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Urban rail departure capacity analysis based on a cellular automaton model*

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As an important traffic mode, urban rail transit is constantly developing toward improvement in service capacity and quality. When an urban rail transit system is evaluated in terms of its service capacity, the train departure capacity is an important index that can objectively reflect the service level of an urban rail transit facility. In light of the existing cellular automaton models, this paper proposes a suitable cellular automaton model to analyze the train departure capacity of urban rail transit under different variable factors and conditions. The established model can demonstrate the train operating processes by implementing the proposed sound rules, including the rules of train departure at the origin and intermediate stations, and the velocity and position updating rules. The properties of train traffic are analyzed via numerical experiments. The numerical results show that the departure capacity is negatively affected by the train departure control manner. In addition, (i) the real-time signal control can offer a higher train service frequency; (ii) the departure capacity gradually rises with the decrease in the line design speed to a limited extent; (iii) the departure capacity decreases with extension in the train length; (iv) the number of departed trains decreases as the train stop time increases; (v) the departure capacity is not affected by the section length. However, the longer the length, the worse the service quality of the urban rail transit line. The experiments show that the proposed cellular automaton model can be used to analyze the train service capacity of an urban rail transit system by performing quantitative analysis under various considered factors, conditions, and management modes.

Keywords: train departure capacity, urban rail transit, cellular automaton model

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1. Introduction

Based on the car-following models and the cellular automaton (CA) models, scholars and experts have researched complicated traffic systems, such as the complicated phenomenon of urban traffic flow[1–25] and have improved public transport operation efficiency, where the microscopic models focus on investigating the micro traffic phenomenon (e.g., the car-following behavior, lane-changing, overtaking, etc.), while the macroscopic models focus on investigating the macro properties of traffic flow (e.g., the relationships among density, speed, and flow) and the simulation of train operation in a railway system.[26,27] As the problem of energy consumption attracts ever-growing attention, many scholars have endeavored to study the energy cost problem in urban traffic systems.[28–32]

As the demand for urban traffic travel increases, the urban traffic facilities confront more pressures in the service capacity supply. As a green, highly reliable, and sustainable travel mode, an increasing number of urban rail transit projects are being planned or constructed. The urban rail transit systems often use a train control and dispatching signal system that combines automatic train protection, automatic driving, and computer interlocking subsystems. They have been adopted to improve the transport capacity of the urban rail transit system. Although the traditional automatic block system is an automation train control system, it still relies on the driver's operation. Owing to human behavior, unreliability is inevitable in the traditional automatic block system. In contrast, the moving block control mechanism can avoid the man-made influence and achieve the fully automatic management and control. Through such an advanced and highly reliable real-time train control system, a higher operational safety and train service capacity is guaranteed and continues to improve.

Many research findings show that the CA is effective in providing a simple physical picture of the urban rail transit system or railway system, and can be easily extended to study different nonlinear phenomena.[33–37] Among the existing models, the Nagel and Schreckenberg model has been successfully used to study the train running process.[38–47] The related models of the rail traffic system can be divided into the moving block CA models[42–44] and the fixed block system models.[40,41,45–47] As for the moving block CA model, Zhou *et al.* presented a quasi-movable block CA model to simulate the delay propagation;[14] Xun *et al.* proposed a train-following CA model with different types of trains;[43] Wang and Qian established a CA model to explore the semi-moving blocking on a double-track railway.[44] As for the fixed block model, Li *et al.* established a model to study the mixed train running, the space–time diagram, and the trajectories of train

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movement;[45] Li *et al.* developed a four-aspect fixed block CA model to study the effects of the train dwell time and other factors on the delay propagation;[46] Fu *et al.* proposed a CA model studying the speed-limited effects with the four-aspect fixed block.[47]

However, the CA models above cannot be used to study the train operation and running process in urban rail transit systems, because they neglect some real factors that are very important for the research of real urban rail transit systems. In an urban rail transit system, overtaking is not considered, the train running process is strictly controlled, any behavior of random acceleration and deceleration is prohibited, and the trains can consist of different carriage numbers and different lengths. In addition, the real train control system typically has some signal delays in the communication process, thus impacting the train operation and affects the train service capacity in an urban rail transit line. Therefore, based on previous studies, we establish a suitable CA model that considers sound and simple rules to simulate the train operation control and running processes. When an urban rail transit system is evaluated, the train service capacity is as important as the vehicle passing capacity in an urban traffic study; the train service capacity can objectively reflect the service level of an urban rail transit facility. By slightly modifying or expanding our model, the proposed CA model can be used to analyze the train service capacity of an urban rail transit system with different design plans by performing a quantitative analysis under various factors, conditions, and management modes.

