Simulation of Crowd Escape Under Hazardous Condition

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This brief report presents a model to characterize evacuees' response to hazardous stimuli during emergency egress, especially in smoke and fire condition. The model is developed in consistency with stress theory, which explains how an organism reacts to environmental stimuli. We integrate the theory in the well-known social-force model and apply the model to simulate crowd evacuation in fire emergency. The algorithm is being tested in FDS+EVAC.

1. Social Force Model and Stress Theory

In physiological or biological study, stress refers to an organism's reaction to a condition perceived as a threat, challenge or physical and psychological barrier. For humans stress is normally perceived when we think the demand being placed on us exceed our ability to cope with, and it can be external and related to the environment, and it becomes effective by internal perceptions. This paper will integrate the stress theory in the well-known social force model. The motivation level v_i^0 and d_{ij}^0 in social force model are the result of our perception, and are adapted to the environmental stressors. As a result, stress refers to agents' response and adaption to the environment, and it is feasible to extend social-force model to characterize the interplay between individuals and their surroundings. As below we present a diagram to describe the interplay between individuals and their surroundings based on the extended social-force model.

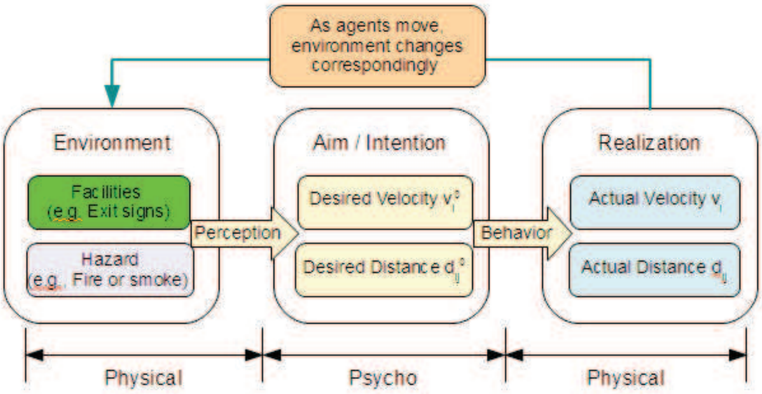


Figure 1. Perception and Behavior in a Feedback Mechanism: The motivation level v_i^0 and d_{ij}^0 in social force model are the result of human perception, and are adapted to the environmental stressor such as fire and smoke, and v_i^0 and d_{ij}^0 could vary both temporally and spatially, and they lead to behavior change in v_i and d_{ij}. The social-force model is extended to characterize the interplay between individuals and their surroundings.

In the above diagram environmental factors include facilities (e.g., alarm, guidance) and hazard (e.g., fire and smoke). The resulting pedestrian motion is a response to environmental stressors, and v_i^0 and d_{ij}^0 could vary both temporally and spatially. In this paper we will focus on emergency egress and essentially present an approach to model how the hazard (i.e., fire and smoke) influence evacuees' escape behavior, we will briefly explain how to apply the above model in simulation of crowd evacuation. The method has been tested in FDS+Evac, a well-known open-source simulator written by Fortran, and it is composed of fire module and evacuation module so that we can test how evacuees respond to hazard such as smoke and heat in emergency escape.

Table 1 On Conception of Stress in Social-Force Model

	Opinion (Psychological Characteristics)	*Behavior (Physic-Based Characteristics)*	*Difference between subjective opinion and objective reality*	*Forced-Based Term for Newton Second Law*
Time-Related Stress: Velocity	desired velocities $\mathbf{v}_i^0 = v_i^0 \mathbf{e}_i^0$	actual velocities $\mathbf{v}_i = v_i \mathbf{e}_i$	***Time-Related Stress: Velocity*** $\mathbf{v}_i^0 - \mathbf{v}_i$	***Self-Driving Force*** $f^{drv} = m_i(\mathbf{v}_i^0 - \mathbf{v}_i)/\tau$
Space-related Stress: Distance	desired distance d_{ij}^0	actual distance d_{ij}	***Space-related Stress: Distance*** $d_{ij}^0 - d_{ij}$	***Social Force*** $f_{ij} = A_i exp((d_{ij}^0 - d_{ij})/B_i)$

In Stokes and Kite, 2001, stress is the result of mismatch between psychological demand and realistic situation, and Table 1 characterizes the mismatch in terms of velocity and distance: the psychological demand is represented by desired velocity $\mathbf{v}_i^0$ or distance d_{ij}^0 while the physical reality is described by the physical velocity $\mathbf{v}_i$ and distance d_{ij}. The gap of two variables measures the intensity of stress people are perceiving, and thus are motivated into certain behavior. Such behavior is formulated as the self-driving force and social force in Equation (1).

