Modeling and simulation of high-speed passenger train movements in the rail line*

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In this paper, we propose a new formula of the real-time minimum safety headway based on the relative velocity of consecutive trains and present a dynamic model of high-speed passenger train movements in the rail line based on the proposed formula of the minimum safety headway. Moreover, we provide the control strategies of the high-speed passenger train operations based on the proposed formula of the real-time minimum safety headway and the dynamic model of high-speed passenger train movements. The simulation results demonstrate that the proposed control strategies of the passenger train operations can greatly reduce the delay propagation in the high-speed rail line when a random delay occurs.

Keywords: simulation, dynamic model, control strategies of train movements, high-speed passenger train

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1. Introduction

There are many studies on traffic and transportation problems from the viewpoint of physics.[1–8] Various kinds of traffic and transportation models have been presented, such as car-following model, cellular automaton (CA) model, gas kinetic model, hydrodynamic model, and so on.[9–31] The characteristics of train movement in rail traffic are quite different from those of vehicle movement in road traffic. Recently, Li and Guan[32] proposed a new traffic model for simulating train movements in railway traffic based on a car-following model. In the model, some realistic characteristics of train movements were considered, such as the headway and the safety stopping distance. Using the proposed traffic model, they analyzed the space–time diagram of traffic flows, the trajectory of train movements, etc. Yang *et al*.[7] presented a discrete-time model for the movements of a group of trains, in which some operational strategies, including traction operations, braking operations, and influence of stochastic disturbance, are considered.

With the rapid railway development and successive construction of a high-speed passenger rail line in China, the speed of railway transport is gradually increasing and railway traffic density is also increasing at the same time. Meanwhile, railway passenger requirement for punctuality of train operations is also increasing. However, high density of passenger train movements in the high-speed rail line and in the random events of running interference can easily lead to large-scale disorder in the running of trains, which brings a great challenge to efficiently controlling train movements. The control of high-speed passenger train movements is that when the actual state of train movements deviates from the originally scheduled one, it needs to adjust the train movements into the original scheduled train movements as much as possible. The control of the high-speed passenger train movements should be based on the original timetable and it has characteristics of high real-time and strong constraints.

The passenger train movement in a high-speed rail line is different from the train movement in a low speed rail line and has its own characteristics. For example, the train velocity can reach 350 km per hour and the inter-departure time can be shorter than 5 min. The passenger train may be delayed because of unexpected interruption, but it cannot depart from the docking station earlier than the prescribed departure time in the original timetable. In this paper, we consider modeling and simulation for the control of high-speed passenger train movement from the viewpoint of physics and show the dynamic characteristics of high-speed train traffic flows.

The rest of the paper is organized as follows. In Section 2, we introduce the basic principles of the moving-block system (MBS) and propose a new formula of the real-time minimum safety headway based on the relative velocity of consecutive trains. In Section 3, we provide a dynamic model of passenger train movements in the high-speed rail line based on the proposed formula of the real-time minimum safety headway and present the control strategies of the passenger train movements based on the proposed formula of the real-time minimum safety headway and the dynamic model of the high-speed passenger train movement. The simulation results and analytical discussions are presented in Section 4. Section 5 concludes the paper with a summary of this research and two research issues that need to be addressed in the future.

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2. Improved minimum safety headway in the MBS

The headway between the two consecutive trains is the distance from the head of the following train to the rear of the front train. It is the technical index to measure the interval distance between trains. The value of headway is updated when deceleration, or stopping, or acceleration occurs. When multiple trains run along the same track in the same direction, a sufficient tracking interval distance between two consecutive trains is needed to guarantee a certain degree of safety distance between two consecutive trains, so as to avoid non-normal braking, stopping or collision. The minimum safety headway between two consecutive trains is closely related to the signaling system, train performance, braking performance, dwell time, velocity limit, etc. Advanced MBS can effectively shorten the minimum safety headway between two consecutive trains and thus greatly increase traffic capacity of the rail line.

MBS is a new block system which was developed based on the interval blocking principle. It is comparable to the fixed block system; the most notable feature of MBS is the abolition of the fixed-block section with the separated signals. The real-time minimum safety headway between trains is determined by the real-time position and operating status of the trains on the rail line. So the block section constantly moves forward and is adjusted by the real-time position and operating status of the trains.