2. CA model for urban rail system

2.1. Model assumption

The train running process in the urban rail transit system is similar to the carfollowing process on ordinary roads. We can use the CA model for the process simulation. In the model, the primary consideration is to maintain the tracking safety interval between adjacent trains. For discussion convenience, some assumptions are listed as follows:

i) Herein, the studied urban rail line is single directional. An urban rail line typically has two tracks for the train operation.

ii) The trains running on an urban rail line are restricted by the maximum velocity limitation.

iii) The trains' lengths are equal because the train units of the same type are always used.

iv) The trains will stop at each station for a certain time for the passengers to board and alight.

v) Overtaking between trains is not considered in our model because in an urban rail transit system, the trains run in sequence and stop at every station.

vi) Each station has limited tracks for train stopping according to the real operation situation.

2.2. Symbol definition

L_{train} is the length of a train (a train consists of a number of carriages). Each carriage is approximately 20 m long. The specific length of a train is determined by the number of carriages. $V_{\max}$ refers to the allowed maximum running speed on a rail transit line, which is also called the design speed for a rail transit line. The speed that can be considered is between 90 km/h and 60 km/h; V_{lim} represents the upperlimit speed at which trains enter into a station; a and b denote the acceleration and deceleration of the trains, respectively; X_n and V_n are the location and real-time velocity of the n-th train respectively; D is the section length between adjacent stations; L_{safe} is the braking distance for the rear train to avoid bumping into the forward one; h is the distance headway from a train to another train or a station; L_{R} are the running distances before the trains take action, in which the equation is $L_{\text{R}} = t_{\text{R}} \times V_{\max}$, where t_{R} is the reaction time of the signal control system.

2.3. CA model

In this section, the train operating and running process are elaborated as a CA model. In the model, the rail line consists of L cells, and the state of each cell is empty or occupied by a train. The stations occupy no space on the simulated rail line, but each possesses a unique space. All cells are updated every second. The details of the model are discussed in the following subsections.

2.3.1. Departure of trains at origin station and intermediate stations

A train will depart from two locations to start running where one is the origin station, which is the first station on the rail line, and the other is the intermediate station behind the origin station. When a train departs from a station, the safety headway constraints must be satisfied, which are described below.

(i) Origin station

As shown in Fig. 1, when the train departs from the origin station, it is only necessary to determine whether the front safety headway constraint is satisfied, as shown below.

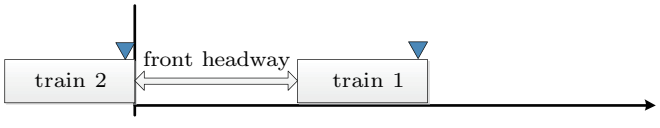


Fig. 1. Headway constraint for train departure at an origin station.

i) If the rail line is empty, a train departs from the origin station with $X_n = 0$ and $V_n = 0$.

ii) If the first section is occupied by a train, the distance headway for the departing train must ensure the front safety headway

$$h_{\text{front}} \geqslant L_{\text{safe}} + L_{\text{R}}. \tag{1}$$

(ii) Intermediate station

As shown in Fig. 2, when the train begins to depart from an intermediate station, both the front safety and the rear safety constraints must be satisfied.

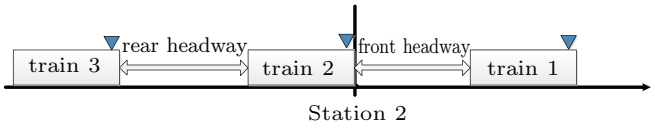


Fig. 2. Headway constraint for train departure at an intermediate station.

If the front section is occupied by a train, the train departure headway must satisfy the front safety headway (1) for the train departure at an intermediate station.

