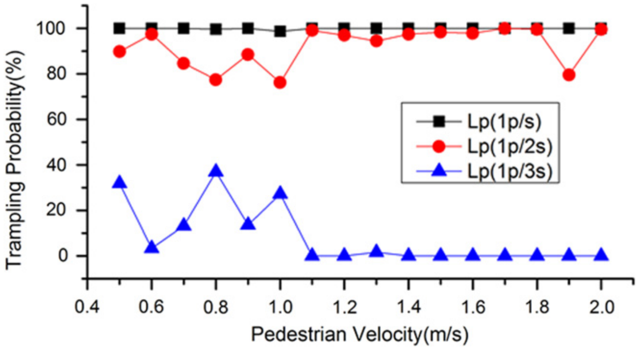


Fig. 8. The changes in P_t with pedestrian traffic ($V_e = 0.5$ m/s).

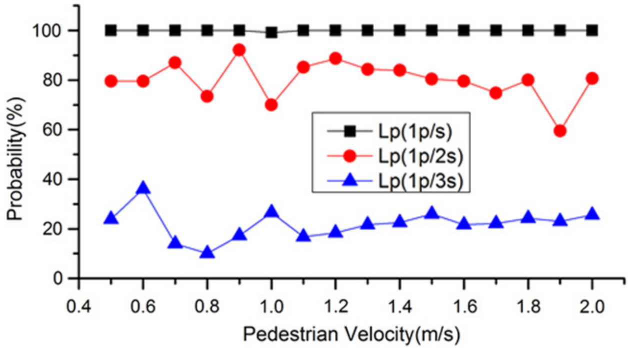


Fig. 9. The changes in P_t with pedestrian traffic ($V_e = 0.3$ m/s).

Table 5
The average P_t in each scenario.

L_p	1 p/s	1 p/2 s	1 p/3 s
Average P_t	99.89%	92.32%	8.00%

Table 6
The average P_t in each scenario.

L_p	1 p/s	1 p/2 s	1 p/3 s
Average P_t	99.95%	79.92%	21.86%

L_p was 1 p/3 s, the changes in P_t could also be divided into 2 segments at the pedestrian velocity of 1.0 m/s: when V_p was lower than 1.0 m/s, the values of P_t fluctuated more significantly than those when V_p was greater than 1.0 m/s, and the average P_t in the former segment (21.06%) was greater than that in the latter segment (0.17%).

(3) The impact of pedestrian traffic when V_e was 0.3 m/s.

The changes in P_t with V_p in each L_p are graphed in Fig. 9, and the average values of L_p are listed in Table 6.

Again, the rule that P_t increased with an increase in L_p can be found from Table 5. When the values of L_p were 1 p/s, 1 p/2 s, and 1 p/3 s, the values of P_t were 99.95%, 79.92%, and 21.8%, respectively. The detailed patterns can be found in Fig. 9. When L_p was high (1 p/s), P_t remained at a high level, with slight fluctuations for all the values of V_p. When L_p was 1 p/2 s or 1 p/3 s, the fluctuation features of P_t were demarcated into 2 segments by V_p at 1.0 m/s. In both scenarios, P_t fluctuated more significantly when V_p was lower than 1.0 m/s than when V_p was higher than 1.0 m/s; however, the average values of P_t were nearly equal in both segments of each scenario: when L_p was 1 p/2 s, the average value of P_t was 80.29% in the segment where V_p was lower than 1.0 m/s and was 79.70% in the other segment, and when L_p was 1 p/3 s, the values were 21.29% and 22.19%, respectively.

5.2. The impact of the escalator velocity on the trampling probability

In this section, the picking-up duration was set to 1 s, and the pedestrian traffic was held constant at 1 p/s, 1 p/2 s, or 1 p/3 s. The changes in the trampling probability with the escalator velocity were studied based on these choices. Here, we

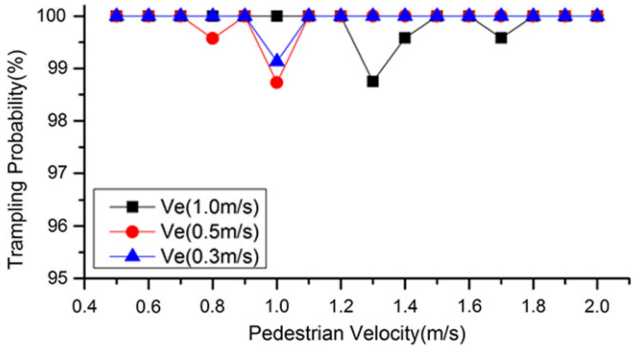


Fig. 10. The changes in P_t with the escalator velocity ($L_p = 1$ p/s).

