Automation in Construction xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Automation in Construction

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

Simulation-based route planning for pedestrian evacuation in metro stations: A case study

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A R T I C L E I N F O

Article history:
Received 27 October 2015
Received in revised form 1 May 2016
Accepted 19 August 2016
Available online xxxx

Keywords:
Simulation
Pedestrian evacuation
Route planning
Case study
Metro station

A B S T R A C T

This paper develops a systematic simulation-based multi-attribute decision approach to route choice planning, in which uncertainties and dynamics underlying pedestrian behaviors during an evacuation are modeled given the complex interaction between pedestrians and the traffic is taken into account. Three factors, namely the *length of evacuation route*, *time of evacuation process* and *density of pedestrian flow*, are identified to have significant impacts on the efficiency of the evacuation process, especially at peak hours in a metro station. Two route planning strategies, as specified in Scenarios I and II, respectively, are proposed to simulate the pedestrian evacuation performance. Four key performance indicators (KPIs), namely *average pedestrian density*, *average evacuation length*, *average evacuation time* and *average evacuation capacity*, are put forward to assess the evacuation performance within different route planning strategies. The values of these KPIs on a metro station in the Wuhan metro system, China, are measured and compared in different scenarios. Results indicate that the performance of the evacuation efficiency can be significantly improved when the route planning strategy (that is specified in Scenario II) is implemented during the pedestrian evacuation. The developed approach can provide valuable theoretic and practical insight into a deep understanding of route planning strategies during the pedestrian evacuation, and thus, the improvement of safety and economic objectives can further be achieved in the design or re-design of metro evacuation systems.

1. Introduction

In recent years, with the continuous and rapid development of the Chinese economy, a large number of people have migrated into cities, such as Beijing and Shanghai in China, imposing a rigorous challenge on urban transportation systems [1]. Due to advantages of large transportation capacity, low pollution, high speed, easy traffic and low energy consumption, subways are regarded as the modernized urban rail transportation system, and play a significant role in transiting large passenger flows in large cities [2]. However, the predominant disadvantages of the subway systems are densely distributed occupants and highly restrained evacuation since the number of people usually reaches durative summits in density during the operating time, especially traffic peaks and holidays [3]. Due to the heavily crowded population and the situation of underground space, the magnitude of injuries and casualties will be overwhelmingly disastrous in case of an emergency [4]. According to statistics, during the year of 2014, more than 32 people got injured because of crowd accidents in metro stations in China [5,6]. In general, how to guide pedestrians to find out a more efficient route for evacuation under emergency conditions attracts much of the public's attention, and it is, therefore, necessary to investigate a solution for optimizing evacuation route planning strategies in metro stations.

Evacuation of pedestrians in metro stations is identified to be a key issue in safety management of subway systems [7]. The challenges lie in the pedestrians who are generally considered as the largest uncertainties since their motives and actions are dynamic and independent [8]. Evacuation route planning is a strategy that seeks to minimize the loss of life or harm to the public security, and is commonly used to handle emergency situations. In recent years, more and more scholars in the world have paid attention to the metro evacuation, in which the behavioral and psychological features of pedestrians and evacuation models have been studied. For instance, Liu et al. [9] made a theoretical calculation and analysis on the evacuation transportation capacity for an emergent phenomenon in different types of metro stations. Galea et al. [10] conducted testing and modeling on comparisons of the merge process at the floor stair connection place. Shi et al. [14] proposed an engineering calculation method for the metro station evacuation time, in which the simulation of evacuation process in different fire cases was conducted by using an agent-based model. Lei et al. [1] conducted a simulation of the process of pedestrian crowds' evacuation from a huge transit terminal metro station and investigated the impacts of occupant density,

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http://dx.doi.org/10.1016/j.autcon.2016.08.031
0926-5805/© 2016 Published by Elsevier B.V.

exit width and automatic fare gates on evacuation time. Li et al. [16] proposed a pedestrian evacuation model on metro platforms with panic spread mechanisms of passengers taken into account. In total, more than 20 kinds of evacuation models have been proposed officially [14, 17], which are divided into optimization type, modeling type and risk assessment type according to application purposes.

Existing pedestrian movement and behavior models mainly focus on pedestrian evacuation simulation and route choice. Those models are most often stochastic and oriented towards pedestrian dynamics and seldom incorporate the interactions between pedestrians and the traffic [18]. Airault et al. [19] indicated that in pedestrian-to-pedestrian (or pedestrian-to-traffic) interactions, pedestrians' options include deceleration and deviation. It is easy to understand that one pedestrian will move fast when the traffic is smooth while the pedestrian will move slowly when the traffic is crowded. How to consider the interactions between pedestrians and the traffic as to plan a more efficient evacuation route in heavily over-crowded metro stations is a challenging task, which falls into the scope of this research. In those metro stations which are generally situated underground, a large number of pedestrians get out from trains understand and stream into escalators to upstairs on a constant manner, particularly in metro junction hubs. If not dealt with properly, newly arrived passengers from the trains will increase the total volume of the pedestrians stranded underground, which is very likely to cause stampede accidents. The main purpose of this research is to answer those questions: (i) What kind of factors should be considered in order to come up with the best evacuation planning strategy during the pedestrian evacuation in metro stations; (ii) How to validate the pedestrian movement and behavior models that are stochastic and oriented towards pedestrian dynamics; (iii) How to assess and improve the efficiency of the evacuation performance. In regard to those issues, a systematic multi-attribute decision approach with detailed step-by-step procedures is developed for route choice planning. The major novelty of this research is that the uncertainties and dynamics underlying the pedestrian behaviors during the evacuation process are modeled given the complex interaction between pedestrians and the traffic is taken into account. Two scenarios, namely Scenario I and II are constructed and compared to identify the better route planning strategy for pedestrian evacuation. Some key performance indicators (KPIs) are proposed to assess the performance efficiency of the evacuation route planning strategies in different scenarios, in order to verify the effectiveness of the developed approach in this research.

