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An integrated metro operation optimization to minimize energy consumption ☆

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ABSTRACT

Energy efficient techniques are receiving increasing attention because of rising energy prices and environmental concerns. Railways, along with other transport modes, are facing increasing pressure to provide more intelligent and efficient power management strategies.

This paper presents an integrated optimization method for metro operation to minimize whole day substation energy consumption by calculating the most appropriate train trajectory (driving speed profile) and timetable configuration. A train trajectory optimization algorithm and timetable optimization algorithm are developed specifically for the study. The train operation performance is affected by a number of different systems that are closely interlinked. Therefore, an integrated optimization process is introduced to obtain the optimal results accurately and efficiently.

The results show that, by using the optimal train trajectory and timetable, the substation energy consumption and load can be significantly reduced, thereby improving the system performance and stability. This also has the effect of reducing substation investment costs for new metros.

1. Introduction

As urban populations have grown significantly over the past decade, metro systems have gained in popularity because of their convenience, efficiency and speed. In the meantime, metro operators are facing ever more pressure to save energy due to increasing environmental concerns. As two of the main foundations of metro operation, the train trajectory and timetable play a key role in metro energy consumption. An energy-efficient timetable is able to minimize substation energy usage by taking full advantage of train regenerative braking energy. Appropriate train trajectories between stations can also provide a means of minimizing energy consumption during train operation. However, the timetable and train trajectory are not independent elements of metro operation and so should be considered jointly.

A number of researchers have studied various methods designed to improve railway operation performance. Chang introduced an appropriate coasting control method to optimize train movement using a genetic algorithm (Chang and Sim, 1997). Bocharnikov presented a novel approach to calculate the best train coasting operation using a mixed searching method including a genetic algorithm in combination with fuzzy logic (Bocharnikov, 2007). Lu developed a distance-step single train movement model, and implemented one exact algorithm (dynamic programming) and two exhaustive search methods (an

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ant colony optimization and a genetic algorithm) to optimize a single train trajectory. A comparison of the results has shown that the exact algorithm produces more accurate results but with a longer computation time than the exhaustive search methods (Lu et al., 2013). In order to reduce the searching time, a number of researchers have developed mathematical models and computer programs to optimize the single train trajectory from a theoretical point of view (Liu and Golovitcher, 2003; Howlett, 2000; Howlett et al., Nov 2009). The authors have previously presented a multiple train trajectory optimization paper to consider the balance between energy consumption and train delays (Zhao et al., 2015). However, only a small number of trains were included in the methodology. Therefore, the network is too small to be considered as a timetable. Methods have been proposed to obtain optimal synchronized timetables to minimize waiting times for passengers when transferring to other lines, or onto buses (Xiong et al., 2015; Parbo et al., 2014). Yang proposed a scheduling approach to optimize the metro timetable so that the regenerative braking energy from braking trains could be directly used by motoring trains within the same power network (Xin et al., 2013). Bin presented an integrated method to optimize train headway by adjusting the train arrival time at platforms to improve train headway regulation (Bin et al., 2015). The use of train regenerative braking is recognized as the main method to improve railway energy efficiency (López-López et al., 2014; Tian et al., 2014). In order to achieve a global optimality of driving strategy and optimal timetable, Shuai Su analyzed a hierarchy of energy-efficient train operation and proposed an integrated algorithm to generate a globally optimal operation schedule (Shuai et al., 2014; Su et al., 2013). Xiang and Hong developed a joint model to optimize timetable and train speed profile based on Genetic Algorithm. The results show at the maximum energy saving rate is around 25% (Li and Lo, 2014; Xu et al., 2016).

Most of the previous works have discussed train optimization for single-objective problems. In practice, train operation performance is affected by a number of different systems that are closely interlinked. For example, the inter-station journey time plays a key role in not only the train trajectory optimization (energy-saving purpose), but also the timetable optimization (regenerative braking efficiency purpose). Therefore, the calculation of the inter-station journey time should be considered by both optimizations simultaneously. Furthermore, the timetable optimization should consider the performance of all the trains in the whole network in order to take the full advantage of the train regenerative braking. An integrated optimization method is therefore developed for this purpose.

In this paper, a vehicle movement modeling is first presented, followed by a description of the proposed integrated optimization method, which includes train trajectory optimization and timetable optimization. The aim of the method is to find the train movement mode sequence, inter-station journey times, and service intervals, which minimize the substation energy consumption for a whole day of metro operation.

2. Vehicle movement modeling

It is first necessary to consider the fundamental physics of train motion in order to develop the optimization algorithms. The methods used to solve the dynamic movement equations are based on the equations of motion of the railway vehicle subject to the constraints imposed on the vehicle by the route and driving style (Hillmansen and Roberts, 2007; Hsi and Chen, 2001; Hull and Roberts, 2009). The general equation of vehicle motion, known as Lomonossoff's equation, can be written as Eq. (1), which is based on Newton's second law of motion.

$$\begin{cases} M_{tr}\frac{d^2s}{dt^2} = F(v) - R(v) - F_{grad} \\ R(v) = a + b|v| + cv^2 \\ F_{grad} = M_{rs}g\sin(\alpha) \\ M_{tr} = M_{rs}(1+\lambda_w) + M_p \end{cases} \tag{1}$$

where M_{tr} is the effective mass; M_{rs} is the rolling stock mass; M_p is the passenger mass; s is the train position; t is the time; v is the train speed; α is the gradient angle; λ_w is the rotary allowance; F is the traction force or braking force depending on the movement mode; F_{grad} is the force due to the gradient. R is the resistive force, the constants a, b, c being empirical and related to the track and aero-dynamic resistance known as the Davis equation (Loumiet and Jungbauer, 2005).

In the vehicle movement model, time is the dependent variable. The state equation of the train motion can be presented as shown in Eq. (2).

$$\begin{cases} \dot{s} = v \\ M_{tr}\dot{v} = u_f \cdot F_{tr}(v) - u_b \cdot F_{br}(v) - R(v) - F_{grad}(s) \end{cases} \tag{2}$$

where u_f and u_b are the control signals for forwards traction effort and backwards braking effort respectively; F_{tr} is the traction force; $F_{br}(v)$ is the braking effort at the current vehicle speed $v(t)$. The boundary condition, initial condition, final conditions are imposed as follows:

$$\begin{cases} v(0) = 0,\ s(0) = 0 \\ v(T) = 0,\ s(T) = S_t \end{cases} \tag{3}$$

where S_t is the train position at the terminal station.

Some other constraints are shown as follows: