Properties of train traffic flow in a moving block system*

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The development direction of railways is toward the improvement of capacity and service quality, where the service quality includes safety, schedule, high speed, and comfort. In light of the existing cellular automaton models, in this paper, we develop a model to analyze the mixed running processes of trains with maximal speeds of 500 km/h and 350 km/h respectively in the moving block system. In the proposed model, we establish some sound rules to control the running processes of a train, where the rules include the departure rules in the intermediate stations, the overtaking rules, and the conditions of speed limitation for a train stopping at a station or passing through a station. With the consideration of the mixed ratio and the distance between two adjacent stations, the properties of the train traffic flow (including capacity and average speed) are simulated. The numerical results show that the interactions among different trains will affect the capacity, and a proper increase of the spatial distance between two adjacent stations can enhance the capacity and the average speed under the moving block.

Keywords: train traffic flow, moving block, cellular automaton model, simulation

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1. Introduction

To date, more and more people have emphasized the travel speed and the service quality of any travel mode. However, the demands of transportation (including passenger and freight) cannot be satisfied by the existing railway systems, which has produced many economic losses in China.[1,2] In order to reduce the economic losses, some new technologies (e.g., automatic train protection, automatic driving, computer interlocking) have been adopted to improve the capacity of the railway.[3,4] Compared with the traditional automatic block system, the moving block has the following merits. 1) It is an advanced system, since it can be realized by combining wireless communication, computer, and automatic control technologies. 2) It is suitable for different speed trains mixed running. 3) It can shorten the interval between two adjacent trains. 4) It can improve the capacity of the rail traffic system.

However, existing rail systems (including those that are under construction) are mainly used for the passenger transportation. In rail systems, all trains have their own speeds, and the speeds often have different attributes. In view of these, much attention has been paid to developing models and methods to study how to reasonably design the train timetable and how to improve the capacity of the railway.[5−8] Meanwhile, a wealth of research results show that the cellular automaton (CA) is simple to implement on computers, provides a simple physical picture of the system, and can be easily modified to deal with and simulate different aspects of nonlinear traffic phenomenon.[9−15] Among the existing models, e.g., models proposed by Nagel and Schreckenberg,[16] Biham *et al.*,[17] Hardy *et al.*,[18] Li *et al.*,[19] Knosp *et al.*,[20] the Nagel and Schreckenberg's model has been successfully used to study the train traffic flow,[21−23] and the model can be divided into the moving block model[24−26] and the fixed block model.[22,23,27−30] As for the moving block model, Zhou *et al.*[14] presented a quasi-movable block system model to simulate the delay propagation, the length of the location unit, and the initial delay; Xun *et al.*[25] proposed a train-following model with different types of trains; Wang and Qian[26] established a model to explore the semi-moving blocking section on a double-track railway and the effects of composing rate and overtaking distance. As for the fixed block model, Hua and Liu[27] proposed a single-line model to simulate the train operation under a working di-

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agram; Li *et al.*[28] established a model to study the mixed train running, the space-time diagram, and the trajectories of train movement; Li *et al.*[29] developed a four-aspect fixed block system model to study the dwell time in the station and the effects of other factors on the delay propagation; Fu *et al.*[30] proposed a cellular automaton model for speed-limited sections under the four-aspect fixed block.

However, the above CA models cannot be used to study the operation process of trains, since some of them just consider the case of a single station or section and some only analyze a train running in one kind of or with uniform speed. According to the existing models, in this paper, we establish some sound rules to control the operation process and present a new CA model with the consideration of mixed trains and the distance between adjacent stations to study the moving block system.

2. CA model for moving block system

2.1. Model hypothesis

For the convenience of the following discussion, some conditions are assumed as follows.

1) There are two kinds of trains running on the line, high-speed trains each with a maximum velocity of 500 km/h and low-speed trains each with a maximum velocity of 350 km/h. Their lengths are equal.

2) The two kinds of trains must stop at fixed stations at least 120 s for boarding and landing of passengers. And the low-speed trains can stop at any station for being overtaken by the high-speed trains.

3) The capacities of receiving and dispatching of the stations are infinite, which means that there is no limit of tracks in each station.

4) The distances between the adjacent stations are equal.

