Energy-saving Performance Evaluation of Urban Rail Transit: A Time Schedule Perspective

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Abstract. Improvement of the cost efficiency of urban rail transit system has been a research focus in the past decade. The energy-saving capability generally consists of two levels. The macro level determines the train operation mode and the time schedule according to the traffic demand. The micro level calculates and tracks the energy efficient target speed profiles of the trains. Different from conventional evaluation works about the energy-saving performance, in this paper the evaluation in the macro level is concerned using a time schedule perspective, and the utilization of the advanced energy efficient traction control solution in the micro level is integrated to predict the achievable energy conservation capability. The relationship between the derived performance level and the schedule-related factors are investigated, including the average speed and spatial-temporal distribution of the passenger flow. Field data from Beijing Metro is adopted to validate the presented solution in evaluating energy-saving performance of the practical time schedule. Results show its potential in improving the environmental friendly characteristics of the urban rail transit system in the field operation.

1. Introduction
The urban rail system is attracting attention all over the world because of its large capacity and typical advantages as a public transportation mode. The conventional research and development works focus on the realization and optimization of the system by using some advanced communication, control and manufacturing technologies [1, 2]. In recent years, as the rapid development of urban rail networks in many cities, the rising environmental issues and the requirement of system’s life-cycle cost efficiency are considerable. Reduction of the energy consumption level of the urban rail transit system has been one of the major target in the operational management activities [3].

Based on the analysis of the current operation status, it is found that the traction control of a train plays a major role in energy consumption [4]. Therefore, more and more research and development works are carried out to optimize the design, operation and maintenance of the traction system. There have been a lot of results on the energy efficient speed profile topic [5]. An advanced speed profile enables an enhanced running strategy for the train operation, with which the tractive energy consumption and carbon emission can be effectively reduced. In order to deeply investigate energy-saving approaches, some efforts have been made in developing the regenerative braking solution and the effective energy storage equipments [6], which use the electric motor as an electric generator during the braking phase under an energy recovery scheme. However, it has to be noticed that both the optimized speed profile solution and the regenerative braking approach are based on the train-ground cooperative operation scheme according to the time schedule plans. In order to evaluate the energy consumption level for a large scale transit network, the influence of the time schedule has to be
considered, and that would give different results from conventional solutions using only the static time schedule.

In this paper, the energy efficient operation solution for the urban rail transit is considered from a time schedule perspective. Aiming at optimizing and adjusting the urban rail timetable in both design and maintenance stages, an evaluation method of the energy-saving performance is presented, where the energy-relevant factors of the time schedule are cooperatively investigated with the tractive energy consumption. Data from the field operation is utilized to demonstrate the capability of this solution.

2. Energy Efficiency-related Factors of Time Schedule

2.1. Average Operational Speed

From the time schedule of the urban transit rail system, the status of movement of all planned trains can be described and even predicted by using the timetable information. It is clear that the timetable only provides the expected time consumption during the operation between two adjacent rail stations. That means only the average operational speed in each track section can be quantitatively calculated when the geo-spatial information of the rail tracks and rail stations are known. This speed information cannot be utilized to describe the speed profile of each train for the energy consumption calculation or speed control along the longitudinal direction. However, it provides useful information to evaluate the dynamic situations of all the planned trains and even the whole mobility status of the rail network. The difference between the speed profile and the derivation of the average operational speed can be found in Fig. 1 using an example in Beijing Metro Batong Line. It should be noticed that the mobility of the trains has to be supported by the power supply of the traction control systems. For a static urban rail transit network with different dynamic train operation modes, the energy consumption levels of the same scheduled trains may vary significantly. Therefore, we are encouraged to investigate the relationship between the average operational speed and the whole energy consumption level of the time schedule, which is meaningful to the adjustment of the timetable with an energy-saving purpose.

![Figure 1. Difference between Speed Profile and the Average Operational Speed](image)

2.2. Spatial-temporal Distribution of Passenger Flow

In the calculation of tractive energy consumption, the weight of the train is one major parameter which describes the load of traction force. Besides the original weight of a train, the number of passengers is another decisive factor. Different from the constant train body weight, the number of passengers is uncertain and time-varying due to the characters of the passenger flow. Usually, the passenger flow is modelled with a certain statistical assumption according to the knowledge and prediction of its spatial and temporal distribution. Fig. 2 demonstrates the statistical results of the passenger volume per working day from the Beijing Metro Batong Line in September 2017. It can be found that the daily
 passenger volume varies with time and it is difficult to estimate precisely using a simple mathematical model. Therefore, in the evaluation of the energy consumption performance we have to determine the spatial-temporal distribution condition of the passenger flow associated with a timetable and consider its influence to the achievable energy saving capacity.

