A novel peak power demand reduction strategy under a moving block signalling system

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Abstract

The Moving Block Signalling (MBS) system is a system where the tracking target point of the following train is moving forward with the leading train. In the MBS system, a dense queue of trains starting (or re-starting) in very close succession would cause an overload of the substations. The time delay and acceleration rate limit are introduced in the traditional approaches to solve this problem. However, such approaches increase the travel time between the successive stations, and the service quality decreases. In this paper, a novel approach 'Service Headway Braking' (SHB) is proposed based on some knowable extra station dwell time. It can efficiently avoid the peak electrical demand problem without increasing the time delay. The simulation result shows that, with flexible adjustment of the start (or restart) time and velocity, the passenger waiting time can be shortened while considering energy saving.

Keywords: peak power demand, moving signalling block system, station time delay, energy saving.

1 Introduction

Moving-block signalling (MBS) was proposed a few decades ago [1] to reduce headway among successive trains in a track line. Theoretically, two successive trains are separated by a distance equivalent before the braking point of the following train to brake to a complete stop from its current speed, as well as a safety margin. The separation can be reduced and changed with the limit for the given operating speed and train characteristics, such as train length and braking rate.

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In moving block signalling system, successive trains in a line with maintain a safety stopping points, when a leading train stops for a long time, the following trains will stop at the tail of the leading train. When the leading train re-starts, the following trains will start almost simultaneously, this will cause further synchronization of the peak demand of each train and increase the total peak power demand significantly. This could lead to overload of the nearby substations and how to reduce it is called "Peak Demand Reduction" problem in this paper.

There are two kinds of traditional PDR techniques, one is called STD, which introduce a Starting Time Delay to each of the following train and the other is called ARL, which means the acceleration of the following trains are limited to a certain extent (or different extents). H. Takeuchi and his patterns discuss these techniques in [2-4]. Simulation results show that the graded Acceleration Rate Limit technique is the best solution to reduce the peak power demand.

In the traditional techniques, time delay is introduced and quality of service is degraded. T.K. Ho and K.K. Wong use an expert system [5] to help the operators for decision making, and it is focuses on the balance between time delay and peak power demand.

In this paper, for some knowable extra station dwell time, we propose a novel approach, Service Headway Braking (SHB). Considering energy saving and passenger waiting time minimization, nonlinear programming is used to model the problem and the simulation results shows that, compared with the best traditional PRD techniques the new approach can achieve the same performance of the peak power demand reducing without increasing arrival time delay.

2 Novel peak demand reduction techniques

2.1 Tracking model in a moving block system

Under MBS, the tracking target point of the following train moves forward continuously as the leading train travels. The instantaneous distance ($L_z(t)$) of two successive trains could be calculated by eqn (1),

$$L_z(t) = S_{leading}(t) - S_{following}(t) \tag{1}$$

where

$S_{leading}(t)$ is the position of the leading train's head;

$S_{following}(t)$ is the position of the following train's head.

The distance intervals between two successive trains will not less than safety margin at any moment even if the leading train comes to a sudden halt, so we have

$$L_z(t) \geq L_{safe} + L_t + {V_{following}(t)^2}\big/{2b} \tag{2}$$

where

L_t is the length of the train;

L_{safe} is the length of safety margin;

$V_{following}(t)$ is the instantaneous velocity of the following train;

b is deceleration rate.

Based on eqn. (1), eqn. (2) can be derived as:

$$S_{leading}(t) \geq L_{safe} + L_t + S_{following}(t) + {V_{following}(t)^2}/{2b} \quad (3)$$

and from eqn. (3) the instantaneous velocity and position of the following train should obey eqns. (4) and (5).

$$V_{following}(t) \leq \sqrt{2 \times b \times (S_{leading}(t) - S_{following}(t) - L_{safe} - L_t)} \quad (4)$$

$$S_{following}(t) \leq S_{leading}(t) - L_{safe} - L_t - {V_{following}(t)^2}/{2b} \quad (5)$$

2.2 Reasons for the peak power demand problem

The reason for the peak power demand is re-starting of the dense queue and there are two main reasons of formation of the dense queue.

(1) Feathers of moving block signalling system. (Two trains will start simultaneously if the distance interval between them is $L_{safe} + L_t$)

(2) Extra dwell time in station.