2.2. Basic parameters

In our model, l_{train} is the length of a train; $V_j^{\max}$ ($j = 1, 2$ where $j = 1$ refers to the high-speed train, and $j = 2$ the lowspeed train) are the maximum speeds of the two kinds of trains; $V^{\lim}$ represents the highest permitted speed at which to pass through the station; a_j and b_j denote the accelerations and the decelerations of the two kinds of trains, respectively; X_j^n and V_j^n are the locations and the realtime velocities of the n-th train of the j-th kind, respectively; N is the number of sections in the system; D is the distance between adjacent stations; L_j^{safe} is the necessary braking distance for the rear train to avoid bumping into the forward one; g is the distance from a train to another train or a station (the computing formulas are given in the following); r is the ratio of high-speed trains to all the trains (the high-speed and low-speed trains); and L_j^{R} are the running distances before the trains take action, the calculating equation is

$$L_j^{\text{R}} = t_{\text{R}} \times V_j^{\max}, \tag{1}$$

where t_{R} is the reaction time.

2.3. CA model

In this section, the process of mixed trains running is described in detail. We assume that the rail line consists of L cells, and each cell is empty or occupied by a train. The stations are labeled sequently by $0, 1, \ldots, 6$. The station labeled by 0 occupies no space, but the others each possess a respective space. We stipulate that the high-speed trains must stop at station 3, some low-speed trains must stop at stations 2 and 4, and the others must stop at stations 3 and 5. All cells are updated every second. In the model, we adopt the open boundary. The model is discussed in the following five subsections.

2.3.1. Generation of the train

1) If the rail line is empty, the system produces a j-th kind of train with the location and the velocity of 0 according to the mixed ratio.

2) If the first section is occupied, the system must test the following departure conditions based on the kind of train to depart.

a) For a low-speed train, if the condition $g \geq L_2^{\text{safe}} + L_2^{\text{R}}$ is satisfied, which means that the gap is large enough for safety, the train enters into the system and updates according to the updating rules.

b) For a high-speed train, the conditions are related to the type of front train. If the front train is a high-speed one, the departure condition is satisfied if $g \geq L_1^{\text{sfae}} + L_1^{\text{R}}$, because when the departing train is in the accelerating process, the gap is augmenting before it reaches the maximum speed. If the front train is a low-speed one, in order to avert the situation that the departing train is influenced by the front low-speed train, we calculate the gap needed in advance as

$$g = D - \frac{(V_1^{\max})^2}{2a_1} + (V_1^{\max})^2 \times \left[\left(D - X_j^n - \frac{(V_2^{\max})^2}{2b_2}\right) \Big/ V_2^{\max} + \frac{V_2^{\max}}{b_2}\right], \tag{2}$$

where g means the appropriate distance for departing. It ensures that the front train stops at the forward station and the gap between them is $L_1^{\rm safe} + L_1^{\rm R}$.

2.3.2. Updating rules

Update the velocity and the location of the train according to the following rules.

1) If $g > L_j^{\rm sfae} + L_j^{\rm R}$,

$$V_j^n = \min(V_j^n + a_j, V_j^{\max}), \tag{3}$$

which means that the train accelerates but the speed cannot excess the maximum speed.

2) If $g = L_j^{\rm sfae} + L_j^{\rm R}$,

$$V_j^n = V_j^n, \tag{4}$$

which means that the train keeps the speed of the previous time step.

3) If $g < L_j^{\rm sfae} + L_j^{\rm R}$,

$$V_j^n = \max(V_j^n - b_j, 0), \tag{5}$$

which means that the train decelerates but the speed cannot be less than 0.

(4) The location updates as

$$X_j^n = X_j^n + V_j^n. \tag{6}$$

2.3.3. Overtaking rules

As the mixed trains run in a section, some low-speed trains will be overtaken by the rear high-speed trains, t_j (the time needed for the two kinds of trains running from their current locations to the forward station) is calculated by the following formula:

$$t_j = (iD - X_j^n)/V_j^{\max}, \tag{7}$$

where $j = 1, 2$. If $t_1 \leq t_2$, the low-speed train must stop at the forward station.

2.3.4. Rules for passing through or stopping at a station

No matter whether passing through or stopping at the forward station, the train must reduce its speed.

If the train is going to stop, it needs to decelerate at a certain location calculated by the following equation:

$$g = i \times D - X_j^n, \tag{8}$$

where $i \times D$ is the specified stopping point at the i-th station, and X_j^n is the real-time location of the train, and when $g \leq L_j^{\rm safe}$, the deceleration process should begin.

If the train is going to pass through the forward station at the limited speed, it should decelerate at a certain location calculated by the following equation:

$$g \leq i \times D - L_{\rm station} - [(V_j^{\max})^2 - (V_j^{\lim})^2]/(2b_j), \tag{9}$$

where $L_{\rm station}$ is the length of the station.

