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Multi-objective re-synchronizing of bus timetable: Model, complexity and solution

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ABSTRACT

This work is originally motived by the re-planning of a bus network timetable. The existing timetable with even headways for the network is generated using line by line timetabling approach without considering the interactions between lines. Decision-makers (i.e., schedulers) intend to synchronize vehicle timetable of lines at transfer nodes to facilitate passenger transfers while being concerned with the impacts of re-designed timetable on the regularity of existing timetable and the accustomed trip plans of passengers. Regarding this situation, we investigate a multi-objective re-synchronizing of bus timetable (MSBT) problem, which is characterized by headway-sensitive passenger demand, uneven headways, service regularity, flexible synchronization and involvement of existing bus timetable. A multi-objective optimization model for the MSBT is proposed to make a trade-off between the total number of passengers benefited by smooth transfers and the maximal deviation from the departure times of the existing timetable. By clarifying the mathematical properties and solution space of the model, we prove that the MSBT problem is NP-hard, and its Pareto-optimal front is non-convex. Therefore, we design a non-dominated sorting genetic (NSGA-II) based algorithm to solve this problem. Numerical experiments show that the designed algorithm, compared with enumeration method, can generate high-quality Pareto solutions within reasonable times. We also find that the timetable allowing larger flexibility of headways can obtain more and better Pareto-optimal solutions, which can provide decision-makers more choice.

1. Introduction

Providing effective bus service is a critical and difficult task for every bus transit company in the world. Under budgetary restrictions, the effectiveness of bus service strongly relies on bus network planning. This global planning problem is very complex and it is usually divided into a set of subproblems including line planning, timetable generation, vehicle scheduling and crew scheduling (Ceder, 2007; Guihaire and Hao, 2008). These subproblems are usually solved sequentially (Desaulniers and Hickman, 2007). The bus timetabling (BT) is a principal stage, since its solution determines the service quality and

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subsequent subproblems (i.e., the vehicle and crew scheduling). The BT problem designs the departure time of each trip of all lines in the bus network, aiming at maximizing the service quality.

Considering the practical operation of bus network timetabling in China, the bus network timetables with even headways (i.e., separation time between consecutive bus trips) are often generated using line by line timetabling approach. This timetabling approach is easy to implement, but it does not consider timetable synchronization between different bus lines. In reality, passengers are often forced to transfer either to or from a bus to complete a trip. This phenomenon commonly exists in large bus transit systems. During the transfer, passengers spend a lot of time waiting for connecting bus that serves on the line without synchronized timetable. Petersen et al. (2013) reported that using non-synchronized timetable the waiting time for one transfer is an average of about 9.75 min on each weekday in the Greater Copenhagen area. A synchronized timetable, with good coordination between buses at transfer nodes so that passengers can enjoy smooth transfer service, is quite important for an attractive bus transit service. In order to provide this kind of service, decision-makers (i.e., schedulers) intend to synchronize vehicle timetables of different lines at transfer nodes to facilitate passenger transfers by adjusting the departure times of the existing bus timetable. However, timetable synchronization between different lines often causes deviations from the existing timetable. Large deviations from the departure times of the existing timetable not only destroy regular timetable service that is easily remembered by passengers, but also confuse the accustomed trip plans of passengers and cause massive recalculation of following scheduling tasks, such as the vehicle and crew scheduling. In other words, the deviations from the existing timetable and improving the timetable synchronization between different lines are naturally in conflict. Therefore, there is a need to propose a multi-objective method, allowing the decision-makers to consider how much deviation from the existing departure times of lines they can accept at each specific level of timetable synchronization.

Most studies on synchronization of bus timetabling (SBT) problem, however, use a single objective approach such as maximizing the number of synchronized bus arrivals at transfer nodes, without considering the impact of a completely different timetable on the users who get used to comply with the current timetable. Ceder et al. (2001) initially developed a mixed integer programming (MIP) model for the SBT problem. An extension has been made by Eranki (2004), where synchronization is redefined as the arrivals of two trips at a transfer node with a separation time within a small time window instead of simultaneous arrivals. Based on the work of Ceder et al. (2001) and Eranki (2004), Ibarra-Rojas and Rios-Solis (2012) studied a flexible SBT problem that is characterized with oriented synchronization, almost evenly spaced departures and preventing bus bunching. Several studies seek to minimize the total transfer waiting time experienced by passengers, and consider evenly spaced departure times in the SBT problem (e.g., Shafahi and Khani, 2010; Cevallos and Zhao, 2006; Jansen and Nielsen, 2002). Wong et al. (2008) investigated the timetable synchronization problem in a railway system. The authors proposed a MIP model to minimize the total transfer waiting time by adjusting train's run times and station dwell times. Mollanejad et al. (2011) developed a MIP model for the SBT problem with uneven headways and trips before and after a planning horizon. Khani and Shafahi (2011) studied the SBT problem in order to minimize the transfer waiting time by changing headways and departure times of intersecting lines. The proposed model in this work includes two parts: the headway setting model and the departure time setting model. Parbo et al. (2014) studied a bi-level timetable optimization problem, aiming at minimizing the weighted transfer waiting time. With this approach, passengers' route choice is considered by the lower level to obtain accurate passenger weights in the timetable optimization. Kang et al. (2015a) focused on the coordination of last trains aiming at reducing the number of cases that passengers miss the connecting trains within one headway time. A stochastic version of SBT is studied by Y.H. Wu et al. (2015), in which bus travel times are stochastic, and slack time is added into the timetable to mitigate the randomness of travel times so that the rate of transfer failures is reduced. With the consideration of time-varying passenger demand, Wang et al. (2015) proposed an event-driven model for the train scheduling problem of a rail transit network. Using this model, the authors try to minimize the total travel time of all passengers and the energy consumption of trains. Niu et al. (2015) proposed a train schedule synchronization approach for two interconnected high-speed rail lines under given time-dependent origin–destination demand.

The SBT considering the impact on original timetable has been addressed only by a few studies. For example, Guihaire and Hao (2010) addressed the problem of modifying a bus network timetable to improve the number and quality of transfers while maintaining an initial vehicle schedule and limiting a deviation of an initial timetabling. The authors implement a tabu search to solve their single-objective optimization model. A bi-objective model has been proposed by Kwan and Chang (2008), who studied the train timetable synchronization problem by minimizing the cost of the number of transfers and the cost caused by the deviation from an initial train timetable. The authors focus on designing meta-heuristic algorithms to solve their proposed model.

Recently, Kang et al. (2015b) proposed a rescheduling model for last trains with consideration of delays. In the proposed model, the authors not only attempt to maximize the average transfer redundant time and the railway network accessibility, but also try to minimize the difference between the original timetable and the rescheduled one. Krasemann (2012) developed a greedy algorithm for the re-scheduling problem of railway traffic with the occurrence of disturbances.

In this paper, we investigate a multi-objective re-synchronizing of bus timetable (MSBT) problem measured by two performances: the total number of passengers benefited by smooth transfers and the maximal deviation from the departure times of the existing timetable. The MSBT problem aims to adjust the original bus timetable in order to benefit more passengers by synchronizing bus arrival times at transfer nodes. Our motivation is to define an approach to take into account the trade-off between these two performances by optimizing the SBT decision. To achieve this, we propose a multi-objective optimization approach for the MSBT. We manage to answer questions such as: how to improve smooth passenger transfers at minimum deviation from the existing timetable? How many transferring passengers are benefited by allowing one more