An Optimization Approach for Real-Time Headway Control of Railway Traffic

Jing XUN†*, Member, Ke-Ping LI†, Nonmember, and Yuan CAO††, Member

SUMMARY  Headway irregularity not only increases average passenger waiting time but also causes additional energy consumption and more delay time. A real-time headway control model is proposed to maintain headway regularity in railway networks by adjusting the travel time on each segment for each train. The adjustment of travel time is based on a consensus algorithm. In the proposed consensus algorithm, the control law is obtained by solving the Riccati equation. The minimum running time on a segment is also considered. The computation time of the proposed method is analyzed and the analysis results show that it can satisfy the requirement on real-time operation. The proposed model is tested and the consensus trend of headways can be observed through simulation. The simulation results also demonstrate that the average passenger waiting time decreases from 52 to 50 seconds/passenger. Additionally, the delay time is reduced by 6.5% at least and energy consumption can be reduced by 0.1% at most after using the proposed method.

key words: consensus algorithm, cooperative train control, headway regularity, CBTC

1. Introduction

Headway control pertains to the process of establishing and maintaining a desired range between a following vehicle and the vehicle preceding or leading it [1]. In a rail transit system, headways between trains are equalized when they depart from the origin. It will generally lose the equalization because there are a variety of disturbances during their operation [2]. Especially in a line with high speed and high density, transit operations are frequently disturbed because of the short buffer time. The factors of disturbance include unique driving experience for each driver, reaction time of signaling system, dwell time at stations, and unexpected conflict at junction area. The combined effect of these factors results in the irregularity of headways. Headway irregularity discourages passengers from using the transit system.

In railway traffic with high frequency, if a train is delayed by failure of a point or another, the following trains will have to stop, which forms a queue. The stop is unexpected and called an unnecessary stop. The unnecessary stop will cause train delay and increase energy consumption. The way for the first following train to avoid an unnecessary stop is to slow down and run at a proper speed. It speeds up until it is noticed that the accident is resolved. The similar approach is used by drivers on other following trains, based on their experience. This means that the recovery process is controlled manually. If the driver lacks experience in solving such problems, the headway between successive trains will be disturbed seriously. According to Ding’s work [3], the average passenger waiting time will be raised. This problem, which is called headway recovery problem in this paper, is common on China’s High-speed railway line.

The train control system used for China’s high-speed railway line is CTCS (Chinese Train Control System), which is a kind of CBTC (Communication Based Train Control) system. Currently, CBTC system is widely used in railway transportation, because of its advantages of improvement in capacity and reduction of fixed infrastructure costs. In a CBTC system, traditional fixed-block track circuits are not necessary for determining train position. Instead, the system depends on knowledge of the precise location and speed and direction of each train, which is determined by a combination of several sensors: active and passive markers along the track, and train borne tachometers and speedometers. Transmission of operation related information relies on continuous two-way digital communication between each controlled train and wayside control center. The control center generates a movement authority (MA) for each train, which makes the block locations and lengths consistent with train location and speed. Theoretically, line side signals are unnecessary and blocks become movable.

One of CBTC features is the wide usage of automatic train operation (ATO) system. ATO system plays a key role in ensuring accurate stopping, operation punctuality, energy saving and riding comfort. It controls the train speed to achieve safe and efficient driving. ATO system consists of two levels of control actions [4]: High-level control for calculating and updating the optimal trajectory and Low-level control for tracking the target speed and feedback. Based on ATO, a cooperative level could be set up for coordinated train control (Fig. 1), where the proposed approach is intended to kick in.

