Discrete event model-based simulation for train movement on a single-line railway*

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The aim of this paper is to present a discrete event model-based approach to simulate train movement with the considered energy-saving factor. We conduct extensive case studies to show the dynamic characteristics of the traffic flow and demonstrate the effectiveness of the proposed approach. The simulation results indicate that the proposed discrete event model-based simulation approach is suitable for characterizing the movements of a group of trains on a single railway line with less iterations and CPU time. Additionally, some other qualitative and quantitative characteristics are investigated. In particular, because of the cumulative influence from the previous trains, the following trains should be accelerated or braked frequently to control the headway distance, leading to more energy consumption.

Keywords: train movement, discrete event model, railway, energy saving

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1. Introduction

Train movement related to operation safety, energy consumption, and train timetables, etc., has attracted a lot of attention from researchers.[1–5] From the energy saving perspective, when a train is running on a railway line, its mass and the railway conditions are fixed. Therefore, the energy consumption of this train is determined by its speed profile to a large extent. For this case, Howlett and Pundney[1] presented lots of studies on energy-efficient train control. Considering the continuously varying gradient on the railway track, Howlett and Cheng[2] investigated optimal driving strategies for a single train. Further, Howlett[3] studied the determination of an optimal driving strategy for the train control problem with the consideration of a generalized equation of motion.

For the energy saving movements of a group of trains, Yang *et al.*[4] applied a discrete-time movement model to simulate the traffic flow on a single railway line, where some stochastic disturbances were also taken into account, and the simulation time step was fixed. Ye and Li[5] considered the energy saving speed profile and simulated the train movement on a single-track by using the car-following model. Li and Fan[6] investigated the relationship between energy consumption and train delay in railway traffic by using an improved cellular automation model. Moreover, for simulating the train traffic on a railway network, Li and Guan[7] applied a random walk model in their simulation. Considering the global information of a railway network, Yang *et al.*[8] formulated an efficient mathematical model to optimize train movement strategies, where a genetic algorithm was used to search for the optimal solution. In addition, for more studies about optimizing the schedule of a group of trains, we can refer to Higgins *et al.*,[9] Zhou and Zhong,[10] Yang *et al.*,[11] Xu *et al.*,[12] and Yang *et al.*[13,14] For more details about energy consumption and exhaust emission of transportation, we can refer to Tang *et al.*[15–17]

It is obvious that most simulation approaches for train movement are developed based on the discrete time model, which leads to lots of simulation steps. However, the interactions among trains can be concluded in a few categories, such as controlling the safety margin and changing the operating mode. That is, if those discrete events can be grasped entirely, and the corresponding movement strategies can be designed at each event, the simulation procedure may be accelerated because the simulation time step is greater than that in a discrete time model. Therefore, compared with the discrete time model-based (DTM-based) simulation approach, the simulation method, which involves a discrete event model, may reduce the iterations and CPU time for the same problem to a great extent. This assumption has been proved by Dorfman and Medanic,[18] Li *et al.*,[19] and Xu *et al.*,[20] Dorfman and Medanic[18] developed a local feedback-based travel advance strategy (TAS) by using a discrete event model (DEM) of train advances along railway lines. Li *et al.*[19] improved the TAS method by considering two kinds of collisions among the trains: relative deadlocks and absolute deadlocks. In order to search for a balanced schedule with the lowest delay-ratio, Xu *et al.*[20] modified some advance strategies in TAS and optimized train velocity. However, few researches involved a DEM model, which may accelerate the simulation of the

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train flow on a single railway line, that were used to graph the dynamic characteristics of the train flow. Therefore, to investigate train movement more quickly, in this paper we shall present a new simulation approach for the train movement on the basis of a discrete event model, denoted by the DEM-based simulation approach.

The rest of this paper is organized as follows. In Section 2, the basic knowledge for energy-saving train control is introduced. A discrete event model-based simulation approach will be proposed in Section 3. To demonstrate the proposed model and approach, some numerical simulations are presented in Section 4. Lastly, a conclusion is drawn in Section 5.

