Energy consumption and travel time analysis for metro lines with express/local mode

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ABSTRACT

In recent years, some innovations have appeared in the operation of metro system to save energy consumption and speed up trains. Compared with the standard stop mode, in which a train stops at every station, express/local stop mode can lead to lower energy consumption and less travel time. This paper aims to find the relationship among energy consumption, travel time and timetables, and then obtain a more optimized solution via adjusting timetables. After analyzing the characteristics of express/local stop mode, we linearly formulate energy consumption and passenger travel time, and propose a bi-objective programming model to better understand the relationship between lowering energy consumption and reducing travel time. Taking Beijing Metro Line 6 as a numerical example, we compare the express/local mode and standard stop mode both in total travel time and energy consumption, illustrating the applicability of express/local mode.

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1. Introduction

Due to its large-capacity and high-reliability, metro system has been adopted as a main type of rapid transit in many big cities. In the past decades, as the increase of environmental pressure, some important innovations have appeared in the operation of metro system to lower energy consumption, with little or no reduction on service quality, such as travel time. One of these innovation is designing more applicable stop modes, which may give rise to reduction both in energy consumption and travel time.

According to the characteristics of passenger flow, many metro systems have developed special stop modes, in which some trains need not stop at every station. Generally, there are three basic types of special stop modes (Vuchic, 2005), namely, *skip-stop,zonal* and *express/local*. For the first two operation modes, readers can refer to Vuchic (1973, 2005). In this paper, we focus on metro lines with express/local mode, which is the only way to provide regular service at all stations as well as higher-speed service at major stations. Express/local mode is adopted in some big cities with a large number of suburban commuters, such as Paris, Tokyo and New York, and sooner, it will be used in Beijing and Shanghai.

Since trains stop less in the express/local mode, which means that there are less accelerations and decelerations, energy consumption of train traction is reduced compared to that in the standard stop mode. However, the calculation of energy consumption is much more difficult if the express/local mode is used. The first reason is that, due to the introduction of express/local mode, passengers have more routes to choose, making it difficult to calculate passenger number in trains. As is known, the distribution of passengers affects traction energy consumption. The second reason is that, interaction

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between trains is much greater in the express/local mode. Note that in the express/local mode, an express train may overtake a local train at stations which are equipped with overtaking facilities. In order to ensure that overtaking happens at the right time and stations, timetables of express trains and local trains are highly interrelated, which complicates the calculation of energy consumption.

In this paper, we aim to reveal the relationship among energy consumption, travel time and timetables under the condition of express/local stop mode, and then propose a better solution, which leads to reduction both on energy consumption and travel time. Based on the analysis of route choice and energy consumption, we formulate linear functions for energy consumption and travel time in different OD (origin-destination) cases. Then, we build a bi-objective programming model to further understand the relationship among energy consumption, travel time and timetables. Specifically, the decision variables are timetables of express and local trains; the constraints set of the model, which mainly ensures the safety of operation, consists of link running time constraints, station dwelling constraints, and headway constraints. Taking Beijing Metro Line 6 as a numerical example, we compare the express/local mode and standard stop mode both in energy consumption and travel time. Moreover, we find that there exists a Pareto frontier between energy consumption and travel time.

Noted that trains in metro system are driven by electricity, and the actual electricity (fuel) consumption is roughly in proportion to energy consumption. For this reason, we use energy consumption to represent electricity consumption in this paper. The rest of this paper is organized as follows. Section 2 reviews relevant literature in recent years. In Section 3, the background of express/local stop mode is introduced, and the assumptions used in this paper are summarized. In Section 4, we formulate the model for energy consumption and travel time in detail. In Section 5, some numerical experiments are implemented to show the effectiveness of the proposed model and methods. Finally, a conclusion is made in Section 6.

2. Literature review

This paper aims to gain a better solution on energy consumption and travel time for a metro line with express/local mode via adjusting train timetable, so we first review some relevant literature on energy consumption of metro system. As pointed out by Tolliver et al. (2013) and Wang et al. (2014), rail is low energy-consumption in transiting per unit of passenger or freight, compared with road and air transportation. However, as environmental pressure is increasing in recent years, fuel conservation has become a hot issue in rail transport. Roughly speaking, fuel conservation methods includes energy-efficient operation and energy-efficient scheduling/timetable. The former applies the optimal control theory to optimize the speed profile between successive stations to minimize traction energy consumption, and relevant literature includes Howlett and Pudney (1995), Albrecht (2008) and Mensing et al. (2013). The latter aims to lower traction energy consumption via optimizing scheduling plans or timetables of trains, which is actually what this paper will do. In recent years, more and more researchers have used the latter methods in metro systems. Yang et al. (2012) made a preliminary theoretical discussion about the utilization of recovery energy, and presented a cooperative scheduling model for timetable optimization in subway systems. They first proposed cooperative scheduling rules and defined the overlapping time, and then an integer programming model was formulated to maximize the overlapping time, which was solved by a designed genetic algorithm. González-Gil et al. (2014) proposed an holistic approach to reduce the overall energy consumption of urban rail. The authors gave an insightful overview of energy usage in urban rail systems, and proposed a methodology to help implement energy saving schemes. Li and Lo (2014a) formulated an integrated energy-efficient model, jointly optimizing the timetable and speed profile as well. They further used genetic algorithm to solve the model and present some numerical experiments on Beijing Metro Yizhuang Line, the results of which showed significant improvement in energy consumption. Integrating the fluctuant passenger flow of metro line, Li and Lo (2014b) proposed a dynamic train scheduling and control framework to save energy. They first forecast the passenger demand, and then optimized timetables for the next cycle of the metro line. Moreover, they also optimized the speed profile of trains to reduce traction energy consumption and increase the storage of regenerative energy.

Train timetable problem always involves travel time, which is a significant indicator of service level. What is more, lowering energy consumption and reducing travel time is conflicting to some extend. As a result, some researchers simultaneously consider these two objectives in a model. Ghoseiri et al. (2004) developed a multi-objective programming model for the passenger train timetable problem, trying to lower fuel consumption cost and shorten passenger travel time simultaneously. To solve the model, the Pareto frontier was first determined via the $\epsilon-$constraint method, and then detailed multi-objective optimization was performed via the distance-based methods. Chevrier et al. (2013) proposed an approach to compute train running times by concurrently minimizing both energy consumption and running time. They gave a detailed analysis of speed profiling, and provided a set of tradeoff-solutions for decision-makers with the help of evolutionary algorithms. Sun et al. (2014) simultaneously investigated average travel time and energy consumption for high-speed trains, and an improved GA was designed to solve the problem. Yang et al. (2015) proposed an optimization method to schedule trains to simultaneously reduce energy consumption and travel time. An integer programming model with timetable and speed control was formulated. Then, they designed an optimal train control algorithm and an adaptive genetic algorithm to solve the model.

To our best knowledge, there is no analysis of energy consumption and travel time for metro lines with express/local mode in existing literature. Compared with that in standard stop mode, there are fewer stops and therefore fewer acceleration and deceleration phases in express/local mode, which indicates that energy consumption and travel time may be effec-