3. Energy-saving Performance Evaluation Approach

3.1. Main Structure of Evaluation Approach

The evaluation of the energy-saving performance is carried out based on the fundamental database of the rail line, including the timetable data, the train parameters, rail track profile, passenger volume and the calculation models. Based on the above analysis, the evaluation is investigated based on a specific passenger volume condition, and thus the relationship with different energy-efficiency factors can be analyzed to establish possible correlation models using the data-driven method. Fig. 3 shows the main structure of the energy-saving performance evaluation approach.

![Figure 3. Main Structure of the Energy-saving Performance Evaluation Approach](image)

3.2. Fundamental Design Scheme and Profile Data

As the second step of the evaluation process, the collection of the fundamental data set is crucial to the results of evaluation. It is utilized to describe practical parameters of the rail track, the locomotive and the operation conditions along the whole trip. The track profile data can be obtained from the design or the construction stages. By using the profile data, including the rail mileage, speed limit, gradient and curvature, the force analysis can be realized according to distribution of different operating conditions,
i.e. the traction, cruising, coasting and braking. In each traction or the cruising sub-section, the traction force can be calculated according to the traction characteristics of the locomotive and the track profile. Thus, the energy consumption of a planned train can be determined by the model as

\[
E_i = \sum_{j=1}^{P_i} e_j = \sum_{j=1}^{P_i} (e_{j,\text{Trac}} + e_{j,\text{Cru}}) = \sum_{j=1}^{P_i} \left( \int_0^{S_{j,\text{Trac}}} [f(s) - r(s)] ds + \int_0^{S_{j,\text{Cru}}} r(s) ds \right)
\]

(1)

Where \( E_i \) is energy consumption of the \( i \) th planned train in the time schedule, \( e_j \) denotes the tractive energy consumption of the \( i \) th train in the \( j \) th track section within \( P_i \) track sections, \( e_{j,\text{Trac}} \) and \( e_{j,\text{Cru}} \) represent the energy consumption in the traction condition and cruising condition respectively, \( S_{j,\text{Trac}} \) and \( S_{j,\text{Cru}} \) denote the length of the track sections where the target train is in the traction and cruising condition, and \( f(s) \) and \( r(s) \) are the traction force and resistance at the location \( s \).

To quantitatively evaluate the energy-saving performance, both a referencing traction control solution and an energy efficient traction solution have to be considered. The energy consumption results from two solutions are compared to show the space that could be achieved to each of the planned train if the feasible energy efficient control strategies can be derived and adopted in the practical operation. It has to be noticed that the weight of the train is adjusted by the passenger carrying rate, which means the adopted passenger flow condition will directly influence the performance evaluation result.

3.3. Correlation Analysis for Planned Trains
Based on the single train calculation, all the planned trains can be covered in the comparison between the referencing and the energy efficient traction control solutions. By using all the evaluation results, the statistical model can be built to describe the relationship between the energy-saving performance and a specific factor, especially the planned running speed within a section between two adjacent rail stations. Different correlation models can be established with the given time schedule and fundamental data sets. The results will provide the knowledge about the energy-saving capability and performance profile estimation in practical operation processes. The operation of the rail transit line can be adjusted using the updated time schedule according to the requirement of cost efficiency in the future.

4. Field Results and Analysis
In order to demonstrate the presented energy-saving performance evaluation method, field data from Batong Line of Beijing Metro is adopted to enable the calculation of energy consumption level and the correlation model with energy efficiency-related factors. The workday time schedule data is utilized in the evaluation, which contains 219 planned trains in both the uplink and downlink directions. All the 219 planned trains from SiHui Station to TuQiao Station participate in test. The corresponding results and analyses are given as the following sub-sections.

4.1. Validation of Energy-efficient Traction Control Solution
An improved traction control solution is adopted to predict the achievable energy-saving performance against the referencing solution using the conventional traction calculation method. Fig. 4 and Fig. 5 depict the speed profiles of the train #072027 using two solutions, where both the speed-distance curve and speed-time curve are drawn in the figures. It can be found that the maximum traction target speed and the duration of the cruising condition by two solutions vary obviously, and these differences lead to the possibility in reducing the energy consumption in carrying out the given time schedule. Table 1 summarizes the statistical results of the energy-saving performance of this scheduled train by using the improved traction control solution, with which a maximum saving rate of 9.87% per rail section can be achieved for the planned train’s operation under test. It has to be noticed that the section with a large
amount of saved tractive energy does not indicate a maximum energy saving rate at the same time, and the later value is able to reflect the energy efficient capability more effectively.