2. Energy-saving train control model

In practice, for railway companies, it is better to reduce the energy consumption as much as possible. Generally speaking, energy consumption is related to the train's mass and speed profile. Specifically, train movement consists of four operating modes: acceleration with traction, cruising, coasting, and deceleration with braking, where phases of acceleration and cruising cause energy consumption, and the energy consumption in coasting and deceleration is zero.

As we know, the resistance in the cruising phase is small. If the train overcomes the resistance, the train's speed will be a constant, which leads to less energy consumption. That is to say, without the considerations of gradient and specific speed limit, the procedure that a train firstly accelerates its speed to an appropriate value, called cruising speed, and then retains the cruising speed before its braking, is an optimal train movement mode for energy saving.[5] Figure 1 illustrates the aforementioned train speed profile, where A is the start position and B is the destination of the train. In what follows, we shall introduce the above optimal speed profile in detail. Some parameters are listed in Table 1, which may help us to describe and understand the problem more conveniently.

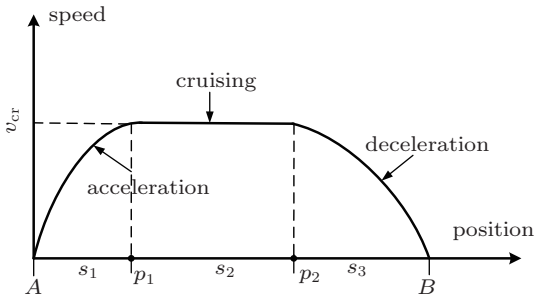


Fig. 1. A simple optimal speed profile.

Table 1. Subscripts and parameters used in formulation.

Symbol	Definition	Symbol	Definition
F	maximum traction force/unit mass	R	running resistance/unit mass
B	maximum braking force/unit mass	v_{cr}	cruising speed
M	the mass of train	T	section trip time
L	length of the section AB	E	total energy consumption

Let t_1, t_2, and t_3 be the acceleration time, cruising time, and braking time, and s_1, s_2, and s_3 the acceleration distance, cruising distance, and braking distance, respectively. For simplicity, we assume that the train acceleration and deceleration are constants whose values are $F-R$ and $B+R$, respectively. Then the following equations can be concluded

$$\begin{cases} s_1 = v_{cr}^2/2(F-R), \\ s_2 = L - v_{cr}^2/2(F-R) - v_{cr}^2/2(B+R), \\ s_3 = v_{cr}^2/2(B+R), \end{cases} \tag{1}$$

and

$$\begin{cases} t_1 = v_{cr}/(F-R), \\ t_2 = \dfrac{1}{v_{cr}}(L - v_{cr}^2/2(F-R) - v_{cr}^2/2(B+R)), \\ t_3 = v_{cr}/(B+R). \end{cases} \tag{2}$$

From the time perspective, $T = t_1 + t_2 + t_3$, according to Eqs. (2), we have

$$\frac{v_{cr}}{2(F-R)} + \frac{v_{cr}}{2(B+R)} + \frac{L}{v_{cr}} = T. \tag{3}$$

From Eq. (3), we obtain the solutions of v_{cr}

$$v_{cr} = \frac{T \pm \sqrt{T^2 - 2(F+B)L}}{1/(F-R) + 1/(B+R)}, \tag{4}$$

if $T^2 - 2(F+B)L > 0$. In the real world application, we know that the longer T is, the smaller v_{cr} will be, so we choose v_{cr} as

$$v_{cr} = \frac{T - \sqrt{T^2 - 2(F+B)L}}{1/(F-R) + 1/(B+R)}. \tag{5}$$

Further, in order to guarantee the reality of v_{cr}, we set

$$T_{min} = \sqrt{2(F+B)L}, \tag{6}$$

which is defined as the minimum section trip time, that is, the trip time for a train on the section should not be less than T_{min}. Besides, positions p_1 and p_2 in Fig. 1 are named switching points.

Let parameter e_x be the energy consumption of a train at the x-th meter from position A, thus $e_x = f(x) * M * 1$, where $f(x)$ represents the traction force for the train at x-th meter.

