Transportation Research Part C 63 (2016) 126–146

Contents lists available at ScienceDirect

Transportation Research Part C

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

Optimizing train stopping patterns and schedules for high-speed passenger rail corridors

Yixiang Yue [a,*], Shifeng Wang [a], Leishan Zhou [a], Lu Tong [a], M. Rapik Saat [b]

[a] School of Traffic and Transportation, Beijing Jiaotong University, Beijing 100044, China
[b] Rail Transportation and Engineering Center, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA

ARTICLE INFO

Article history:
Received 2 July 2015
Received in revised form 10 December 2015
Accepted 12 December 2015
Available online 30 December 2015

Keywords:
Train scheduling
Railway service plan
Train stopping pattern
Column generation

ABSTRACT

High-speed railway (HSR) systems have been developing rapidly in China and various other countries throughout the past decade; as a result, the question of how to efficiently operate such large-scale systems is posing a new challenge to the railway industry. A high-quality train timetable should take full advantage of the system's capacity to meet transportation demands. This paper presents a mathematical model for optimizing a train timetable for an HSR system. We propose an innovative methodology using a column-generation-based heuristic algorithm to simultaneously account for both passenger service demands and train scheduling. First, we transform a mathematical model into a simple linear programming problem using a Lagrangian relaxation method. Second, we search for the optimal solution by updating the restricted master problem (RMP) and the sub-problems in an iterative process using the column-generation-based algorithm. Finally, we consider the Beijing–Shanghai HSR line as a real-world application of the methodology; the results show that the optimization model and algorithm can improve the defined profit function by approximately 30% and increase the line capacity by approximately 27%. This methodology has the potential to improve the service level and capacity of HSR lines with no additional high-cost capital investment (e.g., the addition of new tracks, bridges and tunnels on the mainline and/or at stations).

1. Introduction

The planning process for public transportation consists of several consecutive planning phases. The process begins with network design, which is typically then followed by line planning, timetabling, and vehicle and crew scheduling (Schöbel, 2012). Train timetables specify the arrival and departure times of trains between yards, terminals, sidings and every given point along a rail line or network. Train timetable scheduling plays an important role in the management and operation of complex railway systems.

Before scheduling train timetables, a railway operator usually defines a train service plan – a framework for train service and timetables based on certain strategic decisions, including origin–destination pairs for travel demand, station settings, operating capacities and planning parameters (Chang et al., 2000). Different train service plans produce passenger service schemes with different characteristics, such as the frequency, trip time and stopping patterns between different stations along a rail line. The level of service is a key factor that affects travelers' decisions in choosing their preferred transportation

* Corresponding author.
E-mail address: yxyue@bjtu.edu.cn (Y. Yue).

http://dx.doi.org/10.1016/j.trc.2015.12.007
0968-090X/

modes (Tong et al., 2012). Indirectly, the train service plan affects the fare revenue and profitability of a train operator. This "profit" factor is important to consider when scheduling train timetables.

Many scholars have provided excellent surveys of the inherent connections among different optimization problems in the field of railway routing and scheduling (Caprara, 2010), such as backtracking search (Adenso-Dıaz et al., 1999), look-ahead search (Sahin, 1999), and the continuous approximation approach (Freyss et al., 2013). Over the past four decades, researchers have quite extensively studied the Train Timetable Problem (TTP), leading to the development of various railway operation models and techniques (Assad, 1980; Hansen, 2009; Walker et al., 2005; Cacchiani and Toth, 2012). Previous TTP optimization models have typically focused exclusively on train scheduling or passenger service demands, although additional models have attempted to consider both factors at small scales.

