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A stochastic model for the integrated optimization on metro timetable and speed profile with uncertain train mass

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A B S T R A C T

The integrated timetable and speed profile optimization model has recently attracted more attention because of its good achievements on energy conservation in metro systems. However, most previous studies often ignore the spatial and temporal uncertainties of train mass, and the variabilities of tractive force, braking force and basic running resistance on energy consumption in order to simplify the model formulation and solution algorithm. In this paper, we develop an integrated metro timetable and speed profile optimization model to minimize the total tractive energy consumption, where these real-world operating conditions are explicitly considered in the model formulation and solution algorithm. Firstly, we formulate a two-phase stochastic programming model to determine the timetable and speed profile. Given the speed profile, the first phase determines the timetable by scheduling the arrival and departure times for each station, and the second phase determines the speed profile for each inter-station with the scheduled arrival and departure times. Secondly, we design a simulation-based genetic algorithm procedure incorporated with the optimal train control algorithm to find the optimal solution. Finally, we present a simple example and a real-world example based on the operation data from the Beijing Metro Yizhuang Line in Beijing, China. The results of the real-world example show that, during peak hours, off-peak hours and night hours, the total tractive energy consumptions can be reduced by: (1) 10.66%, 9.94% and 9.13% in comparison with the current timetable and speed profile; and (2) 3.35%, 3.12% and 3.04% in comparison with the deterministic model.

1. Introduction

Metro system has received rapid development around the world because of its high reliability and large transport capacity. For example, only 3 cities in mainland China (i.e., Beijing, Shanghai and Guangzhou) have metro lines in 2000. By the end of 2014, the number of cities has increased to 22 with 88 metro lines and a total distance of more than 3000 km (Online News, 2015). Along with this rapid expansion is the sharp increase in total energy consumption in metro systems. Almost half of the energy is used by the tractive system for accelerating trains. Take the Beijing Metro system as an example, the total energy consumption and the tractive energy consumption of some main metro lines in 2012 are shown in Fig. 1.

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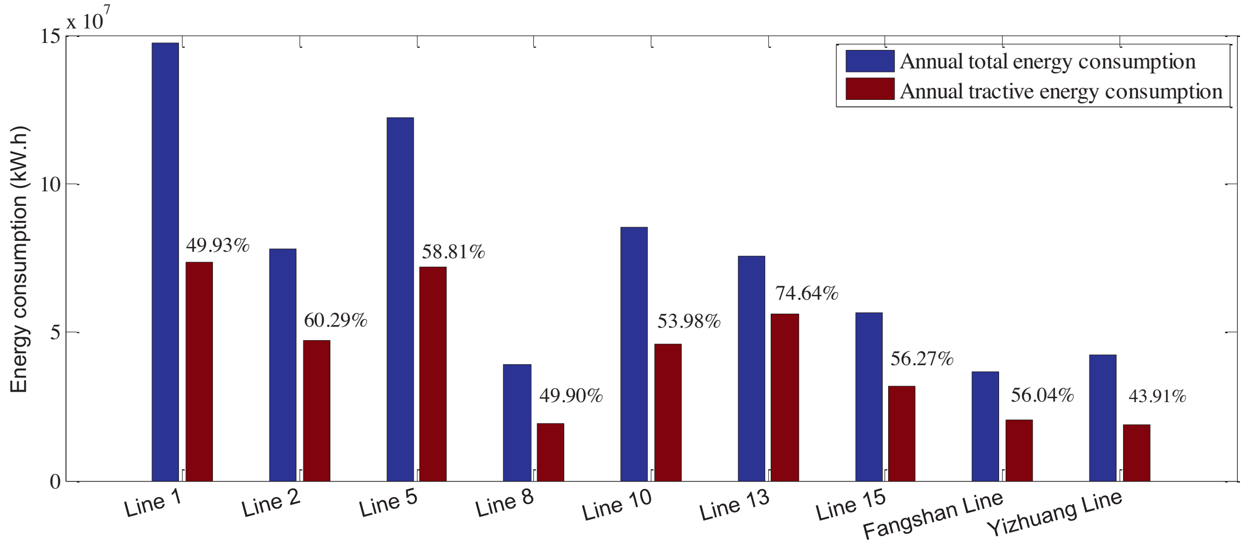

Fig. 1. Energy consumption of some main metro lines in Beijing in 2012 (Source: Zhang (2013)).

Due to the rising environmental concerns and energy prices, energy conservation has attracted much attention in recent years. Energy-efficient train operations can make a significant contribution to reduce the tractive energy consumption. However, traditional studies on energy-efficient train operations, including timetable optimization (Ghoseiri et al., 2004; Yang et al., 2014), speed profile optimization (Ke et al., 2009; 2012) and integrated optimization (Li and Lo, 2014a; 2014b), usually assume the train mass, tractive force, braking force and basic running resistance as constant parameters. In real-world metro systems, the tractive force, braking force and basic running resistance are variable according to the train speed variation. Train mass consists of the empty vehicle mass and the variable mass of passengers on the train. The former is considered fix (or deterministic), while the latter is highly variable (or stochastic) at different inter-stations and at different operational periods (e.g., peak hours, off-peak hours and night hours).

The purpose of this paper is to develop a two-phase stochastic programming model for the integrated timetable and speed profile optimization problem with the aim of minimizing the total tractive energy consumption. Compared to previous studies, this paper has the following contributions and differences.

(1) Compared to Yang et al. (2013) and Yang et al. (2015a), which only optimize the timetable to reduce the energy consumption, this paper develops a two-phase stochastic programming model to optimize both timetable and speed profile for achieving better energy performance.
(2) Compared to Li and Lo (2014a) and Li and Lo (2014b), which assume deterministic train mass and fixed tractive force, braking force and basic running resistance as constant parameters for simplifying the model formulation and solution algorithm, this paper explicitly considers the uncertainty of train mass and the variability of tractive force, braking force and basic running resistance in the integrated timetable and speed profile optimization problem. In addition, this paper analyzes the convergence property and formulation complexity of the developed model.
(3) Compared to Yang et al. (2015b), which also assume the train mass, tractive force and braking force as constant parameters, and a predetermined maximum train speed in the optimal train control algorithm (Howlett and Pudney, 1995), this paper designs a more general optimal train control algorithm that can generate an energy-efficient speed profile without presupposing a maximum train speed. Furthermore, this paper provides an existence proof of an optimal speed profile for a given inter-station with a reasonable running time.

The remainder of this paper is organized as follows. In Section 2, we review the literature on the energy-efficient train operations. In Section 3, we describe the problem statement and motivation of this study based on real-world metro systems, such as the Beijing Metro System. In Section 4, we develop a two-phase stochastic programming model to determine the optimal timetable and speed profile. In Section 5, we design a simulation-based genetic algorithm procedure incorporated with the optimal train control algorithm to find the optimal solution. In Section 6, we present a simple example and a real-world example based on the operation data from the Beijing Metro Yizhuang Line. Conclusions are provided in Section 7.

2. Literature review

In metro systems, energy-efficient train operations have gained attention in recent decades because of the good achievements in reducing energy consumption. The literature on energy-efficient train operations include timetable optimization, speed profile optimization, and integrated timetable and speed profile optimization.