Transportation Research Part E 87 (2016) 130–148

Contents lists available at ScienceDirect

Transportation Research Part E

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

Capacity-oriented passenger flow control under uncertain demand: Algorithm development and real-world case study

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ARTICLE INFO

Article history:
Received 3 June 2015
Received in revised form 3 December 2015
Accepted 4 January 2016
Available online 2 February 2016

Keywords:
Subway station
Station service capacity
Uncertain demand
Genetic algorithm
Data envelopment analysis
Simulation optimization

ABSTRACT

This paper proposes a problem of passenger flow organization in subway stations under uncertain demand. The existing concepts of station service capacity are extended and further classified into three in different demand scenarios. Mathematical models are put forward to measure the three capacities and a unified simulation-based algorithm is developed to solve them. To increase computing speed, data envelopment analysis (DEA) and genetic algorithms (GA) are embedded in this algorithm. A case study will demonstrate the performance of the proposed algorithm and give a detailed procedure of passenger flow control based on station service capacity in various demand scenarios.

1. Introduction

1.1. Background

Passenger congestion problem has made it urgent to construct new subway systems and expand old ones in metropolis of China. Many subway stations have been suffering from very high passenger density, for example, passenger density in crowded area has reached 4–5 persons/m^2 in peak hours approaching the safety standard value in Code for Design of Metro (GB 50157-2003). Such problems mainly take place on platforms, walkways and stairs. As to station platforms with limited passenger holding capacity, passengers have risks being pushed into the tracks if the capacity is exceeded (Tirachini et al., 2013; Seriani and Fernández, 2015a). As to walkways and stairs, especially in transfer stations, safety risks will increase when crowding occurs (Guo and Wilson, 2011; Shi et al., 2012). However, it is difficult to enhance station capacities due to long construction period, large cost and physical restrictions of stations. Strategies such as boarding limiting (Delgado et al., 2012) can dynamically adjust passenger flow volume and relieve some demand pressure in crowded stations with fixed facilities. The control of passenger flow is easier to implement and is in exigent need.

Currently, passenger flow control strategies have been widely used in Beijing. Inbound passenger volume will be restricted by station managers once the total passenger volume reaches 70% of the station capacity in Beijing Subway

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http://dx.doi.org/10.1016/j.tre.2016.01.004
1366-5545/

(DB11/T 1166-2015). And transfer passenger volume is controlled with optimal policies in daily operation of transport terminals (Sun et al., 2012). In fact, total passenger volume consists of three parts (inbound, outbound, and transfer passenger volume) in transfer stations, of which the third takes proportion over 60% in peak hours and should be paid more attention to. Present control policies are usually formulated by subjective experience in Beijing, while lack mathematical formulation and accurate methods (Xu, 2015). Furthermore, demand uncertainty should be considered to deal with the changing passenger demand volume and its characteristics in recent years as shown in Fig. 1 (data from Automatic Fare Collection (AFC)). In short, quantitative analysis approach to passenger flow control with demand uncertainty is indispensable, particularly in Beijing.

The optimal solution of passenger flow control is to transport most passengers while acceptable security and comfort level are ensured (Yang et al., 2000; Baee et al., 2012). The former objective falls under station capacity problem while the latter pertains to the domain of level of service (LOS) (Fruin, 1971; Hsu and Chao, 2005; Correia et al., 2008). Station capacity is maximum total volume a station can accommodate, a static benchmarking to organize passenger flow in macroscopic scale. In reality, there are usually only one or two types of passenger flow with crowding and it will not work to control passenger flow based on total demand. So to obtain smart control strategies, changing volumes of each type should be added and station capacity should be relatively dynamic. Hence, it is necessary to include LOS in the definition of station capacity.

The main objective of this paper is to introduce a new concept of Station Service Capacity under uncertain demand with both passenger volume and characteristic variations to control passenger flow in peak hours. The paper describes indicators to find the optimal number of served passengers and to analyze the type and the number of passengers limited in typical scenarios. Models for quantitatively evaluating these indicators are discussed and a new unified simulation-based hybrid algorithm is proposed. They are then applied to passenger flow control in a Beijing subway station, which can be extended to other stations. To build the groundwork for the contributions of this paper, a literature review is provided in Section 1.2 and the contributions of the paper are discussed in Section 1.3.

1.2. Related literature

Despite the importance of understanding how passenger demand characteristic and LOS interact through station capacity to move toward passenger flow control, previous studies of such member interactions are limited in the field of demand and supply management and related areas. With regard to demand, passenger volume and characteristics have long been significant issues in the subway domain. Gutiérrez et al. (2011) developed a rapid response ridership forecast model to estimate the number of passengers boarding at each station in Madrid Metro network. Wei and Chen (2012) predicted short-term passenger flow in metro systems with empirical mode decomposition and neural networks. Aguiléra et al. (2014) conducted some experiments in Parisian underground transit system to measure passenger flows by cellular data. Reyes and Cipriano (2014) implemented online estimation of metro station system state variables such as numbers of passengers boarding trains and waiting at stations using a particle filter.

Likewise, subway station capacity is a hot topic along with the rapid increase of traffic demand during recent years. Chen et al. (2012) proposed a capacity model of staircases and corridors for passenger evacuation in consideration of facility layout in metro stations. Quaglietta and Punzo (2013) identified an optimal configuration of infrastructure components and operational schedule by a Sobol variance-based method. Xu et al. (2014) developed a queuing network model of station capacity from a macro-point of view to identify bottleneck facilities for improving capacity.

At the same time, a vast amount of subway capacity literature focuses on facility capacity in stations. Davidich et al. (2013) evaluated the impact of waiting pedestrians and proposed a cellular automata model for analysis and prediction waiting zone capacity in critical situations. Seriani and Fernández (2015b) analyzed capacity in metro–bus interchange space

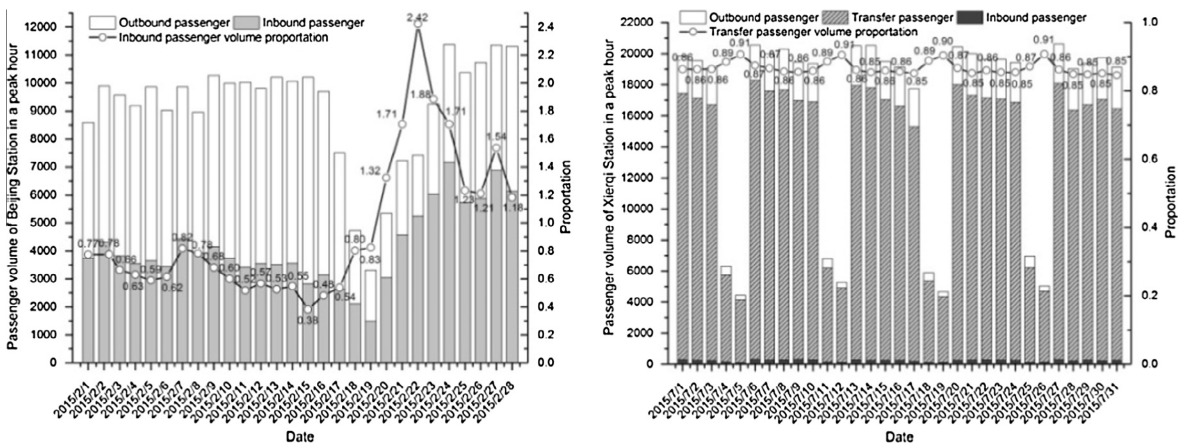

Fig. 1. Passenger flow changes in Beijing subway stations in peak hours of a month.