An Optimized Method for the Energy-Saving of Multi-metro Trains at Peak Hours Based on Pareto Multi-objective Genetic Algorithm

Muhan Zhu, Yong Zhang, Fei Sun and Zongyi Xing

Abstract Urban rail train starts and brakes frequently in it's movement. It is important to improve the utilization efficiency of electric energy and reduce the traction energy consumption in the field of metro transit. At peak hours, the overlap time between two trains in the same power supply interval is longer and there is much more renewable energy generated by the train's braking due to a large increasement in passenger flow and the number of departure. In this paper, a method based on pareto multi-objective genetic algorithm is proposed to optimize energy consumption. By optimizing the stopping time of trains in each station, train schedule is optimized and the regenerative braking energy can be used more efficiently.

Keywords Train energy-saving · Multi-objective optimization
Genetic algorithm · Train timetable optimization

1 Introduction

Urban rail transit traction energy consumption occupies a larger proportion in the social power consumption demand. Considering subway train's traction performance and it's characteristic of frequent start and stop, energy-saving slope and regenerative braking [1, 2] can greatly improve the utilization efficiency of electricity. At present, the research on regenerative braking energy mainly includes installing energy absorption device [3], designing and developing contravariant feedback device [4, 5], optimizing metro train's timetable and so on. The optimization of train schedule has gained many achievements which is both economical and practical.

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Yang et al. [6] took stop time as the control variable, the maximization of overlap time as the objective function, established an integer programming model and used genetic algorithm to solve this problem. PeñaAlcaraz et al. [7] adopted the method of mixed integer programming to optimize the off-peak hours train schedules. Nasri et al. [8] took stop time as the optimized object, established an objective function aimed at maximizing the exchange of energy between two trains and built an optimal model combined with genetic algorithm. Feng Jia et al. [9] established a kind of schedule optimization model considering the regenerative energy, an adjusted energy saving model based on passenger flow volume, a traction energy consumption and transport efficiency assessment model respectively and illustrated the result based on some cases. This paper adopts Pareto multi-objective genetic algorithm and builds an energy-saving optimization model of multi-trains at peak hours.

2 Pareto Multi-objective Genetic Algorithm

2.1 Multi-objective Optimization

The optimal control for train's energy saving is a typical multi-objective optimization problem, it's mathematical model can be described as:

$$\begin{cases} MinF(x) = [f_1(x), f_2(x), f_3(x), \ldots, f_n(x)] \\ s.t. \begin{cases} h_i(x) = 0,\ 0 \le i \le I \\ g_j(x) \le 0,\ 0 \le j \le I \end{cases} \end{cases} \tag{1}$$

where $x = [x_1, x_2, \ldots, x_l]$ are control variables; $F(x)$ are optimization objectives; $h_i(x)$ and $g_j(x)$ are equation constraint and inequation constraint.

2.2 Pareto Non-dominated Solution

$x \in S$ are feasible solutions of multi-objective optimization problem, if and only if there doesn't exist any $y \succ x$ in S, which means x are non-dominated individuals in S, x are the Pareto non-dominated solutions [10] for multi-objective optimization problem.

2.3 NSGA-II Algorithm

NSGA-II [11] is an improved algorithm based on NSGA. The algorithm steps are listed below.

Step 1: Initialize parameters.
Step 2: Generate initial population randomly.
Step 3: Solve fitness value.
Step 4: Do non-dominated sorting and calculate individual's congestion distance
Step 5: Select elite individual and merge them with parent population.
Step 6: Do crossover and mutation operations and obtain a new population.
Step 7: If the interaction has not reached the maximum times, go back to step 4, if not, finish the interaction calculation.

3 Multi-train Energy-Saving Optimization Model

Multi-train's movement at peak hours is a complicated problem [12]. To simplify the energy-saving problem, we need to make the following assumptions:

- The regenerative braking electricity energy can only be used by the accelerated trains in the same power supply interval.
- The power supply system of two lines is separated, trains in one line don't use the braking energy generated by other trains in different lines.
- Trains running in the same direction between two stations share the same running time and stop time.
- All the trains in one line share a same model, we suppose that train's weight equals to a constant and ignore the change of passengers on the train.