In daily railway operation, there may be some exceptions, such as a passenger may shut in the door or a short-term surge in passenger flow (the end of a football game). In these circumstances, adjusting the whole timetable is not convenience, because the circumstances only exit in a short period. So we will arrange the train to stay a little longer. In this case, we can know the extra station dwell time. Based on these kinds of knowable extra station dwell time, we could reduce peak power demand by avoiding the formation of the dense queue. In order to achieve this goal, we should analysis the relationship between extra dwell time and the number of delayed trains.

2.2.1 Station delay propagation model

In this section, we focus on the relationship between the '*delay time*' and the number of delayed trains. Generally speaking, each train at a station has a required dwell time. If the train stops longer than the required dwell time, we could call the extra time '*delay time*'. In moving block signalling system, the '*delay time*' may impact the following trains and cause a dense queue. Fig. 1 shows the operation intervals among trains.

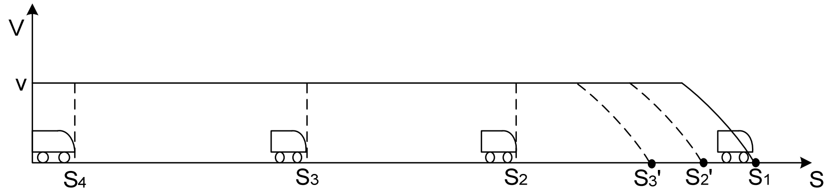

Figure 1: Formation of a dense queue.

As it is shown in Fig.1, there are *m* trains in the track: train 1, 2, …,*m*. Train 1 is the leading train and it stops in station A. the position of station A is S_1 . The dwell time of station A in the timetable is T_{dwell}. According to the normal condition, each train arrives at station A and stops for T_{dwell} and then starts to run.

When train 1 starts, the positions of following trains are: S_i $(i \in N,\ i \geq 2)$ and the tracking time interval between two successive trains is $\Delta t_{tracking}$. However, the following trains may become a dense queue if train A does not run immediately after T_{dwell}. Defining T_{delay} is the '*delay time'* of the leading train after T_{dwell} and n is the total number of the delayed trains caused by T_{delay}, $n \in N,\ n \geq 2$. Based on eqn. (5), train *i* which is delayed should stop at point $S_i^{'}$, in other words, $S_i^{'}$ is the stop position of the ith train in the dense queue. Defining Δt_i is the running time that train i arrived at $S_2^{'}$. Based on eqn. (2), we have:

$$S_1 - S_2^{'} = L_t + SM\ ,\ S_1 - S_3^{'} = 2(L_t + SM)\ ,\ S_1 - S_4^{'} = 3(L_t + SM)\ ,\ldots,$$
$$S_1 - S_n^{'} = (n-1)(L_t + SM)$$

and

$$\Delta t_2 = \Delta t_{tracking} - T_{dwell} - \frac{L_t + SM}{v}\ ,\ \Delta t_3 = 2\times\Delta t_{tracking} - T_{dwell} - 2\times\frac{L_t + SM}{v},\ldots,$$

$$\Delta t_n = (n-1)\times\Delta t_{tracking} - T_{dwell} - (n-1)\times\frac{L_t + SM}{v}$$

Let $T_{delay} \geq \Delta t_n$, we have

$$T_{delay} \geq (n-1)\Delta t_{tracking} - T_{dwell} - (n-1)\times\frac{L_t + SM}{v} \tag{6}$$

then we could get n through eqn. (6) and the final formation is:

$$n \leq \frac{T_{delay} + T_{dwell}}{\Delta t_{tracking} - {(L_t + SM)}/{v}} + 1 \tag{7}$$

2.3 Peak power demand reduction technique

From the analysis above, we know re-start of the dense queue in a small area leads to peak power demand and both of the two traditional PDR techniques are carry out after the formation of the dense queue. In this section, we propose a novel operation strategy to reduce the peak power by avoid the formulation of a dense queue.

2.3.1 Tracking dynamics in a moving signalling block system

In order to analyze the two successive trains tracking dynamics when the leading train starts to move while the following train triggers the brake profile, a simulation is done as follows:

$L_t = 140$ (m), $L_{safe} = 50$ (m). The Leading train stops at Station A where the position is 400 m. $S_{leading}(0) = 400$ (m). Let the following train starts from the point in braking profile, the velocity and position of the following train is calculated by eqn(4) or (5), the results are in the table 1.