2.3.5. Departure rules at intermediate stations

The trains stopping at the station for being overtaken or boarding and landing of passengers depart if the front and the rear constraints are satisfied. The high-speed trains possess the priority to depart first, the low-speed trains have to queue up until all the high-speed trains leave. The constraints are as follows.

1) If the train waiting for departing is a high-speed one, then the front constraint is $g > L_j^{\rm safe} + t_{\rm R} \times V_j^{\max}$, where

$$g = X_j^n - i \times D - L_{\rm train} \tag{10}$$

if the front train is a high-speed one, and

$$g = (i+1) \times D - V_1^{\max} \times \Big[(i+1) \times D - X_j^n - \frac{(V_j^n)^2}{2b_2} \Big/ V_2^{\max} + \frac{V_2^{\max}}{b_2}\Big] \tag{11}$$

if the front train is a low-speed one. The rear constraint is $g > L_j^{\rm safe} + t_{\rm R} V_j^{\max}$, where the gap is calculated by formula (8).

2) If the train waiting for departure is a low-speed one, then the front constraint is $g > L_j^{\rm safe} + t_{\rm R} \times V_j^{\max}$, where the gap is calculated by the following formula:

$$g = X_j^n - i \times D - L_{\rm train}. \tag{12}$$

The rear constraint is $g > L_j^{\rm safe} + t_{\rm R} \times V_j^{\max}$, where

$$g = (i+1) \times D - V_1^{\max}\Big[\Big(D - \frac{(V_2^{\max})^2}{2a_2} - \frac{(V_2^{\max})^2}{2b_2}\Big) \Big/ V_2^{\max} + \frac{V_2^{\max}}{a_2} + \frac{V_2^{\max}}{b_2}\Big] \tag{13}$$

if the rear train is a high-speed one, and

$$g = i \times D + \frac{(V_2^{\max})^2}{2a_2} - X_j^n + \frac{(V_2^{\max})^2}{a_2} - L_{\rm train} \tag{14}$$

if the rear train is a low-speed one.

3. Simulation and analysis

3.1. Parameter calibration

We calibrate the parameters used in the CA model, $V_1^{\max} = 500$ km/h and $V_2^{\max} = 350$ km/h, which are corresponding to 138.9 cells/s and 97.2 cells/s; $a_1 = 0.5$ cells/s^2, $b_1 = 1.1$ cells/s^2, $a_2 = 0.45$ cells/s^2, $b_2 = 0.75$ cells/s^2; $t_{\rm R} = 3$ s;

$L_{\text{train}} = 200$ cells; a cell corresponds to a meter. The total distance of the system is $i \times D$, where $i = 6$, and D changes from 55000 cells to 100000 cells. The model operates 17400 s each time, and the data of 0–3000 s are discarded to avoid the temporary effects.

3.2. Diagram of trajectory

Figure 1 shows the trajectories of the trains running in the system during $t = 7000$–17400 s.

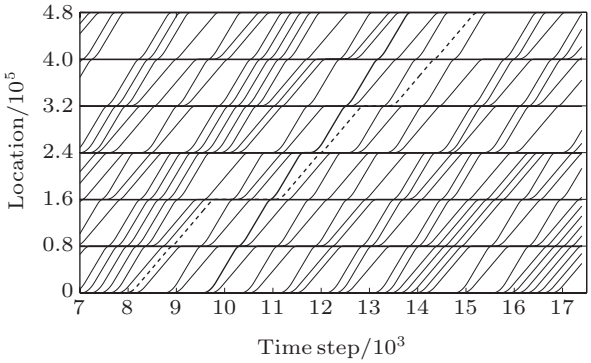


Fig. 1. Trajectory diagram of trains running in the system ($r = 0.4$, $D = 80000$).

The black bold line represents the trajectory of the high-speed train produced at 9549 s by the system. It shows that the train passes through the first two stations, stops at the third station, and then departs when its dwell time exceeds 120 s and the departure conditions are satisfied.

The dashed line denotes a low-speed train produced at 8134 s by the system. It shows that the train stops at stations 2 and 4 at 9129 s and 12244 s, respectively. The low-speed trains stop longer than the high-speed trains due to the following two reasons. The low-speed trains overtaken by the high-speed ones must stop at the forward stations. And the prescriptive stopping time of the low-speed trains is longer than that of the high-speed ones.

