A scheduling and control integration optimization method for regenerative braking energy utilization

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Abstract. The utilization of regenerative braking energy is of great significance to the energy saving of subway. Therefore, this paper proposes an optimization method for scheduling and control integration, which not only adjusts the timetable but also optimizes the speed curves of trains. When there is a train braking, this method will try to find a train that accelerates to absorb the regenerative energy generated by the braking train. Firstly, this paper establishes the timetable energy saving optimization model, based on which the speed curves will be optimized. Furthermore, we design a scheduling optimization algorithm based on genetic algorithm, and optimizes speed curves of trains by binary search method to obtain a good solution. Finally, simulations are given using the real data of Beijing Metro Line 4 to evaluate the proposed method, and the results show that the integrated scheduling and control optimization method can reduce energy consumption by 15.18%. In the random disturbance simulations, the proposed method shows good robustness, which makes it possible to apply this method to the real subway operations.

1 Introduction

With the acceleration of urbanization, the subway systems are also developing rapidly. The energy cost of subway has attracted significant attentions. In early studies (e.g., [1,2,3]), the researchers optimized the speed curve of a single train to reduce traction energy. The optimal condition was analyzed by using the Pontryagin's Maximum principle, and the optimal speed curve of the train includes four operating conditions: Maximum Acceleration(MA), Cruising(CR), Coasting(CO) and Maximum Braking(MB). The core of solving the energy-saving speed curve is to calculate the operating condition switching points for MA-CR and CR-CO.

After the regenerative braking technique is widely applied to subway trains in the recent years, researchers have also paid more attention to the utilization of regenerative braking energy to save the energy consumption. The utilization of regenerative braking energy can be realized in the stage of timetabling[4]. Pavel et al. [5] proposed a novel two-step linear optimization model to calculate energy-efficient timetables in metro railway networks,

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which could maximize the utilization of regenerative energy produced by braking trains. The proposed model took into account the three decision variables of running time, dwell time and headway, and they found the optimal solution by genetic algorithm. Yang et al. [6] developed a bi-objective programming approach to minimize the net energy consumption and total travel time with provision for dwell time uncertainty. Yang et al. [7] further developed an energy-efficient rescheduling approach under delay perturbations for subway trains, which aimed to minimize the net energy consumption under the premise of reducing or eliminating the delay altogether by adjusting running time. Yang et al. [8] formulated an optimization model incorporating energy allocation and passenger assignment to balance energy use and passenger travel time. The Non-Dominated Sorting Genetic Algorithm II was applied and the core components were redesigned to obtain an efficient Pareto frontier of irregular timetables for maximizing the use of regenerative energy and minimizing total travel time.

Based on the above studies, this paper proposes an integrated scheduling and control optimization method for regenerative braking energy utilization, which not only coordinates the acceleration and deceleration processes of trains by timetable optimization, but also optimizes the speed curves based on timetable, so as to utilize the regenerative braking energy to the maximum extent.

2 Optimization model

2.1 Timetable optimization model

This paper builds a periodic or off-peak timetable optimization model which takes dwell time, running time and headway as the decision variables. The planned timetable is adjusted to the aperiodic timetable, so that the traction and braking processes of trains in the same power supply section can reach the optimal match to reduce the energy consumption.

The following is the related constraints analysis of timetable decision variables. The adjustment $t_{i,n}^{D,A}$ of dwell time for train i at the station n satisfies the boundary constraint:

$$-\delta_D \le t_{i,n}^{D,A} \le \delta_D \tag{1}$$

And the adjustment $t_{i,n}^{R,A}$ of running time for train i in the inter-station (n, n+1) has to satisfy:

$$-\delta_R \le t_{i,n}^{R,A} \le \delta_R \tag{2}$$

The constraints for the accumulative adjustment of dwell times and running times of each one-way train are:

$$\begin{gathered} -\xi \le \sum_{n=1}^{N_S} t_{i,n}^{D,A} + \sum_{n=1}^{N_S-1} t_{i,n}^{R,A} \le \xi \\ -\xi \le \sum_{n=N_S+1}^{2N_S} t_{i,n}^{D,A} + \sum_{n=N_S+1}^{2N_S-1} t_{i,n}^{R,A} \le \xi \end{gathered} \tag{3}$$