Take the speed profile in Fig. 1 as an example, for different positions, we have

$$f(x)=\begin{cases} F, \text{ if } 0<x\le p_1, \\ R, \text{ if } p_1<x\le p_2, \\ 0, \text{ otherwise.} \end{cases} \tag{7}$$

Therefore, the total energy consumption E for the train at section AB can be calculated as

$$E=\int_0^L e_x\,\mathrm{d}x=\int_0^{p_1} FMx\,\mathrm{d}x+\int_{p_1+1}^{p_2} RMx\,\mathrm{d}x. \tag{8}$$

Remark 1 In fact, equation (8) denotes the work that the train does at section AB. According to the energy-conservation equation and the locomotive traction efficiency, the volume of fuel or electricity (i.e., energy consumption), which is directly proportional to E in Eq. (8), can be calculated. For simplicity, we use E to indicate the energy consumption.

3. Discrete event model-based simulation approach

3.1. Determination of a discrete event

From the macroscopic perspective, if there is no disturbance when a train runs on a section, this train's speed will track the speed profile as shown in Fig. 1 to save energy, and its cruising velocity is v_{cr}. However, if there are at least two trains on the same section simultaneously, the following train(s) may be influenced by the previous train(s). In order to keep the safety margin, denoted by SM, between the focus train and its previous train, the focus train may be forced to reduce its speed. Thus, the focus train cannot finish its trip during the pre-planned section trip time. For this case, the rest of the trip of the focus train on its section can be set as a new virtual section and the trip time of this new section can be determined according to Eq. (6), which can help the focus train to finish its trip as soon as possible. It should be pointed out that there may be more than one virtual section in a real-world section because of the multi-influence from previous trains, and the cruising velocities in different sections are different.

Suppose that train $i-1$ is the previous train and train i is the following train, N is the scalar number of trains, t is the current system time, section k links station k and station $k+1$ and its length is L_k, the section trip time on section k is T_k, x_k is the position of station k, $s_i(t)$, $v_i(t)$, $m_i(t)$, $a_i(t)$, and $b_i(t)$ are the position, velocity, operating mode, acceleration, and deceleration of train i at time t, respectively, and i_{vcr} is the cruising velocity in a virtual section. Notation $m_i(t)=1,2,3$, respectively represent train i in the acceleration phase, cruising phase, and braking phase. Based on the aforementioned analysis, we categorize the trains on a section into two classes: leading trains and following trains. We develop Algorithms 2 and 3 to simulate the movements for the above two groups of trains, respectively. Besides, Algorithm 1 is designed to prepare the necessary foundation data.

In this paper, we roughly determine three kinds of discrete events: (i) a train arrives at or departs from a station; (ii) the distance between train i and train $i-1$ is close to the given critical value; and (iii) a train changes its operating mode. Let Δt_i be the time interval between one discrete event and its next discrete event for train i. Take Fig. 1 as an example. The train leaving station A is a discrete event, and the train changing its operating mode from acceleration to cruising at position p_1 is also a discrete event. Besides, because of the influence from the previous train(s), some special discrete events should be identified in the simulation procedure. For more details, we can refer to the developed algorithms given below, and figure 2 illustrates the flowchart of these algorithms.

Algorithm 1

Step 1 Calculate v_{cr} according to Eq. (5), where $L=L_k$ and $T=T_k$;

Step 2 Calculate the maximum braking distance $sb=\sqrt{v_{\mathrm{cr}}^2/2a_i(t)}$ and braking distance $sbmin=\sqrt{v_i(t)^2/2a_i(t)}$.

