Transportation Research Part E 97 (2017) 22–37

Contents lists available at ScienceDirect

Transportation Research Part E

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

Bi-objective programming approach for solving the metro timetable optimization problem with dwell time uncertainty

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ARTICLE INFO

Article history:
Received 3 September 2015
Received in revised form 28 October 2016
Accepted 30 October 2016

Keywords:
Metro systems
Timetable optimization
Energy consumption
Bi-objective

ABSTRACT

For optimization of timetables in metro systems with regular cyclic operation, this paper develops a bi-objective programming approach addressed to minimization of net energy consumption and total travel time with provision for dwell time uncertainty. Firstly, we formulate the bi-objective timetable optimization problem as an expected value model with speed profile control. Secondly, we use the ε-constraint method within a genetic algorithm framework to determine the Pareto optimal solutions. Finally, numerical examples based on the real-life operation data from the Beijing Metro Yizhuang Line are presented in order to illustrate the practicability and effectiveness of the approach developed in the paper.

1. Introduction

1.1. Motivation

Due to their high reliability, large passenger capacity and environmental friendliness, metro systems have played an important role in many metropolitan cities (Jin et al., 2014; Yang et al., 2016a). Metro systems and metro timetables in particular have been a widely studied topic in recent years. The construction of a metro timetable includes scheduling the arrival and departure times of a set of trains at each station, and defining the operating speed profile of trains on each section. Speed profiles and travel times have substantial impacts of different kinds - on operational efficiency, on the convenience of passengers and on levels of pollutant emissions. For this reason, it is appropriate to treat timetable optimization as a multi-objective decision problem. Energy consumption and travel time are two important indices for evaluating the effectiveness of a timetable. The former is required by the operating companies and benefits the environment, and the latter is of more concern to passengers. In addition, metro train delays often occur at busy stations due to delays caused by intermittent passenger crowding, especially during the peak hours. Therefore, the dwell time uncertainty should not be ignored in the timetable optimization problem.

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http://dx.doi.org/10.1016/j.tre.2016.10.012
1366-5545/

1.2. Literature review

The literature on train scheduling can be categorized as to the types of schedule involved, namely cyclic or acyclic. Cyclic timetables are mainly applied to passenger railways such as metro, and acyclic timetables are often used for freight railways. For cyclic timetables, Peeters (2003) provided a good overview for the relevant studies before 2003, and discussed their advantages. Kroon et al. (2008) made a stochastic improvement of cyclic timetables by considering the random disturbances in real-world operations. Heydar et al. (2013) developed a mixed integer programming model to minimize both the length of the dispatching cycle and the total dwell time. For acyclic timetables, the early optimization models were summarized in a survey by Cordeau et al. (1998). In 2002, Caprara et al. proposed a graph theoretic formulation for the train timetabling problem using a directed acyclic multigraph. Cacchiani et al. (2010), on the other hand, studied the acyclic train timetabling problem and analyzed the existing optimization models. Because the present research is concerned with cyclic scheduling, the remainder of this review is concerned (except where otherwise stated) with literature on the cyclic case.

In recent years, timetable optimization models have been developed with a variety of criteria, including capacity (Abril et al., 2008), transport demand (Kuo et al., 2010; Canca et al., 2014), robustness (Cacchiani and Toth, 2012; Burdett and Kozan, 2014), delay time (Liebchen et al., 2010; Corman et al., 2012b), overlapping time (Yang et al., 2013), energy consumption (Li and Lo, 2014a,b), passenger waiting time (Niu et al., 2015), and utilization of regenerative energy (Yang et al., 2015a).

Yang et al. (2015a) focused on optimizing the dwell time at each station to improve the utilization of regenerative energy, where the running time and speed profile on each section were considered as constant parameters. With those assumptions, the total tractive energy consumption is also a constant parameter. It may be noted that the main differences between the present research and that of Yang et al. (2015a) are: (a) the decision variables in the present research are speed profiles and running times instead of dwell times; and (b) the present research adopts minimization of travel time as an objective, alongside efficiency of energy utilization.

Because different stakeholders with different interests are involved, it is natural to treat timetable optimization as a multi-objective decision problem. For example, Higgins et al. (1996) proposed a nonlinear mixed-integer programming model to minimize the delay time and the train operation cost, and solved the integer program using a branch-and-bound procedure. Ghoseiri et al. (2004) developed an optimization model to minimize the fuel consumption cost and the total passenger time using the ε-constraint method to find a set of non-dominated solutions that forms the Pareto frontier. Yang et al. (2009) developed an expected value programming model to minimize the delay time and the total passenger time, in which the number of passengers boarding/alighting the train at each station is considered as a fuzzy variable. Corman et al. (2012a) considered the minimization of the consecutive delays between trains and the maximization of the total value of satisfied connections to develop a bi-objective conflict detection and resolution problem.

Li et al. (2013) developed a multi-objective train scheduling model for minimizing the energy, the carbon emission cost and the total passenger time using a fuzzy mathematical programming method to find the optimal solution. Sun et al. (2014) developed a multi-objective optimization model to consider the average travel time, the energy consumption and the user satisfaction and designed a genetic algorithm to solve the model. Yang et al. (2014) developed a bi-objective integer programming model with headway time and dwell time control to increase the utilization of regenerative braking energy and, simultaneously, to shorten the passenger waiting time. On the other hand, Yang et al. (2015b) developed a bi-objective optimization method to determine timetables and speed profiles applying an adaptive genetic algorithm with an optimal train control algorithm to find the optimal solution. Xu et al. (2015) developed a multi-objective timetable optimization model to consider both energy efficiency and service quality for metro systems.

Overall, many studies have considered multiple objectives in the timetable optimization problem, but only a few studies (Li and Yang, 2013; Wu et al., 2015) consider the uncertain factors of the real-world operations in determining the metro timetable. This paper contributes to the current literature by developing a bi-objective programming approach that explicitly considers the dwell time uncertainty in the timetable optimization problem for minimizing both net energy consumption and total travel time. The main contributions of this paper are as follows:

- We consider the uncertain dwell time and formulate the timetable optimization problem as a bi-objective expected value model.
- We use the ε-constraint method within a genetic algorithm framework to obtain the Pareto optimal solutions and determine three optimal timetables suitable for different real-world operation cases.
- We present numerical examples based on the real-world operation data from the Beijing Metro Yizhuang Line to illustrate the practicability of the model as well as the effectiveness of the solution procedure.

1.3. Paper structure

The remainder of the paper is organized as follows. In Section 2, we formulate a bi-objective expected value model to determine the optimal timetable. In Section 3, we design a genetic algorithm combined with the ε-constraint method to solve the developed bi-objective expected value model. In Section 4, two numerical examples based on the real-world data from the Beijing Metro Yizhuang Line are presented. Finally, conclusions are given in Section 5.