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Optimizing train operational plan in an urban rail corridor based on the maximum headway function

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ABSTRACT

The train operational plan (TOP) plays a crucial role in the efficient and effective operation of an urban rail system. We optimize the train operational plan in a special network layout, an urban rail corridor with one terminal yard, by decomposing it into two sub-problems, i.e., the train departure profile optimization and the rolling stock circulation optimization. The first sub-problem synthetically optimizes frequency setting, timetabling and the rolling stock circulation at the terminal without a yard. The maximum headway function is generated to ensure the service of the train operational plan without considering travel demand, then we present a model to minimize the number of train trips, and design a heuristic algorithm to maximize the train headway. On the basis of a given timetable, the rolling stock circulation optimization only involves the terminal with a yard. We propose a model to minimize the number of trains and yard–station runs, and an algorithm to find the optimal assignment of train-trip pair connections is designed. The computational complexities of the two algorithms are both linear. Finally, a real case study shows that the train operational plan developed by our approach enables a better match of train headway and travel demand, and reduces the operational cost while satisfying the requirement of the level of service.

1. Introduction

With the rapid growth of urban populations and automobile ownership, most large cities are suffering from severe traffic congestion. The improvement of urban rail transit has become increasingly important as a means of mitigating traffic problems in these dense population areas. Urban rail transit offers large passenger capacity and high operational speed as well as lower energy consumption and reduced pollution. These safe, fast, comfortable, energy-efficient urban rail systems are crucial for the economic, environmental, and social success of metropolitan regions (Wang et al., 2015). In recent years, operational planning and improved organization of urban rail transit systems have attracted wider attention from the field of transportation optimization (Ceder, 1984, 1986, 2002, 2007; Guihaire and Hao, 2008).

Public transit planning generally involves five basic steps: (1) designing routes; (2) frequency setting; (3) timetabling; (4) rolling stock circulation or vehicle assignment; and (5) crew scheduling (Guihaire and Hao, 2008; Cadarso and Marín, 2014). Designing a model that encompasses all five planning steps at once is rather cumbersome and complex. In most cases, the

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model for each of the five planning steps is developed sequentially. The output of one step provides the input for the next step (Ceder, 2002). In particular, the train operational plan (TOP) normally consists of three of the procedures described above: frequency setting, timetabling, and rolling stock circulation. Each plays a crucial role in the efficient and effective operation of an urban rail transit system.

Frequency setting and timetabling are usually studied jointly. In general, a schedule that incorporates constant headways can reduce the total waiting time if the pattern of passenger arrival times at stations follows particular probability distributions, such as uniform distribution or Poisson distribution (Niu and Zhou, 2013). In keeping with this approach, some researchers have designed multi-phase timetables to implement regular vehicle departure intervals for each time period. Ceder (2009) proposed a modeling framework and developed corresponding algorithms for planning vehicle departure times. The proposed timetable used even headways or even average loads during the same time period as well as smooth transitions between time periods. In contrast, a number of researchers have focused on periodic timetable design. Liebchen (2008) designed a train timetable using a periodic event-scheduling approach based on a well-established graph model. The author generated the periodic schedules for the Berlin subway system. Odijk (1996) proposed a constraint generation algorithm to develop a model with periodic time window constraints. This model used periodic timetables to plan arrival and departure times.

Given that travel demand has large variations (Vuchic, 2005), schedules with fixed headways usually cannot satisfy the fluctuating demands well. Improved results are obtained when transit operators understand the dynamics of passenger demands and respond by designing demand-sensitive timetables to make better use of limited service capacities (Ceder, 2007; Niu and Zhou, 2013). Accordingly, a variety of timetabling methods have been proposed that take into consideration time-varying demand and non-periodic headways. Ceder (2001) developed a scheduling model to replace constant headway by making transit vehicles even-loaded. Jamili and Pourseyed-Aghaee (2015) developed a formulation of finding optimum stop-skip patterns and used a robust approach to obtain headway distributions which fit traffic in different weekdays and holidays. Assis and Milani (2004) presented a method for computing optimal train schedules in metro lines using a linear-programming-based model with predictive control formulation. This train traffic model was comprised of dynamic equations that described the evolution of train headways and train passenger loads. This model also considered the time variation of passenger demand and all relevant safety and operational constraints. Albrecht (2009) pointed out that the economical and attractive operation of suburban railways can be realized only by recognizing the need for flexible headways, adaptation of the network, and capacity of the lines. Albrecht presented a two-level approach to planning and timetabling for a suburban railway. Niu and Zhou (2013) optimized train schedules for an urban rail transit line by including consideration of time-dependent, origin-destination passenger demands under heavily congested conditions with limited train fleet availability. Furthermore, Niu et al. (2015) investigated a method to minimize the total passenger waiting time at stations by computing and adjusting train timetables for a rail corridor with given time-varying O-D demand and skip-stop patterns. Sun et al. (2014) presented three models for designing demand-sensitive timetables, in which the influence of train capacity was considered. The authors showed the advantages of a dynamic timetable built with capacity constraints. Li and Lo (2014) considered time-varying passenger travel demand and proposed a dynamic optimization framework for train scheduling. Jiang et al. (2016) presented a model based on time-driven microscopic simulation to evaluate train timetable with urban rail transit big data.

In the area of railroad operation, train timetables serve as an essential data input to locomotive and crew scheduling, directly impacting the utilization of scarce resources such as engines, cars, and crews (Zhou and Zhong, 2007). In general, train scheduling must consider a number of operational and safety requirements as well as limited resources. Recently, researchers have investigated synchronized timetables, conflict prevention, and resource utilization. Wu et al. (2015) and Xiong et al. (2015) investigated the issues for optimizing synchronized timetables in urban rail transit systems to minimize passengers' waiting time, delay cost, and transfer cost. Wong et al. (2008) focused on coordinated timetables that enabled smooth interchanges with minimal delays and waiting times for passengers. Corman et al. (2010) proposed a bi-objective model to minimize train delays and missed connections in order to provide a set of feasible non-dominated schedules. Carey and Crawford (2007) designed a series of heuristics to find and resolve train conflicts under various operational constraints and objectives. Dündar and Sahin (2013) developed a decision support tool for re-scheduling problems designed to resolve inter-train conflicts. Zhou and Zhong (2005, 2007) proposed a generalized resource-constrained project scheduling formulation that considered segment and station headway capacities as limited resources. Their model addressed the train scheduling problem for planning applications based on the combined objective of minimizing both expected waiting times and total travel times of trains.

In order to utilize existing resources most effectively and avoid conflicts between trains, rolling stock circulation must be considered; otherwise, the timetable cannot be applied in practice. Some researchers have considered an integrated optimization of timetable and rolling stock circulation. Guihaire and Hao (2010) proposed an integrated timetable and vehicle assignment optimization model for a bus transit system in which they optimized the vehicle scheduling plan by using the method proposed by Freling et al. (2001). They embedded these procedures in an iterated local search algorithm capable of finding feasible solutions. Petersen et al. (2012) proposed an integer programming problem to optimize the timetable and deal with the vehicle scheduling problem simultaneously by applying a large neighborhood search metaheuristic. Ibarra-Rojas et al. (2014) studied the trade-off between the level of service and operating costs, including the problems of timetabling and vehicle scheduling. They presented two integer linear programming models for the two problems and then combined them in a bi-objective integrated model. It is notable, however, that the consideration of demand in the above studies