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Optimal timetable development for community shuttle network with metro stations

Jie Xiong[a,1], Zhengbing He[a,2], Wei Guan[a,*], Bin Ran[b,c,3]

[a] Ministry of Education Key Laboratory for Urban Transportation Complex Systems Theory and Technology, Beijing Jiaotong University, No. 3 Shang Yuan Cun, Beijing 100044, China
[b] Wisconsin ITS Program, Department of Civil & Environmental Engineering, University of Wisconsin at Madison, 1415 Engineering Drive, Madison 53706, WI, United States
[c] School of Transportation, Southeast University, No. 2 Si Pai Lou, Nanjing 210096, China

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ABSTRACT

This paper investigates an issue for optimizing synchronized timetable for community shuttles linked with metro service. Considering a passenger arrival distribution, the problem is formulated to optimize timetables for multiple community shuttle routes, with the objective of minimizing passenger's schedule delay cost and transfer cost. Two constraints, i.e., vehicle capacity and fleet size, are modeled in this paper. The first constraint is treated as soft, and the latter one is handled by a proposed timetable generating method. Two algorithms are employed to solve the problem, i.e., a genetic algorithm (GA) and a Frank–Wolfe algorithm combined with a heuristic algorithm of shifting departure times (FW-SDT). FW-SDT is an algorithm specially designed for this problem. The simulated and real-life examples confirm the feasibility of the two algorithms, and demonstrate that FW-SDT outperforms GA in both accuracy and effectiveness.

1. Introduction

Nowadays, transfers between ground buses and metros are very common for a journey from a community in a suburban area to downtown. Clearly, it is very necessary to set up an efficient and robust transit microcirculation system serving these communities to the metro stations nearby. Generally speaking, the transit planning process includes four basic activities, generally performed in such a sequence: route and network design, timetable development, vehicle scheduling and crew scheduling (Ceder and Wilson, 1986; Ceder, 2001, 2002). Among these activities, the timetable development is the simplest and most feasible way in the transit pre-planning process. It only needs the operator to preset or adjust the departure times of some trips, and then an optimal effect may be achieved. This paper thus presents an optimal timetable development problem and its corresponding solutions on a combined bus-metro network.

For timetable development problems, a simple even-headway timetable, which is formulated based on an optimal headway, is often developed in the transit network design problem (e.g. Chang and Schonfeld, 1991; Chien, 2000; Chien et al., 2001a, 2001b; Chien, 2005; Chien et al., 2007; Zhao and Zeng, 2007; Szeto and Wu, 2011). The models developed in these

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[*] Corresponding author. Tel.: +86 139 1057 0120.
E-mail addresses: 10114191@bjtu.edu.cn (J. Xiong), he.zb@hotmail.com (Z. He), weig@bjtu.edu.cn (W. Guan), bran@wisc.edu (B. Ran).
[1] Tel.: +86 159 1066 7682.
[2] Tel.: +86 182 1096 7110.
[3] Tel.: +1 608 262 0052.

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studies usually minimize the total cost (i.e. user and supplier costs) to develop routes and service frequencies leading to the bus timetables. Majority of the related problems are based on a single-mode transit system without considering the coordination among multi-mode transit. Ceder (2009, 2013) proposed an idea of designing an integrated smart feeder/shuttle service, and developed a simulation tool validated by ten different routing strategies. These studies focused on the route and network design of shuttles, while few focused on the coordinated timetable development. Mohaymany and Gholami (2010) and Xiong et al. (2013) designed feeders of rail transit, which include network/routing design and headway determination for a multi-mode transit network. Yet, the transfer cost was not considered in their researches. Some studies (e.g. Quadrifoglio et al., 2006, 2007) addressed the flex-route transit service design problem, in which the feeder of bus scheduling has been involved. Alshalalfah and Shalaby (2012) investigated the feasibility and benefits of using flex-route transit as a feeder transit service for rail stations instead of the fixed-route transit. Since these researches are not specially proposed for the timetable development, the timetables are simply formulated based on the solved optimal frequencies. It lacks the consideration of the passenger arrival rate or the coordinated scheduling problem.

