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An energy-efficient scheduling and speed control approach for metro rail operations

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A B S T R A C T

Due to increasing environmental concerns and energy prices, what is very important but has not been given due consideration is the energy efficiency of metro rail systems. Train energy-efficient operation consists of timetable optimization and speed control. The former synchronizes the accelerating and braking actions of trains to maximize the utilization of regenerative energy, and the latter controls the train driving strategy to minimize the tractive energy consumption under the timetable constraints. To achieve a better performance on the net energy consumption, i.e., the difference between the tractive energy consumption and the utilization of regenerative energy, this paper formulates an integrated energy-efficient operation model to jointly optimize the timetable and speed profile. We design a genetic algorithm to solve the model and present some numerical experiments based on the actual operation data of Beijing Metro Yizhuang Line of China. It is shown that a larger headway leads to smaller energy saving rate, and the maximum energy saving rate achieved is around 25% when we use the minimum allowable headway of 90 s. In addition, compared with the two-step approach optimizing the timetable and speed profile separately, the integrated approach can reduce the net energy consumption around 20%.

1. Introduction

The increased use of metro rail systems is often proposed as a solution to problems caused by urban traffic congestion. Traditional deployment analysis typically covers rail line alignment, scheduling and capacity. Due to increasing environmental concerns and energy prices, what is very important but has not been given due consideration is the energy efficiency of metro rail systems. The emergent question is how the scheduling and speed control of metro rail system can be optimized such that regenerative energy from a braking train can be used by nearby accelerating trains. Studies indicate that maximizing the use of such regenerative energy can lead to substantial improvements in the energy-efficiency of the system.

Train energy-efficient operation is one of the most effective energy saving technologies, and generally consists of two levels. On the first level, the traffic management develops a timetable, includes information on the number of service trains, travel time at sections and dwell time at stations, which aims to improve the utilization of regenerative energy by synchronizing the operations of accelerating and braking trains (Yang et al., 2013). On the second level, the automatic train operation system or the driver assistance system calculates the speed profile with minimum tractive energy consumption under the

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timetable constraints (Su et al., 2013), and guides the drivers to track the speed profile under the supervision of a traffic management center.

Past studies typically consider these two levels separately. However, since timetable and speed profile are closely related and both of them have a direct influence on the tractive energy consumption as well as the regenerative energy utilization, this two-step optimization method is defective from the view of global optimality on energy conservation. Therefore, it is necessary to take into account the speed control and tractive energy consumption on the timetable optimization level. Recently, there have been some papers on minimizing the net energy consumption, i.e., the difference between the tractive energy consumption and the utilization of regenerative energy (Bocharnikov et al., 2010; Dominguez et al., 2012; Rodrigo et al., 2013), but limitations are always observed. The complexity of the rail traffic management system, related to the dynamic characteristic of the train synchronization problem, can be regarded as the main reason (Tuyttens et al., 2013).

In order to achieve a better performance on energy saving, this paper proposes an integrated energy-efficient operation model to jointly optimize the timetable and speed profile with minimum net energy consumption. We design a genetic algorithm and provide a real-life Beijing Metro Yizhuang Line simulation study to demonstrate the efficiency of our approach. Numerical experiments show that a larger headway leads to smaller energy saving rate, and the maximum energy saving rate achieved is around 25% when we use the minimum allowable headway of 90 s. In addition, compared with the two-step optimization method, our approach can reduce the net energy consumption around 20%.

The rest of this paper is organized as follows. In Section 2, we review some recent literature on train energy-efficient operation. In Section 3, we quantitatively analyze the tractive energy consumption, utilization of regenerative energy, and net energy consumption, and formulate an energy-efficient scheduling and speed control model to minimize the net energy consumption. In Section 4, we design a genetic algorithm to obtain a satisfactory solution. In Section 5, we present some numerical experiments based on the actual operation data of Beijing Metro Yizhuang Line of China. At the end of this paper, a brief summary is given.

2. Literature review

Train operation strategy, consisting of the timetable and speed profile, has a great influence on the amount of energy consumption. As one of the most efficient energy saving technologies, train energy-efficient operation employing the mathematical optimization method to seek the operation strategy with better energy performance, has been widely studied and well applied in metro rail system.

Train energy-efficient operation is a very complicated and difficult optimization problem because not only the timetable should be well defined for synchronizing the accelerating and braking actions of trains in the same substation, but also the speed profile should be controlled to reduce the tractive energy consumption under the speed limits, travel time and distance constraints (Tuyttens et al., 2013). Therefore, the traditional studies usually divide it into a timetable optimization problem and a speed profile optimization problem. The former adjusts the number of service trains, travel time at sections and dwell time at stations to maximize the synchronization time between accelerating trains and braking trains such that the regenerative energy from braking trains can be effectively utilized by the accelerating trains, while the latter controls the accelerating, cruising, coasting and braking time and speed such that the tractive energy consumption can be minimized.

Many metro systems have a cyclic timetable, which requires trains to follow each other with a fixed headway, and take the same dwell time at stations and travel time at sections. Voorhoeve (1993) first considered a Periodic Event Scheduling Problem (PESP) based model for the cyclic timetable problem, which was followed by many researchers, e.g., Kroon et al. (2008) and Cordonea and Redaellib (2011).

Regenerative braking is an energy recovery mechanism which can convert the kinetic energy into electricity during the braking phase by using the electric motor as an electric generator. Although regenerative braking can recover about 40% of the tractive energy, little work observed in the literature studies its efficient utilization method. Ramos et al. (2007) proposed a timetable optimization model to maximize the overlapping time between accelerating and braking actions of trains in the same substation. Nasri et al. (2010) studied the influence of headway on the utilization of regenerative energy. They verified that the utilization of regenerative energy is higher if the minimum acceptable headway is used because of the simultaneous presence of braking and accelerating trains. Pena-Alcaraz et al. (2012) designed a mathematical optimization model to synchronize the braking trains with the accelerating trains for improving the utilization of regenerative energy. David et al. (2012) formulated an optimization model to maximize the utilization of regenerative energy by subtly modifying dwell time for trains at stations. A hybrid genetic/linear programming algorithm was implemented to tackle this problem. Yang et al. (2013) proposed a train cooperative scheduling rule to synchronize the accelerating and braking actions of successive trains. Then they formulated a cooperative scheduling model to maximize the overlapping time, and designed a genetic algorithm to solve the optimal timetable. A real-life Beijing Metro Yizhuang Line simulation study showed that the cooperative scheduling model can significantly improve the overlapping time around 22%. Furthermore, Li and Yang (2013) proposed a stochastic cooperative scheduling model focusing on the randomness of departure delay for trains at busy stations, which could save energy around 8% compared with the cooperative scheduling approach. When maximizing the utilization of regenerative energy in timetable optimization model, we should consider the possible increase on tractive energy consumption. Otherwise, the total energy efficiency may be reduced if the increase on tractive energy consumption is larger than the