In particular two types of stressor are considered as shown in Table 1. The first type is a time-related stress which is commonly known as time-pressure, and it is measured by the difference of desired velocity and actual velocity, i.e., $\mathbf{v}_i^0 - \mathbf{v}_i$. The second type is a space-related stress, which refers to proxemics and social norms and is represented by the gap of desired interpersonal distance and actual interpersonal distance, i.e, $d_{ij}^0 - d_{ij}$.

2. Adapting Desired Velocity To Environmental Stressors

When the fire/smoke spread towards people, people normally desire moving faster to escape from danger (Proulx , 1993; Ozel, 2001; Kuligowski, 2009). Thus, we suggest that the desired velocity $\mathbf{v}^0$ should be increased when smoke density increases, and correspondingly the self-driving force is increased. The fact that people may slow down in smoke areas is instead characterized by adding a resistance force which is proportional to the smoke density (SOOT_DENS). This force describes how smoke impedes people's motion. As a result, both of the self-driving force and smoke resistance are increased when people are walking in smoke areas. If the self-driving force is larger than the resistance, people will accelerate, otherwise people will slow down (See Figure 2).

The following plot exemplifies the increasing curve of the self-driving force and smoke resistance when the smoke density increases. When the smoke density increases initially, the smoke is not thick so that people are able to speed up. As the smoke density keeps increasing, the resistance from smoke is predominant and people have to slow down due to reduced percentage of oxygen and poor visibility on the path and surrounding facilities (Was, 2018). In sum, whether people can accelerate or not critically depends on hazard condition. In light smoke people can commonly speed up to escape from danger while in thick smoke it is difficult for people to find the path or exit, and they thus will slow down. In other words, the hazard condition plays an important role.

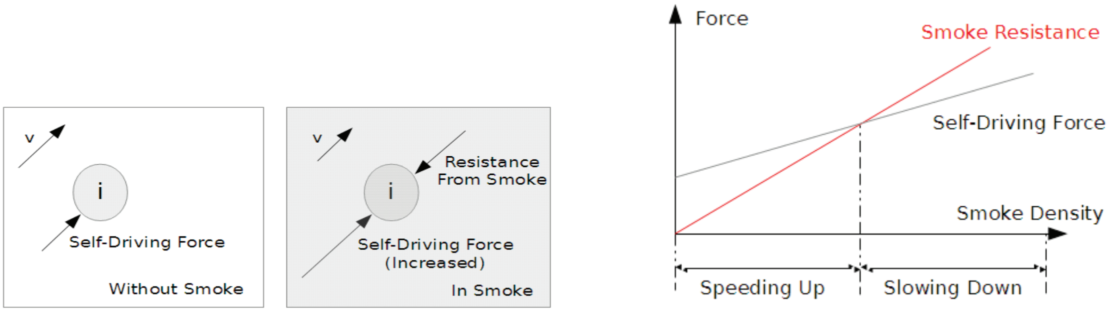


Figure 2. A Model of Walking Behavior in Smoke Conditions: When the smoke density increases initially, the smoke is not thick so that people are able to speed up. As the smoke density keeps increasing, the resistance from smoke is predominant and people have to slow down even if they desire moving faster in escape.

The revised mathematical description of the pedestrian model is given as below.

$$m_i \frac{d\mathbf{v}_i(t)}{dt} = m_i \frac{\mathbf{v}_i^0(t) - \mathbf{v}_i(t)}{\tau_i} + \sum_{j(\neq i)} \mathbf{f}_{ij} + \sum_{w} \mathbf{f}_{iw} + \sum_{h} \mathbf{f}_{ih}\,, \tag{1}$$

where the resistance from hazards is added to the traditional pedestrian model. This resistance is denoted by $\boldsymbol{f}_{ih}$, and it is supposed to be a function of the smoke density. Other hazard characteristics can also be taken into account such as gas temperature and heat radiation. Based on Equation (1), we may consider the hazard characteristics (e.g., smoke) as a kind of "spreading walls" that impede pedestrians' motion. Pedestrian are able to go through such "spreading walls" if the smoke is not thick. An example is that $\boldsymbol{f}_{ih}$ is a linear form of smoke density while the self-driving force (given by desired velocity $\boldsymbol{v}_i^0$) is the square root form or another linear form (See Figure 2). Other specific mathematical description of $\boldsymbol{f}_{ih}$ and $\boldsymbol{v}_i^0$ can also be explored in the future.

