Modeling of Smoke-and-Human Interaction in FDS+Evac

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This brief report presents a model to characterize the walking behavior of evacuees in smoke conditions. The model is based on the well-known social-force model and could be applied to modeling of crowd evacuation in fire emergency.

I. The Original Setting in FDS+Evac

In 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 $\boldsymbol{v}^0$ at the microscopic level. The desired velocity $\boldsymbol{v}^0$ is next coupled with the fire/smoke dynamics: In a non-smoke area $\boldsymbol{v}^0$ 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, $\boldsymbol{v}^0$ 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 $\boldsymbol{v}^0$ such that they move slower than those in non-smoke areas.

II. Our Revision

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 $\boldsymbol{v}^0$ 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 1).

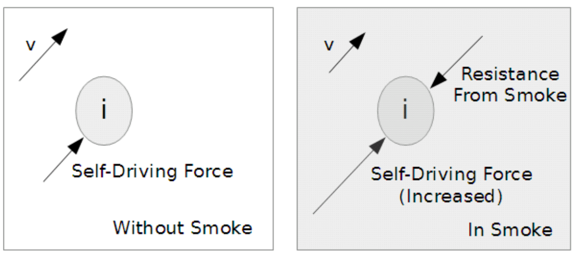

Figure 1.

A. About the magnitude

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. 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.

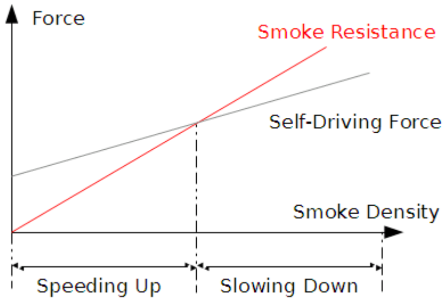

Figure 2.

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

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

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 heat radiation. 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.

B. About the direction of hazardous force

How to select the direction of $\boldsymbol{f}_{ih}$ is an interesting topic, and a component of the resistance is obtained by computing the gradient of the smoke density (i.e., SOOT_DENS) in a 2D space. This planar space is determined by a user-given height called HUMAN_ SMOKE_HEIGHT.

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

The above gradient points in the direction of the greatest rate of increase of the function $SOOT\_DENS\,(x, y)$, and thus the direction of $\boldsymbol{f}_{ih}$ is opposite to $\nabla SOOT\_DENS\;(x, y)$, which points in the direction of the greatest rate of decrease of smoke density. The smoke resistance can be formulated as

$$\boldsymbol{f}_{ih} = -K \times \left(\frac{\partial\, SOOT\_DENS}{\partial\, x}\, i + \frac{\partial\, SOOT\_DENS}{\partial\, y}\, j \right) \times (\mathrm{SOOT\_DENS})$$

The direction of the desired velocity should be determined by the choice of exit first. When smoke is detected by the agents, the moving direction should be modified: if the smoke is not heavy, agents will update $\boldsymbol{v}_i^0$ to bypass the smoke; if the smoke is heavy, agents may change to another exit. This refers to the high-level program of exit selection and a simple example is

If SOOT_DENS>Threshold, an agent change to another known exit

APPENDIX

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. SMOKE_GRAD_FAC is a scaling parameter which tunes smoke resistance with respect to gradient of SOOT_DENS. SMOKE_BLK_FAC is is a damping coefficient which directly slows down agent's movement in smoke conditions.

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

HR%FY_Hazard = -SMOKE_GRAD_FAC*(HUMAN_GRID(II,JJ)%SOOT_DENS – HUMAN_GRID(II,JJ-1)%SOOT_DENS)*HUMAN_GRID(II,JJ)%SOOT_DENS - 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)

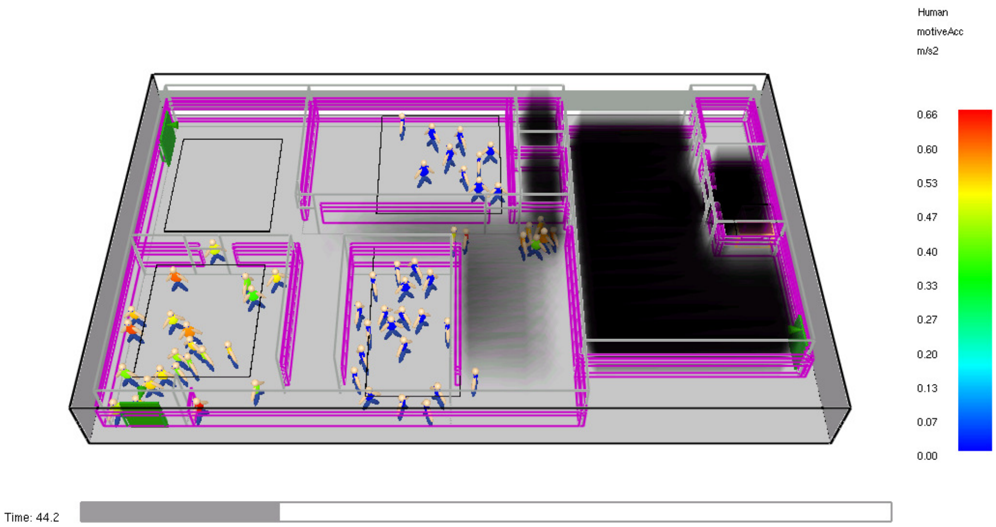

Figure 3. Simulation of Crowd Evacuation with Smoke

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