In order to achieve high-speed, high-density transport, the MBS adopts advanced control mode based on target distance and real-time train velocity. According to the target point, the target velocity, target distance, line conditions, and train characteristics, the equipped train control system can automatically generate the curve of continuous deceleration in ensuring train safety, high-speed operation, small headway, and high-density movement.

Based on technical analysis, there are many factors influencing headway between trains. In addition to the train control system mentioned above, the real-time headway between trains is largely determined by the train acceleration and braking performance, as well as the slope of the line, the layout of the station throat area and other factors. Therefore, to determine the technical specification for the headway between trains, we should make comprehensive verification and rational planning for the electric multiple units (EMUs), the technical performance of the signaling equipment, as well as the design principles of line and stations.

Under the MBS, each train needs to report its position and velocity to the control center in real time, and the control center calculates the velocity and headway to control the train movement and guarantees its safety. The safety distance is calculated based on the train safety brake mode and an additional distance. It guarantees the following train can safely stop behind the front train under the most adverse conditions to avoid collision. Safety distance is the distance of safe redundancy added to the standard braking distance and it is the key to MBS. Under the MBS, the front train and the following train always maintain a common braking distance coupled with a safe distance from the moving-block interval to avoid collision.

Several types of moving-block schemes have been discussed so far, such as moving space block, moving time block and pure moving-block.[20] In the pure moving-block system, the formula of the minimum safety headway is given as follows:

$$d_n = \frac{v_{\mathrm{f}}^2}{2b} + SM, \tag{1}$$

where b is the deceleration of the train n, SM the safety distance, and v_{f} the real-time velocity of the train k.[20]

With the development of mobile communication technology, the real-time information about train position, velocity, and acceleration would be obtained more easily and accurately. The real-time minimum safety headway is closely related to the velocities and braking performances of the two consecutive trains. Therefore, in this paper, we adopt the MBS scheme based on relative velocity between the two consecutive trains and propose a new formula of the real-time minimum safety headway as follows:

$$d_k(t) = [v_k(t) - v_{k-1}(t)]\left[\frac{v_k(t)}{2\,\mathrm{d}v_k(t)/\mathrm{d}t} + \tau_k\right] + SM, \tag{2}$$

where $v_k(t)$ is the velocity of train k at time t, $\mathrm{d}v_k(t)/\mathrm{d}t$ the derivative of $v_k(t)$, τ_k the reaction time of train k, and $v_0(t) = 0$, for each train k and any time t. We assume that there are K trains in the rail line and they are denoted by 1, 2, ..., K in order of their departure time. As shown in Eq. (2), the real-time minimum safety headway between the two consecutive trains can obviously be reduced when considering the velocity effect of the front train.

3. Dynamic model of high-speed passenger train movement

In this paper, we consider the high-speed double-track railway which has a pair of single tracks and involves running one track in each direction compared with a single-track railway where trains in both directions share the same track. In order to present the dynamic model of the high-speed passenger train movements, we introduce some relevant notations as follows:

$x_k(t)$: the location of train k at time t;

$\mathrm{d}x_k(t)/\mathrm{d}t$: the derivative of $x_k(t)$;

$v_k^{\max}$: the maximum velocity of train k;

$u_k(t)$: the acceleration along the track corresponding to the applied force for train k at time t;

$\alpha_k(t)$: the deceleration due to the random event for train k at time t.

With the automatic moving-block signaling system, the dynamic model of high-speed passenger train movement is given as follows (M1):

$$x_{k-1}(t) - x_k(t) \geq d_k(t), \quad k = 2, 3, \ldots, K, \tag{3}$$

$$x_k(t) \leq x_k^0(t), \quad k = 1, 2, \ldots, K, \tag{4}$$

$$\frac{\mathrm{d}x_k(t)}{\mathrm{d}t} = v_k(t), \quad k = 1, 2, \ldots, K, \tag{5}$$

$$\frac{\mathrm{d}v_k(t)}{\mathrm{d}t} = u_k(t) - r(v_k(t)) + g(x_k(t)) - \alpha_k(t), \quad k = 1, 2, \ldots, K, \tag{6}$$