From table 1, we can see the running times of following train arriving at Station A have little difference when the following train starts from the braking profile. That means if the following train triggers the brake profile when the leading train starts to move, the following train will not brake immediately but to move forward with the leading train by following eqns. (4) and (5), and it is more important that, this can staggered the time points when the two trains reach the highest velocity and avoid the peak power demand moment of the two trains. In order to show the trend of the running process, figure 2 gives the v-t profile when the starting velocity is 8 m/s and starting point is 198m.

Table 1: Running time of the following train.

$S_{leading}(t)$ (m)	$V_{following}(t)$ (m/s)	$S_{following}(t)$ (m)	Running time of train 2 arrives station A (s)
400	16	82	40.26
400	12	138	39.82
400	8	178	39.5
400	4	202	39.42
400	0	210	39.38

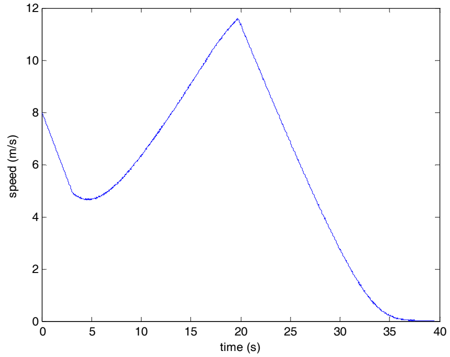

Figure 2: v-t profile of the following train starts form the braking profile.

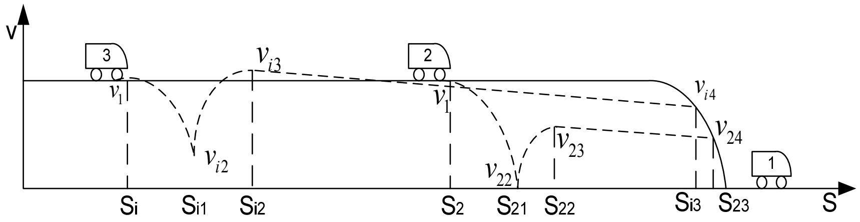

Figure 3: Operation strategy of SHB.

2.3.2 New operation strategy analysis

Based on the above analysis, a new operation strategy is proposed as follows.

As shown in figure 3, the target velocity of the trains in track line is v_1, the leading train (*trian1*) has an extra dwell time, which is T_{delay}. If T_{delay} is long enough to cause a dense queue with *n* trains, then, After T_{dwell}, let train *i(i=2,3,…,n)* brake with service braking deceleration *b* to v_{i2} (the position at this time is S_{i1}), if $v_{i2}=0$, then stops for Δt_{i2} at S_{i2}, then accelerate to v_{i3} with service acceleration *a* (the position at this time is S_{i2}), and then reduce traction force and keep the train moving with a constant deceleration b' to v_{i4} (the position at this time is S_{i3}). At this time, trains *i-1* re-start, and then train *i* starts to track with train *i-1* according to the moving block tracking distance interval until it arrives at station A. In other words, the running time of train *i* between S_i and P_{i3} is equal to T_{delay}.

In this new strategy, the other trains are slowdown when one train re-starts, so the re-start time of the following trains are staggered and the peak power demand is avoid.

2.3.3 New operation strategy modelling

In this section, we built the mathematic model of the operation process. From the above section, we know if the train could follow the new operation strategy, the time points when the trains reach the highest velocity could be staggered and the peak power demand could be reduced. In this situation, we want to minimize the energy consumption and improve the ride comfort, so we hope the traction phase and waiting time period could be as short as possible. At the same time, in order to stagger the re-start time of the trains and arrive station A as soon as possible, we hope v_{i4} could close to v_{ref}. v_{ref} is chosen from table 1. In order to avoid increasing time delay and stagger the peak power demand time of the train, it is suggest choosing $v_1/2$.

The train operation process before triggering the braking profile could be divided into 4 stages: 1 represents braking, 2 represents traction, 3 represents slowdown, 4 represents braking to stop. Stage 4 is only for calculation but not exist in operation.

