Transportation Research Part B 97 (2017) 182–213

Contents lists available at ScienceDirect

Transportation Research Part B

journal homepage: www.elsevier.com/locate/trb

Dynamic passenger demand oriented metro train scheduling with energy-efficiency and waiting time minimization: Mixed-integer linear programming approaches

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A R T I C L E I N F O

Article history:
Received 23 July 2016
Revised 4 January 2017
Accepted 5 January 2017

Keywords:
Metro train scheduling
Energy efficiency
Dynamic passenger demands
Space-time network
Regenerative energy

A B S T R A C T

In the daily operation of metro systems, the train scheduling problem aims to find a set of space-time paths for multiple trains that determine their departure and arrival times at metro stations, while train operations are in charge of selecting the best operational speed to satisfy the punctuality and operation costs. Different from the most existing researches that treat these two problems separately, this paper proposes an integrated approach for the train scheduling problem on a bi-direction urban metro line in order to minimize the operational costs (i.e., energy consumption) and passenger waiting time. More specifically, we simultaneously consider (1) the train operational velocity choices that correspond to the energy consumption of trains on each travelling arc, and (2) the dynamic passenger demands at each station for the calculation of total passenger waiting time in the planning horizon. By employing a space-time network representation in the formulations, this complex train scheduling and control problem with dynamic passenger demands is rigorously formulated into two optimization models with linear forms. The first model is an integer programming model that jointly minimizes train traction energy consumption and passenger waiting time. The second model, which is formulated as a mixed-integer programming model, further considers the utilization of regenerative braking energy on the basis of the first model. Due to the computational complexity of these two models, especially for large-scale real-world instances, we develop a Lagrangian relaxation (LR)-based heuristic algorithm that decomposes the primal problem into two sets of subproblems and thus enables to find a good solution in short computational time. Finally, two sets of numerical experiments, involving a relatively small-scale case and a real-world instance based on the operation data of Beijing metro are implemented to verify the effectiveness of the proposed approaches.

1. Introduction

With the increasing social concerns on carbon emission and global warming problems in big cities (e.g., Tokyo, Beijing, Shanghai, New York), sustainable and environmental friendly transportation modes, involving public transport

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http://dx.doi.org/10.1016/j.trb.2017.01.001

(Daganzo, 2010) and electric vehicles (Li et al., 2016), are paid more and more attention in recent years. As an indispensable part of public transport, urban metro traffic is regarded as an environmental friendly transportation mode with high carrying capacity and low carbon emissions (Yang et al., 2016). For example, Beijing metro owns 18 lines with a total length of 527 km, which can carry as many as 10 million passengers to their destinations within a single day. Meanwhile, the carbon emission for transporting one passenger per kilometer by the metro line is only about 10% compared with that of a single occupancy car (Kennedy, 2002), which enables to release the environmental pressure for carbon emissions and improve the social benefits through the development of urban metro systems.

In general, the daily operations of a metro system are formed on the basis of an extensive daylong planning process, which typically involves train scheduling, rolling stock plan and crew scheduling. In particular, the metro train scheduling process aims to find a set of feasible space-time paths for all the in-service trains to determine their departure and arrival times at the stations of a metro corridor. As indicated in Cordeau et al. (1998), Zhou and Zhong (2007) and Wang et al. (2014), the train schedule has a direct affect on the service quality and operational costs of a metro system. Specifically, the service quality is commonly associated with the train travel time and passenger waiting time, while the operational costs usually refer to the total energy consumption for the movement of trains. In essence, the service level and operational costs are two objectives that may conflict with each other in the metro train scheduling process. For example, the high train departure frequency and short travel time can reduce passenger waiting and travelling time, but will inevitably increase the energy consumption for train operations.