Algorithm 2

Step 1 If $x_{k+1}-s_i(t)>sbmin$, go to step 2, else if $x_{k+1}-s_i(t)\le sbmin$ go to step 3;

Step 2 If $v_i(t)<v_{\mathrm{cr}}$, go to step 2.1; else if $v_i(t)=v_{\mathrm{cr}}$, go to step 2.2;

Step 2.1 $m_i(t)=1$, $\Delta t_i=(v_{\mathrm{cr}}-v_i(t))/a_i(t)$, go to step 4;

Step 2.2 $m_i(t)=2$, $\Delta t_i=(x_{k+1}-s_i(t)-sbmin)/v_{\mathrm{cr}}$, go to step 4;

Step 3 If $i_{\mathrm{vcr}}=0$ and $v_i(t)>0$, go to step 3.1; else if $i_{\mathrm{vcr}}>0$ or $v_i(t)=0$, go to step 3.2;

Step 3.1 $m_i(t)=3$, $\Delta t_i=v_i(t)/b_i(t)$, go to step 4;

Step 3.2 If $v_i(t)=0$, calculate i_{vcr} according to Eq. (5), where $L=L_k-(s_i(t)-x_k)$ and $T=T_{\min}$ (see Eq. (6)), calculate braking distance $sbb=\sqrt{i_{\mathrm{vcr}}^2/2a_i(t)}$;

Step 3.3 If $x_{k+1}-s_i>sbb$, go to step 3.4, else if $x_{k+1}-s_i\le sbb$, go to step 3.5;

Step 3.4 If $v_i(t)<v_{\mathrm{cr}}$, update $m_i(t)=1$, $\Delta t_i=(i_{\mathrm{vcr}}-v_i(t))/a_i(t)$; else if $v_i(t)=v_{\mathrm{cr}}$, update $m_i(t)=2$, $\Delta t_i=(x_{k+1}-s_i(t)-sbb)/v_{\mathrm{cr}}$, go to step 4;

Step 3.5 $m_i(t)=3$, $\Delta t_i=v_i(t)/b_i(t)$, go to step 4;

Step 4 Output $m_i(t)$, Δt_i, and i_{vcr}.

Algorithm 3

Step 1 If $s_{i-1}(t)-s_i(t)>sbmin+SM$, go to step 2; else if $s_{i-1}(t)-s_i(t)\le sbmin+SM$ and $s_{i-1}(t)-s_i(t)>SM$, go to step 3; else if $s_{i-1}(t)-s_i(t)\le SM$, go to step 4;

Step 2 If $v_i(t)<v_{\mathrm{cr}}$, go to step 2.1; else if $v_i(t)=v_{\mathrm{cr}}$, go to step 2.3;

Step 2.1 $m_i(t)=1$, $\Delta t_i=(v_{\mathrm{cr}}-v_i(t))/a_i(t)$; consider the previous train, we give a parameter dt, which can be written in the following form:

$$dt=\begin{cases}(SM-s_{i-1}(t)+s_i(t))/(v_{i-1}-v_i(t)), \text{ if } m_{i-1}(t)=1,\\ ((v_{\rm cr}-v_i(t))-\sqrt{(v_{\rm cr}-v_i(t))^2-2a_i(t)(SM-s_{i-1}(t)+s_i(t))})/a_i(t), \text{ if } m_{i-1}(t)=2,\\ ((s_{i-1}(t)-s_i(t))-\sqrt{(v_{\rm cr}-v_i(t))^2-2b_i(t)(SM-s_{i-1}(t)+s_i(t))})/b_i(t), \text{ if } m_{i-1}(t)=3.\end{cases}$$

Step 2.2 $\Delta t_i=\min(\Delta t_i,dt)$, go to step 5;

Step 2.3 $m_i(t)=2$, $\Delta t_i=(x_{k+1}-s_i(t)-v_{\rm cr}^2/(2b_i(t)))/v_{\rm cr}$; consider the previous train, we have

$$dt=\begin{cases}((v_i(t)-v_{i-1}(t))-\sqrt{(v_{\rm cr}-v_i(t))^2-2a_i(t)(SM-s_{i-1}(t)+s_i(t))})/a_i(t), \text{ if } m_{i-1}(t)=1,\\ \Delta t_{i-1}, \text{ if } m_{i-1}(t)=2,\\ ((v_{i-1}(t)-v_{\rm cr})-\sqrt{(v_{\rm cr}-v_i(t))^2-2b_i(t)(SM-s_{i-1}(t)+s_i(t))})/b_i(t), \text{ if } m_{i-1}(t)=3.\end{cases}$$