The rear headway constraint is

$$h_{\text{rear}} > L_{\text{safe}} + t_{\text{R}} V_{\max}. \tag{2}$$

2.3.2. Updating rules

(i) When the train control system signal has no communication delay, the velocity and the location of the train are updated according to the following rules.

i) If $h > L_{\text{safe}} + L_{\text{R}}$,

$$V_n = \min(V_n + a, V_{\max}), \tag{3}$$

the train accelerates but the speed cannot exceed the maximum speed.

ii) If $h = L_{\text{safe}} + L_{\text{R}}$,

$$V_n = V_n, \tag{4}$$

the train maintains a constant speed.

iii) If $h < L_{\text{safe}} + L_{\text{R}}$,

$$V_n = \max(V_n - b, 0), \tag{5}$$

the train decelerates but the speed must be greater than 0.

iv) The train position updates as

$$X_n = X_n + V_n. \tag{6}$$

(ii) When the train control system signal has a communication delay, the velocity and position of the train are updated according to the following rules.

i) If $V_n \leqslant V_{\text{lim}}$,

$$V_n = V_n, \tag{7}$$

the train maintains a constant speed.

ii) If $V_n > V_{\text{lim}}$,

$$V_n = \max(V_n - b, V_{\text{lim}}), \tag{8}$$

the train decelerates to the limited velocity V_{lim}.

iii) The train position updates as

$$X_n = X_n + V_n. \tag{9}$$

(iii) When the train is about to stop at a station, the velocity and location of the train are updated according to the following rules.

If the train is about to stop, it has to start decelerating at a certain location calculated by the following equation:

$$h_{\text{station}} = iD - X_n, \tag{10}$$

where iD is the specified stopping point at the i-th station, and when $h \leqslant L_{\text{safe}}$, the deceleration process should begin.

(a) If $V_n > 0$,

$$V_n = \max(V_n - b, 0), \tag{11}$$

the train decelerates until the limited velocity V_{lim}. The train decelerates until the speed reaches V_{lim}. This equation is a necessary constraint from the real railway transport systems, which means that the trains must run at the specified speed when the trains enter or pass through a station.

(b) The train position updates as

$$X_n = X_n + V_n. \tag{12}$$

3. Numerical experiment

Herein, the departure capacity is the number of trains departed within a given period, and is considered to be equivalent to the train service capacity of the urban rail transit system. When a rail operator schedules the train timetables, the focus is to provide passengers with sufficient and timely travel services as much as possible to reduce the passengers' waiting time. In particular, in major cities, many passengers commute within the peak hours and over-saturated travel demand has become the norm. Whether trains can depart with high frequency is a very critical service level evaluation indicator. The departure capacity indicator will indicate the level of service capability, such that the decision makers can design the train timetable, analyze the results of the decision plan, and determine the available capacity for future use. For a given urban rail transit system, when more trains are added, whether some capacity remains can also be analyzed by the model. This section primarily discusses the simulation experiments and analyzes the departure capacity of the urban rail transit system with various theoretical conditions.

3.1. Basic parameter setting

Without any special instructions, the simulations use the following parameter values for simulation. When other special situations occur and certain parameters need to be reset to new values, the specific instructions will be given.

The number of sections in a simulated system is 10; the section length D is 2 km. Without any special instructions, the design speed of the line is typically 80 km/h; the deceleration

b = 1 m/s^2, and the acceleration $a = 0.83$ m/s^2. The train generally consists of six carriages and the train length is 120 m. The trains will remain at the station for 80 s, where the primary purpose of the train stop is to wait for passengers to board and alight; the maximum value of t_R is 1 s. The real-time signal departure control is used in the following simulation experiments.

3.2. Analysis of experiment results

3.2.1. Comparison with conventional railway CA model

A critical difference between the urban rail transit train operation and the general railway train operation is whether overtaking is allowed for different priority trains. Here, the processes concerning overtaking are simulated and analyzed separately.