Nevertheless, the current researches that simultaneously consider the above two objectives through a microscopic view are very few, which is partially due to the following two reasons. (1) On one hand, the calculation of passenger waiting time (or travelling time) in a metro line is directly subjected to the complex passenger flow characteristics through a daylong planning horizon. Compared with mainline railways or high-speed railways, in which most passengers make their trip plans according to the given timetable, passengers in a metro system usually do not care about the train timetable before their trips, leading to the evident dynamic (or time-variant) features of passenger demands (Freyss et al., 2013; Yang et al., 2015a). In this sense, a non-periodic timetable, i.e., a timetable with irregular headway between adjacent trains, can be more appropriate to handle the dynamics of passenger demands. However, a non-periodic timetable is usually much more difficult to obtain due to the consideration of time-variant demands, resulting in the nonlinearity of the mathematical formulations (e.g., Barrena et al., 2014b; Niu et al., 2015b); (2) on the other hand, the optimization of energy consumption for train operations is inherently a complex nonlinear problem subject to many external factors, e.g., travel time in each segment, parameters of vehicle dynamic model and rail tracks (e.g., Howlett and Pudney, 1995; Howlett et al., 2009; Ye and Liu, 2016; Yin et al., 2014; 2016a). Additionally, if the regenerative braking energy, which is an effective approach to reduce the total energy consumption by converting train braking energy for the utilization of accelerating trains, is further considered, the metro train scheduling problem will become a highly nonlinear optimization model that is much more challenging to handle.

To address these issues, this paper aims to develop a unified metro train scheduling framework that simultaneously considers the dynamic passenger demands, train traction energy consumption and the utilization of regenerative braking energy. In particular, by using a space-time network analysis, we formulate the problem into two (mixed) integer linear programming models which aim to minimize the total passenger waiting time and energy consumption (i.e., the difference between the train traction energy consumption and regenerative energy). To solve the models more efficiently, we also develop an efficient Lagrangian relaxation-based heuristic algorithm that can obtain a good solution in an acceptable computational time.

1.1. Literature review

The train scheduling problem, which aims to obtain a timetable that is to be carried out by a scale of given fleet, is a very active research field in railway operations (e.g., Cacchiani and Toth, 2012; Cacchiani et al., 2016; Wong et al., 2008; Xu et al., 2015; Kroon et al., 2014; Niu and Zhou, 2013; Niu et al., 2015b; Barrena et al., 2014b; 2014a). In general, the current solution methodologies for the rail train scheduling problem can be divided into three categories: (1) optimization approaches which use the commercial optimization softwares (e.g., CPLEX, GAMS (Yang et al., 2014)) or accurate algorithms (e.g., branch and bound algorithms (Corman et al., 2012; D'Ariano et al., 2007)), (2) heuristic algorithms (e.g., Lagrangian relaxation (Cacchiani et al., 2016; Meng and Zhou, 2014; Zhou and Zhong, 2007)) and (3) simulation methods (e.g., Dorfman and Medanic, 2004; Mu and Dessouky, 2013; Xu et al., 2015). In particular, these researches in rail train scheduling problem mainly focus on the minimization of three types of objectives, involving train delay time (Higgins et al., 1996; Cacchiani et al., 2014; Corman and Quaglietta, 2014; Corman et al., 2010), total travel time (e.g., Zhou and Zhong, 2005; 2007) and fuel consumption costs (e.g., Yang et al., 2015b). For example, Higgins et al. (1996) developed a non-linear integer programming model for the real-time scheduling of trains on a single line corridor. The objective was to minimize the total delay time in case of train conflicts and the operational costs. For the minimization of total travel time, Zhou and Zhong (2007) formulated this problem into a job shop scheduling model, which was solved efficiently by a Lagrangian relaxation combined with branch and bound algorithms.

In a passenger railway, namely a metro system or urban rail transit, it is practically desirable to design a passenger-centric timetable to highlight the convenience, reliability and reduction of passenger waiting times (Niu et al., 2015b). In general, the researches of passenger-oriented timetable design can be divided into two categories. The first kind of re-