Step 2.4 $\Delta t_i=\min(\Delta t_i,dt)$, go to step 5;

Step 3 If $v_i(t)\le v_{i-1}(t)$, go to step 3.1; else if $v_i(t)>v_{i-1}(t)$, go to step 3.4;

Step 3.1 If $v_{i-1}(t)\ge v_{\rm cr}$, go to step 3.2; else if $v_{i-1}(t)<v_{\rm cr}$, go to step 3.3;

Step 3.2 If $v_i(t)<v_{\rm cr}$, $m_i(t)=1$, $\Delta t_i=(v_{\rm cr}-v_i(t))/a_i(t)$; else if $v_i(t)=v_{\rm cr}$, $m_i(t)=3$, $\Delta t_i=(x_{k+1}-s_i(t)-v_{\rm cr}^2/(2b_i(t)))/v_{\rm cr}$, go to step 5;

Step 3.3 $m_i(t)=1$, $\Delta t_i=(v_{i-1}(t)-v_i(t))/a_i(t)$, go to step 5;

Step 3.4 $m_i(t)=3$, $\Delta t_i=(v_i(t)-v_{i-1}(t))/b_i(t)$, go to step 5;

Step 4 If $v_i(t)>0$, go to step 4.1; else if $v_i(t)=0$, go to step 4.2;

Step 4.1 $m_i(t)=3$, if $v_i(t)>v_{i-1}(t)$, $\Delta t_i=(v_i(t)-v_{i-1}(t))/b_i(t)$; else if $v_i(t)\le v_{i-1}(t)$, $\Delta t_i=\Delta t_{i-1}(t)$, go to step 5;

Step 4.2 $m_i(t)=4$, $\Delta t_i=\Delta t_{i-1}(t)$, go to step 5;

Step 5 Output $m_i(t)$, Δt_i, and $i_{\rm vcr}$.

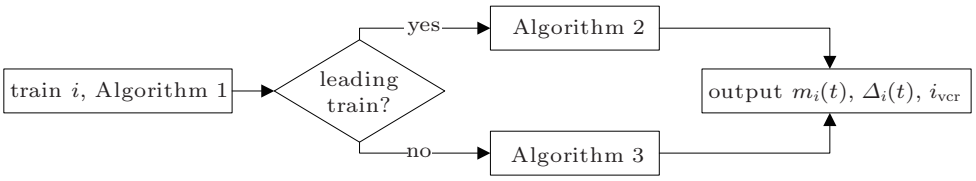


Fig. 2. The flowchart of Algorithms 1, 2, and 3.

3.2. Determination of the system discrete-event time interval

Let Δt be the system discrete-event time interval, which is used as the simulation time step. In order to guarantee that each train's movement mode remains unchanged during Δt, we have

$$\Delta t=\min\{\Delta t_1,\Delta t_2,\ldots,\Delta t_N\}. \tag{9}$$

3.3. System information update

On the basis of the aforementioned analysis, trains during the system discrete-event time interval can be categorized into four classes, i.e., i) trains in the acceleration phase, ii) trains in the cruising phase, iii) trains in the deceleration phase, and iv) trains stopping at their current positions. Even though the phases are different, the information update rules for all trains, including trains' velocities and positions, are the same, which can be calculated as

$$\begin{cases}v_i(t+\Delta t)=v_i(t)+a_i(t)\Delta t,\ 0\le v_i(t)\le v_{\max},\\ s_i(t+\Delta t)=s_i(t)+v_i(t)\Delta t+\frac{1}{2}a_i(t)\Delta t^2,\ 0\le s_i(t)\le L,\\ t=t+\Delta t,\end{cases} \tag{10}$$

where $1\le i\le N$ and $a_i(t)$ can be determined according to the following equations

$$a_i(t)=\begin{cases}F-R, \text{ if } m_i(t)=1,\\ -(B+R), \text{ if } m_i(t)=3,\\ 0, \text{ otherwise.}\end{cases} \tag{11}$$

In order to graph the characteristics of train velocity and record the velocity sequence (which are relevant to train position), here we use $v_i(s)$ and $a_i(s)$ to represent train i's velocity and acceleration at position s, respectively. We then have

$$v_i(s)=\sqrt{v_i(s-1)^2+2a_i(s)\Delta s}, \tag{12}$$

where Δs is a pre-specified discrete distance (e.g., one meter). Moreover, if train i arrives at its destination, it will be excluded from the traffic system.

