Evaluating Influence Factors of Energy Consumption for Urban Rail Timetable Using an Optimized Train Control Method

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Abstract. Energy efficiency of urban rail transit system has become more and more significant due to the environmental concern and the rising cost of energy. The energy consumption of train operation is inevitably influenced by several factors. In this paper, the related factors are investigated based on the consideration of the close correlation between the timetable and specific train speed control profiles in practical operation. Evaluation about two typical factors, including the station dwell time and average travelling speed, is carried out using the real time schedule from Batong Line in Beijing Metro. The results illustrate the relationships and provide suggestions in design of the energy-saving timetables.

Introduction

As one of the most efficient methods for reducing the traffic congestions in large cities, the Urban Rail Transit (URT) system had experienced a rapid development in China during the past years. It has been regarded as an energy-efficient transportation mode. However, it still consumes a large amount of energy each year [1]. Energy demand and consumption of trains in urban rail transit system are of a growing concern for the operators, rail administrators, time table designers and train suppliers. The development and implementation of Automatic Train Operation (ATO) systems in metropolitan lines makes it possible of better utilizing new optimization techniques for eco-driving [2]. Current research mainly focuses on trajectory optimization with specific control modes and optimization algorithms, i.e. genetic algorithm [3], artificial neural networks [4] and differential evolution algorithms [5].

Different from the energy-efficient driving solutions that optimize the speed profiles at sections to reduce the tractive energy consumption under the constraints from the timetable, the energy-saving problem also can be investigated from a point view of the planned time schedule of the trains. As the static information for the train operation, there are several indicators and factors that can represent the specific characteristics of a given timetable. It should not be ignored that the energy-saving capability under the design of the timetable is not independent of the detailed speed control strategies in all the rail sections. There are multiple closely related issues need to be considered in enhancing the energy consumption efficiency with a global view.

In this paper, the influence factors of energy consumption for the URT timetable are analyzed using practical operation data. The optimized train control strategy is utilized to evaluate typical factors and derive the possible suggestions in establishing energy-efficient time schedule for transit trains.

Time Schedule of Urban Rail Trains

In recent years, analytical studies of energy-saving optimization for train operation control have been concerned by both the researchers and operators of the urban rail transit systems. The timetable determines a preoperational schedule for a set of trains and follows the requirement of train operation under specific line capacity and the passenger flow conditions. For each scheduled train from a start station to a target station, a specific time interval can be represented by a number of time points that
describe the departure and arriving time instants. For a whole urban rail line, there would be a number of trains planned in the timetable, and thus the timetable can be represented by a series of time instants corresponding to different trains in specific rail sections.

Actually, the time schedule for train operation corresponding to the timetable is always described by the space-time diagram or the train string diagram as shown in Fig. 1. In this figure, a schedule of 4 trains numbered from 1 to 4 is given. The trains are planned to the running operation between Station A and Station C through Station B. It can be found that a minimum safe headway has to be guaranteed to ensure the safety of each pair of train in stations and rail sections. The traffic efficiency also has to be considered to realize an effective satisfaction to the traffic demand.

![Space-time diagram of timetable and speed curve of train (2) between Station A and B.]

The timetable provides a strict constraint to the practical operation of trains, including the running behaviors within sections and the passage/dwell operations in stations. However, it does not provide further detailed information about the microscope operations of the trains in rail sections. That means the driver or the ATO has to follow a given departure time and arriving time according to a timetable, but they still have different choices to determine the control conditions and at each time instant within the planned intervals or each location between two successive stations. Therefore, the driving modes and behaviors might be different under a certain time schedule and the characteristics of the operation would result in various energy consumption levels, passenger comfort stages and on time capabilities. From a view of energy saving for the scheduled train operation in rail transit system, both the design of the timetable and the operation mode following the schedule would affect the energy consumption characteristics. Therefore, multiple factors related to the two stages have to be considered to achieve an optimized energy-saving capability for the rail system.

**Influence Factors of Energy Consumption Characteristics**

The practical operation of urban rail transit trains might be complicated since there would be many factors that would influence the characteristics of the whole system. The energy consumption of the rail transit timetable is determined by both the pre-design and the in-trip operation process. So, there should be a joint consideration to all those possible factors. Based on the analysis to the influencing factors, the strategies for reducing the energy consumption levels and improving the comprehensive effectiveness could be derived accordingly. Thus, potential influencing factors of energy consumption characteristics will be analyzed in this section.

1. The influence of average travelling speed in rail sections

   The average speed can be evaluated by the length of the sections and the travelling time according to the departure and arriving instants from the timetable. It can be found that the planned or operating speed of trains will affect the energy consumption since the difference in speed profile will determine the distribution of operation conditions, especially traction and cruising. A high speed may result in an increased resistance force. Thus, a higher level of energy consumption would be required.

2. The influence of dwell time in stations

   Trains are planned to stop at stations according to the timetable. From a timetable, it can be found that the station dwell interval differs significantly among the planned trains. An increased dwell time at stations may lead to a reduced time interval for the related railway section, and the corresponding energy consumption may be affected obviously.
3. The influence of train operation control strategies
For both the driver behavior and the ATO system, the train runs according to a specific control strategy that can be described by the speed curve based on the railway line conditions, the scheduled running time and the parameters of the train. There will be many different recommended curves with contradicted targets or varied characteristics. Therefore, the adopted speed curve and running strategy will directly affect the energy saving capability for utilizing the timetable and running schedule.

4. The influence of passenger flow condition
The time-varying and space-varying passenger flow condition determines the weights of the trains running along the rail lines. It is usually difficult to estimate the exact passenger flow at a certain time slot or a station. Thus, uncertainty will always exist in the estimation.

