Physica A 441 (2016) 51–61

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

Comparison study of the reactive and predictive dynamic models for pedestrian flow

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HIGHLIGHTS

- Two higher-order dynamic models, i.e. reactive vs. predictive, for pedestrian flow are formulated and compared.
- The algorithm used to solve the two dynamic models is designed.
- Numerical results show that the two models are able to reproduce the formation of stop-and-go waves and the blocking effect at bottlenecks.
- The patterns of the local structured clusters are distinctly different at bottlenecks due to different path-choice behaviors of pedestrians.
- The strong anticipation consciousness of pedestrians to compression can avoid congestion and thereby reduce accidents in pedestrian traffic.

ARTICLE INFO

Article history:
Received 2 March 2015
Received in revised form 27 July 2015
Available online 8 September 2015

Keywords:
Pedestrian flow
Reactive dynamic user-equilibrium
Predictive dynamic user-equilibrium
Traffic instability
Stop-and-go waves

ABSTRACT

This paper formulates the reactive and predictive dynamic models for pedestrian flow and presents a comparison of the two models. The path-choice behavior of pedestrians in the reactive dynamic model is described that pedestrians tend to walk along a path with the lowest instantaneous cost. The desired walking direction of pedestrians in the predictive dynamic model is chosen to minimize the actual cost based on predictive traffic conditions. An algorithm used to solve the two models encompasses a cell-centered finite volume method for a hyperbolic system of conservation laws and a time-dependent Hamilton–Jacobi equation, a fast sweeping method for an Eikonal-type equation, and a self-adaptive method of successive averages for an arisen discrete fixed point problem. The two models and their algorithm are applied to investigate the spatio-temporal patterns of flux or density and path-choice behaviors of pedestrian flow marching in a facility scattered with an obstacle. Numerical results show that the two models are able to capture macroscopic features of pedestrian flow, traffic instability and other complex nonlinear phenomena in pedestrian traffic, such as the formation of stop-and-go waves and clogging at bottlenecks. Different path-choice strategies of pedestrians cause different spatial distributions of pedestrian density specially in the high-density regions (near the obstacle and exits).

1. Introduction

In recent years, pedestrian traffic problems have attracted considerable attention of scientists from different fields. The study on pedestrian and crowd dynamics can help to develop guidelines for planning and designing pedestrian facilities.

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http://dx.doi.org/10.1016/j.physa.2015.08.047

The modeling of pedestrian crowd dynamics is generally classified into three approaches: the microscopic, mesoscopic and macroscopic modeling approaches. The microscopic modeling approach focuses on the details of features of pedestrian movement and the behavior characteristics of each individual in a crowd. Microscopic models mainly encompass discrete space models (e.g. cellular automaton models [1–4] and lattice gas models [5–8]) which allow pedestrians to walk at or within a fixed note or grid and update the current positions at discrete time intervals, and continuous space models (e.g. social force models [9–11]) which allow pedestrians to move continuously within a pre-defined geometry [12]. Most microscopic models can reveal many interesting phenomena in pedestrian dynamics, e.g. clustering or queuing at bottlenecks, stripe formation and chevron effect [13,14]. Mesoscopic models like gas-kinetic models [15–18] are built based on the mathematical kinetic theory for active particles and have the ability to retain various complexity features of crowds viewed as a living system. For example, pedestrian fundamental diagrams may be generated by individual-based interactions based on kinetic theory methods [19,20]. In the mesoscopic equations, the state of the system is identified by the position and velocity of the microscopic entities, but their representation is given by a suitable probability distribution over the microscopic state [15,16]. This type of models can describe the evolution of this distribution function by introducing numerous undetermined parameters and using nonlinear integro-differential equations. Therefore, they are suitable for a 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 [15].

The modeling and simulation of complex crowd movement based on microscopic and mesoscopic models generally increase the computational complexity and model parameters with the increase of the scale of individuals. In the case of a large group of pedestrians, the movement of pedestrians should behave very similar to gas particles and thus pedestrians in a large group can be treated as a flowing continuum [21]. Therefore, the macroscopic modeling approach has been extensively concerned. So far only a few of macroscopic models for unidirectional and bi-directional pedestrian flows are proposed to investigate macroscopic features of crowd movement (e.g. density, speed and flow) and behavior characteristics of pedestrians on the macroscopic scale. Based on different user-equilibrium (UE) path-choice strategies of pedestrians, namely the reactive dynamic user-equilibrium (RDUE) assignment and the predictive dynamic user-equilibrium (PDUE) assignment, macroscopic models of pedestrian flow can be divided into reactive dynamic models and predictive dynamic models. In the reactive dynamic models, pedestrians tend to choose a path from origin to destination with the lowest instantaneous walking cost based on current traffic information available to them [22–26]. In the predictive dynamic models, pedestrians' path-choice behavior is described under the hypothesis that pedestrians aim to minimize the actual walking cost from/at the current position/time to the destination based on predictive traffic conditions [27–29].

Macroscopic models of pedestrian flow, which use the continuum equation to describe the evolution of traffic density, are called first-order models. The first-order models [21–26] are actually a generalization of the Lighthill–Whitham–Richards (LWR) models proposed for vehicular traffic flow [30]. Compared to the LWR models of vehicular traffic flow, macroscopic models of pedestrian flow need to capture the dynamics of pedestrians walking in a two-dimensional (2D) or three-dimensional (3D) space and the dynamics of the interactions and the overall strategy influenced by environmental conditions [31], therefore they are more complex. The first-order models are shown to be a useful tool for the planning and design of walking facilities, but they assume the existence of an equilibrium speed–density relationship (or so-called fundamental diagram) and a natural trend toward this distribution. This type of models certainly cannot reproduce non-equilibrium phase transitions and various nonlinear dynamic phenomena observed in empirical studies [32,33]. To resolve this problem in the first-order models, higher-order models [31,34,35], which are composed of the conservation of mass and the equilibrium of linear momentum for expressing the pedestrian acceleration/deceleration dynamics, have been studied in recent years for allowing the actual velocity of motion to fluctuate around the equilibrium diagram.

In this paper, we formulate the reactive and predictive dynamic models for unidirectional pedestrian flow and present a comparison of the two dynamic models. The reactive dynamic model consists of a hyperbolic system of conservation laws with relaxation and an Eikonal-type equation [34] and the predictive dynamic model is described as a hyperbolic system of conservation laws with relaxation coupled with a time-dependent Hamilton–Jacobi (HJ) equation. An algorithm used to numerically solve the two models is composed of a cell-centered finite volume method (FVM) for the hyperbolic system of conservation laws and the HJ equation, a fast sweeping method (FSM) for the Eikonal-type equation, and a self-adaptive method of successive averages (MSA) for an arisen discrete fixed point problem. A numerical experiment is carried out to investigate macroscopic features (e.g. the spatio-temporal distributions of density) and route-choice behavior characteristics of pedestrian flow walking in a 2D continuous pedestrian facility scattered with an obstacle. We also compare the patterns of spatial distributions of pedestrian densities obtained by the two dynamic models.

The present work is organized as follows. Mathematical models for pedestrian movement are presented in Section 2. Section 3 gives numerical methods used to solve these models. Section 4 presents numerical results. Section 5 is devoted to summary and discussion.

2. Mathematical formulation

We regard a large group of pedestrians walking in a 2D continuous domain denoted by Ω as a compressible continuum fluid medium. The boundary of Ω consists of inflow boundary Γ_i, outflow boundary Γ_o and solid wall boundary Γ_w. $T = [0, t_{end}]$ (in s) is the modeling period.