As a conclusion, figure 3 illustrates the entire algorithmic framework of the DEM-based simulation procedure.

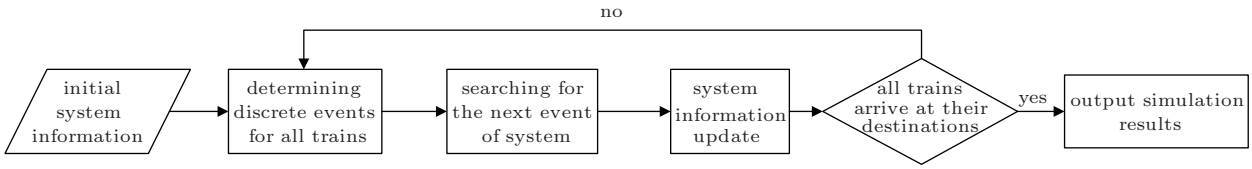


Fig. 3. The flowchart for DEM-based simulation procedure.

4. Numerical simulations

To demonstrate the efficiency and effectiveness of our DEM-based simulation approach, some numerical simulations will be performed in this section. In our experiments, the railway line consists of four stations, denoted by *A*, *B*, *C*, and *D* (see Fig. 4), and three sections *AB*, *BC*, and *CD*. For simplicity, the length of each section and the pre-planed trip time on each section are set to be 20 km and 500 s, respectively. Fifteen trains, denoted by 1, 2, …, 15 are scheduled to traverse in the direction from station *A* (position: 0 m) to station *D* (position: 60 km). Without considering the influence that passengers bring to the train's weight, the train mass is set to be a constant 665 t. For more details of the experiment parameters, we can refer to Table 2, where *d* is the dwell time at a station and *h* is the departure interval. All the experiments are performed on an Intel(R) Core(TM) 2 Duo PC with 2.33 GHz CPU and 1.96 GB of memory, and all the algorithms are implemented in Microsoft Visual Studio 2010 C# on the Windows XP platform.

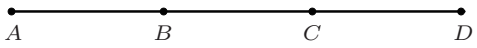


Fig. 4. Map of the tested railway line.

Table 2. Values of some experiment parameters.

Parameter	Value	Parameter	Value	Parameter	Value
F/(N/kg)	0.5	*B*/(N/kg)	0.4	*R*/(N/kg)	0.05
d/s	60	*h*/s	200	*SM*/m	2400

Figure 5 indicates the traffic flow on the tested railway line, where we can see that in section *AB*, except for the leading train 1, all of the following trains are influenced by the previous train(s). From Fig. 5, after dwelling at station *B*, the distance between the previous train and the following train will be extended, thus the following train may switch its role to be a leading train on sections *BC* and *CD*. Actually, if the dwell time is short, the distance between two adjacent trains may not be long enough, and the previous train may influence the following one. Moreover, from the trajectories of trains 3–15, it is clear that the influence of the upstream can be passed to the downstream trains, and this characteristic leads to the cumulative influence. On the basis of Fig. 5, we can conclude that the simulation results demonstrate that our proposed approach is suitable for simulating the train movement on a single railway line.