$$t \in [0, T], \tag{7}$$

where $x_k^0(t)$ is the location of train k at time t when the train operates according to the published timetable and no delay occurs in the movement, $r(v_k(t))$ the resistive deceleration along the track, and $g(x_k(t))$ the acceleration due to gravity and the slope of the track. The inequalities in expression (3) ensure that the headway between the two consecutive trains cannot be smaller than the real-time minimum safety headway. The inequalities (4) show that the train movement may be delayed, but it should be kept in the published timetable. Equation (5) denotes velocity of train k at time t. Equation (6) shows that the acceleration occurs by the applied force for train, gravity, and the slope of the track, and the deceleration includes the resistive deceleration along the track and the deceleration due to the random event. The constraint (7) indicates the time period.

For simulating the high-speed passenger train movements, we discretize the time and let Δt be the small increment of time. Then the discrete-time form of the above model is given as follows (M2):

$$x_{k-1}(t) - x_k(t) \geq d_k(t), \quad k = 2, 3, \ldots, K, \tag{8}$$

$$x_k(t) \leq x_k^0(t), \quad k = 1, 2, \ldots, K, \tag{9}$$

$$x_k(t + \Delta t) = x_k(t) + v_k(t)\Delta t, \quad k = 1, 2, \ldots, K, \tag{10}$$

$$v_k(t + \Delta t) = v_k(t) + (u_k(t) - r(v_k(t)) + g(x_k(t)) - \alpha_k(t))\Delta t, \quad k = 1, 2, \ldots, K, \tag{11}$$

$$t, t + \Delta t \in [0, T]. \tag{12}$$

In this paper, we shall use model (M2) to determine the physical characteristics of train movements in the high-speed rail line, such as acceleration, velocity, location, etc. Generally, the high-speed passenger trains are operated according to the published timetable. When the random events of running interference occurs, high speed and high density of passenger train movements in the high-speed rail line can easily lead to large-scale disorder of train movements, which brings a great challenge to the efficient control of train movement. The control of high-speed passenger train movement is that when the actual state of train movement deviates from the original schedule, the train movement needs to be adjusted into the original scheduled train movement as much as possible. The control of the high-speed passenger train movement should be based on the original timetable and it has characteristics of high real-time, high speed, high density, and strong constraints. The general control strategies for high-speed train movements are summarized as follows:

(i) Any arrival time and departure time can be changed, but the departure times cannot be less than those in the original timetable;

(ii) The arrival-departure order of consecutive arrival trains can be changed at a station, but it cannot be changed in any track segment between two contiguous stations;

(iii) The standard running time of trains can be changed by changing delayed train velocities in a track segment;

(iv) The station operation time for a train can be changed.

The high-speed passenger train movement is remarkably influenced by its front train. To simulate the high-speed passenger train movements, it is necessary to provide the detailed control strategies at different simulation times. Control for the movement of train k depends on the status of its front train $k-1$. Relevant control for the movement of train k includes start-up, acceleration, deceleration and stop, and so on. Let Δt be the small increment of time, then the detailed control strategies for movement of train k will be presented as follows.

i) Deceleration due to the delay of the front train: If $x_{k-1}(t) - x_k(t) < d_k(t)$, compute the deceleration $a_k(t)$ by Eq. (6) and let

$$v_k(t + \Delta t) = \max\{v_k(t) - a_k(t)\Delta t, 0\}.$$

ii) Deceleration due to a random delay. When an unexpected interruption occurs for train k at time t, compute the deceleration $a_k(t)$ by Eq. (6) and let

$$v_k(t + \Delta t) = \max\{v_k(t) - a_k(t)\Delta t, 0\}.$$

iii) Acceleration due to the delay for train k: If $x_{k-1}(t) - x_k(t) \geq d_k(t)$ and $x_k(t) < x_k^0(t)$, compute the acceleration $b_k(t)$ by Eq. (6) and let

$$v_k(t + \Delta t) = \min\{v_k(t) + b_k(t)\Delta t, v_k^{\max}\}.$$

iv) Deceleration due to the original timetable for train k: If $x_k(t) \geq x_k^0(t)$, compute the deceleration $a_k(t)$ by Eq. (6) and let

