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A case study on the coordination of last trains for the Beijing subway network

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ABSTRACT

Passengers may make several transfers between different lines to reach their destinations in urban railway transit networks. Coordination of last trains in feeding lines and connecting lines at transfer stations is especially important because it is the last chance for many travellers to transfer. In this paper, a mathematical method is used to reveal the relationships between passenger transfer connection time (PTCT) and passenger transfer waiting time (PTWT). A last-train network transfer model (LNTM) is established to maximize passenger transfer connection headways (PTCH), which reflect last-train connections and transfer waiting time. Additionally, a genetic algorithm (GA) is developed based upon this LNTM model and used to test a numerical example to verify its effectiveness. Finally, the Beijing subway network is taken as a case study. The results of the numerical example show that the model improves five connections and reduces to zero the number of cases when a feeder train arrives within one headway's time after the connecting train departed.

1. Introduction

As an important transportation mode in the modern metropolis, urban railway transit offering high security, wide accessibility, high energy performance and reliable service with sufficient punctuality has been playing increasingly important roles in relieving growing road congestion and associated environmental pollution (Krasemann, 2012). The last-train coordination problem, which affects passenger transfers, is one of the most important issues in a subway system. Coordination of last trains is especially noteworthy because it is the last chance for many travellers to transfer. There are generally many independent running lines operated by different companies in a large urban railway network like the urban railway transit in Beijing which is operated by Beijing subway and Hong Kong MTR Corporation Limited. It is understandable that companies pursuing their own profits desire to stop service when late-night passenger flow drops down significantly. Because of that tendency, if we do not give special attention to coordinating last trains, then they become quite uncoordinated, leaving passengers without connections to their final destinations, a problem which would further reduce passenger usage of late evening trains.

The reason to consider the train timetabling or scheduling problem is to determine an optimal train working diagram. Such a diagram is subject to a number of operational constraints, including safety requirements and headway requirements. Zhou and Zhong (2005) proposed two phases for generating a train scheduling activity: (1) line planning, which determines routes, frequencies, and stop schedules of trains, and (2) schedule generation, which constructs the arrival and departure

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time for each train at a station. The practical schedule generation problem should be counted one of the most intractable problems in railway planning, and it has recently attracted the increased interest of researchers. Liebchen (2008) developed a timetable that optimized the arrival and departure times at the transfer stations of the metro network in Berlin so that passenger transfer times between the lines were minimized. This appears to be the first methodology for this problem both published and implemented.

Optimization models aiming at minimizing total passenger waiting time at railway stations have been proposed by Domschke (1989), Ceder (1991), Nachtigall (1996), Nachtigall and Voget (1996), Nachtigall and Voget (1997), Odijk (1996), Wong et al.(2008), and Shafahi and Khani (2010). For instance, Wong et al. (2008) developed a mixed integer programming optimization model that minimized all passengers' transfer waiting times in certain railway system for the timetable synchronization problem. The problem in Shafahi and Khani (2010) was also formulated as a mixed integer programming model that gave the departure time of vehicles in lines so that passengers could transfer between lines at transfer stations with minimum waiting time.

In recent years, many researchers determined the timetable with the consideration of schedule synchronization or transfer coordination. Albrecht and Oettich (2002) proposed an algorithm for the dynamic modification of train running time to increase the probability of making connections to other means of public transport. Cevallos and Zhao (2006) used the genetic algorithm to optimize an existing timetable to increase coordination between lines. Bookbinder and Désilets (1992) attempted to minimize overall inconvenience for passengers who must transfer between lines in a transit network. Yan and Chen (2002) and Yan et al. (2006) used time–space networks that consisted of fleet flow time–space networks and passenger flow time–space networks for each origin and destination pair to propose models for intercity bus routing and scheduling. Yan and Chen (2007) developed several coordinated scheduling models by employing network flow techniques that solved for the most satisfactory fleet routes and timetables. Zhao and Zeng (2008) developed a heuristic method for optimizing transit network planning consisting of route network design, vehicle headway setting and timetable creation to minimize passenger costs, including walking time between stops, waiting time at transfer stations and transfer penalty time. Ibarra-Rojas and Rios-Solis (2012) formulated a bus-network timetabling problem with the objective of maximizing the number of synchronizations to facilitate passenger transfers and avoid bus bunching along the network. Kang et al. (2015) constructed a last-train optimization model to minimize the running time and dwell time and maximize the average transfer redundant time and network transfer accessibility.

In highly interconnected timetables or dense railway traffic, a single delayed train can cause a domino effect of secondary delays throughout the entire network; this is a main concern to planners and dispatchers (Goverde, 2007). Therefore, Kroon et al. (2008) described a stochastic optimization model that can be used to allocate the time supplements and the buffer time in a given timetable so that the timetable becomes maximally robust against stochastic disturbances. Liebchen et al. (2010) proposed delay-resistant periodic timetables in which the objective was to optimize the transfer time between any two adjacent trains to not only guarantee successful transferring but also minimize total travelling cost. D'Ariano et al. (2008) introduced a flexible timetable that could plan fewer and solve more inter-train conflicts during operations.

Although there are many works on the study of non-last-trains' timetabling/scheduling problems, few works pay attention to the time coordination of last trains. With the development of urban railway networks, it is increasingly urgent to optimize last-train departure times to facilitate passengers' transferring among late evening trains because transfers are necessary to reach destinations. However, the last-train timetabling problem cannot be solved completely with the non-last-trains' models because synchronizations of last trains and non-last trains in a transfer network are not the same. Additional detailed comparisons between last trains and non-last trains are listed in Table 1.

The contributions of this paper are summarized as follows. First, a mathematical formula is developed to describe relationships between *passenger transfer connection time* (PTCT, the difference between the departure time of the last connecting train and the arrival time of passengers on the last feeder train) and *passenger transfer waiting time* (PTWT, the minimum waiting time for passengers who transfer from the last feeder train to the first-arriving connecting train). This formula can be used to distinguish between last trains and non-last trains. Moreover, a network transfer model is proposed to optimize the last-train coordination problem considering connections and transfer waiting time. The complexity of the problem is based primarily on the use of a large set of discrete variables. A Genetic Algorithm is designed to address the last-train network transfer model (LNTM) in the Beijing subway network. The results of the numerical example show that the model improves five connections and reduces to zero the number of cases when a feeder train arrives within one headway's time after the connecting train just departed (defined as "just miss" in this paper).

Table 1
Characteristics of last-train and non-last-train models.

Item	Last-train model	Non-last-train model
Close time	Need to be considered	Need not be considered
Train coordination	Transfer success/failure, transfer waiting time	Transfer waiting time
Passenger flows	Can be ignored due to low volume	High volume, should be considered
Train capacity	Generally sufficient	Should be considered, especially in the rush hour
Objective	Connections, transfer waiting time	Passenger waiting time, transfer time, travelling time, and so on