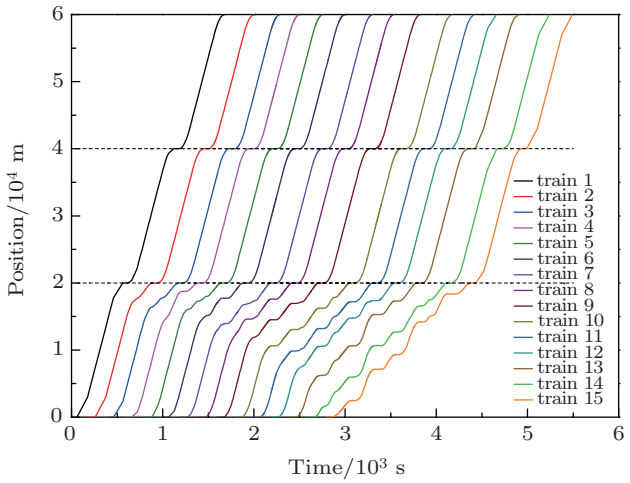


Fig. 5. (color online) The train traffic flow.

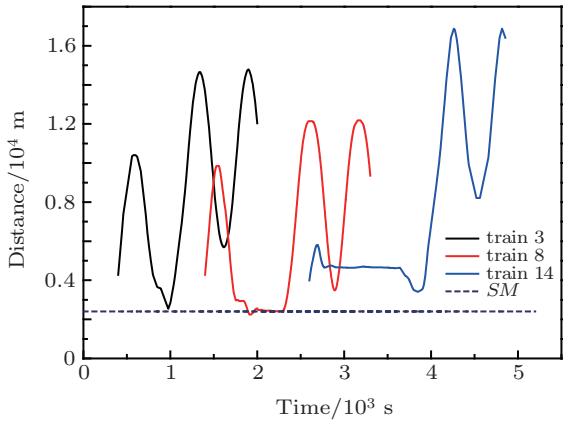


Fig. 6. (color online) Headway distances for different trains.

To investigate whether our DEM-based simulation approach can guarantee the headway distance between two adjacent trains, we randomly select three trains and record the headway distances between the selected trains and their previous trains at each simulation time step. As shown in Fig. 6, trains 3, 8, and 11 are selected and the related headway distances are displayed. From Fig. 6, we see that almost all of the headway distances are larger than the safety margin *SM*. Only a few headway distances are slightly less than *SM* (see

the headway distances of train 8). In fact, this is essentially caused by the rule in our proposed approach that if the headway distance is less than *SM*, the following train should reduce its speed to extend the headway distance. For more details of the speed adjustments, we can refer to Fig. 7, where we can see that on section *AB*, trains 6 and 11 constantly change their speeds to control the distance between themselves and their previous train, and try to track the appropriate optimal cruising velocity (see the speed profile of train 11 at positions 1×10^4 m to 2×10^4 m) to save energy.

As a conclusion, simulation results in Fig. 6 and Fig. 7 demonstrate that our approach can control the headway distance for two adjacent trains and save energy successfully. Besides, we find that the headway distance approximately periodically changes over time, especially for these trains which are not influenced by their pervious train(s) (e.g., train 3 in Fig. 6), and this phenomenon may be caused by the dwelling operation at each station. Moreover, since train 1 is the first train in this traffic system, there is not any influence from other trains. Therefore, the speed profile of train 1 on section *AB* in Fig. 7 is the same to the optimal one as shown in Fig. 1. From Fig. 7, speed profiles of trains 6 and 11 indicate that trains 6 and 11 cannot maintain the highest cruising speed. That is to say, trains 6 and 11 need more time to finish their trip on the same section. Lastly, with the increase of train ID, the number of cycles of acceleration, cruising, and deceleration phases is increased. This is another illustration for the analysis of Fig. 1. That is, the influence of the upstream can be passed to the downstream trains.

