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Passenger-demands-oriented train scheduling for an urban rail transit network

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ABSTRACT

This paper considers the train scheduling problem for an urban rail transit network. We propose an event-driven model that involves three types of events, i.e., departure events, arrival events, and passenger arrival rates change events. The routing of the arriving passengers at transfer stations is also included in the train scheduling model. Moreover, the passenger transfer behavior (i.e., walking times and transfer times of passengers) is also taken into account in the model formulation. The resulting optimization problem is a real-valued nonlinear nonconvex problem. Nonlinear programming approaches (e.g., sequential quadratic programming) and evolutionary algorithms (e.g., genetic algorithms) can be used to solve this train scheduling problem. The effectiveness of the event-driven model is evaluated through a case study.

1. Introduction

Nowadays, urban rail transit systems play a key role in public transportation for big cities (e.g., Beijing, New York, Paris) since they combine high transport capacity and high efficiency. A safe, fast, energy-efficient, and comfortable urban rail system is important for the economic, environmental, and social objectives of big cities. The railway planning process is essential for urban rail transit operations and management, and in general it consists of five phases (Bussieck et al., 1997): demand analysis, line planning, train scheduling, rolling stock planning, and crew scheduling. The focus of this paper is on train scheduling for an urban rail transit network where the aim is to reduce the operation costs of the trains and to enhance passenger satisfaction. Passenger satisfaction can be characterized by the waiting times, the in-vehicle times, and the number of transfers, while the operation costs are determined by the number of train services and the energy consumption of the trains.

In most urban rail transit systems, the transit lines are separate from each other and each direction of a line has a separate rail track. Hence, trains usually do not overtake each other. In addition, passengers may need to make several interchanges between different lines to arrive at their destinations. Therefore, it is important to take passenger transfers into account in the train scheduling to shorten the total travel time of passengers. Hence, the train schedules for different lines should be coordinated in order to enable smooth passenger transfer and to minimize the total travel time of passengers. Moreover,

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the passenger demands may vary significantly along the day at different stations, i.e., the number of passengers getting on and getting off trains depends on the location of the stations and the time of day (e.g., morning-peak hours, afternoon-peak hours, and off-peak hours).

Train scheduling for *inter*urban rail transit systems has been studied for decades (Szpigel, 1972; Petersen et al., 1986; Kraay et al., 1991; Higgins et al., 1996; Cordeau et al., 1998; Ghoseiri et al., 2004; D'Ariano et al., 2007). In interurban rail transit systems the available resources, e.g., the tracks and the crossings, are shared by trains with different origins and destinations. Thus, the trains may overtake and cross each other at some specific locations, such as sidings and crossings. In this paper, we concentrate however on urban rail transit systems, where the lines usually have double tracks, and train overtaking and crossing are normally not allowed during the operations.

Regular schedules with fixed headways are often used in practice for urban rail transit systems, e.g., every seven minutes there is a train entering a station. Kwan and Chang (2005) applied a heuristic-based evolutionary algorithm to optimize the frequency (or headway) between trains, where the operation costs and the passenger dissatisfaction are included in the performance index. Liebchen (2006, 2008) formulated the train scheduling problem as a periodic event-scheduling problem based on a graph model and obtained periodic schedules for the Berlin subway system using genetic algorithms and integer programming. Su et al. (2013) and Li and Lo (2014) optimized the cyclic train schedule together with the driving strategy to minimize the energy consumption through the utilization of regenerative energy. Regular schedules can reduce the passenger waiting time if the passenger arrival process at stations is a uniform process or a Poisson process (Niu and Zhou, 2013; Barrena et al., 2014). However, regular schedules may result in longer passenger waiting times and travel times under time-varying passenger demands.

Cury et al. (1980) obtained a nonperiodic train schedule aimed at minimizing passenger dissatisfaction and operation costs based on a model of the train movements and the passenger behavior. The resulting nonlinear scheduling problem was recast into several subproblems by Lagrangian relaxation and then solved in a hierarchical manner. The headway between trains in the optimal schedules obtained by Cury et al. (1980) varies with time instead of being a constant. Since the convergence rate of the hierarchical decomposition algorithm of Cury et al. (1980) can be quite poor in some cases, Assis and Milani (2004) proposed a model predictive control algorithm based on linear programming to optimize the train schedule. The algorithm proposed by Assis and Milani (2004) can effectively generate train schedules for the whole day. Furthermore, a demand-oriented timetable design has been proposed by Albrecht (2009), where the optimal train frequency and the capacity of trains are first determined and then the schedules of the trains are optimized. Niu and Zhou (2013) optimized the train schedules for an urban rail transit line with consideration of time-varying origin–destination passenger demands in heavily congested situations. In particular, a genetic algorithm was used to solve the resulting nonlinear programming problem. Furthermore, Niu et al. (2015) considered the train scheduling with time-dependent demand and skip-stop patterns to minimize the passenger waiting time. A branch-and-cut algorithm is presented by Barrena et al. (2014) to minimizing average passenger waiting time with consideration of a dynamic passenger demand. Furthermore, in Wang et al. (2015) we proposed an iterative convex programming approach for train scheduling for urban rail transit lines with the aim of minimizing the total travel time and the total energy consumption.

As mentioned before, passenger transfers are important when optimizing train schedules for an urban rail transit system. The passenger transfer behavior and transfer waiting times are considered by Wong et al. (2008), who present a mixed-integer programming optimization model to synchronize the train schedules for different urban rail transit lines in order to minimize the waiting times of the transfer passengers. In addition, Vázquez-Abad and Zubieta (2005) proposed a stochastic approximation approach to adjust the frequencies of different urban transit lines according to the observed variable passenger demands. However, the energy consumption of the trains and the dwell times at stations are not included in the model of Vázquez-Abad and Zubieta (2005).

The current paper extends the previous research in the following aspects:

- In Wang et al. (2015), we have used a time-driven model for the train scheduling. However, in this paper, we present an event-driven model, which has a higher computational efficiency than the time-driven model. With this model, we can characterize the time-varying origin–destination passenger demand.
- In Wang et al. (2015), we have considered a single urban transit line. In this paper, we consider an urban rail transit *network*. In addition, the passenger transfer behavior and the route choice of passengers at transfer stations are also included in the problem formulation.
- The passenger travel time is computed more accurately by including the walking time for passengers from entrances to platforms, the waiting time, the in-vehicle time, the transfer time, and the walking time for passengers from platforms to exit stations.

The rest of the paper is structured as follows. Section 2 introduces the three types of events and formulates an event-driven model for trains. Section 3 describes the performance criteria and constraints of the train scheduling problem. In addition, we also discuss the initial conditions and solution approaches in this section. In Section 4, the performance of the proposed event-driven model is evaluated via a case study. Finally, conclusions and recommendations are provided in Section 5.