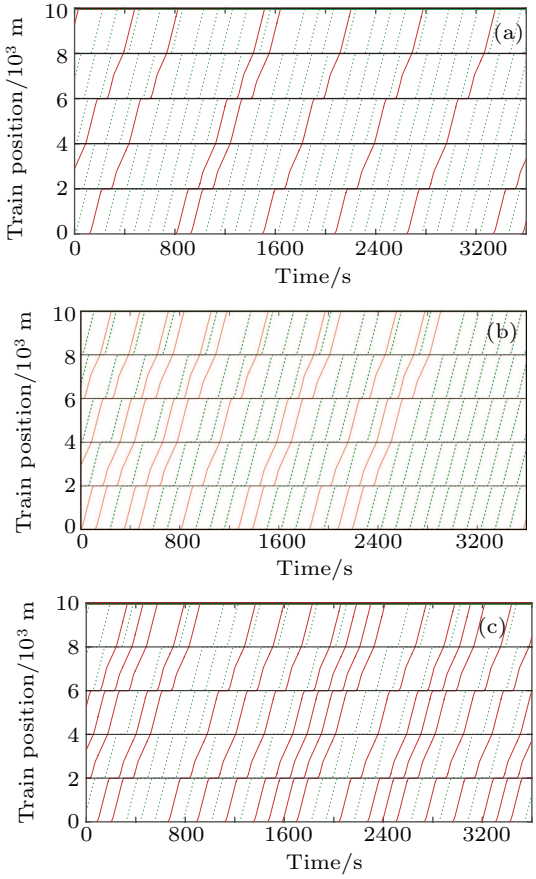


Fig. 3. (color online) Trajectory diagram of trains running in mixed operation mode with different proportions of the high-priority trains.

(i) The departure capacity simulated by considering different priority trains in the conventional railway system

The train departure capacities of the subgraphs in Fig. 3 with different priority trains in the mixed operation mode are compared with the capacity from Fig. 3(a). We found that the capacity remains constant as the ratio of the high-priority train increases. Figure 3(a) shows approximately 10% high-priority trains and the high- and low-priority trains remain consistent during the beginning of the operation in the first two sections. In the last rail line section, the high-priority trains will overtake the low-priority trains, and then the low-priority trains will run following the high-priority trains. The proportions of the high-priority trains in Figs. 3(b) and 3(c) are approximately 30% and 50%, respectively. The train runnings as shown in Figs. 3(b) and 3(c) are approximately similar to the situation of Fig. 3(a).

(ii) The departure capacity under the proposed CA model for urban rail system

We first analyze the conventional operation mode, i.e., all of the trains will stop at each station. The departure capacity data in the conventional mode are prepared for a comparative analysis. Figures 4(a), 4(b), and 4(c) are the train running space–time diagrams that show the specific train position changing over time. The vertical axis is the train position. The horizontal axis is the time step. The situations of the train operation are shown by the subgraphs in Fig. 4. Figure 3(a) shows a line with five sections, figure 4(b) shows a line with 10 sections, and figure 4(c) shows a line with 15 sections. Their passing capacities are 25 trains, 19 trains, and 12 trains, respectively.

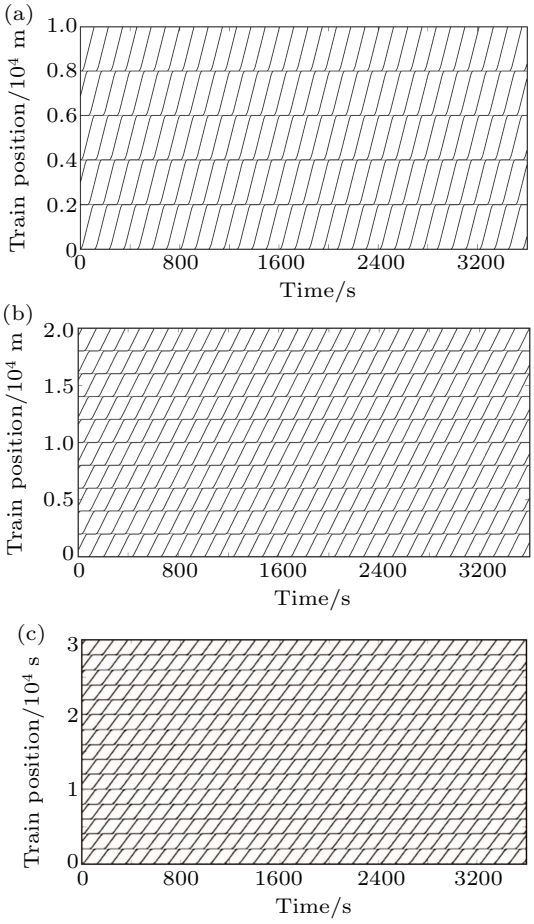


Fig. 4. Trajectory diagram of trains running in the conventional operation mode with different section number: (a) 5 sections, (b) 10 sections, (c) 15 sections.

3.2.2. Train departure control methods

Two methods can be used to control the train departure. In the first method, the train can depart from the origin station according to the signal given by the train control system, known as the real-time signal departure control. In the second method, the time interval departure control allows a train to depart from the origin station after it has waited a certain time.

