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Macroscopic pedestrian flow model with degrading spatial information

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ABSTRACT

This paper presents a macroscopic dynamic model for pedestrian flow with degrading spatial information. In this model, it is assumed that a pedestrian has the ability to realize the local walking cost degrades with the "distance" away from him/her, which is measured by the perceived travel cost incurred between origin and destination. Each pedestrian always chooses a path with the lowest instantaneous perceived walking cost to the specific destination, based on current traffic conditions that is available at the time of decision-making. This model is numerically solved by a cell-centered finite volume scheme and a fixed-point iterative sweeping method. A numerical example for pedestrian evacuation in an L-shaped channel is designed to validate the capability of this model and the effectiveness of the present algorithm.

1. Introduction

Pedestrian dynamics has attracted considerable attention in the past decade due to its importance in effective control and management of pedestrian traffic. The research on pedestrian modeling and simulation can gain insight into microscopic and macroscopic characteristics of pedestrian movement under a variety of circumstances. Many interesting collective effects and self-organisation phenomena of pedestrian dynamics, e.g., arching and clogging in front of the exits, oscillations at bottlenecks and stripe formation in intersecting flows, have been captured based on numerical simulations and experiments [1–3]. These observations can help us optimize pedestrian walking infrastructures and provide support for some theoretical questions, in particular for evacuation situations.

From a conceptual point of view, pedestrian simulation models can be typically classified into three categories: microscopic, mesoscopic and macroscopic models. The microscopic models mainly encompass rule-based models, e.g., cellular automata (CA) models [4–8], lattice gas (LG) models [9–13], social force (SF) models [2,14–17] and agent-based models [18–20]. At present lots of simulation results on pedestrian flows and evacuation process in different scenarios are obtained based on microscopic models [21]. For example, Chen et al. [6] studied the mechanism of T-shaped effects on evacuation behavior by a force-driving CA model. Nagai et al. [10] used an extended LG model to study the dependency of the escape time distributions on the exit configurations without visibility. Ma and Wang [16] adopted a modified SF model to study the relation between the evacuation time and the view radius and proposed useful methods to decrease the evacuation time. Guo and Tang [22] utilized a microscopic pedestrian model to investigate the effects of the corner of walkway and found that increasing the turning degree of corner has negative impact on the pedestrian queues under certain conditions. Vizzari et al. [19] presented an agent-based model to study the adaptive mechanism for the preservation of group cohesion in the T-junction scenario. Recently, hybrid models have been proposed on the basis of the ideas of both microscopic and macroscopic crowd models [23]. Mesoscopic models like gas-kinetic models [24–26] are built based on the mathematical kinetic theory for active particles. The kinetic theory description is used when the state of the system is still identified by the position and velocity of the microscopic entities, but their representation is given by a suitable probability distribution over the microscopic state. This type of models generally describe the evolution of this distribution function introducing numerous undetermined parameters and using nonlinear integro-differential equations [24]. Because of this, these models are suitable for a

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small-scale environment in which the number of individual entities is not large enough to allow the use of continuous distribution functions within the framework of the mathematical kinetic theory.

A good understanding of macroscopic features of pedestrian flow (e.g., flow, density and velocity) is useful and necessary to design pedestrian facilities, control crowd movements and predict the level of service especially in a large-scale environment [27–33]. Colombo and Rosini [27] presented a unidimensional macroscopic model to describe features of pedestrian flow, such as the fall due to panic in the outflow of people through a door. Huang et al. [28] developed a reactive dynamic user equilibrium (RDUE) model for unidirectional pedestrian flow in a railway platform. Xia et al. [29] investigated the beneficial memory effect on pedestrian evacuation based on a macroscopic pedestrian flow model. This model was extended by Jiang et al. [30] to simulate bi-directional pedestrian flow and self-organisation phenomena in intersecting flows were reproduced based on this extended model. Jiang et al. [31] developed a higher-order macroscopic model which is able to describe complex phenomena such as "stop-and-go waves" observed in empirical pedestrian flow. Twarogowska et al. [32] further showed that the higher-order model can reproduce clogging at bottlenecks and Braess paradox, i.e., pedestrian flow through a bottleneck may be increased by placing an obstacle in front of it. As discussed above, the development of macroscopic models for pedestrian flow is still in its infancy, and deserves continued investigation.

In this paper, we present a macroscopic pedestrian flow model with degrading spatial information to simulate macroscopic features and path-choice behaviors of pedestrian flow in a two-dimensional (2D) continuous walking facility. The model consists of a flow conservation equation and a Hamilton-Jacobi (HJ) equation. In this model, we assume that a pedestrian in the facility always walks along the lowest-cost path from origin to destination, due to his/her awareness of the specific destination and surroundings. The perceived local walking cost for each pedestrian degrades with the "distance" away from him/her (i.e. the length of the used path), which is actually estimated by his/her own perceived travel cost within a macroscopic modeling framework. The algorithm for this model is composed of a cell-centered finite volume (FV) scheme for the flow conservation equation and a fixed-point iterative sweeping method for the HJ equation on orthogonal meshes. An L-shaped channel for pedestrian evacuation is designed to verify the capability of this model and the effectiveness of the algorithm.