The passenger flow is stable in the specific off-peak period, so the headway should be more uniform. In addition, the total number of trains is kept constant. The adjustment of the headway between train i and train i+1 satisfies:

$$\begin{gathered}
-\delta_H \leq t_i^{H,A} \leq \delta_H \\
\left(\left\lceil \left(t_e^O - t_b^O\right)/t^{H,P} \right\rceil - 1\right)\cdot t^{H,P} < \sum_{i=1}^{N_T/2-1} (t^{H,P} + t_i^{H,A}) < \left(\left\lceil \left(t_e^O - t_b^O\right)/t^{H,P} \right\rceil + 1\right)\cdot t^{H,P} \\
\left(\left\lceil \left(t_e^O - t_b^O\right)/t^{H,P} \right\rceil - 1\right)\cdot t^{H,P} < \sum_{i=N_T/2+1}^{N_T} (t^{H,P} + t_i^{H,A}) < \left(\left\lceil \left(t_e^O - t_b^O\right)/t^{H,P} \right\rceil + 1\right)\cdot t^{H,P}
\end{gathered} \tag{4}$$

where $t^{H,P}$ is the original headway of the planned timetable, and $\left[t_b^O, t_e^O\right]$ is the subway operation period. In the process of timetable optimization, constraints (1) to (4) must be strictly met, so as to maximize energy saving without affecting the normal operation of subway.

2.2 Speed curve optimization based on timetable adjustment

The adjustment of the timetable will change the speed curves of the trains. In order to control the trains to run according to the optimal speed curves, the optimization of the speed curves combined with adjusted timetable has become an important problem.

In order to simplify the illustration, only the speed curve of the traction train is adjusted in Fig.1 (a). In the actual timetable optimization process, the speed curves of braking and traction train can be adjusted separately or simultaneously. It can be seen from Fig.1 (a) that the traction and braking processes of trains in the same power supply section can be optimized in three ways: (1) shift the speed curve; (2) adjust the running time of the train; (3) shift the speed curve and adjust the running time of the train at the same time. The speed curves are generated based on the Pontryagin's Maximum principle[1,2]. Taking the energy consumption of a single train as the optimization goal, we calculate the operating condition switching points for MA-CR and CR-CO.

3 Integrated scheduling and control optimization algorithm

In order to minimize the total energy consumption of subway trains, this paper designs an integrated scheduling and control optimization algorithm based on genetic algorithm. The algorithm flow chart is shown in Fig.1 (b).

The main steps of the algorithm are as follows:

Step 1: Taking dwell time, running time and headway as timetable optimization variables, population initialization is carried out through binary coding. Set the iteration index $m=1$, and timetable population $T_m^Q = \left\{T_{m,k}^q \middle| k = 1, 2, \cdots N_Q\right\}$ is randomly generated.

Step 2: Initialize the index of the individual in the population $k=1$.

Step 3: Decode the individual *k*, and extract the information of dwell times, running times and headways, and construct the timetable $T_{m,k}^q$.

Step 4: The information of the running times of the timetable $T_{m,k}^q$ and the subway line information are input to the energy saving speed curve calculator to solve the optimal speed curve of each train in each inter-station(the set of speed curves $S_{m,k}^V = \left\{v_{i,n}(t) \middle| i \leq N_T, n \leq 2N_S\right\}$).

Step 5: Calculate the total energy consumption of subway operation according to the integrated scheduling and control scheme $\left\langle T_{m,k}^q, S_{m,k}^V \right\rangle$, and take the reciprocal of the energy consumption as the fitness value of the individual.

Step 6: If $k < N_Q$ (N_Q is the population size), set $k = k+1$ and go to Step 3.

Step 7: Produce the next generation by selection, crossover, and mutation.

Step 8: If $m < N_I$ (N_I is the maximum number of iterations), set $m = m+1$ and update the population, go to Step 2; otherwise, output optimized integrated scheduling and control scheme $\left\langle T_{m,k}^{q\ *}, S_{m,k}^{V\ *} \right\rangle$.