$$v_k(t + \Delta t) = \max\{v_k(t) - a_k(t)\Delta t, 0\}.$$

v) The movement of trains:

$$x_k(t + \Delta t) = x_k(t) + v_k(t)\Delta t, \quad k = 1, 2, \ldots, K.$$

4. Numerical simulation

In this section, we will simulate the high speed and high density passenger train movements by the proposed formula and the dynamic model (M1). The length of simulated rail line $L = 60$ km and there are 3 stations in the rail line. The second station is located 30 km away from the origin. All trains will run from station 1 to station 3 and the dwell time in the middle station is 60 s. The maximum velocity of each train $v_k^{\max} = 350$ km/h, the reaction time $\tau_k = 5$ s for $k = 1, 2, \ldots, K$. The simulation time is 2500 s, the safety distance $SM = 4700$ m, and the acceleration and deceleration are both 0.75 m/s^2.

Figure 1 shows the space–time diagram of the published timetable for all high-speed passenger trains in the rail line. There are 14 identical high-speed passenger trains operating according to the published timetable. The interval departure times of all trains are 3 min.

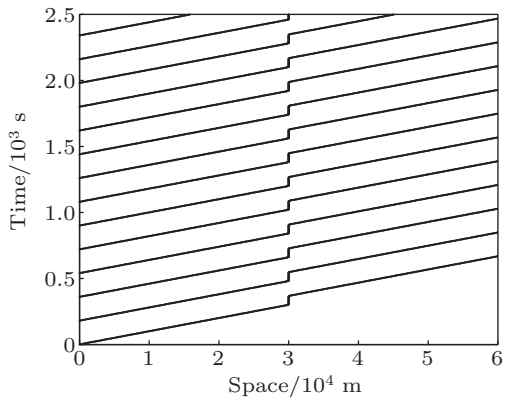


Fig. 1. Space–time diagram of the published timetable.

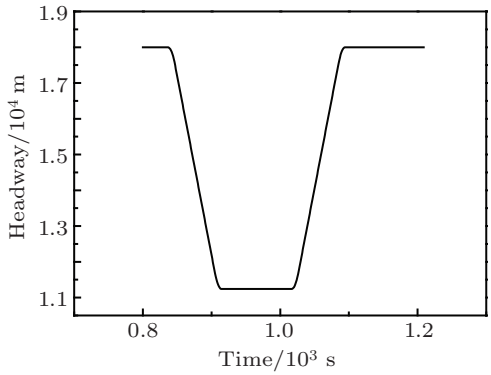


Fig. 2. Real-time headway between train 4 and train 5 under the published timetable.

Figure 2 shows the variation of the real-time headway between train 4 and train 5 in the time period from 800 s to 1200 s when they are operated according to the published timetable. Train 5 departs from the origin station 3 min later than train 4 has departed from the origin station. The headway between train 4 and train 5 is 18 km in the time period from 800 s to 850 s and it decreases to 11.2 km at time 910 s as the front train has stopped at the middle station for 1 min. Moreover, the headway between train 4 and train 5 is 11.2 km in the time period from 910 s to 1020 s and it increases to 18 km at time 1090 s as the following train has stopped at the middle station for 1 min. After the time 1090 s, the headway between train 4 and train 5 is 18 km and it is not changed.

Figure 3 shows the variation of the real-time velocity of train 5 in the time period from 800 s to 1200 s when it is operated according to the published timetable. Train 5 departs from the origin station at the time 720 s and it has run at a constant velocity 350 km/h before it stops at the middle station. After it stops at the middle station for 1 min, it runs at a constant velocity 350 km/h until it stops at the terminal station.

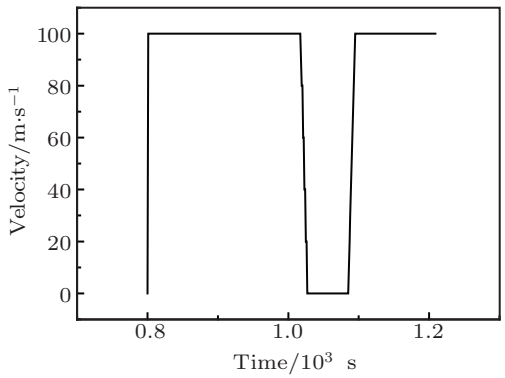


Fig. 3. Velocity of train 5 when it was operated according to the published timetable.