Other settings are not changed with respect to the forced-based model: m_i is the mass of an individual. The desired velocity is $\boldsymbol{v}_i^0$ and the physical velocity is denoted by $\boldsymbol{v}_i$, and both of them are functions of time t. The interaction from individual j to individual i is denoted by $\boldsymbol{f}_{ij}$ and the force from walls or other facilities to individual i is denoted by $\boldsymbol{f}_{iw}$. The detailed mathematical model is introduced in Helbing et. al., 2002 and 2005.

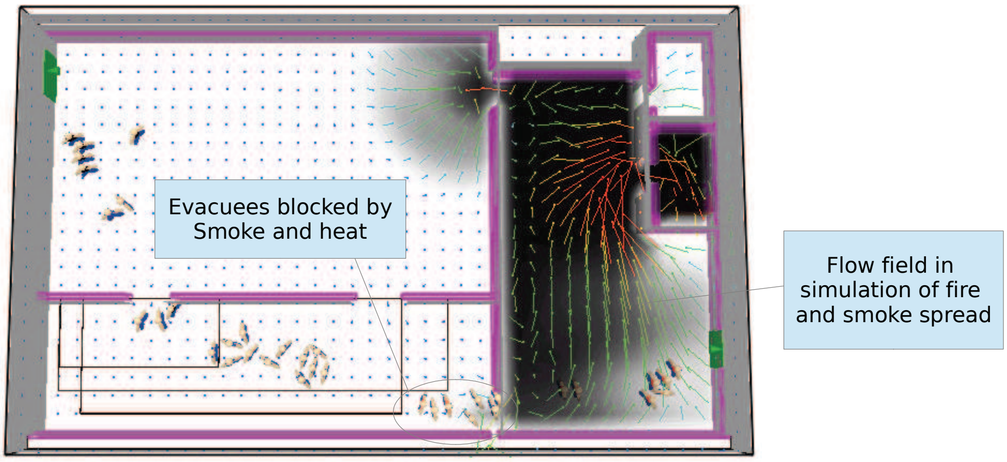


Figure 3. Simulation of Crowd Evacuation with Smoke: Smoke spreads and it is like "moving walls" which block evacuees' movement, and evacuees are not able to get through such "moving walls" if the smoke is thick.

How to select the dirction of $\boldsymbol{f}_{ih}$ is an interesting topic. A common method is assuming $\boldsymbol{f}_{ih}$ always impedes an agent movement in any direction, and thus $\boldsymbol{f}_{ih}$ is always opposite to the direction of moving velocity $\boldsymbol{v}_i$. In FDS+Evac we use (-HR%U, -HR%V) as a major component of $\boldsymbol{f}_{ih}$. Another option is using gradient of hazard intensity. This gradient is useful to represent the direction of heat radiation. The gradient points in the direction of the greatest increasing rate of hazard intensity, where the hazard intensity is described by gas temperature $TMP\_G\,(x, y)$, and thus the direction of $\boldsymbol{f}_{ih}$ is opposite to $TMP\_G\,(x, y)$, which points in the direction of the greatest decreasing rate of hazard intensity.

$$\nabla TMP\_G\,(x, y) = \frac{\partial TMP\_G}{\partial x} i + \frac{\partial TMP\_G}{\partial y} j$$

Another feasible method is using the direction of evacuation flow field. In FDS+Evac each main evacuation mesh generates a flow field with fire and smoke simulation. This flow field is useful to represent the gas flow from the heat source and it is usually consistent with the direction of heat flux and gas flow (See Figure 3). This flow field may also be useful to determine to direction of the hazard force, but we have not tested this method yet.

The direction of desired velocity is determined by way selection algorithm first. When smoke is detected by agents, the direction is modified: if smoke is not heavy, agents will update $\boldsymbol{v}_i^0$ to bypass smoke; in case of heavy smoke agents may shift to another exit. This refers to the high-level subroutine of exit selection and a simple logic is given as below.