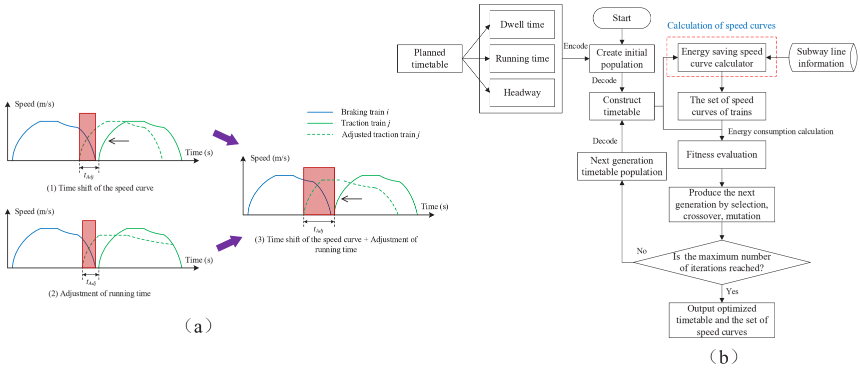

Fig. 1. (a) Schematic diagram of the speed curve optimization for regenerative braking energy utilization; (b) Flow chart of the integrated scheduling and control optimization algorithm.

Based on the optimal control theory, the energy saving speed curve calculator uses binary search method to solve operating condition switching points for MA-CR and CR-CO, then calculates the optimal speed curve through integration.

4 Numerical results

We present numerical examples to illustrate the effectiveness of the proposed integrated scheduling and control optimization method. Simulations are conducted based on real data of Beijing Metro Line 4. The related parameters are listed in Table 1.

Table 1. Related parameters.

Parameters	Value	Parameters	Value
N_T	30	ξ	15s
δ_D	6s	δ_H	10s
δ_R	8s	$t^{H,P}$	240s

The timetable simulation time is: 11:22:06−14:13:55. The planned timetable of this period is periodic, and the passenger flow is relatively small and stable. We test the integrated scheduling and control optimization algorithm based on genetic algorithm with the population size N_Q=800, the maximum number of iterations N_I=1200, the crossover probability P_c=0.65, and the mutation probability P_c=0.1. The energy saving timetable and the set of optimized speed curves are obtained through the algorithm calculation. The total energy consumption of unit mass before and after optimization is $7.9238\times10^5 J$ and $6.7210\times10^5 J$ respectively. The energy saving rate reaches 15.18%, and the absorption ratio of regenerative braking energy is increased by 16.71%.

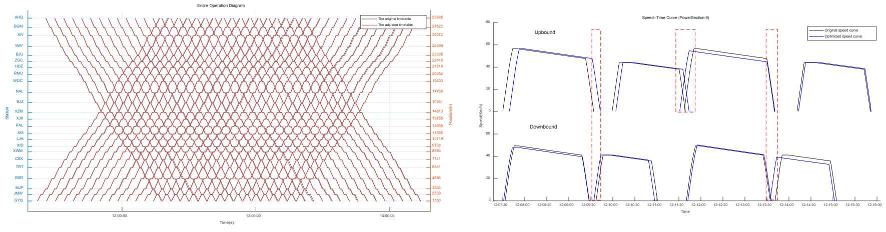

Fig. 2. Simulation results.

The comparison of timetables before and after optimization is shown in Fig.2 (a). After optimization, the planned timetable is changed from periodic timetable to aperiodic timetable. The timetable is only slightly adjusted, and the optimization process strictly meets the constraints, so as not to affect the normal operation of the subway. And the comparison of speed curves before and after optimization in power supply section 9 is shown in Fig.2 (b). It can be seen from the figure that the traction and braking processes of trains match better so as to absorb regenerative braking energy.

Because of the passenger flow and other random factors, the trains may not run in strict accordance with the timetable. To test the robustness of the proposed optimization method, we add random disturbances of [-5s,5s] to the optimized dwell times. When random disturbances are added, the energy saving rate can still reach 11.35%. Therefore, the integrated scheduling and control optimization method shows good robustness.

5 Conclusion

The main contribution of this paper is to propose an integrated scheduling and control optimization method based genetic algorithm to optimize the timetable and speed curves of trains so that the regenerative energy from braking trains can directly be utilized. The proposed model and solution method are evaluated using real data of Beijing metro line 4. The numerical results show that the proposed method can reduce the total energy consumption by 15.18%. The random disturbances test proves that the proposed method has good applicability and robustness, which makes it possible to apply this method to the real subway operations. In the future research, we will consider more real-life factors, such as changing passenger flows, passenger travel time, and complex speed limits in routes.

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