Figure 4 shows the space–time diagram for the movement of 14 trains under random delays with probability 0.05 and velocity decrease of 50 m/s. Generally, the high-speed passenger trains run according to the published timetable. When unexpected interruption occurs, the train movement needs to be adjusted into the original schedule as much as possible. Once an unexpected interruption occurs for a train running in the rail line, its velocity reduces 50 m/s or decreases down to zero. As random delays occur with very small probability 0.05, they cause a minor influence on the operations of trains in the rail line and the movements of trains can be adjusted into the originally scheduled ones under the proposed control strategies.

Figure 5 shows the variation of the real-time headway between train 4 and train 5 in the time period from 800 s to 1200 s under random delays with probability 0.05 and velocity decrease of 50 m/s. Compared with the real-time headway between train 4 and train 5 under the published timetable in Fig. 2, the real-time headway between train 4 and train 5 under random delays with probability 0.05 and velocity decrease of 50 m/s becomes small. The headway is about 17 km in the time period from 800 s to 850 s; it decreases to about 10 km at time 910 s; it remains about 10.5 km in the time period from 910 s to 1020 s and it increases to 17 km at time 1090 s. After the time 1090 s, the headway remains about 17 km.

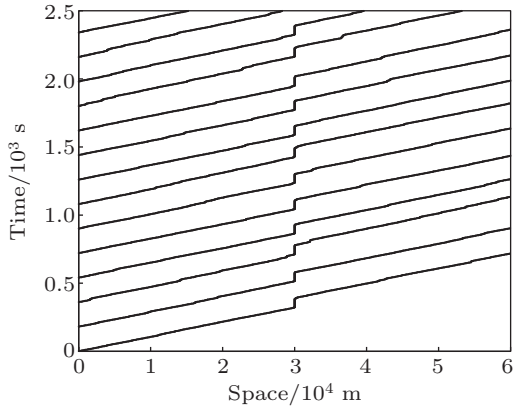


Fig. 4. Space–time diagram for the movement of 14 trains under random delays with probability 0.05 and velocity decrease of 50 m/s.

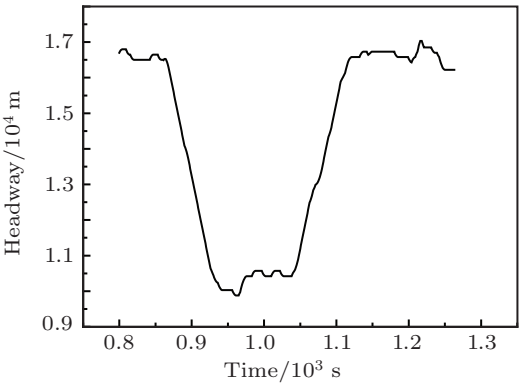


Fig. 5. Real-time headway between train 4 and train 5 under random delays with probability 0.05 and velocity decrease of 50 m/s.

The variation of velocity for train 5 under random delays with probability 0.05 and velocity decrease of 50 m/s is shown in Fig. 6. The unexpected interference occurs 16 times for train 5 in the time period from 800 s to 1200 s. The velocity of train 5 reduces 50 m/s when interference occurs and the random delays affect the movement of the following train 4. So the headway between them becomes smaller as shown in Fig. 5.

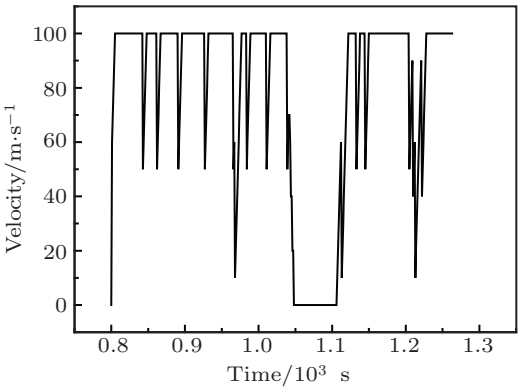


Fig. 6. Velocity of train 5 under random delays with probability 0.05 and velocity decrease of 50 m/s.

