Design of a Simulation Software to Optimize the Train Driving Strategy for Urban Rail Transit

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Keywords: Urban rail transit, Energy-efficient train driving strategy, Train trajectory, Energy allocation.

Abstract. The surge of the operational energy consumption has become a major challenge for the sustainable development with the rapid development of urban rail transit. Traction energy used to provide kinetic energy for the train during operation is about 50% in the total energy consumption of the urban rail transit, so the energy saving potential is considerable. Traction energy between train stations is determined by the driving strategy of the train, therefore, studying energy-efficient train driving strategy to reduce traction energy consumption has a great significance to achieve an environmentally friendly transport system. This paper designs a simulation software of energy-efficient train driving strategy based on the numerical algorithm to optimize energy-efficient train driving strategy with energy allocation. The simulation software can calculate energy-efficient train driving strategy according to any input line data, vehicle condition, and running time. The performance of simulation software is verified through the simulation of the actual data of Yizhuang line in Beijing.

Introduction

In recent years, urban rail transit has attracted wide attention and gained rapid development due to its advantages such as large capacity, high efficiency, and the ability to provide safe, reliable and fast services. By the end of 2016, 29 mainland cities in China have been operating 129 urban rail transit lines with a total operating mileage of 3,832 km [1], and more urban rail transit lines are being planned. In 2016, the total number of passengers transported in urban rail transit reached 16.09 billion. Beijing Subway has become the biggest electricity consumer of industry in Beijing, bringing great challenges of energy conservation and emission reduction to the operation company. Traction energy used to provide kinetic energy for the train during operation is about 50% in the total energy consumption of the urban rail transit, which is determined by the driving strategy of the train. Therefore, studying energy-efficient train driving strategy to reduce traction energy consumption has a great significance to achieve an environmentally friendly transport system.

The research on energy-efficient train driving strategy originated from 1960s. Ichikawa firstly analyzed the train optimization control problem using maximum principle, which lay the foundation for theoretical research of train energy saving control [2]. Khmelnitsky considered all the variables in continuous operation of train such as variable gradients and variable speed limits and established the train optimal control model using kinetic energy as the decision variable [3]. Based on the previous studies, Liu proposed a complete method for calculating the optimal speed profile, which is fast in calculation speed and can also be used to calculate the energy-efficient speed profile between multiple stations and optimize the running time between multiple stations [4]. The Howlett team at the University of South Australia is devoted to the study of discrete operation of train and gave the key equation for judging the switching points among different energy-efficient driving regimes [5]. Based on the studies of optimal control problems of continuous operation and discrete operation, Howlett concluded that any driving strategy under continuous operation can be equivalent to a discrete sequence of traction-coasting control [6]. Chang used genetic algorithm to optimize coast control based on evaluation of the punctuality, energy consumption, and passenger comfort. It can be used to...
generate the coast control lookup table for next interval before the train sets off [7]. Bwo-Ren Ke presented a MAX-MIN ant system of ant colony optimization algorithms to optimize the train speed profile for saving energy and design the block layout. It is shown that the method presents a significant improvement for the reduction of computational burden on the block-layout design [8].

**Problem Description**

**Model Formulation**

Train driving strategy refers to the control regimes, the sequences and the switching points among different regimes, which can be presented by a speed profile. As shown in Fig.1, for a given interval and the running time, there are more than one feasible driving strategies corresponding to different traction positions and distances, which consequently lead to unequal traction energy. The purpose of the study about energy-efficient train driving strategy is to select the train driving strategy with the lowest traction energy under the constraints of line data, train condition and running time.

![Figure 1. Train driving strategies.](image)

The objective function is presented in equation (1)

\[
\min E = \int_0^s \mu(v) F(x) \, dx.
\]  

(1)

where E is the traction energy during train operation, s is the distance of the interval, x is the current train position, v is the current train speed, F is the traction force applied by the train; \( \mu \) is the train traction efficiency.

The movement of trains between stations can be described using the classic kinematics model

\[
\begin{align*}
\frac{dv}{dx} &= \frac{F(x) - B(x) - R(v) - G(x)}{v}, \\
\frac{dt}{dx} &= \frac{1}{v}.
\end{align*}
\]  

(2)

where B is the braking force applied by the train, R is the basic resistance of the train, G is the additional resistance.

The train speed, the running time, the traction and braking force should also satisfy the following constraints

\[
\begin{align*}
v(0) &= 0, & t(0) &= 0, \\
v(s) &= 0, & t(s) &= T, \quad v(s) = 0, \\
0 &< v(x) \leq V(x).
\end{align*}
\]  

(3)

(4)

(5)
0 \leq F(x) \leq F_{\max}(v(x)), \quad 0 \leq B(x) \leq B_{\max}(v(x)). \quad (6)

F(x) \cdot B(x) = 0. \quad (7)

where t is the current running time of the train, T is the running time specified in the timetable, V is the speed limit of the line, F_{\max} and B_{\max} are the maximum traction and braking force applied by the train.