In this paper, we propose an approach to solve the headway recovery problem mentioned in paragraph 2 in this section. In the proposed approach, a consensus algorithm is used to adjust the arrival time to the next segment by calculating the optimal running time on each segment. Based on the optimal running time, current speed and position of each train, an advisory speed profile is generated to guide driving. The rest of this paper is organized as follows: In Sect. 2, we
review literature on approaches to maintain headway regularity for rail transportation systems and also the advisory speed based methods. In Sect. 3, the real-time headway adjustment model is presented. A cooperative control algorithm based on solving the Riccati equation is applied to maintain train headway regularity in a single track line. The simulation and discussion are described in Sects. 4 and 5 respectively. Finally, the conclusions of this approach are presented.

2. Literature Review

To maintain headway regularity, holding control and station skipping were often used [5]–[9]. Their disadvantages are introduced in [3]. As one who is different from the previous two methods, real-time train regulation techniques have attracted scholars’ attention since the 1990s. A linear quadratic (LQ) regulator was applied in a traffic model which is linear and has the disturbance with Gaussian distribution [10]. Chang and Thia [11] tried to use a fuzzy expert system to reschedule in real-time. This approach can describe nonlinear behavior. However, the construction of membership functions needs human expert’s experience on the representation of regularity, headway, and congestion levels. The genetic algorithm is a feasible way to find the optimal regulation actions of the metro line [12], [13]. The obstacle of its application is that the time for evolving the solutions is too long to fit real-time operation. Dual heuristic dynamic programming (DHP) is used by Lin and Sheu first to develop the adaptive critic automatic train regulation system [14], [15]. The disadvantage is that it is sensitive to model error. To overcome this, an adaptive optimal control (AOC) method was presented in [16]. Based on these previous studies, issues regarding energy saving was further considered and a DHP method for designing ATR with energy saving via coasting and station dwell time control is proposed [17]. Ding and Chien [3] proposed a real-time headway control model to maintain desired headways for pairs of successive vehicles by minimizing total headway variance for all stations in an advanced public transportation system environment, such as an automatic train control system and an automatic vehicle location system. In their study, train’s optimal arrival time at the next station is generated by considering the maximum operating speed and the headways to its leading and following trains. Based on it, a train’s departure time at current station can be found. The train driver will be aware of such departure time to guide train operation. By applying their model, the average passenger waiting time is significantly reduced. Here the waiting time means the time for passenger waiting the train at platform.

Except for increasing the average passenger waiting time, headway irregularity may also result in the additional energy consumption and more delay time. Trains with irregular headways arrive at a line’s bottleneck (such as a station) with unequal intervals. Some of these intervals are smaller than the minimum headway. That means the following train is forced to decelerate, even to stop, to wait for the leading train leaving the bottleneck. To regulate train speed in advance can avoid unnecessary train stop and save energy. Mehta et. al. [18] introduced a computer-based train control system which is to reduce energy consumption by sending advisory speeds to the drivers in advance. In their study, the bottleneck is a tunnel with a single-line track. Many track occupation conflicts happen here. Another place where many track occupation conflicts happen usually is station platform. In [19], an analytical based method is introduced to use advisory speed as guidance for a delayed train entering station. The system sends an advisory speed to change the train’s arrival time at bottleneck area, i.e. the headway between two successive trains, which can reduce additional delays and waste of energy. To apply a real-time train regulation method, its impact on decreasing average passenger waiting time, reducing additional train delay and saving energy should be analyzed.

3. Real-Time Headway Adjustment Model

The proposed real-time headway adjustment model is based on an integrated algorithm. The integrated algorithm consists of two main parts: one is a consensus algorithm to adjust the travel time on each segment for each train; another is an algorithm to generate optimal speed profile in each segment for each train. To apply the consensus algorithm, the headway adjustment problem should be constructed as a consensus problem first.