Figures 5(a) and 5(b) are the train space–time diagrams that show the specific train running processes over time. The vertical axis is the train position. The horizontal axis is the time step. Figure 5(a) displays the trains departing and running trajectories under the real-time signal control. Figure 5(b) shows more trains and a higher departing frequency, i.e., 65 trains within an hour. It is higher than the departure capacity of 30 trains under the time interval departure control. Generally, the actual operation does not use the real-time signal control offering such a high train service frequency because the trains often depart in accordance with the quantity of passenger demand in reality. The number of trains departed with real-time signal control is a theoretical value and can provide an evaluation of the service capability level, such that a definite reference can be obtained when scheduling a train timetable and the system capacity used can be determined.

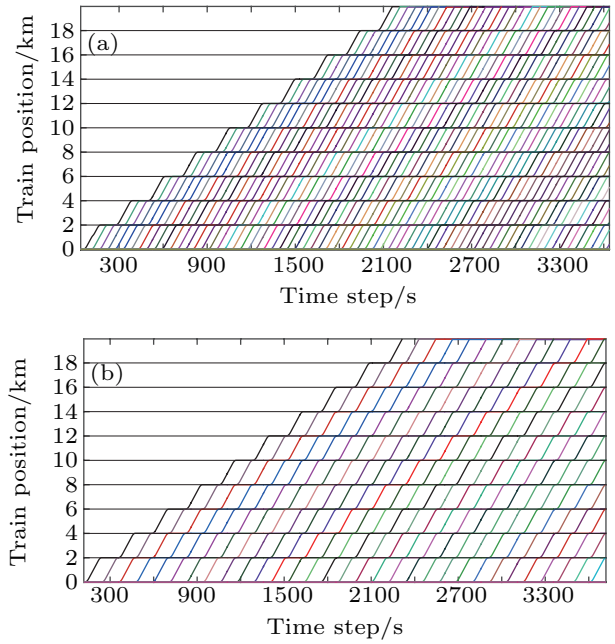


Fig. 5. Trajectory diagram of trains running under different train departure controls, where (a) trains depart by real-time signal control, and (b) trains depart by time interval control.

3.2.3. Influence analysis of line design speed

As shown in Fig. 6, as the line design speed decreases, the line train capacity increases from 51 trains to 54 trains with the speed condition changing from 90 km/h to 60 km/h, approximately a 6% decrease. This is because according to Eqs. (1) and (10), while the line design speed decreases, the train safety headway will be shortened. That is, when the line design speed reduces, the required safety headway for the running train is reduced. Figure 7(a) shows less trains departing than Fig. 7(b) within a given time.

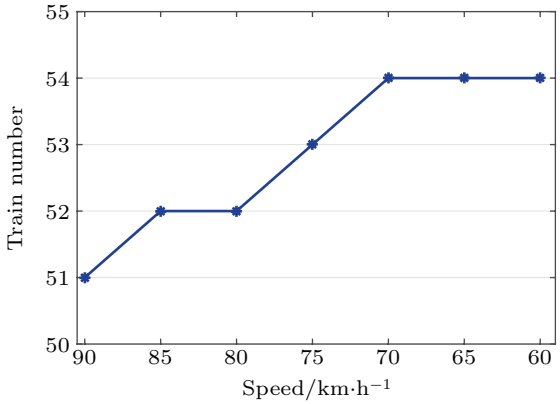


Fig. 6. Trend of departure capacity changing with line design speed.

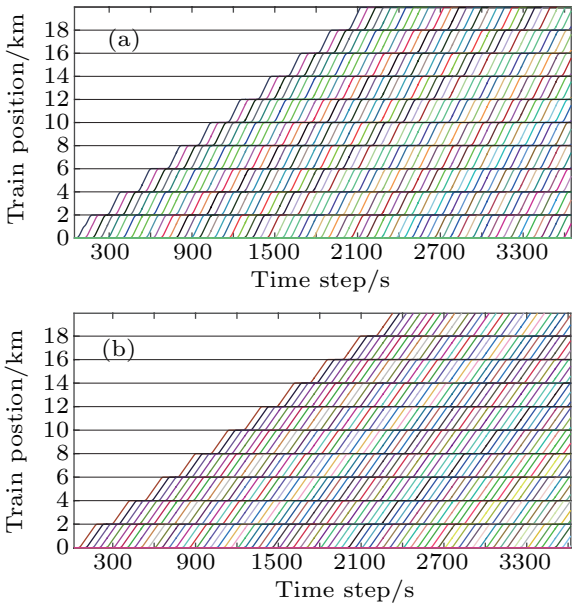


Fig. 7. Train running trajectories under different designed line speeds, where (a) $V_{max} = 90$ km/h and (b) $V_{max} = 60$ km/h.