Based on the analysis above, the problem could be seen as a nonlinear programming problem as follows:

$$\min f = v_{i3} + \alpha \Delta t_{i2} + \beta (v_{i4} - v_{ref}) \tag{8}$$

① when $i = 2$:

$$\begin{aligned}
s.t. \quad & v_{i2} - v_{i3} \le 0 \\
& v_{i4} - v_{i3} \le 0 \\
& v_{i2}, v_{i3}, \Delta t_{i2} \ge 0 \\
& v_{i4} \ge v_{ref} \\
& \Delta T_{i1} + \Delta t_{i2} + \Delta T_{i2} + \Delta T_{i3} \\
& = \frac{v_{12} - v_{11}}{b} + \Delta t_{i2} + \frac{v_{13} - v_{12}}{a} + \frac{v_{14} - v_{13}}{b'} = T_{delay} \\
& \Delta S_{i1} + \Delta S_{i2} + \Delta S_{i3} + \Delta S_{i4} \\
& = \frac{v_{i2}^2 - v_{i1}^2}{2 \times b} + \frac{v_{i3}^2 - v_{i2}^2}{2 \times a} + \frac{v_{i4}^2 - v_{i3}^2}{2 \times b'} + \frac{v_{i4}^2}{2 \times b} = S_1 - S_i - SM - L_t
\end{aligned} \tag{9}$$

② when $i \ge 3, i = 3, 4 \ldots, n$

$$\begin{aligned}
s.t. \quad & v_{i2} - v_{i3} \le 0 \\
& v_{i4} - v_{i3} \le 0 \\
& v_{i2}, v_{i3}, \Delta t_{i2} \ge 0 \\
& v_{i4} \ge v_{ref} \\
& \Delta T_{i1} + \Delta t_{i2} + \Delta T_{i2} + \Delta T_{i3} \\
& = \frac{v_{i2} - v_{i1}}{b} + \Delta t_{i2} + \frac{v_{i3} - v_{i2}}{a} + \frac{v_{i4} - v_{i3}}{b'} = T_{delay} + T_{dwell} + \Delta T_{i-1} \\
& \Delta S_{i1} + \Delta S_{i2} + \Delta S_{i3} + \Delta S_{i4} \\
& = \frac{v_{i2}^2 - v_{i1}^2}{2 \times b} + \frac{v_{i3}^2 - v_{i2}^2}{2 \times a} + \frac{v_{i4}^2 - v_{i3}^2}{2 \times b'} + \frac{v_{i4}^2}{2 \times b} = S_1 - S_i - SM - L_t
\end{aligned} \tag{10}$$

where:

α, β are penalty factors, $\alpha, \beta > 0$;

v_{ij} is the status switching velocities of the *i-th* train, *i=2,…,n, j=1,2,3,4;*

S_{ij} is the position of the *i-th* train in v_{ij}, *i=2,…,n, j=1,2,3,4;*

Δt_{i2} is the waiting time of the *i-th* train in S_{i2}, *i=2,…,n;*

ΔT_{ij} is the running time of the *i-th* train in stage *j, i=2,…,n, j=1,2,3;*

ΔS_{ij} is the running distance of the *i-th* train in stage *j, i=2,…,n, j=1,2,3,4.*

ΔT_{i-1} is the running time of the *(i-1)-th* train from $S_{(i-1)3}$ to S_1, *i=2,…,n.*

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2.3.4 Power demand and energy consumption calculation

The power demand for the *i-th* train ($P_i(t)$) is calculate by eqn. (11)

$$P_i(t) = F_i(t) \times v_i(t) \tag{11}$$

where

$F_i(t)$ is instantaneous traction force of the *i-th* train;

$v_i(t)$ is instantaneous velocity of the *i-th* train.

The total power demand ($P_{total}(t)$) is calculate by eqn. (12)

$$P_{total}(t) = \sum_{i=2}^{n} P_i(t) \tag{12}$$

where

n is the number of delayed following trains.

The energy consumption of the *i-th* train ($E_i(t)$) is calculate by eqn. (13)

$$E_i(t) = P_i(t) \times t \tag{13}$$

where

t is running time of the *i-th* train;

The total energy consumption ($E_{total}(t)$) is calculate by eqn. (14)

$$E_{total}(t) = \sum_{i=2}^{n} E_i(t) \tag{14}$$

where

n is the number of delayed following trains.