5. The influence of passenger load rate
The passenger load rate is another factor corresponding to the passenger flow. It can be described by the capacity rate of a fully loaded train. The load rate provides an indication to the rationality of the capacity utilization of the whole transit system. In addition, it directly determines the weight of a train and thus the energy consumption of the traction will be highly affected.

Optimized Train Control for Energy-saving

Evaluation of the influencing factors as above mentioned requires the knowledge about the field operation. Compared to the uncertain passenger flow and load rate, the average running speed and the station dwell time are usually employed to analyze the characteristics of a timetable. By considering the correlation between these factors and the train control strategy, the energy-saving capability can be evaluated, which is meaningful to improve the design of an enhanced time schedule in pursuing an energy conservation target.

In recent years, the energy-saving train control has attracted more attention in both the academic and industry field. Establishment and utilization of a specific recommended speed curve allow us to meet the requirement of energy conservation and many additional targets, i.e. the punctuality and the riding comfort. The advanced swarm intelligence-based optimization methods, i.e. the PSO (Particle Swarm Optimization) and bacterial foraging algorithm, make it possible of optimizing the design of the speed curve considering multiple issues.

Regardless of the differences in rail signaling modes, the transit trains will only be in one of the four possible operation modes, including traction, cruising, coasting and braking. Under each mode, four parameters, including the initial speed \(v_0\), initial time \(t_0\), final speed \(v_f\) and the duration time \(T_d\), can be used to describe the exact shape in a speed-distance or speed-time curve. The whole operation curve is represented by a sequence of the operation conditions as shown in the right Fig. 1, which can be indicated by a set of control notches as \(C= \{(v_0, t_0, v_f, T_d)_1, \ldots, (v_0, t_0, v_f, T_d)_n\}\). Using an optimization method, the problem of determining an energy efficient train operation sequence can be solved with derived optimal control notch set. Thus, the energy-saving rate over a conventional control solution is derived and the relationship between it and other influencing factors can be evaluated.

Figure 2. Distribution of rail stations of Batong Line in Beijing Metro.
Evaluating Results and Analysis

Transit trains operating in Batong Line in Beijing Metro is taken in the evaluation. Fig. 2 shows all 13 rail stations in this line. Only SiHui and SiHuiDong are transfer stations. There are 12 sections in total. The workday timetables for both directions (SiHui-TuQiao and TuQiao-SiHui) are employed to obtain the original time information and the statistical results about the influencing factors.

With a BFO (Bacterial Foraging Optimization) solution for deriving an energy-saving speed curve to specific planned trains running between TuQiao and SiHui, the energy conservation capabilities of all the 12 sections with the timetable-based constraints can be evaluated. The derived energy-saving rate over a reference solution without optimization ranges from to 1.43% to 11.62%, and an average rate of 6.47% is realized under the given condition and reference solution. Taking these saving rates to represent the achievable capability for all the 12 rail sections, the distribution and statistical results of station dwell time and designed average travelling speed correlated to the energy conservation levels are summarized based on the timetable for both operating directions, as shown in Fig. 3 to Fig. 6.

![Figure 3](image1.png)

**Figure 3.** Occurrence frequency of different station dwell time in rail sections with specific energy-saving rates (Left: from TuQiao to SiHui, Right: from SiHui to TuQiao).

![Figure 4](image2.png)

**Figure 4.** Statistical results of station dwell time in rail sections with specific energy-saving rates (Left: from TuQiao to SiHui, Right: from SiHui to TuQiao)

From the following given figures, some conclusions can be obtained as follows.

1. The energy conservation levels against a reference operation solution vary significantly among different sections under the same timetable.

2. The energy-saving characteristics and the correlation with timetable influencing factors differ obviously in different directions, especially for the station dwell time.

3. The most frequent dwell time value of 40s occurs in the 12th section with an energy-saving rate of 6.25% for the schedule from TuQiao to SiHui. The extreme value of 30s occurs in the same section for the schedule from SiHui to TuQiao. A small dwell time is suggested in the design of timetable to realize a desirable energy consumption level considering the traffic efficiency and passenger flow.

4. The most frequent design speed of 45km/h can be found in the 12th section for the scheduled operation from TuQiao to SiHui. A same speed can be found in the 11th section with an energy-saving rate of 5.64% for the schedule from SiHui to TuQiao. A reduced average travelling speed level in the timetable is highly recommended, which illustrates a higher percentage of the coasting operation and a limited resistance level to achieve the expected energy efficiency.
5. The X-axes of these figures just indicate the representative values at the rail section level, which cannot reveal the high-resolution results for each scheduled train in the timetable. However, they have reflected the relationship between the achievable energy-saving capability and the two typical factors that may greatly affect the energy consumption level for a given timetable.

Figure 5. Occurrence frequency of different average travelling speed in rail sections with specific energy-saving rates (Left: from TuQiao to SiHui, Right: from SiHui to TuQiao).

Figure 6. Statistical results of different average travelling speed in rail sections with specific energy-saving rates (Left: from TuQiao to SiHui, Right: from SiHui to TuQiao).

Conclusion and Future Plans

In this work, the influencing factors of energy consumption of URT timetable are investigated and analyzed. By using practical time schedule data and an optimized train control solution, the influence from station dwell time and average travelling speed are analyzed numerically. Specific suggestions are derived for the design of energy-saving timetables coordinating with optimization of speed control profiles. In future research, more factors will be integrated with field data. High-resolution evaluation in each section for every scheduled train will be carried out to establish the quantitative models.

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References