3.1 Model of Train's Movement

At peak hours, adjacent trains can run cooperatively and utilize the regenerative braking energy to an extreme through optimizing trains' stop time under the condition of keeping the running time between intervals constant. In the same power supply interval, the longer the overlap time of two trains is, the more energy generated by trains in braking state can be utilized by other tractive trains.

In the same traction power supply interval, the running situations of former and latter trains can be divided as follows:

(1) Situation 1

The former train accelerates to drive out of the station and the latter train brakes to drive into the station. There are four cases in this situation:

Case 1: The former train has ended up accelerating, while the latter train has not yet started braking, the overlap time is zero.
Case 2: The former train has not yet started accelerating, while the latter train has ended up braking, the overlap time is zero.
Case 3: The time that former train stops accelerating is earlier than the time that latter train stops braking. This case is shown in Fig. 1.
Case 4: The time that latter train stops braking is earlier than the time that former train stops accelerating. This case is shown in Fig. 2

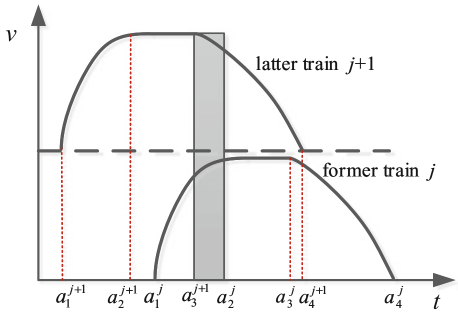

Fig. 1 Former train stops accelerating earlier than latter train stops braking

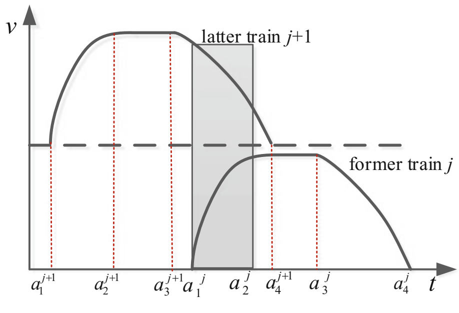

Fig. 2 Latter train stops braking earlier than former train stops accelerating

The calculating formula of overlap time for situation 1 is summarized as follows:

$$F_1 = \begin{cases} 0 & a_2^j \le a_3^{j+1} \\ \min[T_z^{j+1}, (a_2^j - a_3^{j+1})] & a_1^j < a_3^{j+1} \le a_2^j \\ \min[T_a^j, (a_4^{j+1} - a_1^j)] & a_3^{j+1} < a_1^j \le a_4^{j+1} \\ 0 & a_4^{j+1} \le a_1^j \end{cases} \quad (2)$$

where F_1 is the overlap time of adjacent trains in case 1, a_1^j and a_2^j are the time that the jth train starts and stops accelerating, a_3^j and a_4^j are the time that the jth train starts and stops braking, T_a^j and T_z^j are the accelerating and braking time of the jth train.

(2) Situation 2

The second situation is the former train brakes to drive into the station and the latter train in different interval accelerates to drive out of the station. There are also four cases in this situation.

Case 1: The former train has ended up braking, while the latter train has not yet started accelerating, the overlap time is zero.
Case 2: The former train has not started braking, while the latter train has stopped accelerating, the overlap time is zero.
Case 3: The former train stops braking earlier than the latter train stops accelerating, this situation is shown in Fig. 3.
Case 4: The latter train stops accelerating earlier than the former train stops braking, this situation is shown in Fig. 4.

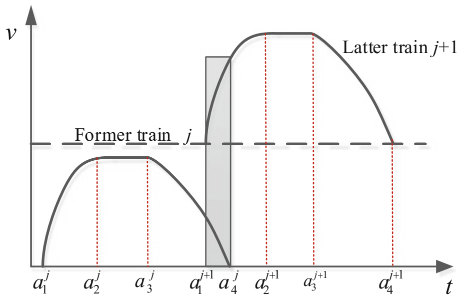

Fig. 3 Former train stops braking earlier than latter train stops accelerating

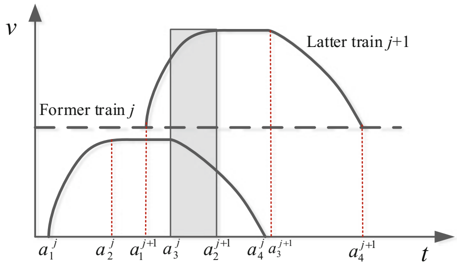

Fig. 4 Latter train stops accelerating earlier than former train stops braking

Considering these two trains are running in different intervals, they may working in various power supply interval. It is necessary to judge whether these two trains are running in the same interval. The calculating formula of overlap time for situation 2 is summarized as follows, $\lambda = 1$ signifies these two trains are running in the same power supply interval, $\lambda = 0$ signifies they are not running in the same power supply interval.