3.1 Problem Definition

In a single track high-speed line, overtaking could not be allowed. Generally, trains that run on this line have similar characteristics, such as maximum acceleration/deceleration rate, length and so on. If we set a series of check points (CP) along the line, we could have the arrival time at each point for every passing train. Then, the headway for train $i$ is

$$h_i = a_{i+1} - a_i$$

Where $a_i$ means the arrival time at point $j$ for train $i$. Arrival time $a_i$ can be expressed by $r_{j-1,i}$, which is the travel time in segment between CP $j$ and $j-1$:

$$a_i = a_{i-1} + r_{j-1,i}$$

Fig. 1 Cooperative control in a higher level for ATO.
Then the equation below is derived:
\[ h^i_j = h^i_{j-1} + t^{i+1}_{j-1,j} - t^i_{j-1,j} \] (3)

The equation above is not difficult to understand. For train \( i + 1 \), its headway with the leading train at CP \( j \) is decided by two parts: one is their headway at last CP \( j - 1 \); another is the difference between their travel times on the segment from CP \( j - 1 \) to \( j \). Assume the train fleet to a set of agents \( A = a_i, i = 1, \ldots, N \), where \( N \) is the number of trains in the fleet. If trains could communicate with its leading and following train, a graph whose every node is connected to its 2 nearest neighbours on a line can be obtained, i.e. the Laplacian matrix is given as
\[
L = \begin{pmatrix}
1 & -1 & 0 & 0 & 0 \\
-1 & 2 & -1 & 0 & 0 \\
0 & -1 & 2 & -1 & 0 \\
0 & 0 & -1 & 2 & -1 \\
0 & 0 & 0 & -1 & 1
\end{pmatrix}
\] (4)

**Notations**

\( H \) \quad \text{Scheduled headway (preset), Unit: s;}
\( E(h) \) \quad \text{Mean headway, Unit: s;}
\( \sigma^2(h) \) \quad \text{Headway variance, Unit: s^2;}
\( h^k_i \) \quad \text{Headway between two successive trains \( k \) and \( k + 1 \) at point \( i \), Unit: s;}
\( d^k_i \) \quad \text{Arrival time of train \( k \) at point \( i \), Unit: s;}
\( t^k_{i-1,i} \) \quad \text{Travel time of train \( k \) in segment \((i-1,i)\), Unit: s;}
\( p^k_i \) \quad \text{Departure time of train \( k \) at point \( i \).}

Obviously, \( d^k_i = p^k_i \) if no stop, Unit: s;
\( T_{\text{min}} \) \quad \text{Minimum travel time, Unit: s;}
\( P^k(t) \) \quad \text{Position of train \( k \) at time \( t \), Unit: m;}
\( V^k(t) \) \quad \text{Speed of train \( k \) at time \( t \), Unit: m/s;}
\( P_{\text{obj}} \) \quad \text{Objective position, Unit: m;}
\( T_{\text{obj}} \) \quad \text{Scheduled travel time, Unit: s;}
\( T_{\text{norm}} \) \quad \text{Travel time with initial speed, Unit: s;}
\( V_{\text{obj}} \) \quad \text{Objective speed when trains exit a segment, Unit: m/s;}

**Assumptions**

The development of the proposed model is based on the following assumptions:

- There is only one type of train runs on the corridor which is a single-track high-speed line. Overtaking is not allowed in the line.
- The corridor is divided into several equalized segments, whose length is \( \Delta D \). The end point of each segment is called check point (CP), which is indexed by \( i = 1, 2, \ldots \).
- Choose a leading train and the number of controlled trains \( N \) first. Then the leading train with \( N - 1 \) following trains fleet is under the control of the proposed model. The advisory speed information is sent to trains when they pass the end point of each segment.