3.3. Analysis of capacity and average speed

3.3.1. Departing capacity and passing capacity

The trend of the departing capacity is displayed in Figs. 2(a) and 2(b).

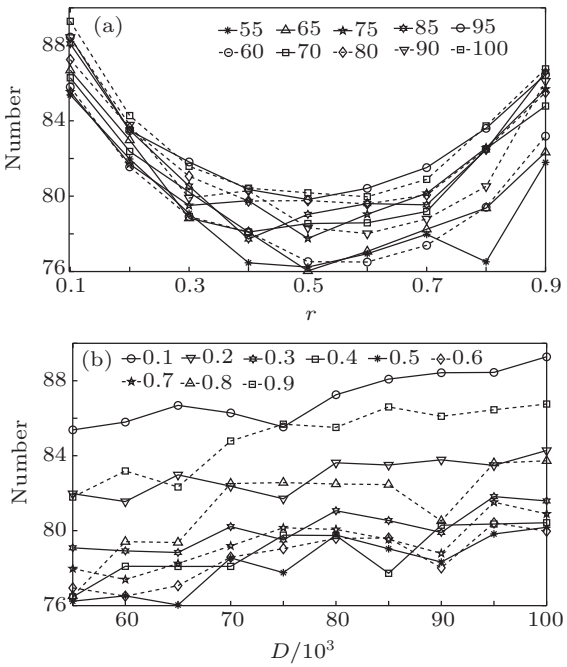


Fig. 2. Departing capacities varying with (a) r and (b) D.

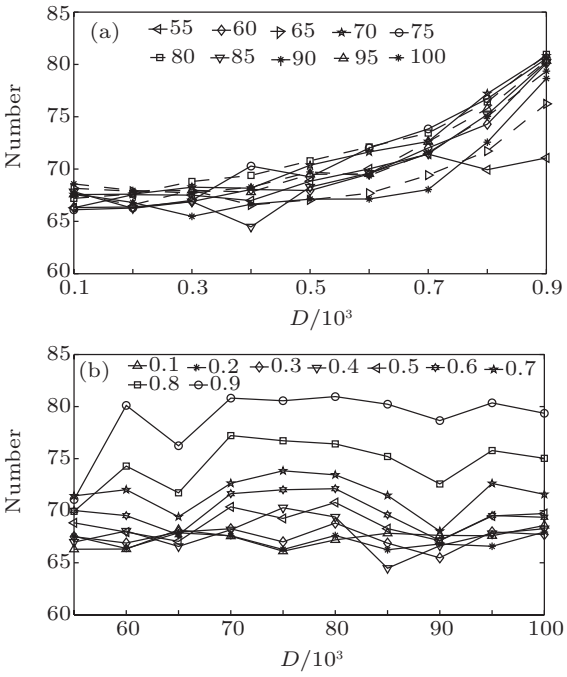


Fig. 3. Passing capacities varying with (a) r and (b) D.

As shown in Fig. 2(a), when we take a fixed value of D, the departing capacity first decreases with the increase of r, and reaches the lowest point when r is between 0.4 and 0.6, then increases with the increase of r. It proves that the two kinds of trains running together badly influence each other when their numbers are almost equal, which is in agreement with the situation in a real railway system.

As shown in Fig. 2(b), when we take a fixed value of r, the departing capacity fluctuates with the change of D, but the general trend is that it increases with the increase of D. When $r = 0.1$ and 0.9, the curves are above the other ones, but when $r = 0.5$, 0.6, and 0.4, the curves twist together and are almost below the other ones. This well corresponds to the case in Fig. 2(a).

The passing capacity is the number of trains that have reached the last station, while the departing capacity just records the number of trains meeting the departure conditions, but they may not reach the last station in the process of simulation.

We can see from Fig. 3(a) that when we take a fixed value of D, the passing capacity increases with the increase of r. In Fig. 3(b), for most fixed values of r, the passing capacity sharply falls at a certain value of D, including $D = 6500$ or 9000, then begins to increase.

3.3.2. Analysis of average speed

Here we take the reconciling average speed as the average train speed, which reflects the service level. Although we obtain the maximal passing capacity, the service quality (including safety, punctuality rate, high speed, and comfort) ought to be considered.

3.3.2.1. Variation of the average speed of high-speed trains

Figure 4 shows the trends of the average speed of high-speed trains with respect to r and D.

