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Behavioral effect on pedestrian evacuation simulation using cellular automata

Dewei Li [a,*], Baoming Han [b]

[a] State Key Lab of Rail Traffic Control & Saftey, Department of Traffic and Transportation, Beijing Jiaotong University, Beijing 10044, China
[b] Department of Traffic and Transportation, Beijing Jiaotong University, Beijing 10044, China

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ABSTRACT

A pedestrian evacuation simulation model based on the extended cellular automata is proposed with the consideration of heterogeneous behavioral tendencies in humans. We investigated two behavioral tendencies, namely, familiarity and aggressiveness. Our simulation experiments tested the values of the behavioral parameters and the pedestrian flow composition. The model is calibrated and validated by using hand calculation, fundamental diagrams of traffic flow and evacuation experiments. The results show that the evacuation time decreases exponentially with an increase in the evacuees' site familiarity and increases when pedestrians are either too conservative or too aggressive. The optimum evacuation was associated with higher familiarity and no aggressive preference. Altering the conservative compositions of pedestrian groups showed that there is a turning point for each density, depending on the proportions of conservative pedestrians. Prior to this point, the evacuation time is a relatively constant value. After this point, the evacuation time increases and fluctuates. This finding demonstrates that at high densities, a few leaders in pedestrians can significantly reduce the evacuation time. The model is able to simulate evacuation effectively given the diverse behavior strategies of evacuees, such as herding and communication between evacuees. In addition, the model can explain some basic principles of fundamental diagrams of traffic flow. Furthermore, the model is applied to optimize buildings to reduce evacuation times. Case studies show that the evacuation time can be dramatically decreased if a building is optimized to reduce interactions between different groups of pedestrians by separating flows or expanding the exit width. However, such strategies are effective only under high pedestrian densities. Placing signs and guides is also helpful for improving the evacuation performance. We conclude that behavioral tendencies have a strong influence on evacuation time.

1. Introduction

As an important branch of safety research, pedestrian evacuation has been studied extensively. The period of evacuation is one of the most crucial lifesaving periods during disasters such as fires (Lerup et al., 1978). It is essential to estimate pedestrian evacuation times accurately. For engineers, studying pedestrian evacuation can help them optimize architecture design to decrease the number of injury and death due to disordered evacuations. The total evacuation time has two major components (DiNenno, 2008): (1) the delay time to starting the evacuation movement and (2) the time needed to travel to a safe place. This paper mainly focuses on the latter component.

An evacuation trial is a straightforward method to obtain the evacuation time. However, it is too expensive, time consuming and dangerous. Therefore, simulation models are widely used in evacuation studies. Basically, existing evacuation simulation models can be classified as macroscopic models or microscopic models based on the representation form of the pedestrian in the model. The latter can be classified as a continuous model or discrete model in terms of the spatial representation. Each model can also be classified as a movement model or behavioral model according to whether the model simulates the effect of pedestrian behavior.

Macroscopic evacuation models are based on a queue network (Løvås, 1994). They construct a physical environment as a network of nodes connected by arcs. Pedestrians are modeled as flow. Pedestrian flow moves from one node to another via arcs without exceeding the capacity of each node or arc. The transfer speed is determined by the relationship between speed and density in fundamental diagrams of traffic flow. EVACNET4 model (Kisko et al.,

* Corresponding author.
E-mail addresses: lidw@bjtu.edu.cn (D. Li), bmhan@bjtu.edu.cn (B. Han).

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1998), EESCAPE (Kendik, 1995), EGRESSPRO (Simenko and Peter, 2001) and TIMTEX (Harrington, 1996) are widely known as macroscopic evacuation models. One of the most critical issues of the macroscopic evacuation models is that they are all based on the assumption of pedestrian homogeneity, which cannot explain the interactions between different types of pedestrians. Thus, it is difficult to reproduce pedestrians' collective behavior with these models.

Microscopic evacuation models describe the physical environment as a geometric setting and pedestrians as individuals. These models can address the pedestrian homogeneity problem. Based on the theory they adopt, microscopic evacuation models can be further classified as continuous models or discrete models. Continuous models consider a pedestrian as a particle in a continuous space. In continuous models, Reynolds (1987) simulates pedestrian behaviors, such as flocking, schooling, and herding. Physics theory was first employed in an evacuation simulation study by Okazaki and Matsushita (1993), who used a magnetic model to simulate pedestrians' evacuation in buildings and queuing areas. Pedestrians were compared to atoms with attractive and repulsive forces. The model parameters were not validated by the empirical study. Helbing et al. (2000) developed a social force model to simulate human evacuation. The model provides a way to show the forces among crowd pedestrians and the interactions between pedestrians and obstacles. The concept of social force reflects some of the psychological effects of humans in an evacuation, but no evidence shows it is suitable for the fundamental diagram. Schadschneider et al. (2010) developed a simple asymmetric exclusion model. In another model distilled from the physics of gas dynamics, Hoogendoorn and Bovy (2000) proposed a gas-kinetic model to illustrate pedestrian flow characteristics. Simulex (Thompson and Marchant, 1996) and ASERI (Schneider, 2001) are two evacuation tools based on continuous models. However, in Simulex, the assumptions of a regular pedestrian distribution, the sequential update rule and neglecting inter-pedestrian interactions are not appropriate. ASERI attempts to add more behavioral factors by using priority rules. However, these are rules limited to the pre-evacuation stage.