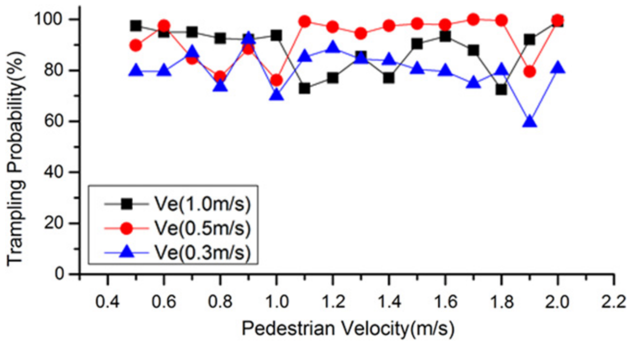


Fig. 11. The changes in P_t with the escalator velocity ($L_p = 1$ p/2 s).

Table 7
The average P_t in each scenario.

V_e (m/s)	1.0	0.5	0.3
Average P_t	99.87%	99.89%	99.95%

Table 8
The average P_t in each scenario.

V_e (m/s)	1.0	0.5	0.3
Average P_t	88.36%	92.32%	79.92%

assume that the escalators run at a constant velocity so that a pedestrian will stand on the escalator to move forward at the same velocity.

(1) The impact of the escalator velocity when L_p was 1 p/s.

As can be seen from Fig. 10, all the curves of P_t in the 3 escalator velocities remained at high levels. Although the values of P_t dropped somewhat at several V_p points, the changes were slight, and the absolute values at these points were all above 98%. This pattern was also confirmed in Table 7, in which the average values of P_t were 99.87%, 99.89%, and 99.95% in the 3 escalator velocities. The results show that the trampling probability is influenced mainly by L_p when L_p is relatively high. If someone stops to pick up something in this situation, he will almost certainly be trampled and injured.

(2) The impact of the escalator velocity when L_p was 1 p/2 s.

As shown in Fig. 11, the curves of the 3 scenarios fluctuated at similarly high levels. All the curves could be separated into 2 segments at the pedestrian velocity of 1.0 m/s, but the detailed patterns were somewhat different: when V_e was 1.0 m/s, the trampling probabilities were higher and more stable at the side where V_p was lower than 1.0 m/s compared with the other side. The pattern was the opposite when V_e was 0.5 m/s: the trampling probabilities were lower and rougher at the side where V_p was lower than 1.0 m/s compared with at the other side. However, when V_e was 0.3 m/s, the values and the fluctuations were similar on both sides of the split point. Generally speaking, the trampling probabilities in these scenarios remained at high levels, as reflected by the average values listed in Table 8.

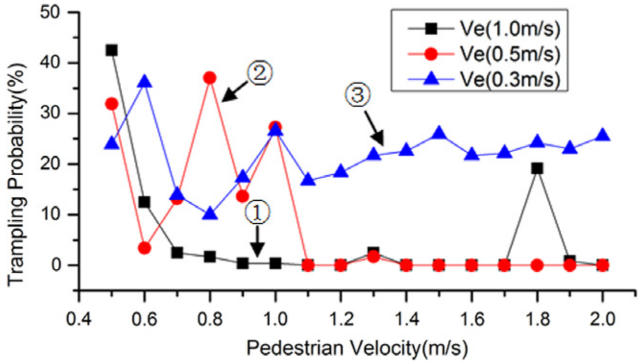


Fig. 12. The changes in P_t with the escalator velocity ($L_p = 1$ p/3 s).