**State Function for train’s headway**

In order to obtain the equally spaced traffic flow, arrival time at CP should be controlled. Arrival time \( d^k_i \) can be expressed by travel time at segment \((i-1,i)\):
\[
d^k_i = d^k_{i-1} + t^k_{i-1,i}
\] (5)

The headway \( h^k_i \) between train \( k \) and \( k + 1 \) at CP \( i \) can be determined by:
\[
h^k_i = p^k_i - p^{k-1}_{i-1,i}
\] (6)

Then the equation below is derived:
\[
h^k_i = h^k_{i-1} + t^k_{i-1,i} - t^{k-1}_{i-1,i}
\] (7)

Where, \( t^{k-1}_{i-1,i} \) is train \( k-1 \)’s travel time in segment \((i-1,i)\). It is a given constant when train \( k-1 \) passed segment \((i-1,i)\). Adjustment of \( t^{k-1}_{i-1,i} \) will change \( h^k_i \), \( e^k_i \) is the optimized value of \( t^{k-1}_{i-1,i} \). After optimization, arrival time at CP \( i \) changes (shown in Table 1).

If the headway between two successive trains is seen as a state of the following train, the state function for train’s headway can be defined as follows:
\[
h^k_i = h^k_{i-1} + u_i + \sum_{j=0}^{N} F^{kj} h^j_{i-1}
\] (8)

### Table 1: Train arrival time before and after optimization.

<table>
<thead>
<tr>
<th>Train#</th>
<th>Arrival time before optimization</th>
<th>Arrival time after optimization</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( a^1_i )</td>
<td>( a^1_i )</td>
</tr>
<tr>
<td>\ldots</td>
<td>\ldots</td>
<td>\ldots</td>
</tr>
<tr>
<td>( k-1 )</td>
<td>( a^{k-1}_i )</td>
<td>( a^{k-1}_i )</td>
</tr>
<tr>
<td>( k )</td>
<td>( a^k_i )</td>
<td>( p^k_i = e^k_i(t) )</td>
</tr>
<tr>
<td>( k+1 )</td>
<td>( a^{k+1}_i )</td>
<td>( p^{k+1}_i = e^{k+1}_i(t) )</td>
</tr>
<tr>
<td>\ldots</td>
<td>\ldots</td>
<td>\ldots</td>
</tr>
<tr>
<td>( N )</td>
<td>( a^N_i )</td>
<td>( p^N_i = e^N_i(t) )</td>
</tr>
</tbody>
</table>

3.2 Application of consensus algorithm in railway traffic

Based on the problem definition in Sect. 3.1, headway control in railway traffic flow with one type of train can be seen as a consensus problem. In railway traffic, the headways between trains are influenced by trains’ dynamics. If the dynamic model of headway can be constructed as shown in Eq. (8), a feedback loop can be designed to accomplish consensus. The loop is shown in Fig. 3. The feedback gain matrix \(-K(k)\) is a linear time-varying parameter. So, the cost function for each train can be defined as follows:
\[
J = \sum_{i=1}^{N} (h^k_i - h^{k-1}_i)^T Q^{ij} (h^k_i - h^{k-1}_i)
\] (9)

\( \min(h^1_i, \ldots, h^N_i) \leq h^k_i \leq \max(h^1_i, \ldots, h^N_i) \)

Where \( Q^{ij} \) is a symmetric and positive definite matrix, \( N \) is
the number of trains.

The following algorithm is designed to apply the proposed method.

**Algorithm**

- Step 1 Start the algorithm when headway variance \( \sigma^2(h) > \sigma_0 \) or mean headway \( E(h) > E_0 \). \( E_0 \) and \( \sigma_0 \) is an initial selection;

- Step 2 Obtain a feedback gain matrix \(-K(k)\), by solving the following Riccati equation:

\[
-K(k+1) = 2N^tQ^j - \frac{1}{2}K(k)(R^i)^{-1}K(k) \quad (10)
\]

- Step 3 Find the control law \( u^*_t \):

\[
u^*_t = -\frac{1}{2}(R^i)^{-1}K^iH^t \quad (11)
\]

- Step 4 Obtain the travel time of train \( k \) in segment \((i-1, i)\):

\[
F^{ij} = 2(K^i)^{-1}Q^{ij} \quad (12)
\]

\[
i_{i-1,i} = i^{-1}_{i-1,i} + u_i + \sum_{j \in \mathbb{N}} F^{ij}h^i_{i-1} \quad (13)
\]

- Step 5 Check and revise \( i_{i-1,i} = T_{\text{min}}^i(t) \) if \( i_{i-1,i} < T_{\text{min}}^i(t) \);

- Step 6 Generate optimal speed profile in segment \((i-1, i)\);

- Step 7 End the algorithm when \( \sigma^2(h) < \sigma_0 \) and \( E(h) < E_0 \).