3.2.4. Influence analysis of train length

Figure 8 shows that the departure capacity changes under different train lengths. Because the number of train carriages increases, the train length increase leads to the departure capacity reduction from 39 to 34, a 12.8% decrease. According to Eq. (9), the train length is an important factor that affects the time that a train occupies and leaves the track and station, in that the time from entering into until leaving the region will become longer. Therefore, the time that a longer train remains in the system will increase. However, the total available service time of the system is fixed; when the train length is longer, more service capacity of the system is consumed.

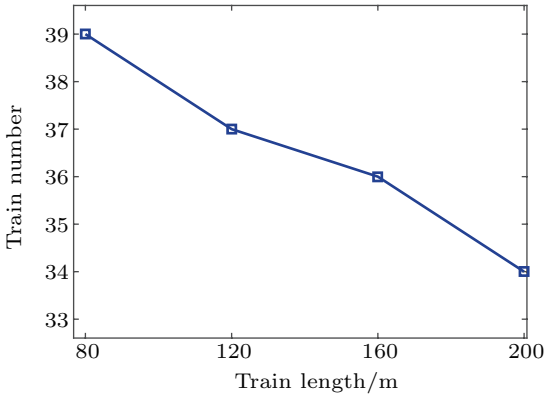


Fig. 8. Departure capacity changing with the train length.

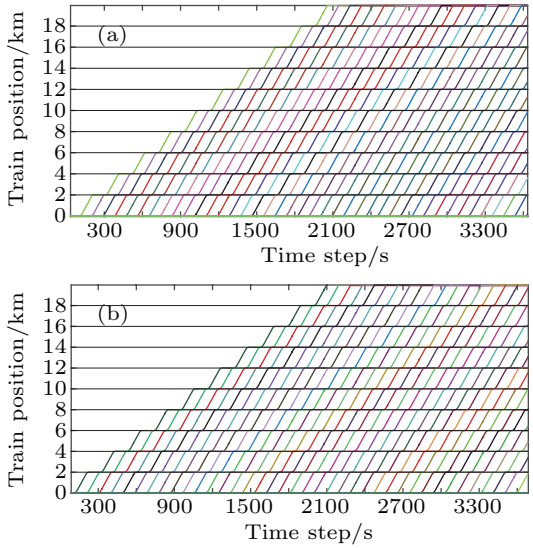


Fig. 9. Train running trajectories under different train lengths, where (a) $L_{\text{train}} = 80$ m and (b) $L_{\text{train}} = 200$ m.

3.2.5. Influence analysis of train stop time

Figure 10 shows that when the stop time increases, the number of departed trains gradually reduces, from 43 with 60-s stop time to 37 under 120-s stop time, a 14% decrease. Figures 11(a) and 11(b) show the specific train running trajectories. It is clear that the stop time will affect the total train travel time from the origin station to the destination station.

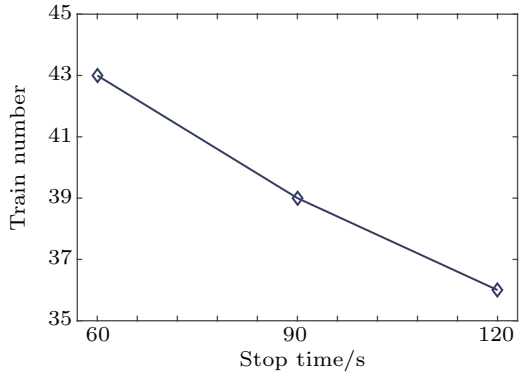


Fig. 10. Departure capacity changing with the train stop time.

The longer the train stops, the more service capacity of the system is consumed. In an actual operation, if the passenger demand at a station is large, the train has to stop for a longer time, and vice versa. The stop time has a significant impact on the departure capacity.