Considering a passenger arrival distribution at bus stops will make the timetable development problem more complex. Ceder (1986, 2003) presented two methods to formulate timetables with smooth transitions, i.e. even average loads and even maximum load on individual vehicles. These models were mainly based on the real-time stop data while neglects the passenger's waiting cost or fleet size constraint. Newell (1971) assumed a given passenger arrival rate as a smooth function of time, and analytically showed that the frequency of transit vehicles and the number of passengers served per vehicle varied with time approximately as the square root of the passenger arrival rate. Osuna and Newell (1972) developed a control strategy that either held back a transit vehicle or dispatched it immediately with the objective of minimizing the passenger's waiting time. The findings and dispatching policy were examined and extended by Wirasinghe (1990, 2003). Palma and Lindsey (2001) proposed a method to design an optimal timetable for a given number of trips with the objective of minimizing the total schedule delay based on each rider's preferred travel time. The optimal analytical solutions were presented when the rider's arrival was uniformly distributed over time. Peeters and Kroon (2001) employed a mixed integer non-linear programming formulation to optimize a cyclic railway timetable. The objective is to minimize passenger's travel time, to maximize the robustness of the timetable, and to minimize the number of trains. Gallo and Di-Miele (2001) introduced a model for the special case of dispatching buses from a parking depot to minimize the shunting cost. However, these studies were mostly based on an idealized transit system in which only a single line is included and no consideration of realistic operational factors such as vehicle capacity and transferring among multi-mode transits.

When incorporating a multi-mode transit network into the timetable development problem, factors such as transfer time needs to be considered. Shrivastava and O'Mahony (2006) developed a new model combining the network design problem with the coordinated schedule problem. An optimized feeder bus network and a coordinated timetable of each route were determined simultaneously. The results of a case study indicated that the overall loading factor was improved considerably compared to the former model presented by Shrivastava and Dhingra (2001). Similar research can be seen in Shrivastava and Dhingra (2002) and Shrivastava and O'Mahony (2009). However, only even headways were considered and determined by solving optimal service frequencies of feeder buses. They might fail to meet dynamic temporal passenger demands on a microscopic level. Chakroborty et al. (1995) formulated an optimal scheduling problem for the urban transit network based on some certain passenger arrival rates at stops. The model considered both passenger's initial waiting cost and transfer cost, but only one transfer stop was involved in the problem formulation. Moreover, the model assumed vehicles could be loaded unlimitedly and the fleet size constraint was not considered. Both Ceder et al. (2001) and Wong et al. (2008) presented a mixed-integer-programming optimization model to formulate synchronized timetables. The former one (Ceder et al., 2001) aimed at maximizing the number of simultaneous arrivals on a bus network, while the latter (Wong et al., 2008) presented the problem to minimize the overall transfer waiting time based on a rail mass network. Kwan and Chang (2008) developed a model to formulate a new measurement for timetable synchronization by means of a total passenger dissatisfaction index and a total deviation index. To solve the model, a multi-objective evolutionary algorithms (MOEA) was combined with local search techniques. In addition, to seek for a flexible scheduling and control tool for the urban transit, Adamski (1998) and Dessouky et al. (1999) addressed a dynamic optimal dispatching problem at transfer terminals. Numerical simulations were used by both of them to validate the effectiveness of their proposed dynamic schedule control strategies.

This paper develops a synchronized timetable for shuttles linked with metro service based on certain passenger arrival distributions at stops. To our best knowledge, very few studies developed synchronized timetables based on temporal varying passenger demand and simultaneously considered both vehicle capacity and fleet size constraint. Neglecting these factors may make the problem simpler but unrealistic. Thus, it is more realistic to incorporate them into the problem.

A robust service provided by community shuttles linked with metros should satisfy a series of principles, e.g. meeting passenger's demands, reducing passenger's waiting time, transfer time, and avoiding overcrowding as much as possible. To this end, this paper thus seeks for an optimal synchronized timetable that minimizes the total cost of passenger's schedule delay cost and transfer cost. Two constraints are considered, i.e., vehicle capacity and fleet size, distinguishes our problem from the existing synchronized timetable development problems in the literature. In formulating the problem, the first constraint is modeled as a soft constraint, and the second one is handled by a proposed timetable generating method. To solve the problem, a GA is employed, and then a Frank–Wolfe algorithm combined with a heuristic algorithm of shifting departure times (FW-SDT) is proposed specifically. Two algorithms are compared in simulated and real-life examples. The results show