This paper is organized as follows: In Section 2, the social force model is introduced as the fundamental theory for simulating behavioral dynamics of pedestrians. In Section 3, a systematic simulation-based decision approach is developed for the evacuation route planning. In Section 4, one metro station in China is selected as a case to simulate the pedestrian evacuation process, and observations are monitored and compared with simulation results for model validation. In Section 5, the performance efficiency of the proposed evacuation route planning strategy is assessed using the proposed KPIs. In Section 6, a discussion on how to apply the developed simulation model in the industry is presented. In Section 7, conclusions and future works are drawn.

2. Literature review

Pedestrians during evacuation exhibit complex and variable patterns of behavior, and understanding these patterns is extremely important for improving evacuation procedures and relevant regulations. The development of pedestrian dynamics for evacuation is an interesting and ongoing research topic in traffic science and engineering since the early 1990s [20]. In order to simulate the uncertainties and dynamics of pedestrians' behaviors, several famous models have been put forward in the domain of evacuation, such as cellular automaton model [21,22], agent-based model [23,24], and social force model [3]. Cellular automation is a discrete dynamic system with grid-based motion decision, which consists of a regular grid of cells, each in one of a finite number of states. The agent-based model simulates pedestrians with virtual agents and establishes social structures on a basis of a “bottom-up” order. However, it usually costs more computation time [25]. The social force model is in a continuous space and introduces the desired force to describe the inner drive of pedestrians to escape, especially under stressful situations [26].

Among the aforementioned models, the social force model is considered as one of the widely accepted models for simulating individual movement behaviors [3], especially in over-crowded situations. This is due to the fact that (i) the social force model is suitable to describe crowd dynamics since it can qualitatively reproduce some self-organizing phenomena, such as lane formation and arching [27]; (ii) the social force model as a continuous space model can allow pedestrians to move continuously within a pre-defined place by defining some forces while the discrete space model, such as a cellular automata, cannot allow pedestrians to move around in an unrestricted manner [28]; and (iii) the social force model is capable of importing psychological and sociological factors in the real world by considering physical and motivation forces [29]. Thus, we choose to use the social force model as the basic model to study the crowd dynamics during the evacuation process in subway stations.

The conception of “social force” was introduced to keep reasonable distances among individuals in 1951. The social force model was proposed by Helbing and Molnar [26] based on the fluid dynamics equation in 1995, where the pedestrians were driven by three forces: namely the desired force, the interaction force between pedestrians, and the interaction force between a pedestrian and walls. The original social force model of 1995 was improved by Johansson et al. [30] where an evolutionary optimization algorithm was used to determine optimal parameter specifications for the social force model based on suitable video recordings of interactive pedestrian motion and improved tracking software. A simple social force model is shown in Fig. 1, where the corresponding mathematical expression of each pedestrian i can be represented by Eq. (1).

$$m_i \frac{\mathrm{d}\vec{v}_i(t)}{\mathrm{d}t} = \vec{f}_i^{\,0} + \sum_{j(\neq i)} \vec{f}_{ij} + \sum_{w} \vec{f}_{iw} \tag{1}$$

where, m_i stands for the mass of pedestrian i; $\vec{v}_i(t)$ stands for the actual walking velocity; $\vec{f}_i^{\,0}$ represents the diagram of the desired force; $\vec{f}_{ij}$ represents the interaction force between pedestrians i and j; $\vec{f}_{iw}$ represents the interaction force between pedestrian i and walls.

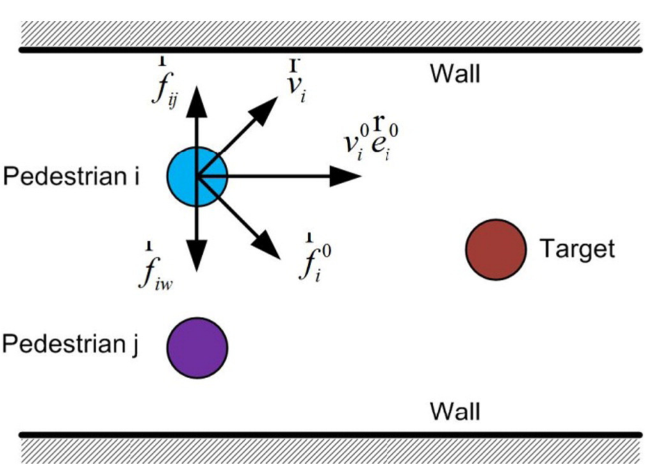

Fig. 1. Diagram of the social force model.

Please cite this article as: L. Zhang, et al., Simulation-based route planning for pedestrian evacuation in metro stations: A case study, Automation in Construction (2016), http://dx.doi.org/10.1016/j.autcon.2016.08.031