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Train routing and timetabling problem for heterogeneous train traffic with switchable scheduling rules

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A B S T R A C T

This paper proposes a mathematical model for the train routing and timetabling problem that allows a train to occasionally switch to the opposite track when it is not occupied, which we define it as switchable scheduling rule. The layouts of stations are taken into account in the proposed mathematical model to avoid head-on and rear-end collisions in stations. In this paper, train timetable could be scheduled by three different scheduling rules, i.e., no switchable scheduling rule (No-SSR) which allows trains switching track neither at stations and segments, incomplete switchable scheduling rule (In-SSR) which allows trains switching track at stations but not at segments, and complete switchable scheduling rule (Co-SSR) which allows trains switching track both at stations and segments. Numerical experiments are carried out on a small-scale railway corridor and a large-scale railway corridor based on Beijing–Shanghai high-speed railway (HSR) corridor respectively. The results of case studies indicate that Co-SSR outperforms the other two scheduling rules. It is also found that the proposed model can improve train operational efficiency.

1. Introduction

While rail transportation provides economic mobility for both passengers and freight across the world, its efficiency faces an unprecedented challenge because its limited capacity receives increasingly growing passenger and freight transportation demands (Xu et al., 2015). Urban railway transit system also faces such issues (He et al., 2016). This highlights the need for planning efficient train timetables and routes that can best utilize the limited railway capacity throughout the time while guarantying the safety operation. One outstanding challenge to these operations is scheduling heterogeneous trains (e.g., fast trains and slow trains) on high-speed railway with aims to meet different customers' transportation demands. However, such arrangements likely cause excessive travel delay, particularly when a fast train follows a slow one. To address this challenge, Mu and Dessouky (2013) firstly proposed a switchable dispatching strategy (SDS) for a double-track railway link, which essentially enables a fast train to overtake its slow front train by using the opposite directional track when it is in vacancy. Their results showed that the SDS can be able to reduce a fast train's knock-on delay by as much as 30% compared with the dedicated dispatching policy. Inspired by this, we propose a mathematical model to obtain the optimal scheduling solutions for heterogeneous trains on HSR corridors with consideration of switchable scheduling rules based on the SDS in Mu and Dessouky (2013), aiming to produce efficient timetables without infrastructure extensions. With this model, it can

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find the optimal scheduling solutions while the slow and fast trains have optional chance to be scheduled on the opposite track, which is different from previous work where the faster trains were always dispatched on opposite track with SDS (Mu and Dessouky, 2013).

1.1. Literature review

Generally, the goal of the train timetable problem (TTP) is to minimize railroad system operational costs (often measured by the total train delay) by optimally scheduling these arrival, departure times as well as the orders inside and outside stations without causing collision risks or violating certain side constraints (Hansen and Pachl, 2014). TTP is an important issue for train operation and is also known as a hard problem due to large problem scales and complex problem structure. Numerous research has been conducted to solve TTP with mathematical programming techniques and heuristic algorithms in the past few decades (Bešinović et al., 2016; Cacchiani et al., 2016; Zhou and Zhong, 2005, 2007). Cacchiani and Toth (2012) presented an overview of the main works on nominal and robust train timetabling problems. Recently, Caimi et al. (2017) surveyed practical applications and the combinatorial optimization models for railway timetable problem.

While, the train routing problem (TRP) is to select a sequence of tracks for a train from its origin to destination, with the objective of minimizing the knock-on/secondary delay and/or increasing the capacity of railway networks (Mu and Dessouky, 2013). To obtain the optimal solutions for train operations, TTP and TRP are often considered simultaneously as one joint optimization problem, i.e., train timetabling and routing problem (TTRP) (Caimi et al., 2011; Lamorgese et al., 2016; Lee and Chen, 2009; Meng and Zhou, 2014; Samà et al., 2017; Zhou and Teng, 2016). Lee and Chen (2009) proposed a fast heuristic algorithm for the TTRP, where the operation time of trains depends on the assigned track, and the minimum headway between the trains depends on the trains' relative status. Caimi et al. (2011) considered sequentially timetabling and routing problem, at the macroscopic level, the timetable was produced by a periodic event scheduling problem model with continuous variables rather than the event times, then adopted Resource Tree Conflict Graph model to resolute the conflict at stations at the microscopic level. Similarly, Lamorgese et al. (2016) proposed an exact micro–macro approach to cyclic and non-cyclic train timetabling, where the routing problem involved the track choices at stations in the decomposition problem and the master problem was the line problem that finds the arrival/departure time at each station. For scheduling the freight trains, Mu and Dessouky (2011) considered fixed and flexible paths to enhance utilization rates of infrastructures. For real-time train traffic management, Törnquist and Persson (2007) first present a mathematical formulation based on a discrete-event theory for train rescheduling and rerouting problem, then they developed it in an optimization-based computational re-scheduling support for railway traffic networks (Törnquist Krasemann, 2015). On the basis of discrete-event theory, Qi et al. (2016) present a track choice-based bi-level formulation for integrating multi-track station layout design and train scheduling models problem. Meng and Zhou (2014) reformulated the train rerouting and rescheduling on an N-track network by considering a vector of cumulative flow variables and provided an efficient decomposition solution algorithm based on Lagrangian relaxation. Zhou and Teng (2016) furtherly built an integer linear programming for the simultaneous passenger train routing and timetabling problem in a space-time discretized network. A Lagrangian relaxation decomposition framework together with a heuristic method was proposed to solve it. Samà et al. (2017) designed a variable neighborhood search algorithm for fast train scheduling and routing during disturbed rail traffic situations. Fang et al. (2015) surveyed the recent models and methods on train rescheduling in railway networks.

Over the last decade, simulation techniques emerged in TTRP area. Dorfman and Medanic (2004) proposed a discrete-event model (DEM) to schedule the two-way train traffic on a single-track railway line. In this work, train movements were controlled by local feedback-based travel advance strategies. Their work was further improved by Li et al. (2008) into a global feedback-based travel advance strategy for train timetabling problem. Later, an optimal scheduling model with DEM was proposed to find the optimal velocity for each train running on the railway line (Xu et al. (2014). They further applied the DEM to scheduling heterogeneous traffic on high-speed railway corridor considering train switchable scheduling rules (Xu et al., 2015). Besides, Xu et al. (2016) proposed an improved discrete-time model for heterogeneous high-speed passenger train movements. All these studies focus on numerical heuristic solutions by assigning tracks to trains according to local information. Despite the breakthroughs of these studies, they do not ensure solution optimality.

1.2. Main focuses of this study

Although most existing studies consider arrival/departure times and routes along train trips, the switchable scheduling rules (SSRs) in the train timetable design process are rarely investigated. Besides, most existing literature addressed the train timetabling problem neglected the layouts of stations (Qi et al., 2016; Törnquist and Persson, 2007; Törnquist Krasemann, 2015), which may cause infeasible train timetables. Therefore, this study intends to provide the following contributions to the train routing and timetabling problem optimization methods.

(i). Based on the train switchable dispatching rules in Mu and Dessouky (2013, 2014), we first propose an integer linear programming formulation for the train routing and timetabling problem with switchable scheduling rule (SSR). Different from the methodology of queue theory in Mu and Dessouky (2013) that could be applied to a small-scale network, and the heuristic simulation method in Xu et al. (2015) that uses the local information-based switchable dispatching rules to identify feasible solutions, the proposed mathematical models in this paper can obtain a feasible