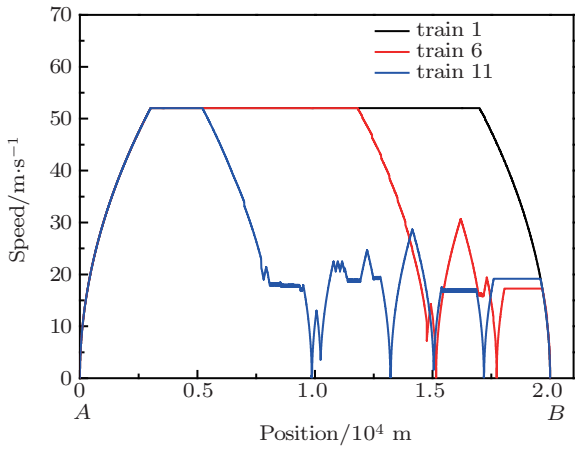


Fig. 7. (color online) Speed profiles for different trains at section *AB*.

Figure 8 indicates the energy consumption of different trains. It is clear that in most of the cases, the energy consumption of the following train is greater than that of the previous one. This phenomenon is easy to explain. As described above, in order to control the headway distance, the following train has to frequently change its speed to meet the safety margin, and these acceleration and deceleration operations can lead to more energy consumption.

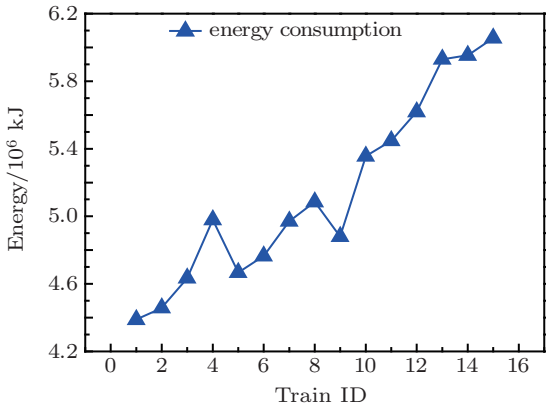


Fig. 8. (color online) Energy consumptions for different trains.

Finally, to investigate the efficiency of the DEM-based approach, we take different numbers of trains into account in the experiments and record the related iterations (the number of simulation time steps) and CPU time. As described in Section 1, the time interval of each simulation step in both the DTM-based approach and the car-following model is fixed (i.e., one second[4–7]). Therefore, for the simulation case with the DTM-based approach, we use the last train's arrival time at its destination station as iterations. Figure 9 displays the iterations of the DTM-based and DEM-based approaches for different numbers of trains, where we can see that the iteration of the DEM-based approach is much less than that of the DTM-based approach for each simulation case, especially for these cases with small numbers of trains. Moreover, from Fig. 8, the CPU time of the DEM-based approach for each case is only several seconds. That is to say, the proposed DEM-based approach can effectively simulate the movement for a group of trains on a railway line within a short time.

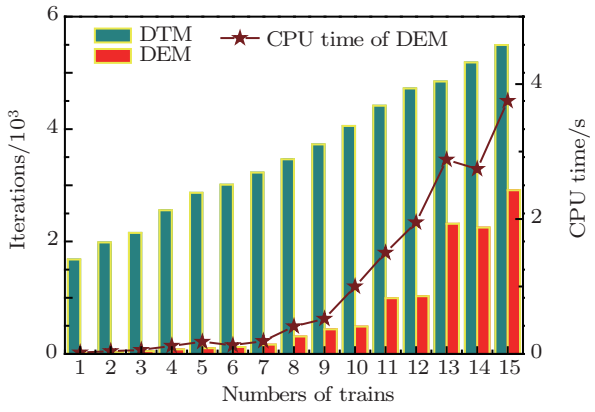


Fig. 9. (color online) Iterations and CPU time for different numbers of trains.

5. Conclusions

Since interactions among trains are classifiable, studying this essential characteristic may help to improve the simula-

tion approach for the train traffic. To this end, on the basis of a discrete event model, this paper proposed a new simulation approach for the train movement on a single railway line. Using the proposed approach, we presented several numerical experiments. Simulation results indicated that due to the high-efficiency of the discrete event model, the proposed approach can successfully simulate the movements of a group of trains on a single-line railway with less iterations in a short time.

What should be pointed out is that the acceleration and deceleration in our model are constants, which is impractical and will be improved in our future studies. Besides, if the traffic environment is complex, the definition of a discrete event may be complex, which is a planned study in our future researches.

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