Due to complex calculations, it is very difficult to simulate complicated geometries and large-scale scenarios with continuous models. Consequently, discrete models have been introduced in pedestrian evacuation simulations. The cellular automaton (CA) is the most widely used discrete simulation model in pedestrian evacuation. It considers space as a grid with discretized cells that pedestrian can occupy. At each time step, pedestrian movements are driven by a fixed set of rules. Gipps and Marksjö (1985) proposed a cost–benefit model. This model is an initial form of the cellular automata (CA) model in pedestrian simulation. In this model, open areas are represented as a grid that is made up of cells. Pedestrians move from one cell to its neighbor cells based the shortest path rule. This model simplified pedestrian movement to a number of rules, which is useful for describing pedestrian interactions in simulation. However, the cost–benefit model suffers from the arbitrary scoring of cells and pedestrians. The wide use of CA in pedestrian simulations began in the 1990s, when Blue and Adler (1998, 2000) used five simple rules to simulate pedestrian flow effectively.

To date, many different types of CA models have been adopted to simulate pedestrians. In terms of pedestrian motion-driven rules, they can be classified as a Two Process Model (Blue and Adler, 1998, 2000), Lattice Gas Model (Muramatsu and Nagatani, 2000; Takimoto et al., 2002; Tajima et al., 2002; Isobe et al., 2004), Floor Field Model (Burstedde et al., 2001; Kirchner and Schadschneider, 2002; Kirchner et al., 2003; Zhang et al., 2008; Zhang and Han, 2011; Zhang, 2015), Pre-fixed Probabilities Model (Weifeng, 2003; Jian et al., 2005), Dynamic Parameters Model (Yue, 2007), Real-coded CA Model (Yamamoto, 2007) or Multi-grid Model (Song, 2006). The common characteristic of these models is that the probabilities for a pedestrian's route choice are decided by either the long-range environmental conditions, the short-range pedestrian dynamics or both. Evacuation models such as EGRESS (Simenko and Peter, 2001), Pathfinder (Cappuccio, 2000) and PedGo (Klupfel and Meyer-Konig, 2003) have been developed based on the CA model. In summary, most of the CA models represent pedestrians as a multiple particle system. These models are overly concerned with pedestrian movement, not pedestrians' social behavior (Santos and Aguirre, 2004). Models such as EXODUS attempt to incorporate sociological behavioral factors, including gender, age, maximum running speed, maximum walking speed, response time, agility and patience, into the model. However, pedestrian movement is still determined by the same rule and not influenced by these factors. Under this assumption, the behaviors of pedestrians (especially the rules for route selection) are similar among individuals. There is little relationship between pedestrian movement and individual characteristics. In reality, as a social system, the safety and efficiency of pedestrian evacuation are highly affected by the heterogeneous behavioral effects of individual participants' characteristics. For example, in the same high density crowd scenarios, only a few resulted in panics (Fruin, 1971). Those panics were always caused by the tension or aggressive behavior of some pedestrians. Even in the same scenario, a different composition of pedestrian groups may result in different outcomes. Currently, some researchers have recognized the problem, yet few studies related to the effects of evacuees' behavioral characteristics have been conducted. Luh et al. (2012) established a network-flow model that took into account the effect of blocking effects on crowd movement. Hoogendoorn and Bovy (2000) noted that people's cognitive and emotional states and overt behavior should be taken into account in evacuation models. Zheng (2009) noted that psychological and physiological elements affecting individual and collective behaviors should also be incorporated into evacuation models.

A summary of the evacuation models and related features is shown in Table 1. In Table 1, only the models that are publicly available are refereed. These models are listed according to eight properties. The classification property indicates whether the model is macroscopic (Macro) or microscopic (Micro). Moreover, if a model is a cellular automata model (CA), it is marked separately; the physical environment property shows the way the model represents the physical environment. The physical environment is modeled as a network, square grid, hexagonal cells or continuous space. The pedestrian property shows whether a pedestrian is represented homogeneously or heterogeneously in the model. The movement model property shows the driving mechanism of pedestrians in the model. Most of the model assigns the speed to individuals based on the pedestrian density or a set of rules. Only one model uses the density of smoke. The behavioral model property indicates whether the model fully contains ($\surd$), partially contains (○) or does not contain ($\times$) behavior. The process property indicates whether the simulation is deterministic or stochastic. The validation property indicates the validation method of the model; generally, the validation can be performed by comparing the total evacuation time by simulation with code requirements (C), past drills (D), experiments (E), and other models (M). In the table, most of the existing models are calibrated by comparing the total evacuation time with a drill or evacuation experiment. For some models, no indication of validation is provided. These models' validation properties are marked as "*N*". The building optimization property indicates whether the behavioral part of the model is used to optimize the building.

To date, the literature on pedestrian evacuation has given little attention to the extensive behavioral characteristics of pedestrian