**Model Solution**

According to the maximum principle, minimizing train traction energy means to maximize the following Hamiltonian function

$$H = \frac{p_1}{mv}(F - B - R - G) - \frac{F}{\mu} + \frac{p_2}{v}. \quad (8)$$

Hamiltonian function is analyzed from the following five cases [9]

- When $p_1/mv < 0$, $F=0$, $B=B_{\max}$, reflect to the full braking driving regime.
- When $p_1/mv = 0$, $F=0$, $0 < B \leq B_{\max}$, reflect to the partial braking driving regime.
- When $0 < p_1/mv < 1/\mu_{\max}$, $F=0$, $B=0$, reflect to the coasting driving regime.
- When $p_1/mv > 1/\mu_{\min}$, $F=F_{\max}$, $B=0$, the full power driving regime.
- When $1/\mu_{\max} \leq p_1/mv \leq 1/\mu_{\min}$, $F=F_{\max}$, $B=0$, reflect to the full power driving regime.

To summary, only four types of energy-efficient train driving regimes are available: full power(FP), coasting(C), partial braking(PB), full braking(FB).

As shown in Fig. 2, giving a running time T, the corresponding energy-efficient train driving strategy is unique, it means that the minimum traction energy E is uniquely determined, and vice versa. Paper [9] gave a numerical algorithm to optimize the energy-efficient train driving strategy.
based on energy allocation. The energy-efficient train driving strategy is calculated by distributing the energy units reasonably with max energy efficiency. The algorithm flowchart is shown in Figure 3

**Simulation Software**

The energy-efficient train driving strategy simulation software is designed to calculate the energy-efficient train driving strategy and the corresponding speed profile according to the input conditions such as line data, vehicle information and running time. At the same time, the traction energy and simulating time is required. The specific function modules are planned according to the demand analysis, as shown in Figure 6:

![Diagram of Simulation Software](image)

Figure 6. The structure diagram of simulation software.

The line data input module is used to input the line data to the simulation software, including gradients, speed limits, and stop information. There are large amounts of data due to the complexity of gradients and speed limits of the line, thus, the gradients, speed limits and stop information are respectively saved into three matrices in the same mat file. When performing the simulation, load the file first, read the variables, and use them to calculate.

The vehicle information input module is used to input the vehicle information to the simulation software, mainly including the train quality, the traction and braking curve. In this paper, the traction curve is written into the function F.m, while the maximum traction is inputted through the interface. Since the braking force during operation is not greatly changed, it is simplified to a constant, which is also inputted through the interface.

The numerical algorithm decreases the running time of the train between stations to meet the given running time by distributing the energy units continuously. The running time is given by timetable or designed by operator. After inputting the running time manually, it is first compared with the maximal and minimal running time of the interval. If the input running time is not satisfied, an error dialog box pops up asking to re-enter it. Otherwise, it is used as the target running time to compare with the calculated running time during the loop process.

The interface of the simulation software mainly consists of the intervals, the vehicle information, setting and simulation result. After loading the line data by clicking the “loading ...” button, the corresponding simulation intervals are automatically identified. Then input the vehicle information and set the running time, click “Start” button to start the simulation. Finally, the energy-efficient train driving strategy as well as the corresponding speed profile are calculated. The interface of the simulation software is shown in Figure 7:
The designed simulation software of energy-efficient train driving strategy can easily modify parameters such as train quality, traction force, braking force, and running time, and also be able to overlay a new speed profile on the original one so as to observe and compare the change clearly.

Case Study

The performance of simulation software is verified through the simulation of the actual data of Yizhuang line in Beijing.

The first case simulated the interval between Jiugong station and Yizhuangqiao station, with a total length of 1975 meters and a running time of 132 seconds on the timetable. The simulation result is shown in Figure 8, where the straight line at the top represents the speed limit, the black rectangles in the lower part represent the gradients, and the sections of the interval according to gradients and speed limits are implied by the symbol ‘*’. The energy-efficient speed profile calculated by simulation software is shown in Figure 8.

The actual traction energy of the train running from Jiugong station to Yizhuang station under the current driving strategy is 20 kWh. While the traction energy corresponding to simulated energy-efficient train driving strategy is 13.4 kWh, saving 33% of the traction energy. In addition, the simulating process takes only 0.36 seconds, with the great potential for online optimization to generate the complete target speed profile for the next interval before the train sets off.

The second case simulated the intervals between Songjiazhuang station and Xiaohongmen station with Xiaocun station between them. The total line is 3906 meters in length and the train stops at
Xiaocun station at 2631 meters. For intervals between multiple stations, do the simulation by regarding the middle stations as special cases of zero speed limit. The simulation result is shown in Figure 9. The traction energy is 29.3 kWh, and the optimized running time between each two stations changed. The reason is that when simulating intervals between multiple stations, the given running time is the total running time of the whole line and after optimization, the running time is reassigned. As a result, it can also optimize the running time between multiple stations from the view of energy-saving.

Solution

This paper designs a simulation software of energy-efficient train driving strategy based on the numerical algorithm to optimize energy-efficient train driving strategy with an energy allocation method. The simulation software can calculate energy-efficient train driving strategy and corresponding speed profile according to any input line data, vehicle condition, and running time. The simulation software requires few calculating time and thus has great potential for online optimization. Besides, it can also optimize the running time of single train between multiple stations without changing the total running time. The simulation results of Beijing Yizhuang line show that the simulation software can achieve 33% energy-saving effect.

Acknowledgement

This work was supported by Beijing Laboratory of Urban Rail Transit, Beijing Key Laboratory of Urban Rail Transit Automation and Control, and the projects funded by “the Fundamental Research Funds for the Central Universities” (No. 2015JBZ006) and Project U1434209 supported by National Natural Science Foundation of China.

References