In Step 6, the optimal speed profile in a segment is generated by an independent algorithm, which will be introduced next.

**3.3 Generation of Optimal Speed Profile in Each Segment for Trains**

The problem can be stated as follows: a train of mass \( m \) is planned to departure from its current position with initial speed \( V_0 \) and to arrive at its destination in \( T \) seconds with objective speed \( V_{\text{obj}} \). The distance between its current position and destination is \( L \). The speed limits, grades and curvatures along the track are known a priori. The characteristics of the trains (i.e., performance of traction and braking, rolling resistance) are also assumed to be known. The problem is to find the optimal speed profile that can satisfy the minimization of energy consumption, punctuality or passenger ride quality, which is up to the operation demand. The above problem is also called optimal control strategy for a single train. The research on this problem can be classified into three categories: The first one is based on one or several search heuristics. This method can find an optimized solution, which is possibly global, with the short-age is time-consuming; the second one is based on applied mathematics and numerical analysis. This method can find a global optimization solution theoretically. It needs a strong background of mathematics [20]. The last one is based on an idea that the energy consumption is minimized when the train runs at the lowest speed compatible with its target [21].

The third method is a sub-optimal approach. Compared with the first two methods, the third one can reduce the involved computational complexity to ensure real-time control. So it is used to generate speed profile in our study. An algorithm which is developed by Lu and Dessouky [22] is used to determine the minimum travelling time of trains \( T_{\text{min}} \) in a segment. It considers the initial speed of trains when they arrive at the entrance of segment.

**3.4 Intervention of Automatic Train Protection System**

By adjusting travelling time between stations for each train, it may cause track occupation conflicts, especially in areas which are in close proximity to the platforms. If a train’s arrival time is adjusted earlier than the schedule, it may have an impact on its speed profile for entering station while the preceding train is still stopped at the station. The impact is caused by the intervention of Automatic Train Protection (ATP) system. The ATP system is a key equipment to make sure trains operate safely. The proposed method should be under ATP control. If the speed profile generated by the proposed method is conflicted with limit speed from ATP, the train should follow limit speed to run. Obviously, the ATP system will decrease train speed, even to stop a train if two trains run too close. Usually it can be avoided by sending advisory speed information to guide the following train entering station. This method is proposed in [19].

**3.5 Approach Based on Integrated Algorithm**

Integrating the above algorithms in two levels, an approach to generate an optimized speed profile for a train is shown in Fig. 4. What we need to notice is there is the limitation of the minimum running time \( T_{\text{min}} \). After adjustment, the scheduled travel time \( T_{\text{obj}} \) should be larger than \( T_{\text{min}} \), otherwise make \( T_{\text{obj}} \) equal to \( T_{\text{min}} \). If not considering the limitation of \( T_{\text{min}} \), we can only get the theoretical result, which can’t be achieved in practice. According to the architecture in Fig. 1, The speed profile generated could be seen as a reference, whether manual or automatic driving.
4. Simulation

Based on the described problem, a train-following scenario is established by using the data from a section of Wuguang High-speed railway line. The Wuguang High-speed railway line is a 968 kilometer typical Chinese high-speed railway line. It’s operated by CRH2C and CRH3C (China Railway High-speed) trains since the first commercial train left Wuhan and Guangzhou in 2009. Currently, the minimum dispatch headway is 5 minutes. The average dispatch headway is 15 minutes. There would be 5 to 7 stops during one journey which depends on its schedule (Train Number). In the simulation scenario, there are two stations A and B linked by a line AB. With a constant dispatching headway $H = 70$ seconds, 5 trains leave the original station A successively. During their trips, headways between them are disrupted randomly and will become unequal gradually. The simulation is implemented based on CA (cellular automata) model in [23]. The parameters used in the simulation are as follows:

1. Maximum Train acceleration $a = 1 m/s^2$;
2. Maximum Train deceleration $b = 1 m/s^2$;
3. Train length $L_t = 201 m$;
4. Safe distance $L_s = 100 m$;
5. Maximum train speed $V_{max} = 100 m/s$;
6. Speed limit of line $S_{L_i} = 100 m/s$, $i \in (1, L_i)$;
7. Length of the line $L_t = 240000 m = 240 km$;
8. Length of the simulation time $T = 2000 s$.

The line’s slope and curve is not taken into account in simulation. The theoretical result is shown in Fig. 5. When not considering the minimum running time, we find that all of the lines which represent 4 headways with initial value 100, 80, 70 and 122 seconds respectively are concentrated into one line after 40 iterations. This demonstrates that the headway can be consensus theoretically; however the practical effect needs to be verified by considering the minimum running time. When the minimum running time is considered, headways can’t converge into a single value. In Fig. 6, we find that the variation of headways has a trend of closing up. The headways between 5 trains are 123, 100, 80 and 70 seconds respectively before applying the proposed method. The variance is 411. After applying the proposed method, the headways become 109, 110, 112 and 100 seconds respectively. The variance decreases to 21. The differences between headways are narrowed. As seen in Fig. 7, the adjustment starts at $t = 400$ and ends at $t = 1000$. The traffic flow becomes more even. In Fig. 7, Train 1 is the leading train. It decelerated from maximum speed when the algorithm started so that the following trains can catch up to reduce their headways. In order to avoid the negative impact caused by the enlargement of headway between Train 1 and its preceding train, we should choose a train whose headway with its preceding train is smaller than the minimum line headway as the leading train.

When the headway is adjusted, the limitation from the ATP system should be analyzed. In Fig. 8, the solid line de-
Fig. 7 The space-time diagram.

Fig. 8 Time-space diagram with minimum headway between each couple of successive trains.

Fig. 9 Variation of parameter $\rho$.

Fig. 10 Variation of parameter $\upsilon$.

Table 2 CPU Time.

<table>
<thead>
<tr>
<th>Number of Trains</th>
<th>CPU time (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.0271</td>
</tr>
<tr>
<td>10</td>
<td>0.0386</td>
</tr>
<tr>
<td>15</td>
<td>0.48</td>
</tr>
<tr>
<td>20</td>
<td>0.4915</td>
</tr>
<tr>
<td>25</td>
<td>1.5332</td>
</tr>
<tr>
<td>30</td>
<td>1.5343</td>
</tr>
<tr>
<td>40</td>
<td>2.5128</td>
</tr>
</tbody>
</table>

Where $H_n$ is the headway between train $n$ and $n + 1$, $H_E$ is the mean value of all headways. Figures 9 and 10 show the curve of $\rho$ and $\upsilon$ from simulation time $t = 400$ to 1000 respectively. The trend of curve changing indicates that headways among these trains are equalized.

To satisfy the requirement of real-time operation, the real-time adjustment of headways should be implemented in short time. In Table 2, the CPU time presented is the time from triggering the algorithm to obtaining the speed profile on each segment for each train. The CPU time increases with the increases of the number of trains in simulation. All the simulations are conducted on a PC with an Intel Pentium 4 3GHz Processor and 1.5G RAM. The operating system is Ubuntu 8.04. The model is programmed in the MATLAB language.

