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An energy-efficient scheduling approach to improve the utilization of regenerative energy for metro systems

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ABSTRACT

Regenerative braking is an energy recovery mechanism that converts the kinetic energy during braking into electricity, also known as regenerative energy. In general, most of the regenerative energy is transmitted backward along the pantograph and fed back into the overhead contact line. To reduce the trains' energy consumption, this paper develops a scheduling approach to coordinate the arrivals and departures of all trains located in the same electricity supply interval so that the energy regenerated from braking trains can be more effectively utilized to accelerate trains. Firstly, we formulate an integer programming model with real-world speed profiles to minimize the trains' energy consumption with dwell time control. Secondly, we design a genetic algorithm and an allocation algorithm to find a good solution. Finally, we present numerical examples based on the real-life operation data from the Beijing Metro Yizhuang Line in Beijing, China. The results show that the proposed scheduling approach can reduce energy consumption by 6.97% and save about 1,054,388 CNY (or 169,223 USD) each year in comparison with the current timetable. Compared to the cooperative scheduling (CS) approach, the proposed scheduling approach can improve the utilization of regenerative energy by 36.16% and reduce the total energy consumption by 4.28%.

1. Introduction

Metro system is a safe and reliable direct current (DC) electric railway in an urban area, which is generally located either underground tunnels or on elevated rails above street level. Compared to other modes of urban transport, the metro system has a larger transport capacity and is much more energy efficient. Therefore, it has received rapid development around the world (Yang et al., 2012; González-Gil et al., 2014). Although per capita energy consumption in metro systems is low, the total energy consumption is considerable. Take the Beijing Metro Yizhuang Line as an example. About 42.53 millon kW h of electricity is consumed each year, which is equal to the total yearly electricity demands of 22,000 homes in Beijing, and about half is used by the tractive system for accelerating trains (Zhang, 2013). Therefore, the study on energy saving for metro systems has a significant impact on reducing the operation cost. Traditional studies mainly focus on vehicle mass reduction (Carruthers et al., 2009), energy consumption reduction of comfort functions (Kumar and Kar, 2010), and

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energy-efficient operation (Howlett and Pudney, 1995). With the regenerative braking technique being used in recent years, researchers have also paid more attention to the utilization of regenerative energy.

Regenerative braking is an energy recovery mechanism that converts the kinetic energy during braking into electricity. This is in contrast to the conventional braking systems, where the extra kinetic energy is converted to heat by friction in the brake linings and therefore wasted. In metro systems, the most common form of regenerative braking involves using an electric motor as an electric generator during the braking phase of trains to recover the kinetic energy as electricity (Hasegawa and Uchida, 1999). The principle of regenerative braking is shown in Fig. 1. Generally speaking, the regenerative energy is primarily used to supply the auxiliary and comfort functions of the train itself. The surplus energy is fed back into the overhead contact line and can be immediately used to accelerate trains located in the same electricity supply interval. However, if any feedback energy cannot be used timely, it will be wasted by heating resistors installed on the overhead contact line.

The regenerative braking technique has been considered in some metro systems (e.g., the New York Subway, the Beijing Metro, the London Underground, etc.), but existing studies mainly focus on how the regenerative energy is stored. Although there are also several researchers considering the regenerative energy by scheduling trains, most of them only take into account adjacent trains or the opposite trains at the same station without using real-world speed profiles. Taking more real-life factors (the current speed profiles, the structure of power supply network, the layout of metro line, etc.) of metro systems into consideration, this paper develops an energy-efficient scheduling approach to coordinate the arrivals and departures of all trains located in the same electricity supply interval, such that the regenerative energy from braking trains can be more effectively used to accelerate trains.

The motivation of this paper is to enhance the utilization of regenerative energy by making minor adjustment of the dwell times to the current timetable, while using the real-world speed profiles and keeping the cycle time and number of trains unchanged. Compared to the previous studies, the proposed approach may have the following contributions:

(1) We apply the real-world speed profiles obtained from the Beijing Mass Transit Railway Operation Corporation Limited to determine an energy-efficient schedule.
(2) We keep the cycle time and the number of trains unchanged in the metro operations to: (a) reduce the operation costs for metro companies, (b) maintain service quality for passengers, (c) and make it easier for testing and applying the results to the real-world metro systems.
(3) We design an allocation algorithm combined with the genetic algorithm to improve the efficiency of the genetic algorithm.

The rest of this paper is organized as follows. In Section 2, we review the literature on regenerative braking technique for metro systems. In Section 3, we formulate an integer optimization model with real-world speed profiles to minimize the energy consumption of the metro tractive system. In Section 4, we design a genetic algorithm and an allocation algorithm to solve the formulated optimization model. Based on the data from the Beijing Metro Yizhuang Line, we conduct two numerical examples in Section 5. In Section 6, conclusions are presented.

2. Literature review

Regenerative braking technique is an energy recovery mechanism used in metro systems to recover the tractive energy during braking into electricity. In order to maximize the utilization of regenerative braking energy, three major methods have been studied in the literature.

The first one focused on equipping vehicles with energy storage devices that temporarily accumulate the excess regenerated energy and release it for the next acceleration phase (Barrero et al., 2008; Mir et al., 2009; Miyatake and Matsuda, 2009; Allègre et al., 2010; Lambert et al., 2010; Ciccarelli et al., 2012; Teymourfar et al., 2012; Iannuzzi and Tricoli, 2012).

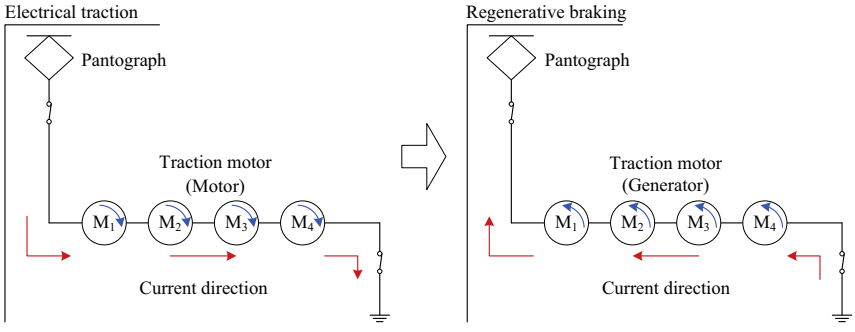

Fig. 1. Principle of regenerative braking.