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A bi-level model for single-line rail timetable design with consideration of demand and capacity ☆

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ABSTRACT

This paper proposes a bi-level model to solve the timetable design problem for an urban rail line. The upper level model aims at determining the headways between trains to minimize total passenger cost, which includes not only the usual perceived travel time cost, but also penalties during travel. With the headways given by the upper level model, passengers' arrival times at their origin stops are determined by the lower level model, in which the cost-minimizing behavior of each passenger is taken into account. To make the model more realistic, explicit capacity constraints of individual trains are considered. With these constraints, passengers cannot board a full train, but wait in queues for the next coming train. A two-stage genetic algorithm incorporating the method of successive averages is introduced to solve the bi-level model. Two hypothetical examples and a real world case are employed to evaluate the effectiveness of the proposed bi-level model and algorithm. Results show that the bi-level model performs well in reducing total passenger cost, especially in reducing waiting time cost and penalties. And the section loading-rates of trains in the optimized timetable are more balanced than the even-headway timetable. The sensitivity analyses show that passenger's desired arrival time interval at destination and crowding penalty factor have a high influence on the optimal solution. And with the dispersing of passengers' desired arrival time intervals or the increase of crowding penalty factor, the section loading-rates of trains become more balanced.

1. Introduction

Timetable design problem aims at determining the arrival and departure time at each station for a set of trains and follows some operational requirements. In a fierce competitive multi-modal transportation market, how to create a high efficient timetable to attract passengers has become one of the most crucial issues for urban rail transit systems.

A fundamentally important element for designing public transit timetables is passenger demand. Without an in-depth understanding of variable characteristic of passenger demand, a straightforward and commonly adopted strategy is optimizing frequencies and designing timetables with the demand which is assumed to be evenly distributed during the study periods and represented by a set of matrices corresponding to different hours in a typical day (e.g., Furth and Wilson, 1981;

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Oudheusden and Zhu, 1995; Chen, 2014; Sels et al., 2016). This strategy is easy to apply and performs well when the capacity of a vehicle is sufficient. However, due to the unsteady distribution of passenger arrival rate and the limitation of vehicle capacity in reality, timetable designed by using the strategy above may fail to meet the temporal demand under congested conditions or strong temporal demand heterogeneity (Sun et al., 2014).

To deal with the variable feature of passenger demand, timetable designers gradually paid their attentions to dynamic passenger demands. In the previous studies, dynamic passenger demands are commonly considered as a set of time-dependent origin-destination (OD) demand matrices (e.g., Barrena et al., 2014; Niu et al., 2015) or time-varying arrival rates (e.g., Ceder 1987, 2001; Yalçınkaya and Bayhan, 2009). However, these demand data are collected by the automatic fare collection systems (AFCS) under the situation that trains are running on the pre-optimized timetable. The adjusting behaviors of passengers to a new timetable are rarely taken into account.

In fact, passengers' adjusting behaviors are widespread in public transportation systems. To avoid, e.g., an undesired arrival time at destination caused by failure-to-board or an uncomfortable feeling incurred by crowding in a vehicle, passengers will adjust their departure time based on their daily travel experience and timetables of public transportation systems (e.g., Nuzzolo et al., 2001, 2012; Poon et al., 2004; Hamdouch and Lawphongpanich, 2008; Hamdouch et al., 2011). Due to the adjusting nature of passenger demand, the arrival rate of passengers at the origin stops when facing a new timetable will show a very different pattern with the historical one which is collected under the situation that trains are running on the pre-optimized timetable (Zhu et al., 2013). Then, an inherent gap may exist between the theoretical optimal timetable and the optimized timetable without considering passengers' adjusting behaviors.

This paper aims to close the inherent gap mentioned above. The objective is proposing a scheduling model, which can fully consider passengers' adjusting behaviors to a new timetable, for an urban rail line. The remainder of the paper is organized as follows. Section 2 reviews the related previous studies on timetable design problem and states the contributions of this study. The overall problem statement and underlying assumptions are presented in Section 3. In Section 4, the bi-level is proposed for the problem. The solution algorithm is presented in Section 5. For illustration, two numerical examples and a real case study are provided in Section 6 and Section 7, respectively. Conclusions are made in Section 8.

2. Literature review

As an important optimization application in transportation, timetable design problem has received much attention in the past few decades. It can be divided into two different categories: periodic scheduling problem and non-periodic scheduling problem.

Periodic scheduling problem attempts to set up a periodic timetable that is constantly repeated. Based on the repetition form of the designed timetable, periodic scheduling problem can also be classified into two kinds. The first is to create a regular timetable with even interval departures. This kind of problem was introduced to public transportation systems as setting service frequencies or headways. Furth and Wilson (1981) developed a model to find optimal frequencies for bus networks. The frequencies for peak and off-peak hours were set respectively. With the consideration of crowding cost, Koutsopoulos et al. (1985) extended the above model using a non-linear programming model. Ceder (1984) summarized four different methods to optimize the bus frequency based on two different types of data collection procedure, namely point check and ride check. Khani and Shafahi (2011) proposed an optimization model to determine the headways and the departure time of the first train jointly for transit networks. Aksu and Akyol (2014) proposed a model to find the optimal headway and section travel time of each route by minimizing total system cost consisting of the in-vehicle, waiting, and transfer costs for all passengers and the operating cost for operators. Liebchen (2008) adopted the periodic event scheduling approach and a well-established graph model to optimize the timetable of Berlin underground. The second kind of periodic scheduling problem is to design a cyclic timetable with fixed departures at each period, e.g., a timetable with departures at 7, 25 and 50 min every hour. This kind of problem has been widely investigated in railway systems (Schrijver, 2001; Kroon et al., 2009; Sels et al., 2016). For urban rail transit systems, Wang et al. (2013) proposed a train diagram formulation model to minimize the total passenger transfer waiting time. In general, periodic timetable is simple, compact, and easy to remember for passengers (Wardman et al., 2004). And it can perform well in reducing total waiting time when the passenger arrival pattern at stations follows some particular probability distributions such as uniform distributions (Niu and Zhou, 2013). However, in practice, passengers' arrival rate varies with time and can be hardly described by particular probability distributions. Therefore, to provide a more efficient timetable which can deal with the variable feature of passengers' arrival rate, some researchers shift their focus from periodic scheduling to non-periodic scheduling.

Non-periodic scheduling problem is known as designing a non-periodic timetable in that headways between any two successive departures may vary across the whole planning horizon. With this variable feature in headways, a designed non-periodic timetable can have a great response to the time-varying demand, and that is the reason why it is favored by researchers (e.g. Newell, 1971; Ceder, 1987, 2001). In recent years, the emergence of the AFCS provides a data-rich environment for a further study on non-periodic scheduling method. Niu and Zhou (2013) developed a binary integer programming modes to design a non-periodic train timetable for a heavily congested urban rail line. Sun et al. (2014) presented three optimization models to design demand-sensitive timetables by demonstrating train operation using equivalent time interval. The case study in their research shows that non-periodic timetables can performance better than peak/off-peak timetable with even-headways. Hassannayebi et al. (2014) introduced a two-stage genetic algorithm (GA)-based simulation