5. Discussions

In this section, simulation results on average passenger waiting time, energy consumption and delay time are discussed. In [3], a way to estimate average passenger waiting time for a transit route while considering stochastic vehicle and passenger arrivals at stations:

$$E(W) = E(h)/2 + \sigma^2(h)/2E(h)$$

Figure 11 shows the estimated average passenger waiting times during the simulation period. Without control, the average passenger waiting time increases as the simulation time increases. Under control, the average passenger waiting time decreases from 52 to 50 seconds/passenger.

In general, the calculation model of energy consumption is based on Principle of Conservation of Energy. When the train runs, the energy consumption equals the works to

$$\rho = \sum_{n=1}^{N} (H_n - H_E), \quad \upsilon = \sum_{n=1}^{N} (H_n - H_E)^2$$

notes the time-space curve for each train. The dotted line denoted the position where the following train has to decrease its speed because of ATP limit speed. These two kinds of line do not intersect, which means the intervention from ATP system is avoided. In order to demonstrate the effect of adjustment, we introduce tow parameters: $\rho$ and $\upsilon$ to measure the degree of dispersion.
overcome all resistance on train plus the variance of train’s kinetic energy, i.e.:

\[
E = \sum F_i S_i + (1/2 m V_1^2 - 1/2 m V_2^2)
\]  

(16)

Where, \(m\) is the weight of train, \(V_1\) and \(V_2\) is the initial and final velocity of train respectively, \(S_i\) is the work distance of resistance \(F_i\). The resistance of train includes air resistance, rolling resistance, gradient resistance, and so on. Here we use the Davis formula to calculate the resistance of train:

\[
F = r_0 + r_1 V + r_2 V^2
\]  

(17)

Where \(r_0 = 16.6, r_1 = 0.1017, r_2 = 0.002\). [24]

In Table 3, the delay time and total energy consumptions with different number of trains are collected through simulation. The mass of the train used in energy consumption computation is 370.8 tons, the typical value of CRH-2C which is coupled by 6 motor coaches and 2 trailer coaches. When trains don’t adjust their headways by the proposed approach, they run as fast as they can. Energy consumption for one trip and delay arrival time at Station B is calculated respectively. In order to minimize the effect of randomness, we conducted 10 rounds of simulation and averaged the results to obtain a mean value. Because the first objective is to decrease delay time, the delay time is reduced by 6.5% at least and the energy consumption is reduced by 0.1% at most when using the proposed model.

6. Conclusions

Maintaining headway regularity has advantages in reducing energy consumption and delay time. In this paper, we proposed an optimization approach to adjust train operation in real time to equalize headways. A real-time headway adjust model is designed to maintain headways between two successive trains by adjusting the running time at each segment. An algorithm is also developed to apply this model in operation. The effect of its application is analyzed through simulation. From simulation results, the consensus trend of headways can be observed by using the proposed model. In our study, energy consumption can be reduced by 0.1% at most and the delay time can be reduced by 6.5% at least. Its computation time satisfies the requirement on real-time.

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References


Table 3  The comparison on delay time and total energy consumptions.

<table>
<thead>
<tr>
<th>Train #</th>
<th>Headway(s)</th>
<th>Energy Consumption (MJ)</th>
<th>Delay Time(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without Proposed Approach</td>
<td>With Proposed Approach</td>
<td>Reduced (%)</td>
</tr>
<tr>
<td>1</td>
<td>60</td>
<td>1801</td>
<td>1801</td>
</tr>
<tr>
<td>2</td>
<td>70</td>
<td>1846.3</td>
<td>1844</td>
</tr>
<tr>
<td>3</td>
<td>75</td>
<td>1841.5</td>
<td>1840.4</td>
</tr>
<tr>
<td>4</td>
<td>70</td>
<td>1847</td>
<td>1845.3</td>
</tr>
<tr>
<td>5</td>
<td>55</td>
<td>1830</td>
<td>1838.5</td>
</tr>
</tbody>
</table>

Fig. 11  Total average passenger waiting time versus simulation time.


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