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A reliability-based assignment method for railway networks with heterogeneous passengers

Guangming Xu[a], Wei Liu[b,c,*], Hai Yang[d]

[a] School of Traffic and Transportation Engineering, Central South University, Changsha, Hunan 410075, China
[b] School of Computer Science and Engineering, University of New South Wales, Sydney, NSW 2052, Australia
[c] Research Centre for Integrated Transport Innovation, School of Civil and Environmental Engineering, University of New South Wales, Sydney, NSW 2052, Australia
[d] Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China

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ABSTRACT

Travel reliability can play an important role in shaping travelers' route choice behavior. This paper develops a railway passenger assignment method to capture the reliability-based route choices, where the trains can have stochastic delays. The overall travel reliability has two components: the travel time reliability (of trains) and the associated transfer reliability (of connections). In this context, mean-and-variance-based effective travel cost is adopted to model passengers' evaluation of different travel options in the railway network. Moreover, passengers are heterogeneous as they may evaluate the effective travel cost differently, and they may have different requirements for the successful transfer probability (if transfers are involved in the trip). The determination of travel time reliability (of trains) is based on the travel delay distribution, and the successful transfer probability is calculated based on the delay probabilities of two trains in the transfer process. An algorithm has been designed for solving the model, and numerical examples are presented to test and illustrate the model.

1. Introduction

Railway is a high capacity transport mode for passengers with medium-to-long distance journeys in many countries, especially in China with a very dense population. It is reported that China has a railway network with over 1,210,000 km track at the end of 2015, and the volume of passenger traffic is 3004.7 billion passenger kilometer in 2015 (Gov.cn, 2016). Particularly, China has the world's longest high-speed railway network with over 19,000 km of track in service as of January 2016 (Railway Gazetter, 2016). These facts highlight that railway systems have been playing a crucial role in passenger transportation. For better railway service management and/or rail line planning and scheduling, it is necessary and relevant for the system planners and operators to understand passengers' travel choices, and thus to model and forecast the passenger flows in the railway network appropriately and accurately.

Due to many different internal or external factors such as traffic incidents, weather conditions, temporary passenger flow control, and limited capacity of railway lines or stations, trains may arrive at stations unpunctually, i.e., the trains can have stochastic delays. It then becomes relevant that when passengers plan their trips (routes, departure times, etc.), they will take into account the potential stochastic delays of trains. It follows that travel time reliability of trains can play an important role in shaping passengers' route choices. Moreover, if there is no direct train available between the origin and the destination stations, passengers have to make

* Corresponding author at: School of Computer Science and Engineering, University of New South Wales, Sydney, NSW 2052, Australia.
E-mail address: Wei.Liu@unsw.edu.au (W. Liu).

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transfers. The delays of trains might further result in missing connecting trains. The transfer reliability, which is associated with the stochastic delays of trains, could also affect the passengers' route choice significantly. This is often the case for large-scale railway networks in, e.g., China, where there are quite some low-frequency trains in the system. The mentioned stochastic delays and travel reliability can substantially complicate the modeling and predicting for passenger flows in a railway network. This paper tackles the mentioned challenge.

There is a branch of studies focusing on the travel reliability of road traffic and public transit. Herman and Lam (1974) analyzed the variations of travel time from day to day by individuals. Later, Jackson and Jucker (1982) investigated the effects of travel time variability on the actual decisions of travelers, and showed that the perceived reliability is an important factor in travelers' route choice. Abdel-Aty et al. (1995) further confirmed that the travel time reliability was one of the most important factors for route choice decisions. Some empirical studies also suggested that travel time variability has impacts on both travelers' route and mode choice behaviors (Lam and Small, 2001; Brownstone et al., 2003; de Palma and Picard, 2005). For road networks, a common way to incorporate the travel time variability into the route choice is to introduce the travel time budget (TTB) (Uchida and Iida, 1993; Lo et al., 2006; Shao et al., 2006; Lam et al., 2008). Another branch of studies developed the so-called α-reliable mean-excess traffic equilibrium model that explicitly considers both reliability and/or unreliability aspects of travel time in the route choice decision process (Chen and Zhou, 2010; Chen et al., 2011; Xu et al., 2014, 2017).