3 Simulation and discussion

In this section, a simulation is used to test and verify the new strategy. The length of train (L_t) is 140 (m), safety margin (L_{safe}) is 50 (m), service tracking headway is 120 seconds, dwell time (T_{dwell}) is 10 seconds, target velocity (v_1) is 16 m/s, service acceleration rate (a) is 1m/s^2, service barking deceleration rate (b) is 1 m/s^2.

In order to choose b', we analyze the practical data of coasting phase from Dalian Fast Track. Because the velocity in coasting phase declines very slowly,

Table 2: Measured value of the coasting data.

Velocity range (km/h)	Slop (m/s^2)	Average error (m)
37-31	-0.0147	0.0227
41-40	-0.0125	0.0361
43-42	-0.0147	0.0364
54-48	-0.0213	0.0236
60-59	-0.0237	0.0296
62-61	-0.0210	0.0301
79-75	-0.0315	0.0237

so the profile of velocity-time could be seen as a straight line and he slope of the line could be seen as the deceleration rate of coasting phase. We use least-square procedure to fit the velocity-time date sectional and the results are in table 2.
From table 2, it is clear that the higher of the coasting starting velocity, the higher of the deceleration rate. In order to keep the train moving in a constant deceleration *b'* while supply traction force as low as possible, we choose $b' = 0.01$ m/s^2 is appropriate.

If T_{delay} is 250 seconds, according to eqn (7), 3 trains will be delayed (including the leading train). Based on eqn (8)-(10), we have:

① For train 2:

$$\begin{aligned}
&\min f = v_{22} + 5000\times\Delta t_{22} + 5000\times(v_{24} - 8)\\
s.t.\quad & v_{22} - v_{23} \le 0\\
& v_{24} - v_{23} \le 0\\
& v_{22}, v_{23}, \Delta t_{22} \ge 0\\
& v_{24} \ge 8\\
& -2\times v_{22} + 101\times v_{23} - 100\times v_{24} + \Delta t_{22} = 234\\
& -2\times v_{22}^2 + 101\times v_{23}^2 - 100\times v_{24}^2 - 2948 = 0
\end{aligned}$$

② For train 3:

$$\begin{aligned}
&\min f = v_{32} + 5000\times\Delta t_{32} + 5000\times(v_{34} - 8)\\
s.t.\quad & v_{32} - v_{33} \le 0\\
& v_{34} - v_{33} \le 0\\
& v_{32}, v_{33}, \Delta t_{32} \ge 0\\
& v_{34} \ge 8\\
& -2\times v_{32} + 101\times v_{33} - 100\times v_{34} + \Delta t_{32} - 283.5 = 0\\
& -2\times v_{32}^2 + 101\times v_{33}^2 - 100\times v_{34}^2 - 6788 = 0
\end{aligned}$$

and the results are:

$$v_{22} = 0, v_{23} = 9.57, v_{23} = 8, \Delta t_{22} = 65.66\,.$$

$$v_{32} = 13.043, v_{33} = 13.043, v_{33} = 10.08, \Delta t_{32} = 0\,.$$

Fig. 4 to Fig. 7 and table 3 show the simulation results.

From fig. 4, we can see the two following trains are starting simultaneously from 250 s, so they reach the highest velocity at the same time and the peak power demand is 25.1 kw/t. The arrival time of train 2 and train 3 are 289.38s and 338.76s respectively.

Fig. 5 shows the performance of graded ARL technique. The acceleration rate of rain 2 and train 3 are 0.5 m/s^2 and 0.3 m/s^2. By applying different acceleration rate, the time points when the two trains reach the highest velocity are staggered, so the peak power demand is reduced to 22.07 kw/t, however, the time delay is increased. The arrival time of train 2 and train 3 are 297.78s and 400.36s respectively.

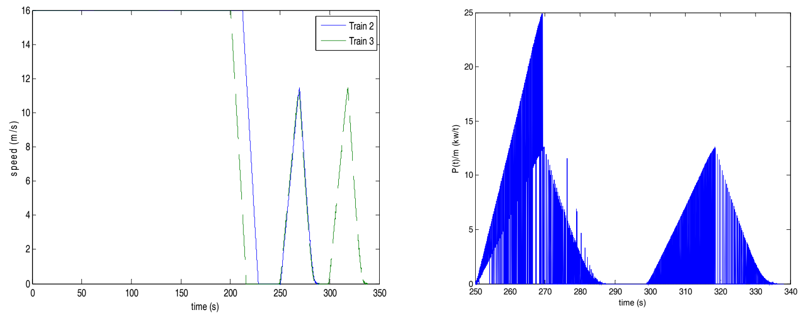

Figure 4: v-t profile and peak demand profile without the PDR technique.