If Hazard_Intensity>Threshold, an agent changes to another known exit

In sum when modeling agents' interaction with outside, we need to differentiate the effect of desired velocity and hazard force. The desired velocity is applied to characterize how agents intent to change the motion such as speed or direction. In contrast the hazard force is used to describe if the outside condition permits such a change or not. The two factor are conflicting, and they function together and give a whole picture of the model.

The difficulty of the above method is quantitative analysis. It is not quite easy to determine how fast evacuees desire moving in emergency egress as well as how evacuees perceive the smoke and heat. However, simulation provides us with a tool to adjust parameters and simulate different scenarios, and there are standard examples of FDS+Evac to test walking speed of evacuees in smoke conditions. Please refer to the section of supplementary data for details.

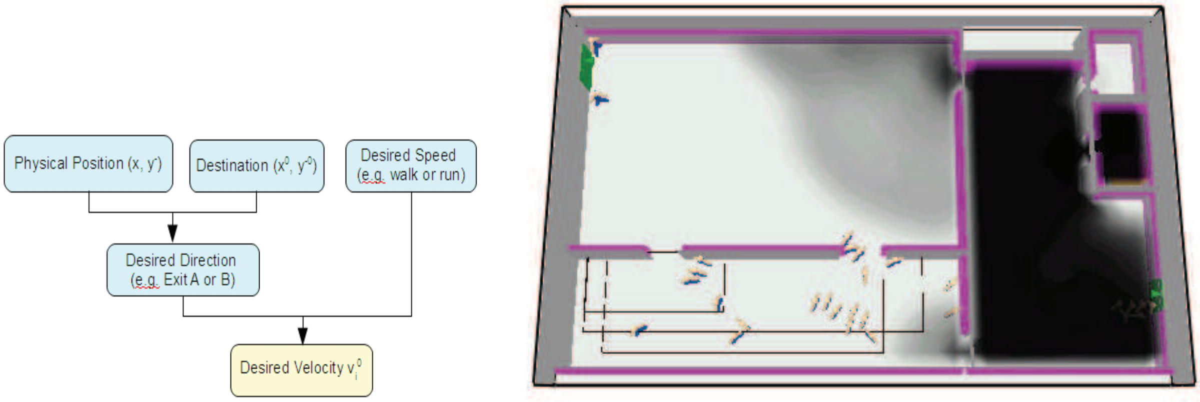


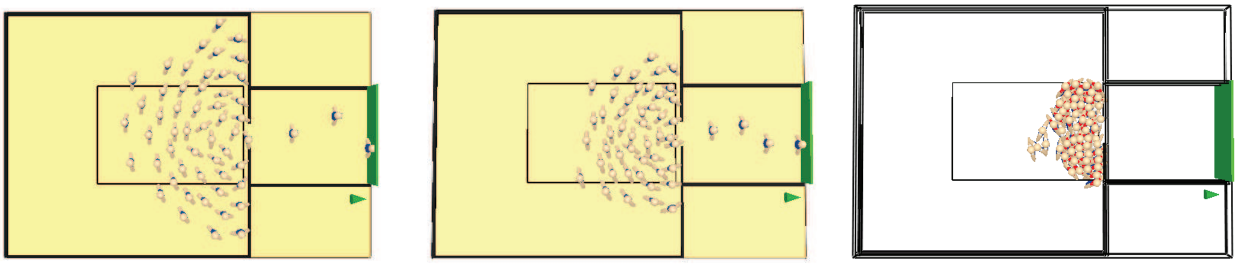
Figure 4. Simulation of Crowd Evacuation with Smoke: Evacuees change their destination and head for the left exit.

3. Adapting Desired Distance To Environmental Stressors

In the field of social psychology, social norms are defined as "representations of appropriate behavior" in a certain situation or environment. From the perspective of crowd modeling, the social norm is indicated by d_{ij}^0. For example in elevators or entrance of a passageway, people commonly accept smaller proximal distance, and the desired interpersonal distance is thus smaller, and d_{ij}^0 is to be scaled down proportionally in these places. In brief, d_{ij}^0 is occasion-dependent, and it varies along with locations.