For public transit networks, Rietveld et al. (2001) coped with the unreliability of public transport chains in Netherlands, with a particular emphasis on delays due to missing connections in a chain with more than one element. Various empirical studies have demonstrated that passengers' route choice behavior is affected by variations in trip time caused by the supply uncertainty of transit networks (Chen et al., 2009; Casello et al., 2009; Habib et al., 2011; Carrel et al., 2013). Given its relevance, there are many studies that have developed stochastic models to capture the effects of transit supply uncertainty (e.g., Yang and Lam, 2006; Li et al., 2009; Zhang et al., 2010; Sumalee et al., 2011; Meng and Qu, 2013; Szeto et al., 2011, 2013; Fu et al., 2014; Jiang and Szeto, 2016). Instead of considering travel reliability due to supply uncertainty, some studies addressed demand uncertainty issues in the transit network (e.g., An and Lo, 2016).

Operation of railway systems, especially the intercity train systems, is very different from those of road traffic and public transit. Passengers usually book their tickets in advance through the internet (for example, www.12306.cn in China), or purchase the tickets at the ticket offices in a pre-sale period, especially when their trip distances are long and travel demand is relatively high. Therefore, travelers usually have to determine their travel routes including the trains and transfer patterns much earlier than the boarding times. In this context, the reliabilities of different options become very important in passengers' trip planning. This is particularly true in China with a very dense travel demand and many long-distance trips. Moreover, railway system operation generally has larger complexities than urban mass transit, since there are many more different departure and destination stations, diversified schedules for different trains, and many more route/time options for passengers in the system. This means that reliability-based studies and methods for conventional road traffic and urban public transit generally cannot be directly applied to the railway networks.

To the best of our knowledge, the travel reliability has not received much attention in modeling passenger assignment for railway networks. Goverde (1998) computed the affected passenger waiting times due to train delays, and reduced the connection time by optimizing the train schedules. Goverde (2007) further used the max-plus system theory to analyze the timetable on its sensitivity and robustness to the train delays. Vansteenwegen and Van Oudheusden (2006, 2007) have calculated the buffer times based on the delay distributions of the arriving trains and constructed improved timetables with ideal buffer times using a linear programming approach. Liebchen et al. (2010) examined delay resistant periodic timetables, where the objective was to optimize the transfer time between any two adjacent trains so as to guarantee successful transfers and minimize the total travel cost. With an empirical approach, Van Loon et al. (2011) studied the impact of travel-time reliability on the number of season-ticket holders for the Dutch rail network using a stated preference survey approach. Later, Cheng and Tsai (2014) investigated the passengers' tolerance for waiting under various scenarios with train delays. Recently, Wardman and Batley (2014) provided an extensive review for late arrival time valuations and demand elasticities, which is related to railway service reliability. However, the above studies generally focused on operational stability of railway systems related to the train delay or travel time reliability, and valuation of reliability. The literature has not offered a systematic modeling framework, which can account for the effect of travel reliability on passengers' route choice behavior. Recently, Shi et al. (2012) incorporated transfer reliability into the passenger assignment for railway networks. However, they considered that the probability of the successful transfer is only related to the delay distribution of the arrival train in the transfer process. They did not systematically take into account the travel time reliability of all trains and how it might affect the successful transfer probability, and how it might affect the overall route choices of passengers.

To fill the mentioned research gap, this paper develops a passenger assignment method to reproduce the reliability-based passenger route choice behaviors. Both potential travel delays and the transfer reliability are considered in the overall evaluation of the travel reliability for passengers. Specifically, we adopt the effective travel cost approach (see e.g., Szeto et al., 2011, 2013; Jiang and Szeto, 2016) to account for the travel time variability and evaluate different options in the network perceived by passengers. In such a model, railway passengers minimize their effective travel cost, which is a combination of the mean and the variance of the random cost variable. Moreover, this paper considers transfer reliability, where the successful transfer probability is determined based on the delay probabilities of two (connecting) trains in a transfer process. Only when the successful transfer probability of a travel option is higher than the required values for the passengers, this option will be feasible for the passengers. The passengers will perceive a transfer time based on this option with a guaranteed successful transfer probability. Furthermore, an algorithm has been designed and tested for solving the developed passenger assignment model. In the end, several numerical examples are presented to test and illustrate the proposed method.

The rest of the paper is organized as follows. Section 2 summarizes the notations, and then describes the railway network