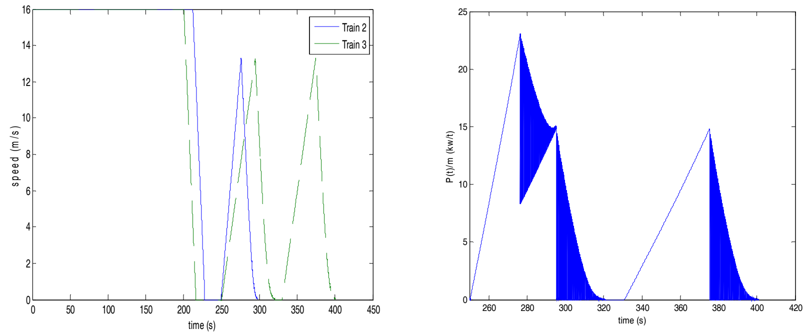

Figure 5: v-t profile and peak demand profile with the graded ARL technique.

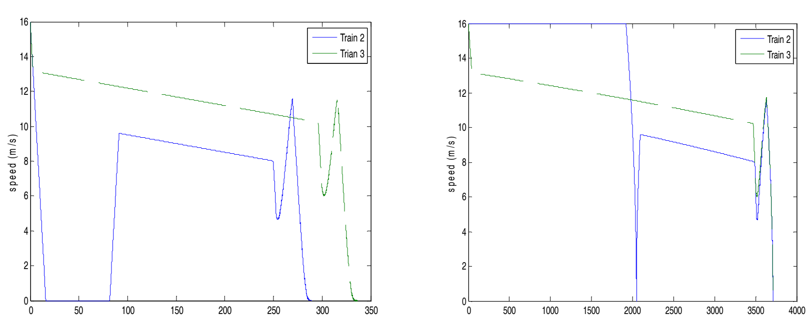

Figure 6: v-t and v-s profile with the SHB technique.

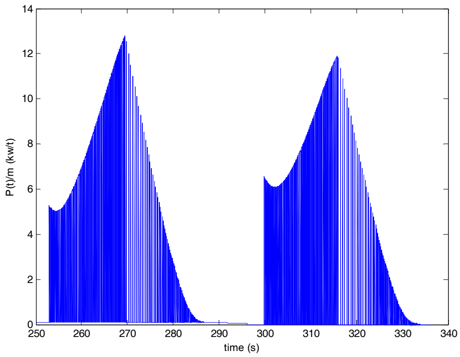

Figure 7: Peak demand profile with the SHB technique.

Table 3: Cooperation of the PDR techniques.

	Arrival time of train 2 (s)	Arrival time of train 3 (s)	Peak power demand (kw/t)	Energy consumption （kwh）	Passenger waiting time (s)	
					Train 2	Train 3
Non PDR	289.38	338.76	25.1	15.9137	130	43.75
Graded ARL	297.78	400.36	22.07	46.3402	130	43.75
SHB	289.5	339.16	13.42	10.5016	65.66	0

The performance of applying SHB technique is shows in fig.6 and fig. 7. As we see, train 2 has a waiting time of 2048m, which is 65.66s, the time points when the two trains reach the highest velocity are staggered, so the peak power demand is reduced to 13.42 kw/t. The arrival times of train 2 and train 3 are 289.5s and 339.16s respectively.

Table 3 shows the result data of the simulation. Graded ARL technique can reduce the peak power demand but the arrival times of the two trains are delayed significantly. SHB technique has great advantages. From table 3, the delayed times of the two train are very short and the energy consumption is also reduced to a low level, even less than value without any PDR technique.

4 Conclusion

A new Peak Demand Reduction technique is proposed. Based on the extra station dwell time, nonlinear programming approach is used to model the operation strategy. Compared with the traditional PDR techniques, the new one has the best performance. It can reduce the peak power demand significantly without increasing the arrival time delay while shorten the passenger waiting time and reduce energy consumption.

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