$$F_2 = \begin{cases} 0 & a_4^j \le a_1^{j+1} \\ \min[T_a^{j+1}, (a_4^j - a_1^{j+1})] \cdot \lambda(j, j+1) & a_3^j < a_1^{j+1} \le a_4^j \\ \min[T_z^j, (a_2^{j+1} - a_3^j)] \cdot \lambda(j, j+1) & a_1^{j+1} < a_3^j \le a_2^{j+1} \\ 0 & a_2^{j+1} \le a_3^j \end{cases} \tag{3}$$

3.2 Objective Function and Constraint Condition

Take the utilization amount of regenerative braking energy as the optimization objective and stop time as the control variable. The objective function $f_1(x)$ is:

$$f_1(x) = \sum_{i=1}^{N-1} \sum_{m=1}^{M} [F_1(h_i(x), d_m(x)) + \lambda(i, i+1) \cdot F_2(h_i(x), d_m(x))] \tag{4}$$

where M is the amount of power supply intervals, N is the amount of trains running in one direction per hour at peak hours. h_i is the departure interval of the ith train, d_n is train's stop time in nth station.

The objective function $f_2(x)$ related to total running hours is:

$$f_2(x) = \left[\sum_{k=1}^{K} (d_k(x)) + \sum_{j=1}^{K-1} (T_j(x)) \right] \tag{5}$$

where d_k is train's stop time in Kth station, T_j is train's running time in jth interval. In order to ensure train running in the normal working condition, take safety index, accurate parking index, comfort index as the constraint condition.

Constraint condition $g_1(x)$ related to safety index is:

$$g_1(x) = K\_V = 0 \tag{6}$$

where K_V is the flag of speeding, $K\_V = 0$ signifies not speeding, $K\_V = 1$ signifies speeding.

Constraint condition $g_2(x)$ related to stop time is:

$$l_{di} \leq g_2(x) = d_n \leq u_{di} \tag{7}$$

where l_{di} and u_{di} are the minimum and maximum value of stop time respectively.

Constraint condition $g_3(x)$ related to departure interval is:

$$l_h \leq g_3(x) = h_i = \left[\frac{3600}{N}\right] \tag{8}$$

where $\left[\frac{3600}{N}\right]$ is the integer of departure interval, l_h is the safe departure interval time.

3.3 Solve Optimization Model

The specified steps of solving multi-train energy-saving optimization model based on Pareto multi-objective genetic algorithm are listed below.

Step 1: Input basic parameters and initialize population.
Step 2: Solve the fitness value of overlap time and total running time.
Step 3: Do non-dominated sorting and calculate individual's congestion.
Step 4: Select elite individual, generate progeny population.
Step 5: Merge elite population with parent population and obtain a new population
Step 6: Do crossover and mutation operation, obtain a new generation.
Step 7: If the interaction has not reached the maximum times, go back to step 2, if not, go to step 8.
Step 8: Save the most optimal Pareto non-dominated solution.
Step 9: Obtain new stop time and timetable after optimization.

4 Experiment Analysis

Take the data of Guangzhou metro line No. 7 for energy-saving optimization simulation analysis. The selected peak hours is from 7 a.m. to 8 a.m. The power supply interval is divided into 6 sections. The expected departure number of trains in up and down lines is 18 respectively from 7 a.m. to 8 a.m. The related parameters settings is shown in Tables 1 and 2.

The simulation result is shown in Fig. 5 and the comparison of schedule between before and after optimization is shown in Table 3.

