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Potential-based dynamic pedestrian flow assignment

Ren-Yong Guo*

School of Economics and Management, Beihang University, Beijing 100191, China
Key Lab of Complex System Analysis and Management Decision, Ministry of Education, China

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ABSTRACT

This study proposes a potential-based dynamic pedestrian flow assignment model to optimize the evacuation time needed for all pedestrians to leave an indoor or outdoor area with internal obstacles and multiple exits, e.g., railway station, air terminal, plaza, and park. In the model, the dynamic loading of pedestrian flows on a two-dimensional space is formulated by a cell transmission model, the movement of crowds is driven by space potential, and the optimization of evacuation time is solved by a proportional swapping process. In this way, the proposed model can be applied to not only efficiently optimize the evacuation process of a crowd with large scale but also recognize local congestion dynamics during crowd evacuation. Finally, a set of numerical examples are presented to show the proposed model's effectiveness for optimizing crowd evacuation process and its application to design a class of variable guide sign systems.

1. Introduction

Increases in urban populations and mass events have raised interest among researchers and authorities in the problems of pedestrian and crowd dynamics. So far, a number of research results on pedestrian and crowd behaviors have been generated. These research results concerned different topics in the field of pedestrian traffic, including pedestrian interacting with visual attractors in the environment (Wang et al., 2014), pedestrian boarding and alighting in metro stations (Seriani and Fernandez, 2015), uni-directional/bi-directional pedestrian flows (Guo et al., 2016), pedestrian flow model considering the impact of local density (Xiao et al., 2016), pedestrian dynamic at signalized intersections (Zeng et al., 2017), measurement of congestion and intrinsic risk in pedestrian crowds (Feliciani and Nishinari, 2018), fine space discretization of microscopic pedestrian models (Fu et al., 2018), pedestrian crossing in congested traffic (Hacohen et al., 2018), and so on. These research results are helpful for maintaining public facility service levels and ensuring pedestrian safety. Readers may refer to Duives et al. (2013), Francisco et al. (2017), and Haghani and Sarvi (2018) for recent development and survey of pedestrian and crowd dynamics in the aspects of both empirical and modeling methods.

In the field of pedestrian traffic, an important research topic is the pedestrian traffic assignment problem (or pedestrian route choice problem). Given the space layout and traffic volumes in a pedestrian facility, the aim of pedestrian traffic assignment is to predict the space distribution of pedestrian flows in the facility. The space distribution measures and reflects walking convenience, comfort, efficiency, and safety in the facility. In this paper, we focus on the subject of dynamic pedestrian flow assignment during evacuation from an indoor or outdoor area with internal obstacles and multiple exits, e.g., railway station, air terminal, plaza, and park. When pedestrians evacuate the area, their route choice is a critical behavioral reaction that affects the efficiency of their evacuation. Once they cannot appropriately select their evacuation routes, a phenomenon in which many individuals collect on a few routes is likely to occur, leading to inefficient evacuation or even accidents caused by jamming. We will design an algorithm for

* Address: School of Economics and Management, Beihang University, Beijing 100191, China.
E-mail address: buaa_guorenyong@126.com.

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optimizing the evacuation efficiency of pedestrians from the area. Our work would lay the groundwork for route planning and finding meaningful locations for signs in pedestrian facilities.

For a pedestrian evacuation, especially emergency evacuation, it is essential to obtain an optimal pedestrian flow assignment pattern on space during the process. An optimal flow assignment pattern provides a criterion or objective for managing evacuation pedestrian flows and planning evacuation routes. In other words, the objective for evacuation management is to make evacuation pedestrian flow assignment approach to an optimal flow assignment pattern as far as possible. In this way, the evacuation efficiency of pedestrians is improved.

The pedestrian flow assignment problem can be studied in either empirical methods (e.g., Helbing et al., 2003; Jeon et al., 2011; Guo et al., 2012, 2013; Gao et al., 2014; Haghani and Sarvi, 2017) or modeling methods. By empirical methods based on observations and experiments, pedestrian data are obtained to provide data support for designing pedestrian facility and making evacuation strategy. Moreover, pedestrian data can also be used to validate and calibrate pedestrian models. Pedestrian flow assignment models can be further categorized into network-based models (e.g., Lin et al., 2008; Chen and Feng, 2009; Pursals and Garzón, 2009; Yuan et al., 2009; Wagoum et al., 2012) and individual-based models (e.g., Hoogendoorn and Bovy, 2004; Huang and Guo, 2008; Kretz, 2009; Asano et al., 2010; Guo and Huang, 2012; Guo et al., 2012, 2013; Gao et al., 2014; Kretz et al., 2014; Abdelghany et al., 2016; Crociani and Lämmel, 2016; Lu et al., 2017).