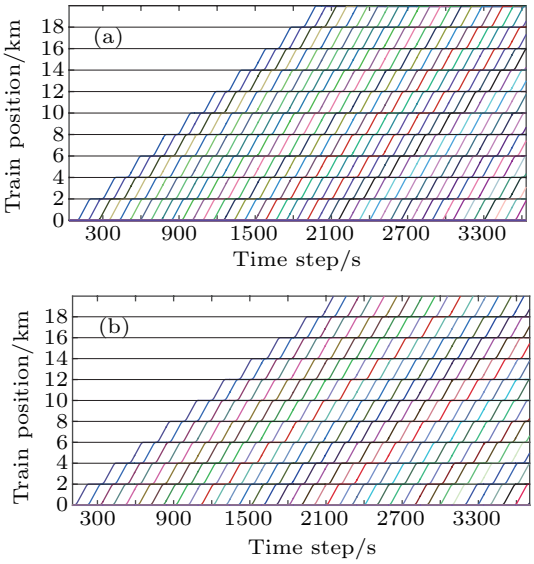


Fig. 11. Train running trajectories under different stop times: (a) 60 s and (b) 120 s.

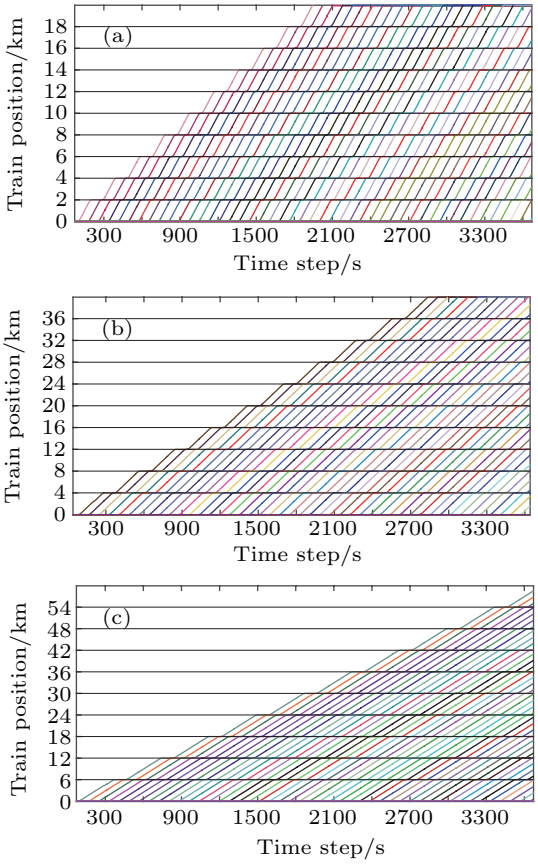


Fig. 12. Train running process under different section lengths: (a) $D = 2$ km, (b) $D = 4$ km, and (c) $D = 6$ km.

3.2.6. Influence analysis of section length

We find that the departure capacity remains stable, as it is not affected by the section length. It remains as 45 whenever

the section length between stations increases in each of the simulation cases. As shown in Figs. 12(a), 12(b), and 12(c), under the condition that only the origin station is qualified for train departure, with the length increasing, it shows a severe waste of line service capacity. Most stations behind the origin station will be without a train service at the beginning. The problem becomes worse when the section length extends. In this case, except for the passengers at the origin station, the passengers in the intermediate stations waiting for trains cannot be served timely. At important intermediate stations with many passengers, it can be set as an alternative origin station preparing for train departure. If more trains can depart from several stations and more train units are to be prepared simultaneously, this not only improves the capacity utilization of the line, but can also reduce the passenger waiting time such that the passengers will be served timely and the services quality will be improved.

4. Conclusion

Based on the existing research, we established a CA model with some sound rules that simulate the running process of trains in an urban rail transit system. In this model, the considered factors include different train lengths, the departing rules in the origin station, the intermediate stations, speed limitations, etc. By analyzing the numerical experimental results, we found that (i) the departure capacity is negatively affected by the train departure control manner, i.e., the real-time signal control can offer a higher train service frequency; (ii) the departure capacity gradually rises with the decrease in the line design speed to a limited extent; (iii) the departure capacity decreases with the extension in the train's length; (iv) the number of departed trains decreases as the train stop time increases; (v) the departure capacity is not affected by the section length. However, the longer the length, the worse the service quality of the urban rail transit line. In future research, more influential factors such as the influence of signal delay occurrence probability, the station stop capacity, and the train turnaround time should be considered to investigate urban rail traffic to improve the model.

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