Brännlund et al. (1998) introduced a Lagrangian relaxation method for searching in the timetabling problem of a railway operator, namely, the scheduling of a set of trains to obtain a profit-maximizing timetable while not violating track capacity constraints. D'Ariano et al. (2007) investigated a new concept of a flexible timetable as an effective policy for improving punctuality without decreasing the capacity usage of the lines. They used three greedy heuristics and a branch-and-bound algorithm for conflict resolution, but they did not test them on different networks. Lee and Chen (2009) used a four-step process to optimize both train paths and train timetables. By decomposing the original complex problem into four parts and solving each part alone, their heuristic method was able to produce solutions for realistic scenarios. Liu and Kozan (2011) addressed train-scheduling problems based on prioritized and non-prioritized trains. Their model was required to conform to blocking and no-wait constraints in specific environments. Corman et al. (2014) presented a thorough assessment of the possible applications of an optimization-based framework for the evaluation of different timetables over a large network. Sun et al. (2014) proposed a multi-objective optimization model to minimize the degree of deviation for train rerouting on a high-speed railway network, considering the average train travel time, energy consumption and user satisfaction. To minimize the total train travel time, Zhou and Zhong (2007) modeled limited track resources via headway constraints and reformulated them as additive constraints to chronologically eliminate train conflicts. Meng and Zhou (2014) developed an innovative integer programming model for the problem of train dispatching on an N-track network by simultaneously rerouting and rescheduling trains using a time–space network-modeling framework. Shafia et al. (2012) illustrated a novel and robust train-timetabling problem for a single-track railway line to compute buffer times. All these models focused on train scheduling under given capacity constraints.

Another subset of previous studies focused on passenger service demands or train service planning. Peeters and Kroon (2008) used a branch-and-bound method to solve the problem of railway rolling stock circulation with a given timetable to meet passengers' demands. Considering passenger flow, Deng et al. (2009) analyzed the relation between stopping schedules and passenger transfer choices. They built a bi-level model considering travel cost and the number of train stops. To decrease passenger transfer waiting time in a network, Petersen et al. (2012) proposed a planning approach that attempted to achieve a favorable trade-off between the two contrasting objectives of passenger service and operating cost by modifying the timetable. Kunimatsu et al. (2012) developed a micro-simulation system to simulate both train operation and passengers' train choice behavior. Niu and Zhou (2013) and Niu et al. (2015) used the overall passenger waiting time as the objective and applied a genetic algorithm that indicated a train departure or no departure at every possible time point to optimize train timetables. Lin and Ku (2013) used two genetic algorithms, namely, a binary-coded genetic algorithm and an integer-coded genetic algorithm, to optimize stopping patterns for passengers to solve real-world problems with excellent performance. Espinosa-Aranda and Angulo (2015) proposed a constrained logit-type choice model that took the behavior of users into account. No models have optimized the train schedule to reach the maximum capacity of the railway lines.

Several previous studies have attempted to consider both train scheduling (including railway line capacity constraints) and passenger service demands, but only at small scales. Caprara et al. (2002, 2006) proposed a graph-theoretic formulation of the problem using a directed multi-graph in which nodes corresponded to departures/arrivals at a certain station at a given instant. Cacchiani et al. (2008) proposed heuristic and exact algorithms for the TTP on a corridor, including periodic and non-periodic. In their integral linear programming (ILP) formulation, each variable corresponded to a full timetable for a train, yielding a problem that was much simpler to solve. Cacchiani et al. (2010) considered the customary formulation of non-cyclic train timetabling, in which they sought a maximum-profit collection of compatible paths in a suitable graph. Their methods offered increased efficiency of the column generation algorithm and improved the experimental results but could not be applied to a large-scale problem. Min et al. (2011) proposed a column-generation-based algorithm focusing on the train-conflict resolution problem. Yang et al. (in press) considered the minimization of the total dwelling time and total delay between the actual and expected departure times to optimize both train stop pattern and train timetabling problems at the tactic level. They also point out, when applying to large real-world instances, an efficient heuristic algorithm is needed to speed up the searching process.

In this paper, we propose a new methodology using a column-generation-based algorithm to simultaneously account for both passenger service demands and train scheduling to optimize train timetables. The framework of our proposed methodology is illustrated in Fig. 1. In our model, the "train service plan" provides input parameters related to passenger service demands. The percentage of the total trains and the total number of trains required for each origin-to-destination (OD) pair on a rail line or network to satisfy the passenger transport demand can be determined by analyzing the passenger flow OD matrix. The decision variables correspond to the "stopping pattern" (specifying at which stations each train stops) and the "stopping time" (specifying how long each train stops at intermediate stations). In the model and algorithm, the first step is to optimize the trains' stopping pattern while guaranteeing the train service plan constraints, whereas the second step is to optimize the train departure times while guaranteeing the stopping duration constraints, headway constraints and station