Variation of d_{ij}^0 can be realized by using a computational fluid model, where d_{ij}^0 is proportional to density of crowd flow. This setting requires a compressible fluid model where flow density varies at different locations. At bottlenecks flow density decreases and flow speed increases, and this effect corresponds to the fact that people intends to decrease their interpersonal distance in order to pass through the bottleneck quickly. Thus, a compressible fluid model is very useful to guide variation of both d_{ij}^0 and v_i^0. In current version of FDS+Evac, only an incompressible fluid model is used to guide variation of v_i^0, and this is to be improved.

In emergencies the social norm is modified such that competitive behavior may emerge, and the model is thus applied to simulation of crowd behavior in emergency egress. In evacuation simulation Equation (1) can be better explained by flight-or-affiliation effect in psychological studies. The self-driving force motivates one to flee while the social force makes one interact with others. This effect may agree with social attachment theory in psychological study (Mawson, 2007; Bañgate et al., 2017). The social attachment theory suggests that people usually seek for familiar ones (e.g., friends or parents) to relieve stress in face of danger, and this is rooted from our instinctive response to danger in childhood when a child seek for the parents for shelter. Affiliated with familiar and trust individuals relieves our stress. Thus, different from the fight-or-flight response (Cannon, 1932), the modified social model well agrees with the flight-or-affiliation effect. Thus, the interpersonal distance in emergency escape is smaller than in normal situation, and people need to talk and exchange information with each other in emergency situation. The social norm is thus modified such that d_{ij}^0 is scaled down also. The parameter of A_i and B_i may also be scaled down so that the social force as a whole is reduced in such an occasion (Korhonen, 2017).



(a) (b) (c)

Figure 5 About Social Force and Faster-Is-Slower Effect: (a) Use large d_{ij}^0 in normal situation such that people obey social norm of large interpersonal distance. The result is decrease of flow rate and less chance of physical interaction. (b) Use small d_{ij}^0 in emergency egress such that people follow the social norm of small interpersonal distance. Flow rate thus increases and physical interaction increase in a stochastic sense. (c) As d_{ij}^0 continues to decrease, the physical interaction causes someone to fall down, and the doorway is thus blocked by those falling-down people.

To testify the above theory, we slightly modify the source program of FDS+Evac to implement the desired interpersonal distance. Below is the simulation result by FDS+Evac, and the example is based on IMO door flow test (IMO, 2007), where the door width is 1*m*, and it is also the door width used in Helbing, Farkas and Vicsek, 2000. The left diagram corresponds to large d_{ij}^0, where we specify $d_{ij}^0 = 3\cdot r_{ij}$, while the middle diagram corresponds to relatively small d_{ij}^0, where $d_{ij}^0 = 2\cdot r_{ij}$ is used. Here r_{ij} is the sum of the radii of individual *i* and *j*, namely, $r_{ij} = r_i + r_j$ (See Figure 2.1). The comparative results suggest that decreasing desired distance d_{ij}^0 moderately will increase the pedestrian flow rate at the bottleneck. This result explains why people tend to reduce their interpersonal distance at the entrance or exit because such behavior increases the egress flow rate and thus reduce egress time. Moreover the numerical testing also suggests that the two types of stressor could transform mutually The emergencies creates a kind of time-pressure which motivates one to speed up in escape. At certain bottlenecks such at entrance or exit people cannot speed up as desired, and thus time-related stressor is transformed into interpersonal stressor in order to pass through the bottleneck quickly (See Table 1).

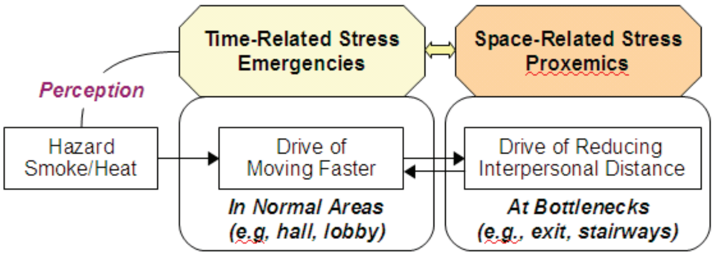


Figure 6. Two Types of Stress Transforming Mutually: The emergencies creates a kind of time-related stress which drives one to speed up in escape. At certain bottlenecks such at exit people cannot speed up as desired, and thus time-related stress is transformed into interpersonal stress in order to pass through the bottleneck quickly.