Table 1 Simulation parameters for train's running

Parameter	Value
Train length (m)	118.32
Maximum speed (km/h)	80
Maximum acceleration (m/s^2)	1.2
Transfer efficiency of regenerative braking energy	0.7
Simulation time step (s)	0.01

Table 2 Total running time and stop time settings

Parameter	Total running time	Maximum stop time	Minimum stop time	
			Transfer station	Non-transfer station
Value (s)	1385	60	30	25

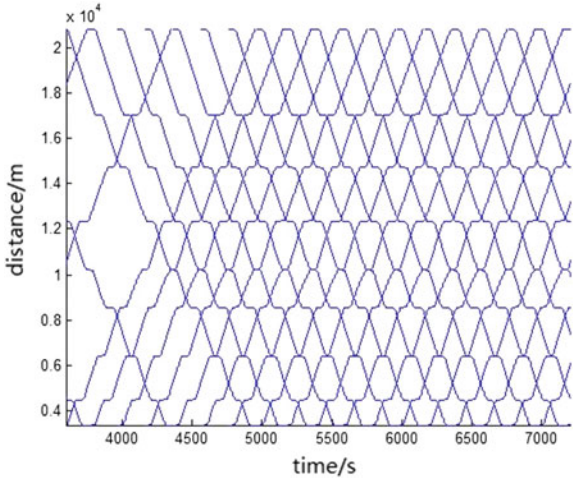

Fig. 5 Trains running simulation result

As shown in Table 3, after the optimization, stop time in Shibi station reduced from 30 to 29 s, stop time in Hanlong changxi station added from 30 to 31 s, stop time in other stations kept unchanged, the total running time remained unchanged but the total overlap time was 1462 s which had raised 53.6% compared with 952 s before optimization.

Table 3 Optimal departure timetable

	Before optimization (s)				After optimization (s)			
Station	Arrival	Departure	Stop	Travel	Arrival	Departure	Stop	Travel
Guangzhou south	200	235	35	80	200	235	35	80
Shibi	315	345	30	121	315	344	29	121
Xiecun	466	491	25	133	465	490	25	133
Zhongcun	624	649	25	108	623	648	25	108
Hanxi changlong	757	802	45	132	756	801	45	132
Hezhuang	933	963	30	155	932	963	31	155
Guantang	1118	1153	35	143	1118	1153	35	143
Nancun	1296	1331	35	218	1296	1331	35	218
Daxuecheng south	1549	1584	35		1549	1584	35	80
Running time	1385				1385			
Overlap time	952				1462			

Table 4 Relations between departure interval and overlap time

Departure interval (s)	200	163	120
Initial total overlap time (s)	952	1911	4963
Initial average overlap time (s)	52.9	86.9	165.4
Optimal overlap time (s)	1462	2121	5495
Average optimal overlap time (s)	81.2	96.4	183.2
Optimization rate	53.5%	10.9%	10.8%

Analyze the influence factor of the utilization of regenerative energy, we can draw a conclusion that the departure interval affects the utilization. Departure interval is inversely proportional to the number of departure in per hour. The change of departure interval can result in a corresponding changing in timetable (Table 4).

Take the data in metro line No. 7 as an example, analyze the relations between departure interval and overlap time.

When the departure interval reduced from 200 to 163 s, the total overlap time raised from 1462 to 2121 s, when departure interval reduced from 200 to 120 s, the total overlap time raised from 2121 to 5495 s. departure interval has a great influence to the total overlap time. The comparison between each train's average overlap time before and after optimization is shown in Fig. 6.

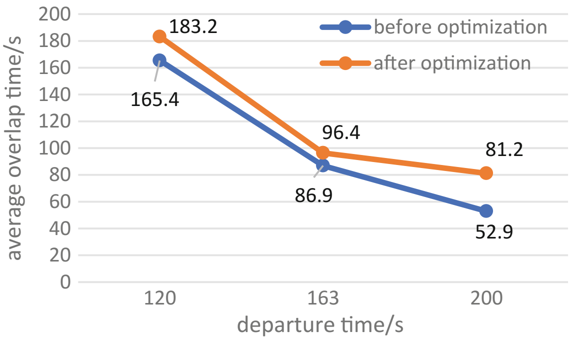

Fig. 6 Comparison of each train's average overlap time before and after optimization

5 Conclusion

This paper proposed a method for multi-train energy saving based on Pareto multi-objective genetic algorithm. The approach of optimizing train's timetable is easy to operate and this method can make the best of regenerative braking energy and reduce total energy consumption in the process of train's running. The simulation result indicates the rationalization and feasibility of this optimization method.

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