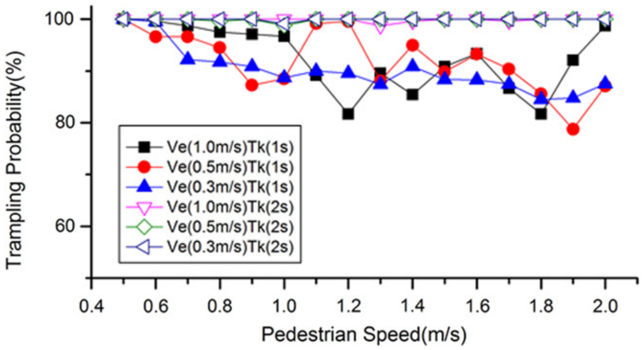


Fig. 13. The changes in P_t with picking-up duration ($L_p = 1$ p/s).

Table 9
The average P_t in each scenario.

V_e (m/s)	1.0	0.5	0.3
Average P_t	5.16%	8.00%	21.86%

Table 10
The average P_t for each scenario.

T_k	V_e (m/s)	Average P_t
1 s	1.0	92.42%
	0.5	91.88%
	0.3	90.10%
2 s	1.0	99.87%
	0.5	99.89%
	0.3	99.95%

(3) The impact of the escalator velocity when L_p was 1 p/3 s.

As shown in Table 9, when L_p was 1 p/s, the average P_t generally increased with the increase in V_e. As shown by the detailed curves (Fig. 12), P_t decreased with the increase of V_p in the scenarios in which V_e was 1.0 m/s and 0.5 m/s. This pattern was obvious, and the curve decreased quickly when V_e was 1.0 m/s (Fig. 12 ①). Although this pattern could also be found in the curve when V_e was 0.5 m/s (Fig. 12 ②), the trampling probabilities fluctuated more dramatically when V_p was lower than 1.0 m/s compared with those when V_p was greater than 1.0 m/s. Another significant feature could be found in the curve when V_e was 0.3 m/s (Fig. 12 ③): the absolute values in the scenario were obviously higher than those in the other 2 scenarios when V_p was greater than 1.0 m/s.

5.3. The impact of the picking-up duration on the trampling probability

In this section, a series of scenarios was simulated to test the impact of the picking-up duration on the trampling probability. The pedestrian traffic was set to be constant at 1 p/s, 1 p/2 s, or 1 p/3 s for each scenario.

(1) The impact of the picking-up duration when L_p was 1 p/s.

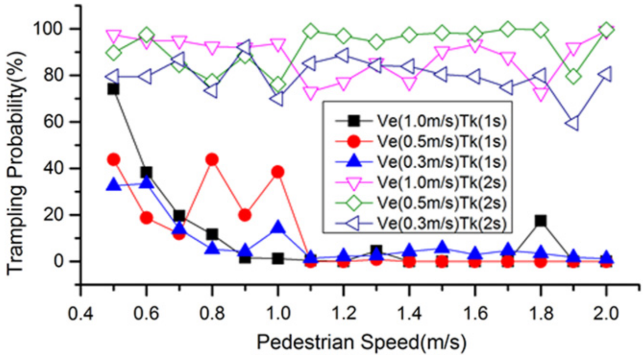


Fig. 14. The changes in P_t with picking-up duration ($L_p = 1$ p/2 s).

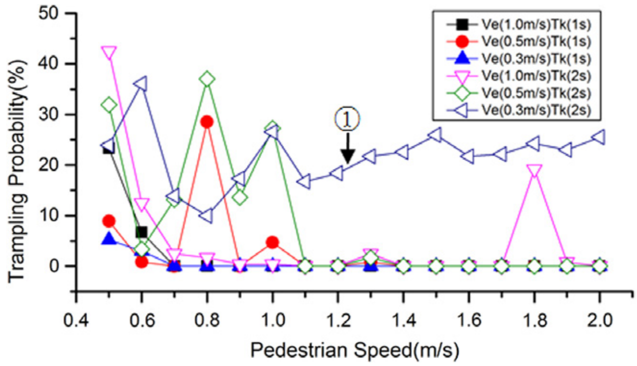


Fig. 15. The changes in P_t with picking-up duration ($L_p = 1$ p/3 s).

Table 11
The average P_t for each scenario.