A common outcome of scaling down d_{ij}^0 is occurance of competitive behavior in crowd. In other words the physical force becomes effective among people and they may have more physical interaction at bottlenecks. As physical force is intensified, someone may fall down. The falling-down people become obstacle to others and thus slow down the egress flow, and they may cause others to fall down and this is so-called stampede disaster in crowd event. In sum the social force model with d_{ij}^0 is useful to investigate crowd behavior when jointly used with a falling-down model. As below FDS+Evac is used to realize the falling-down event where a pedestrian falls down when the physical force exceeds a threshold.

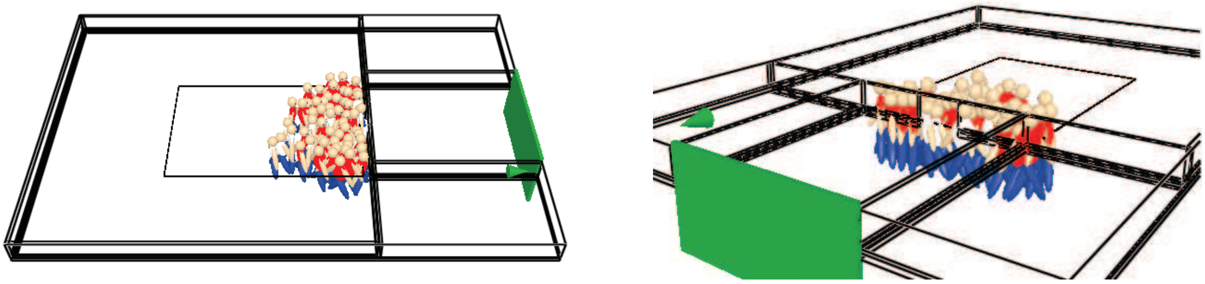


Figure 7. Crowd Escape at Bottleneck with Falling-Down Model: The white agents are falling-down agent who cannot move and are considered as obstacle to the moving agents. They fall down because the physical force exceeds a given threshold. The red agents are moving agent toward exit, and they have to get over the white ones to reach the door and the pedestrian flow rate is thus decreased.

APPENDIX

In the original setting of FDS+Evac an evacuation process is stimulated by using a pedestrian model based on the social-force model, where the psychological desire of individual motion is described by desired velocity v^0 at the microscopic level. The desired velocity v^0 is next coupled with the fire/smoke dynamics: In a non-smoke area v^0 is equal to a preset value called the unimpeded walking speed and this value gives the common speed of one's movement without any obstacles. When smoke density increases, v^0 will decrease in FDS+Evac because smoke reduces visibility over paths and interferes with normal breathing. As a result, people in smoke areas are given smaller v^0 such that they move slower than those in non-smoke areas.

In the evac.f90 the above method is realized as below. HR%FX_Hazard and HR%FY_Hazard are the force elements added to HUMAN_TYPE in type.f90. HEAT_GRAD_FAC is a scaling parameter which tunes smoke resistance with respect to gradient of TMP_G. SMOKE_BLK_FAC is is a damping coefficient which directly slows down agents' movement when agents walk in smoke condition.

```
HR%FX_Hazard = -HEAT_GRAD_FAC*(HUMAN_GRID(II,JJ)%TMP_G – HUMAN_GRID(II-1,JJ)%SOOT_DENS)*HUMAN_GRID(II,JJ)%TMP_G - SMOKE_BLK_FAC*HR%U*HUMAN_GRID(II,JJ)%SOOT_DENS/SQRT(HR%U**2 + HR%V**2)

HR%FY_Hazard = -HEAT_GRAD_FAC*(HUMAN_GRID(II,JJ)%TMP_G – HUMAN_GRID(II,JJ-1)%SOOT_DENS)*HUMAN_GRID(II,JJ)%TMP_G - SMOKE_BLK_FAC*HR%V*HUMAN_GRID(II,JJ)%SOOT_DENS/SQRT(HR%U**2 + HR%V**2)

HR%FX_Hazard = min(HR%FX_Hazard, HR%Mass*2.0_EB)

HR%FY_Hazard = min(HR%FY_Hazard, HR%Mass*2.0_EB)
```

Supplementary data

The supplementary data to this article are available online at https://github.com/godisreal/test-crowd-dynamics. The output data of FDS+Evac is uploaded in the repository. If you have any comment or inquiry about the testing result, please feel free to contact me at wp2204@gmail.com or start an issue on the repository.

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