The remainder of this paper is organized as follows. In Section 2, we present the mathematical model of pedestrian flow with degrading spatial information. Section 3 deals with the numerical algorithm of the model. In Section 4, a numerical example is provided to investigate macroscopic characteristics and path-choice behavior of pedestrian flow in the L-shaped channel. Conclusions are finally provided in Section 5.

2. Problem formulation

In this work, we consider a large group of pedestrians moving through a 2D continuous walking facility whose bidirectional representation is denoted by Ω (in m^2). The boundary of wall delimiting areas in which no pedestrian is allowed to enter or leave is denoted by Γ_w (in m). The exit of the walking facility is expressed by Γ_d (in m). Similar to most physical systems, the pedestrian density, velocity and flow satisfy the following mass conservation law.

$$\rho_t(x,y,t) + \nabla\cdot\mathbf{F}(x,y,t) = 0, \tag{1}$$

where $\rho(x, y, t)$ (in ped/m^2) is the density of pedestrian flow at location $(x, y) \in \Omega$ and time $t \in [0, T]$ (in s) and $\mathbf{F}(x, y, t) = (f_1(x, y, t), f_2(x, y, t))$ (in ped/m/s) is the pedestrian flow vector with fluxes $f_1(x, y, t)$ and $f_2(x, y, t)$ (in ped/m/s) in the x and y directions, respectively. Note that

$$\left\|\mathbf{F}(x,y,t)\right\| = (f_1(x,y,t)^2 + f_2(x,y,t)^2)^{1/2} = U(x,y,t)\rho(x,y,t), \tag{2}$$

where $U(x, y, t) = U(\rho(x, y, t))$ (in m/s) denotes the local walking speed of pedestrian movement, which describes the pedestrian speed-density relationship.

We further define $C(x, y, t)$ (in s/m) as the local walking cost per unit distance of movement at location $(x, y) \in \Omega$ and time t. Here, $C(x, y, t)$ can be location and time dependent to represent pedestrian behaviors such as the preference for walking away from the boundary of wall delimiting areas and the value placed on time at different times of day. The travel cost mainly represents the travel time, and the cost distribution $C(x, y, t)$ is thus defined as the inverse of the walking speed

$$C(x,y,t) = \frac{1}{U(x,y,t)}. \tag{3}$$

Based on the instantaneous flow state at time t, pedestrians evaluate the cost of walking from origin $(x, y) \in \Omega$ to the destination Γ_d by integrating the local cost function $C(x, y, t)$ along the trajectory. To discuss the lowest instantaneous travel cost incurred by pedestrians from origin to destination, we define $\Phi(x, y, t)$ as the cost potential from location $(x, y) \in \Omega$ to the specific destination Γ_d at time t.

It is assumed that a pedestrian at location $(x, y) \in \Omega$ is familiar with the destination and surroundings. Therefore, he/she always chooses a path that minimizes his/her individual walking cost from origin to destination, based on instantaneous traffic conditions that is available at the time of decision-making. In the moving process, the pedestrian has the ability to realize the local walking cost degrades with the "distance" away from him/her, i.e., the length of the used path from location $(x, y) \in \Omega$ to destination. To model this behavior, we assume that

$$[1+\xi(x,y,t)\Phi(x,y,t)]C(x,y,t)\frac{\mathbf{F}(x,y,t)}{\left\|\mathbf{F}(x,y,t)\right\|} + \nabla\Phi(x,y,t) = 0. \tag{4}$$

Here, $\xi(x, y, t)$ is the sensitivity function that represents the rate of information decay and is supposed to increase with density $\rho(x, y, t)$.

$$\xi(x,y,t) = \frac{\xi_0\rho(x,y,t)}{\rho_{\max}}, \tag{5}$$

where ρ_{max} (in ped/m^2) is the maximum density of pedestrian flow and $\xi_0 \in [0, \xi_{max}]$ denotes the degree of sensitivity of pedestrians to the decay of spatial information with a bounded value ξ_{max}. Here, ξ_{max} is generally influenced by the structure of a walking facility (e.g. with or without obstacles).

From Eq. (4), we can obtain the following property (see [28]),

$$\mathbf{F}(x,y,t) \quad // \quad -\nabla\Phi(x,y,t), \tag{6}$$

where "//" indicates that the two vectors are parallel and point in the same direction. In addition, we can show that

$$[1+\xi(x,y,t)\Phi(x,y,t)]C(x,y,t) = \left\|\nabla\Phi(x,y,t)\right\|, \tag{7}$$

which is a "stationary" HJ equation for a fixed time t. Based on Eq. (3), Eq. (7) can be rewritten as

$$\left\|\nabla\Phi(x,y,t)\right\| = \frac{1}{(1/(1+\xi(x,y,t)\Phi(x,y,t)))U(x,y,t)}, \tag{8}$$

where $1/(1+\xi\Phi)U$ represents the perceived local walking speed of pedestrian movement. The discount factor $1/(1+\xi\Phi)$ can be regarded as discomfort perceived by pedestrians when walking along a path with large cost.