T_k	V_e (m/s)	Average P_t
1 s	1.0	10.57%
	0.5	11.11%
	0.3	8.37%
2 s	1.0	88.36%
	0.5	92.32%
	0.3	79.92%

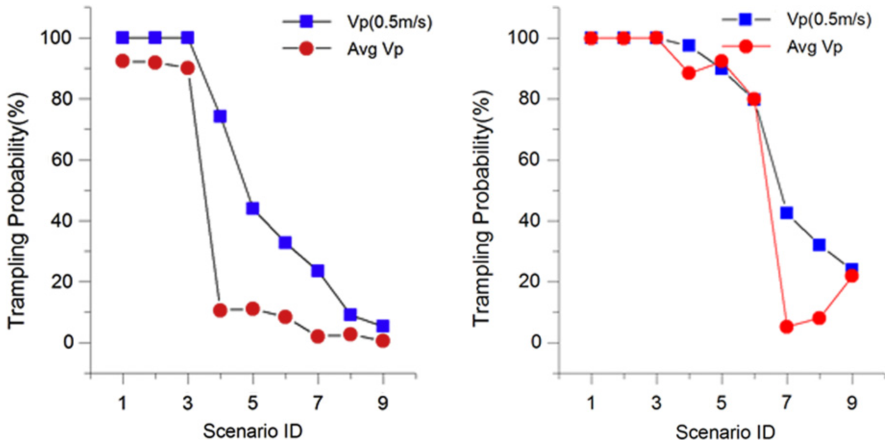
Table 12
The average P_t for each scenario.

T_k	V_e (m/s)	Average P_t
1 s	1.0	1.88%
	0.5	2.74%
	0.3	0.52%
2 s	1.0	5.16%
	0.5	8.00%
	0.3	21.86%

Table 10 shows that the values of P_t decreased with the decrease in the picking-up duration, but the decreases were not very obvious and all trampling risks remained high. Regarding the detailed patterns (Fig. 13), almost all the curves of P_t remained at a high level when T_k was 2 s. When T_k was 1 s, the curves of P_t decreased with an increase in the pedestrian velocity. However, the minimum value of P_t was over 80%, indicating that in this condition, P_t was mainly influenced by the pedestrian traffic.

(2) The impact of the picking-up duration when L_p was 1 p/2 s.

Table 11 shows that the trampling probability decreased with a decrease in the picking-up duration. As shown in Fig. 14, in the scenarios in which T_k was 1 s, the curves in P_t decreased quickly with an increase in V_p, and stability was achieved at



(a) Contrast when T_k was 1 s. (b) Contrast when T_k was 2 s.

Fig. 16. The changes in P_t with pedestrian velocity.

Table 13
Settings in each scenario.

Scenario ID	1	2	3	4	5	6	7	8	9
L_p	1 p/s	1 p/s	1 p/s	1 p/2 s	1 p/2 s	1 p/2 s	1 p/3 s	1 p/3 s	1 p/3 s
V_e (m/s)	1.0	0.5	0.3	1.0	0.5	0.3	1.0	0.5	0.3

the point where V_p was 1.0 m/s, after which the values of P_t were between 0 and 1%. This result indicates that the trampling probability could be reduced by shortening the picking-up duration and by increasing the pedestrian velocity.

(3) The impact of the picking-up duration when L_p was 1 p/3 s.

Table 12 shows that the shortening of T_k could reduce the average values of P_t in all scenarios. The impact was especially distinct when the escalator velocity was 0.3 m/s, in which the average P_t decreased from 21.86% to 0.52% after the shortening of T_k. With respect to the detailed changes (Fig. 15), P_t clearly decreased with the increase in V_p when T_k was 1 s, and the decrease was much quicker compared with when T_k was 2 s. Except for the curve in which T_k was 2 s and V_e was 0.3 m/s (Fig. 15 ①), all the other curves could be divided into 2 segments, at which V_p was 1.0 m/s. In the left segments, the curves of P_t fluctuated more dramatically and remained at higher levels, whereas in the right segments, the value fluctuations were stable and remained at lower levels.

5.4. *The impact of the pedestrian velocity on the trampling probability*

Fig. 16 shows that almost all the values of P_t at the pedestrian velocity of 0.5 m/s were higher than the average P_t of all of the pedestrian velocities in each scenario whose settings can be seen in Table 13. This rule was indeed true for all the scenarios when T_k was 1 s (Fig. 16(a)) and confirms the trends obtained from Figs. 13 through 15 indicating that P_t decreased with the increase in V_p when T_k was 1 s. This result also indicates that a relatively low pedestrian velocity will cause higher trampling risks.