Figure 4. Speed-distance Curves of the Train #072027 Using Two Traction Solutions

Figure 5. Speed-time Curves of the Train #072027 Using Two Traction Solutions

Table 1. Statistical Result of Energy-saving Performance of the Test Planned Train

| Maximum saved energy (kw·h) / Section no. | Maximum energy saving rate (%) / Section no. | Minimum energy saving rate (%) / Section no. | Statistical results |
|------------------------------------------|---------------------------------------------|---------------------------------------------|---------------------|
| 1.95 / 6                                 | 9.87 / 12                                   | 5.27 / 9                                    | Mean energy saving rate (%) | 7.43 | STD value | 0.015 |

4.2. Correlation Modeling of Energy-saving Performance with Average Speed

By using all the speed profile data sets from 219 planned trains under a medium passenger volume per train, the energy consumption levels and energy saving rates can be summarized, and they can be used to build the correlation model using the curve fitting method. Fig 6 shows the fitted models of speed-consumption and speed-saving-rate for every track sections with all the 219 trains.

The fitted model of energy consumption per section with the average speed is written as

\[
\Delta E(\bar{v}_{sec}) = 2.984 e^{-[4(\bar{v}_{sec}-50.81)^{5.135}]^2} + 2.413 \times 10^{-5} e^{-[4(\bar{v}_{sec}-1649.0)^{302.9}]^2}
\]  

(2)

The fitted polynomial model of energy saving rate per section with the average speed is

\[
g(\bar{v}_{sec}) = -3.6275 \times 10^{-5} \bar{v}_{sec}^2 + 0.002116 \bar{v}_{sec} + 0.06379
\]  

(3)

Table 2 shows the statistical result of energy-saving performance in each section for all planned trains. The energy-saving capability by the adopted advanced traction solution varies obviously in
different sections which ranges from near zero to 13.83%. From the fitted model, it can be found that the energy consumption level rises with the planned average running speed but pursuing a higher energy-saving rate suggests a lower average speed within the track section.

Figure 6. Average Speed-related Curve Fitting Models

Table 2. Statistical Result of Section-based Energy-saving Performance for all Planned Trains

| Maximum saved energy (kw·h) | Maximum energy saving rate (%) | Minimum energy saving rate (%) | Statistical results |
|-----------------------------|-------------------------------|------------------------------|---------------------|
| 2.40                        | 13.83                         | 7.91×10^-4                   | Mean energy saving rate (%) 7.92  STD value 0.016 |

4.3. Train Level Analysis of Energy Efficient Performance

The energy-saving performance evaluation is further investigated at the train level. Both the energy consumption and the energy-saving rate of each planned train along the whole trip are calculated and compared. Fig. 7 and Fig. 8 indicate the correlation analysis result with the average running speed of all the covered sections. It can be found that there are several “outliers” in the correlation space since some trains are not planned to cover all the 13 stations in the Batong Line. Therefore, the local views are also provided to describe the details of the fully-covered trains. Table 3 summarizes the statistical results of energy consumption and saving rate of the whole trip. Different from the section-level result, both the maximum and average energy-saving rates are relatively lower since an average behaviour is concerned in this calculation. From the local views, it can be found that the value space is constrained when a lower whole-trip average speed is adopted. Under the currently utilized traction enhancement condition, a lower whole-trip average speed is suggested to achieve a higher possibility to improve the energy-saving performance level.
Figure 7. Train-level Energy Consumption Level vs. Average Running Speed (global and local views)

Figure 8. Train-level Energy-saving Level vs. Average Running Speed (Global and Local Views)

Table 3. Statistical Result of Energy-saving Performance for all Planned Trains

|                          | Maximum saved energy (kw·h) | Maximum energy saving rate (%) | Minimum energy saving rate (%) | Mean energy saving rate (%) |
|--------------------------|-----------------------------|-------------------------------|-------------------------------|-----------------------------|
|                          | 21.79                       | 8.95                          | 6.51                          | 7.63                        |

5. Conclusion and Future Plans

The energy efficiency of the urban rail transit system is a significant concern in both the modern and next generation rail system. A life cycle optimization scheme requires that the design, adjustment and management of the train operation mode fully explore the potential of energy-saving capability. This paper concerns the evaluation of the energy-saving performance based on a time schedule perspective. Different from conventional single train-oriented train operation optimization solutions, the advanced train traction control solution is utilized to all scheduled trains to predict the potential energy-saving ability. Extended consideration is given to the energy consumption characteristics and the correlation with typical influencing factors, especially the average speed at both the section level and train level. Results from analyses using practical data of Batong Line demonstrate the capability of the presented evaluation solution, which is with the potential of providing advisory information to the adjustment of the train operation schedule and the rail organization mode with an environment protection purpose.

In the future works, more analyses will be performed using different train schedules to further enhance the modelling results. More typical passenger load rates will be considered to increase the
coverage of different influencing factors. Customized advisories are expected to be generated based on the model-based knowledge and practical operation data to assist the energy efficiency level optimization for the whole urban rail transit system.

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7. References
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