Figure 7 shows the space–time diagram for the movement of 14 trains. The trains run according to the published timetable and the interval departure times of all trains are 3 min as in Fig. 1. But random delays occur for all trains with probability 0.05 and velocity decrease of 80 m/s. The probability is very small and it is the same as that in the case shown in Fig. 4, but the decrease of velocity is larger than that in the case shown in Fig. 4 and thus random delays bring much disorder to the train flows in the rail line.

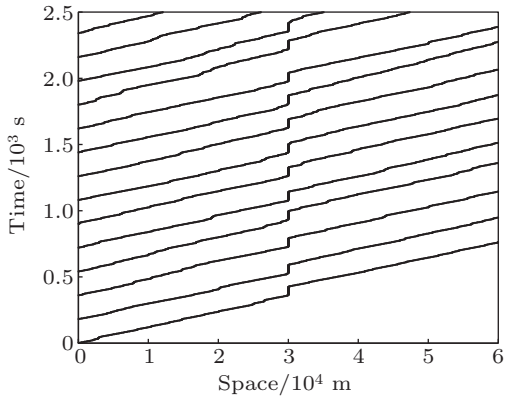


Fig. 7. Space–time diagram for the movement of 14 trains under random delays with probability 0.05 and velocity decrease of 80 m/s.

Figure 8 shows the variation of the real-time headway between train 4 and train 5 in the time period from 800 s to 1200 s under random delays with probability 0.05 and velocity decrease of 80 m/s. Compared with the real-time headway between train 4 and train 5 under the published timetable in Fig. 5, the real-time headway between train 4 and train 5 under random delays with probability 0.05 and velocity decrease of 80m/s becomes small. The headway is about 13 km in the time period from 800 s to 850 s; it decreases to about 6.5 km at time 910 s; it remains about 6 km in the time period from 910 s to 1020 s and it increases to 12 km at time 1090 s. After the time 1090 s, the headway remains about 12 km.

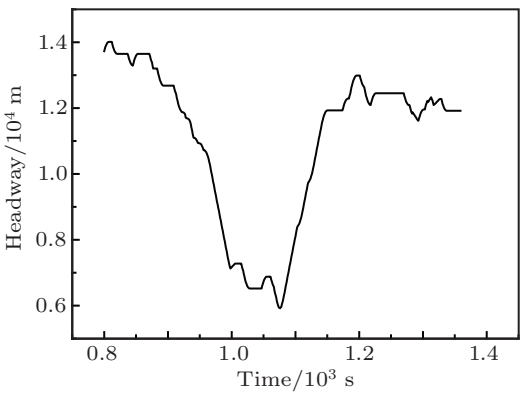


Fig. 8. Real-time headway between train 4 and train 5 under random delays with probability 0.05 and velocity decrease of 80 m/s.

The variation of velocity for train 5 under random delays with probability 0.05 and velocity decrease of 80 m/s is shown in Fig. 9. The unexpected interference occurs 20 times for train 5 in the time period from 800 s to 1200 s. The velocity of decrease for train 5 is 80 m/s when interference occurs and

the random delays affect the movement of the following train 4. So the headway between them becomes smaller as shown in Fig. 5.

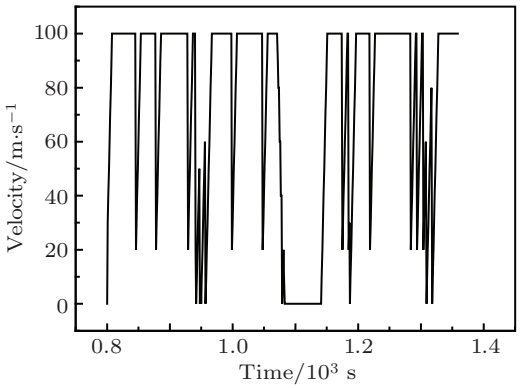


Fig. 9. Velocity of train 5 under random delays with probability 0.05 and velocity decrease of 80 m/s.