6. Conclusions

A five-stage trampling model for individual pedestrians was proposed to describe the trampling process that is caused by a picking-up activity during escalator transfers. The model was composed of the normal stage, the picking-up stage, the knocked-down stage, the being-trampled stage, and the injured stage. The trampling process of a pedestrian is characterized by a shift among these stages. Several trampling scenarios in the transfer aisle were simulated using a modified social force model, and 4 factors, namely, the pedestrian traffic, the escalator velocity, the picking-up duration, and the pedestrian velocity, were tested to determine their impact on the trampling probability. Although the detailed impact of each factor varied in the different scenarios, the following general conclusions can be made:

(1) The impact of pedestrian traffic. The pedestrian traffic is the main factor that influences the trampling probability. The trampling probabilities increase dramatically with an increase in traffic, which was shown throughout the scenarios. (2) The impact of the escalator velocity. The escalator velocity can influence the trampling probability in every scenario; however, no clear trend was noted across all the scenarios. (3) The impact of the picking-up duration. A decrease in the picking-up duration decreases the trampling probability, which was also shown in all the scenarios. (4) The impact of the pedestrian

velocity. If the picking-up duration is short, then the trampling probability decreases with an increase in the pedestrian velocity.

Therefore, these 4 factors can be sorted into the following descending order: pedestrian traffic $>$ picking-up duration $>$ pedestrian velocity $>$ escalator velocity. Based on these conclusions, some countermeasures can be proposed to reduce trampling risks in escalator transfers: (1) special attention should be dedicated to pedestrian traffic, and if the traffic is obviously high, measures to limit the traffic should be taken; (2) pedestrians should be instructed to avoid picking-up activities during their transfers, and if the activity must be conducted, then the duration should be as short as possible; (3) the smooth approach of pedestrians in the transfer aisle should be guaranteed, and if possible, a traffic diverter can be employed.

7. Future studies

This paper focused on the probability that individual pedestrians would be trampled during escalator transfers. It was assumed that once a pedestrian was knocked onto the ground, he would exert no more social forces on other pedestrians, especially the trailing pedestrians. That assumption is rational if the trailing pedestrians can notice and step over the knocked-down pedestrian. However, in real life, there is another case in which the knocked-down pedestrian becomes an obstacle, and the trailing pedestrians will stumble downward if they pay no attention to the knocked-down pedestrian. Moreover, the stumbling pedestrians will become new obstacles for the trailing pedestrians; thus, a trampling spiral occurs, and the trampling accident evolves into a group incident that is a more serious threat to pedestrians' safety. Therefore, such accidents should be further studied in the future.

In the paper, four factors, including the pedestrian traffic, the pedestrian velocity, the response time, and the escalator velocity, were selected in order to identify their influence on a trampling accident. However, other factors, such as the length and the slope of an escalator, the aisle size, and escalators malfunctions like sudden stopping or even reverse, may also influence the trampling risks. Moreover, the paper assumed the floor to be rough so that a pedestrian can stop immediately or in a very short period of time when he wants to pick up something. However, if the floor is very sticky, the pedestrian may possibly trip down, or if the floor is very slippery, the pedestrian may possibly slip down, both of which will also affect the trampling process. Further studies are needed to deal with such scenarios.

In the paper, it was assumed that the escalators run at a constant velocity and that a pedestrian will stand on the escalator to move forward at the same velocity. However, if the pedestrian's velocity differs from the velocity of the escalator, his velocity, or in other words the momentum, will change in a short time at the moment he steps onto an escalator. Additional forces (e.g. the static friction from the escalator) should be employed to model such process in the future.

Additionally, in this paper, we also assumed that pedestrians follow a single flow; however, in reality, some pedestrians may exit the flow when they arrive at a floor, and new pedestrians may join the flow from that floor. Thus, multi-flow intersections occur. Although these intersections can be regarded as local variations in pedestrian traffic and the conclusions from this article could be extended to such variations, their detailed patterns and quantitative impacts on the trampling probability still require further study. Moreover, pedestrians can push a cart when transferring in a supermarket. Although this action can be regarded as an increase in the size of the pedestrian, the detailed impact of this action on the trampling probability also requires further investigation.

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