In these network-based models, the spatial layout of a pedestrian facility is represented by a network based on the facility's actual structure. Accordingly, each node in the network represents a passageway, walkway, or section of the spatial layout irrespective of its physical dimensions. These nodes are connected by arcs that represent the actual openings between separate components. This class of models is generally used to form solutions to optimization problems, which aim to optimize the evacuation routines of pedestrians so as to improve pedestrians' evacuation efficiency. Nevertheless, two issues have to be considered carefully before applying this class of models to pedestrian route choice. First, the dynamic numbers of pedestrians in each section of the spatial layout are regarded as decision variables; however, pedestrians' distributions in each section are not considered in this class of models. In fact, when the number of pedestrians in a section is fixed, pedestrians' distribution in the section significantly affects their evacuation route choice and efficiency (see the first example is subsequent Section 3). Second, local congestion dynamics and interactions among pedestrians and obstacles cannot be formulated in this class of models generally. In fact, these congestion dynamics and interactions are essential factors, which need be taken into account when planning and managing pedestrian traffic. Otherwise, an ineffective flow assignment result may be obtained.

In these individual-based models, each pedestrian is treated as a discrete individual and the position update of each individual is formulated by a continuous or discrete dynamical system. This class of models gives more accurate predictions and more detailed information on evacuation processes than the network-based models. However, this class of models is unsuitable for large, complex, or tall pedestrian facilities due to their complex internal construction and the large amount of computing time required.

To avoid the aforementioned issues, arising in the two classes of models, one method is to establish a cell transmission model for pedestrian traffic. The model is an extension of the cell transmission model for road traffic, firstly proposed by Daganzo (1994, 1995), to the case of two-dimensional space. In the model, a passageway, walkway, or section of pedestrian space is not regarded as a node, but discretized into a number of triangular, square, or hexagonal cells, each of which can be occupied by multiple individuals. At present, several cell transmission models for pedestrian traffic have been proposed to formulate multidirectional flows and strategic route choices (Asano et al., 2007), collection, spillback, and dissipation in pedestrian evacuation (Guo et al., 2011), time-varying pedestrian flow loading in public walking areas (Hänseler et al., 2014), and anisotropic and congested pedestrian flow loading (Hänseler et al., 2017). In this paper, we also concern a cell transmission model for pedestrian traffic. However, we focus on a new issue, which is not mentioned in those existing literatures, namely, how to assign dynamic pedestrian flows on two-dimensional space so as to optimize their evacuation efficiency when the loading of pedestrian flows is formulated by a cell transmission model.

Despite that there have existed some algorithms for dynamic vehicle flow assignment, e.g., Huang and Lam (2002) and Lo and Szeto (2002), these existing algorithms cannot be directly applied to solve the dynamic pedestrian flow assignment problem, involved in this paper, due to the following two reasons. First, these existing algorithms are based on route flow variables generally, i.e., route flow variables need be dealt with and stored in the computation processes of these algorithms. Different from vehicle flows moving on one-dimensional roads, pedestrians can move flexibly in two-dimensional space. Therefore, when the space in a pedestrian facility, especially one with large size and large scale crowd, is discretized into a network with cell representation, there may be flows between any internal node and exit node (i.e., any origin-destination pair). Moreover, any two neighboring nodes (or cells) are interconnected. Thus, the number of routes in the network may be large enough. This results in intolerant computation time when these existing algorithms are applied to solve the dynamic pedestrian flow assignment problem. Second, the objective of performing these existing algorithms is to achieve a dynamic user equilibrium state. However, the objective of assigning pedestrian flows in our problem is to optimize the time needed for all pedestrians to evacuate a public facility.

To efficiently solve the dynamic pedestrian flow assignment problem, we propose a novel node-based algorithm through employing both a space potential formulation (Guo et al., 2011, 2012, 2013) and a proportional swapping process (Smith, 1984). The space potentials reflect the pedestrian walking times from internal cells to exit cells. There are lower potentials at these cells closer to exit cells. The "closer" is measured by the moving times from these cells to exit cells rather than the moving distances. When pedestrian congestion on routes is concerned, a route with a smaller spatial distance does not mean that the moving time on the route is smaller. The potentials drive pedestrians to move towards exits. The proportional swapping process governs the pedestrian flows from each cell to neighboring downstream cells (i.e., neighboring cells with lower potentials). Thus, only the flows between any neighboring cells are dealt with and stored (the number of node flow variables is much less than the number of route flow variables). In this way, the proposed model can be applied to not only efficiently optimize the evacuation process of a large scale crowd but also