Figure 10 shows the space–time diagram for the movements of 14 trains. The trains run according to the published timetable and the interval departure times of all trains are 3 min and random delays occur for all trains with probability 0.1 and velocity decrease of 80 m/s. The decrease of velocity is the same as that in the case shown in Fig. 7, but the probability is larger than that in the case shown in Fig. 7 and thus random delays bring much disorder to the train flows in the rail line.

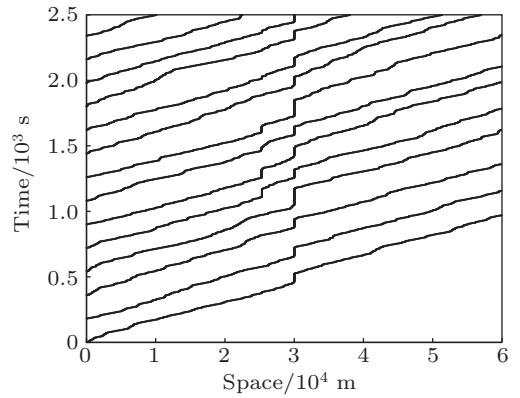


Fig. 10. Space–time diagram for the movements of 14 trains under random delays with probability 0.1 and velocity decrease of 80 m/s.

Space–time diagram for the movements of 14 trains under random delays with probability 0.1 and velocity decrease of 80 m/s.

Figure 11 shows the variation of the real-time headway between train 4 and train 5 in the time period from 800 s to 1200 s under random delays with probability 0.1 and velocity decrease of 80 m/s. Compared with the real-time headway between train 4 and train 5 under the published timetable in Fig. 8, the real-time headway between train 4 and train 5 under random delays with probability 0.1 and velocity decrease of 80 m/s becomes much smaller. The headway is about 0.9 km in the time period from 800 s to 850 s; it decreases to about 5.5 km at time 910 s; it remains about 5.5 km in the time period from 910 s to 1020 s and it increases to 12 km at time 1090 s. After the time 1090 s, the headway remains about 12 km.

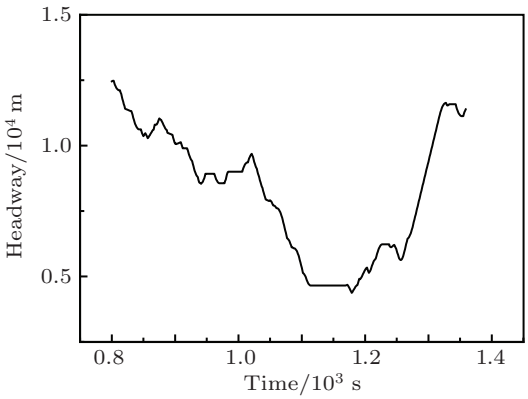


Fig. 11. Real-time headway between train 4 and train 5 under random delays with probability 0.1 and velocity decrease of 80 m/s.

The variation of velocity for train 5 under random delays with probability 0.05 and velocity decrease of 80 m/s is shown in Fig. 12. The unexpected interference occurs more than 20 times for train 5 in the time period from 800 s to 1200 s. The velocity of decrease for train 5 is 80 m/s when interference occurs. The random delays affect the movement of the following train 4 and propagate through the other following trains. So the headway between them becomes smaller as shown in Fig. 8.

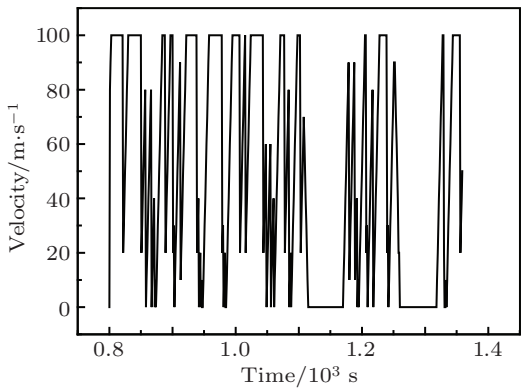


Fig. 12. Velocity of train 5 under random delays with probability 0.1 and velocity decrease of 80 m/s

The total delay times of train 1, train 3, and train 5 under the proposed MBS scheme based on relative velocity with different delay probabilities and velocity decrease of 80 m/s are shown in Fig. 13. The interval departure times of all trains are 3 min, so slight delay of a train cannot affect the movement of its following train. When the probability of random delay is increasing, the total delay time of the train is also increasing. In Fig. 13, the total delay times of the three trains are about 700 s, 750 s, and 790 s respectively under random delays with probability 0.02; they increase to about 1200 s, 1350 s, and 1520 s

respectively under random delays with probability 0.18. When the probability of random delay is larger than 0.08, the delays of trains can affect the movements of their following trains.