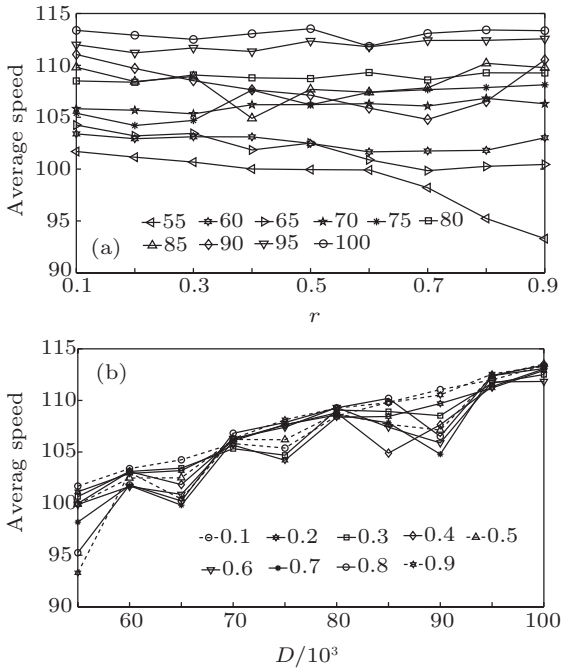


Fig. 4. Average speeds of high-speed trains varying with (a) r and (b) D.

It is illustrated that when we take a fixed value of D, the average speed of high-speed trains levels off with a little fluctuation with respect to r, just as in the case with $D = 55000$, it decreases with the increase in r.

When we take a fixed value of r, the average speed of high-speed trains rises in a brokenline manner with the increase of D. Because when D is small, the time for accelerating and decelerating of high-speed trains would occupy more shares, which leads to the average speed slowing down.

3.3.2.2. Variation of the average speed of low-speed trains

According to Fig. 5, when we take a fixed value of D, the average speed of low-speed trains decreases with the increase of r. The reason is that the increase of r means a decrease of the number of low-speed trains in the system, which offers them more chances to be overtaken, a longer waiting time, and fewer chances for meeting the departure condition at the intermediate stations.

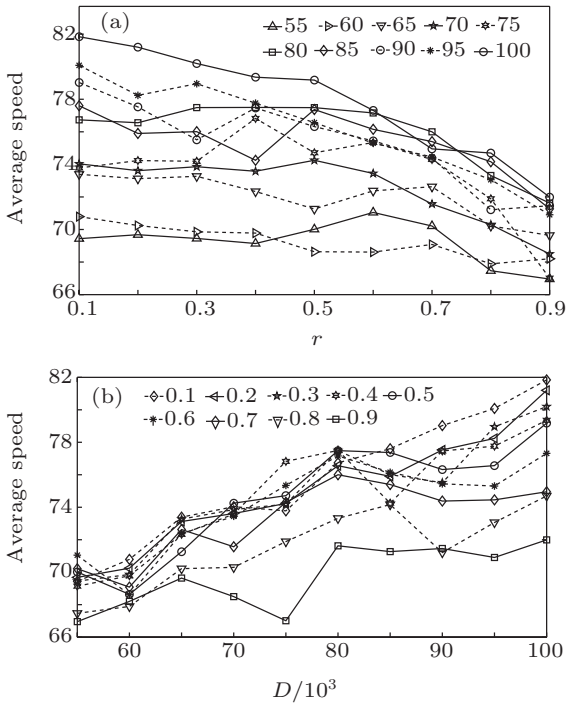


Fig. 5. Average speeds of low-speed trains varying with (a) r and (b) D.

When we take a fixed value of r, the general trend is that the average speed of low-speed trains ascends with the increase of D, which is similar to that of high-speed trains. It can be stated that the larger D is, the longer time the low-speed trains run with high speeds, which is beneficial for their average speed.

4. Conclusion

According to the existing research, we present a CA model and establish some sound rules to control and simulate the running process of trains, where the rules include the departure rules in the intermediate stations, the overtaking rules, and the conditions of speed limitation for trains stopping at a station or passing through a station. With the analysis of the simulation results, we obtain the variations of the section capacity and the average speeds of two kinds of trains with the mixed proportion and the distance between successive stations. The departing and the passing capacities of the section ascend with the increase of the distance between successive stations. And when the numbers of the two kinds of trains are almost equal, the departing capacity is badly affected; the passing capacity gradually rises with the increase of the mixed ratio. A clear conclusion is that the larger distance between the successive stations helps the trains on a special passenger line exploit their advantage of high speed in the moving block system. But for proper values of distance between successive stations and mixed ratio, many factors, such as transportation demand, should be considered. In the further research, more influential elements should be taken into account to investigate the moving block system.

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