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Equity-based timetable synchronization optimization in urban subway network

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A B S T R A C T

In the urban subway transportation system, passengers may have to make at least one transfer traveling from their origin to destination. This paper proposes a timetable synchronization optimization model to optimize passengers' waiting time while limiting the waiting time equitably over all transfer station in an urban subway network. The model aims to improve the worst transfer by adjusting the departure time, running time, the dwelling time and the headways for all directions in the subway network. In order to facilitate solution, we develop a binary variables substitute method to deal with the binary variables. Genetic algorithm is applied to solve the problem for its practicality and generality. Finally, the suggested model is applied to Beijing urban subway network and several performance indicators are presented to verify the efficiency of suggested model. Results indicate that proposed timetable synchronization optimization model can be used to improve the network performance for transfer passengers significantly.

1. Introduction

Recently, the optimization of timetable synchronization problem for urban subway network (USN) has attracted much interest. Generally, passengers usually have to make at least one transfer during their travel. Therefore, how to design an optimized timetable to improve the transfer efficiency becomes an important issue in the USN operation. Mohring et al. (1987) found that passengers value their waiting time almost twice of what it actually is. Besides, passengers usually show their impatience and complain a lot when waiting for the connecting trains with a long time. In view of this, synchronous timetables, with less transfer waiting time, are significantly important in the urban subway.

There is a wealth of literatures on the timetable optimization for the urban subway traffic. Many models were presented to minimize the total transfer waiting time. Some researchers made the assumption that all headways, running time, and dwelling time were fixed but only dispatch time can be relatively varied. Domschke (1989) proposed a model to minimize the waiting time of passengers who want to change lines at the transfer station. Bookbinder and Désilets (1992) proposed a quadratic semi-assignment model by minimizing the mean disutility of transfers for bus trip using the probability distributions of the train arriving and departing time. However, many factors will have a great impact in the real operation which causes the uncertain operation parameters, such as run times and headways. Serafini and Ukovich (1989) proposed a mathematical model for scheduling activities of periodic type with particular time constraints. Nachtigall (1996) introduced

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periodic networks to research the periodic event scheduling problem (PESP). Through a branch and bound approach, a global objective depending on all local waiting time was minimized. Liebchen and Möhring (2002) proposed many criteria such as amount of rolling stock required, average passenger changing time, average speed of the trains, and the number of cross-wise correspondences to be optimization objectives when constructing timetables for the Berlin underground. Wong et al. (2008) developed a mixed integer programming optimization model which minimizes transfer waiting time of all passengers in a subway system for the timetable synchronization problem in Hong Kong Mass Transit Railway (MTR). The model considered headways not as fixed but as decision variables. Cevallos and Zhao (2006) used the genetic algorithm to change an existing timetable in order to have more coordination between lines. In their researches, a shift in the timetable was used to reduce the transfer time. In the further studies, trains running deviating from the schedules should be considered, and to get a sense of deviating, the following research will illustrate this point. Clearly, in daily operations, trains do not always run according to schedules exactly. Knoppers and Muller (1995) investigated the possibilities and limitations of coordinated transfers in public transit. The object was to minimize passenger's transfer time. This study showed that optimal transfer time can be defined only if fluctuations in passenger arrival time at the boarding point can be contained within certain time limits. Suhl et al. (2001) considered real-time dynamic dispatch of vehicles at a transfer station and discussed the design of dispatching support systems for railway passenger traffic from the viewpoint of passenger orientation. Various dispatching strategies were evaluated by simulation and an optimization model was presented. What needs further research is the optimization model because the total transfer waiting time in their model is only approximated. Hadas and Ceder (2010) introduced synchronized (timed) timetables to diminish the waiting time caused by transfers, and an objective function which was composed of the travel time and average waiting time of all public transit passengers was developed. Dotoli et al. (2013a) addressed the train rescheduling problems for regional railway networks, and presented a model to minimize the stop times along the railway line and the travel times along the connection tracks, by means of which, train dispatcher is able to minimize the propagation of delays and the inconvenience for passengers.

Other researchers have considered the total cost as objective to design the optimized timetable. Yan and Chen (2002), and Yan et al. (2006) presented a model for intercity bus routing and scheduling. The model used time–space networks that consist of two types of networks, fleet flow time–space networks and passenger flow time–space networks for each O–D pair. The objective of the model was to minimize the total cost, consisting of operating cost, waiting cost, etc. Gallo et al. (2011) considered a weighted sum of transit user costs, car user costs, operator costs and external costs as the objective function, where transit user costs depend on on-board time, waiting time and access/egress time. Chowdhury and Chien (2001) formulated a time varying total cost function which includes connection delay and missed-connection costs and vehicle holding cost. A procedure was developed to dynamically optimize the dispatching time for each ready vehicle by minimizing the time-varying objective function. Vansteenwegen and Oudheusden (2006) computed the ideal buffer time for each connection and constructed a new periodic timetable by a linear program for Belgian railway network, and a waiting cost function, weighting different types of waiting time and late arrivals, is designed and minimized. Dotoli et al. (2013b) presented a periodic event scheduling approach which took the passenger travel time minimization into account with constraints on travel times, station stopping time, connections, synchronizations, rolling stock inversions, and safety standards. Goverde (1998) divided passenger waiting time into two main classes which are primary waiting and secondary waiting time. A systematic mathematical model was been developed to compute all affected waiting time of initial train departure delays. The delay propagation was modeled as a discrete event dynamic system to explore the effect of buffer time to compensate for arrival delays.

Besides, some researchers optimize timetable with other objectives. Ceder et al. (2000) presented a MIP model to maximize the number of simultaneous arrivals of buses from different lines to transfer stations. In this model, the headways were not fixed, but a range was considered for the headways in each line. Niu and Zhou (2013) focused on optimizing a passenger train timetable in a heavily congested urban rail corridor in which a binary integer programming model is presented to represent passenger loading and departure events. Krasemann (2012) presented a greedy algorithm which in short time delivers good rescheduling solutions to the railway traffic disturbance management problem. Dotoli et al. (2013c) took co-model transportation route planning into account, and presented a decision support system aiming at costs, time, and gas emissions minimization. Recently, Kang et al. (2015a,b) proposed the timetable optimization models of last trains in the urban subway network.

Table 1 presents a classification of papers dealing with the timetable problem, from which it can be seen that previous research works mainly focus on the minimization of the total transfer waiting time or the total cost in the timetabling. However, the inequitable waiting time in all interchange directions may be induced with this optimization objective, which leads to the inhomogeneity of waiting time in transfer stations. For the transfer directions with long waiting time, the passengers waiting to interchange impose connecting trains with longer dwell time and thus cause the delay. It is undesirable that the delay in network operation propagates across the network and incurs negative influence to the integration of dispatch and operation management. To overcome the drawback mentioned above, we proposed a timetable synchronization optimization model to reduce the longest passengers' waiting time of all transfer directions on interchange stations in the USN. Through adjusting running time, dwelling time, departure time and headways of each line, the worst transfer waiting time can be decreased. In addition, to verify our model, a series of performance indicators are proposed to evaluate the solution. Note that, our paper is to develop a synchronized timetable by minimizing the worst transfer of all transfer stations in the pre-planning period. Therefore, the real time adjustment of timetable is not considered in this paper.