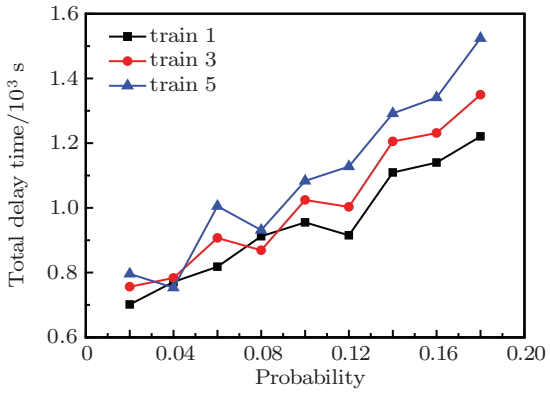


Fig. 13. (color online) Total delay times of the three trains under the proposed MBS scheme based on relative velocity with different delay probabilities.

The total delay times of train 1, train 3, and train 5 under the pure moving-block scheme and the minimum safety headway given in Eq. (1) with different delay probabilities and velocity decrease of 80 m/s are shown in Fig. 14. The interval departure times of all trains are 3 min, so slight delay of a train cannot affect the movement of its following train as shown in Fig. 13. When the probability of random delay is increasing, the total delay time of the train is also increasing. In Fig. 14, the total delay times of the three trains are about 710 s, 750 s, and 790 s respectively under random delays with probability 0.02; they increase to about 1300 s, 1540 s, and 1890 s respectively under random delays with probability 0.18, which are much larger than those in Fig. 13. When the probability of random delay is larger than 0.08, the delays of trains can remarkably affect the movements of their following trains.

The simulation results given in Figs. 13 and 14 demonstrate that the proposed control strategies of the passenger train operations under the proposed MBS scheme based on the formula of the real-time minimum safety headway given in Eq. (2) and the dynamic model (M1) can remarkably reduce the delay propagation when the random delays increase.

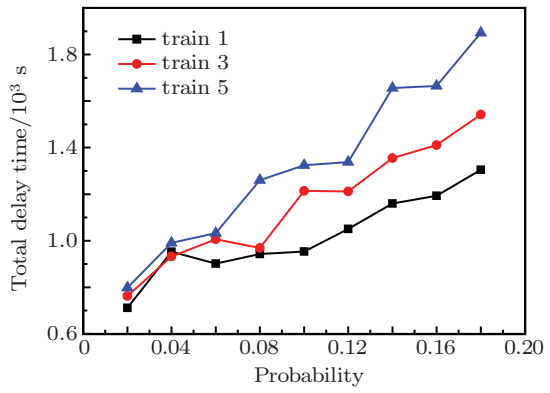


Fig. 14. (color online) Total delay times of three trains under the pure moving-block scheme and the minimum safety headway given in Eq. (1) with different delay probabilities.

5. Conclusions

In this paper, we have studied modeling and simulation for the control of the high-speed passenger train movements in the rail line. First, we introduce the basic principles of MBS and propose a new formula of the real-time minimum safety headway based on the relative velocity of consecutive trains to increase the traffic capacity of the rail line. Second, we present the control strategies of the train operations based on the proposed formula of the real-time minimum safety headway and the dynamic model of high-speed passenger train movements, including traction operation, braking operation, and entering-station operation. Finally, the simulation results demonstrate that the control strategies of the passenger train operations based on the proposed formula of the minimum safety headway and the dynamic model could greatly reduce the delay propagation in the rail line when the random delay occurs.

There are two possible issues for future study. One is the control problem for high-speed passenger train movement in the rail network, and the other is the adjustment problem for high-speed passenger train movement with random demands.

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