

Research Article

An Alternative Approach for High Speed Railway Carrying Capacity Calculation Based on Multiagent Simulation

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It is a multiobjective mixed integer programming problem that calculates the carrying capacity of high speed railway based on mathematical programming method. The model is complex and difficult to solve, and it is difficult to comprehensively consider the various influencing factors on the train operation. The multiagent theory is employed to calculate high speed railway carrying capacity. In accordance with real operations of high speed railway, a three-layer agent model is developed to simulate the operating process of high speed railway. In the proposed model, railway network agent, line agent, station agent, and train agent are designed, respectively. To validate the proposed model, a case study is performed for Beijing–Shanghai high speed railway by using NetLogo software. The results are consistent with the actual data, which implies that the proposed multiagent method is feasible to calculate the carrying capacity of high speed railway.

1. Introduction

Carrying capacity of high speed railway is an important index to evaluate the utilization efficiency of high speed railway infrastructure. In practice, carrying capacity of high speed railway is affected by various factors, including internal factors, like infrastructure and timetables, and external factors, like uncertainty of running time, stop time and interference between different levels of trains, and so forth [1]. Therefore, it is a complex and challenging work to calculate the carrying capacity of high speed railway and optimize the utilization efficiency of high speed railway infrastructure. Based on a large amount of literature, the method that calculates the carrying capacity of high speed railway can be divided into three types: analytical method, optimization method, and simulation method [2].

It is a multiobjective mixed integer programming problem that calculates the carrying capacity of high speed railway based on mathematical model method [3–13]. The model is complex and difficult to solve, and it is difficult to comprehensively consider the influence of various factors on the train operation. Computer simulation is a process that

simulates the structure, function and behavior of the goal system, and thinking process and behavior of humans that participate in system control, and it is an important approach to study the operation behavior and to reveal the regular pattern of the system [14–20]. Compared with the traditional mathematical methods, computer simulation technology has the advantages of good repeatability, high adaptability, strong controllability, good economy, and so on, and it has become an effective method to calculate the carrying capacity of high speed railway.

The key is the modeling and simulating of the train operation process when use computer simulation technology to calculate the carrying capacity of high speed railway. However, due to diversity of simulation objects, complexity of operation conditions, concurrency of train state adjustment, and relevance of state evolution, it is often difficult to construct the train operation process model to simulate train flow which is in line with the actual situation. Multiagent technology provides a new perspective to solve the above problems.

At present, some scholars have carried out preliminary research in the field of traffic system simulation based on

multiagent and have achieved some results. References [21, 22] proposed train operation adjustment method based on multiagent with the characteristics of urban rail transit. Development process of train operation adjustment plan was abstracted as an occupation and reservation process of railway stations and lines by multiuser (train). On the basis of this, the agent model is established. Reference [23] introduced the multiagent theory into the field of road traffic modeling and simulation and presented the agent model of each element of road traffic system and developed the communication and negotiation mechanism between the agents. Reference [24] proposed three-tier architecture of multiagent based traffic flow microscopic simulation model, including vehicle agent, road agent, and road network agent. Through the coordination and cooperation of the three parts, realize the simulation of the traffic system from the microscopic behavior of the vehicle to a variety of control strategies. Reference [25] proposed three-layer framework model of microtraffic simulation system based on multiagent, taking vehicle, road, intersection, and signal light and traffic control center as the core five agents. Furthermore, together with the advantages of fuzzy control technology, the fuzzy decision method is applied to various driving behavior decision. Reference [26] used multiagent collaboration technology to build subway train agent and designed subway train operation adjustment algorithm, and subway train operation adjustment control strategy based on rule was given.

Since multiagent simulation is regarded as a valid approach which has been extensively applied in traffic system simulation, it is considered to be an alternative approach for calculating carrying capacity of high speed railway. In this work, a three-layer agent model for operation simulation of high speed railway is proposed, and railway network agent, line agent, station agent, and train agent are designed, respectively. A case study is performed for Beijing–Shanghai high speed railway with NetLogo software. The results well support the validation of the proposed approach.

2. Concept of Multiagent and Application Thinking

2.1. Concept of Multiagent. Multiagent system (MAS) is an important branch of distributed artificial intelligence, which is used to solve the large and complex problems which are beyond the capacity of single agent. The multiagent system is a set of multiple agents, whose goal is to decompose the large and complex system into small, mutually communicating and coordinating, and easy to manage system. The agent is an entity that can run independently under a certain environment, which is influenced by its own living environment, and can continuously acquire knowledge from the environment to improve its own ability [27]. The agent has the following basic characteristics.

- (1) *Autonomy.* According to the changes of external environment, agent can adjust the behavior and state automatically and not only accept the external stimulation but also have the ability of self-management and self-adjustment.

- (2) *Reactivity.* Agent can respond to external stimuli.
- (3) *Initiative.* Agent can take the initiative to take action for changes in the external environment.
- (4) *Society.* Agent has the ability to cooperate with other agents or people. Different agents can interact with other agents according to their intention to solve the problem.
- (5) *Evolutionary.* Agent can accumulate or learn the experience and knowledge and modify its behavior to adapt to new environment [28].

2.2. Application Thinking. Railway transportation system is a large scale network system, which is composed of a large number of stations, sections, vehicles, and other equipment, which is in line with the conditions of the application of multiagent system. Train operation process can be abstracted as an occupation and reservation process of railway stations and lines by multiuser (train) and on this basis to establish a multiagent model. Lines and stations are abstracted as resource agents. Train is abstracted as a user agent. The multiagent system is composed of resource agent and user agent.

3. Train Operation Process and Parameters

3.1. Train Operation Process. The train from generation to disintegration has experienced a process as shown in Figure 1.

In Figure 1, the train operation process is divided into two parts, the operation in stations and that in sections [29].

- P1: the train leaves the station, starting from one end of the section, gradually running to the other end of the station. Include normal traffic in section and stopping in station.
- P2: the train goes into station and stops, including two cases: end to stop and wait to go.
- P3: the train stays on the arrival-departure line of a station.
- P4: the train departs, including two cases: depart from starting station and intermediate station.
- P5: the train does not stop at the station and goes through according to the speed limit.

Train operation is under the control of the signal system, according to certain rules and procedures. In the course of train operation, the signal system conveys the train's safe running condition and directly controls the train operation. Signal system relates to station signal control system and section signal control system.

3.2. Train Operation Parameters

3.2.1. Minimum Tracking Interval Time of High Speed Train. Ordinary train usually adopts the hierarchical speed control mode curve. Differently from this, the high speed railway in China mainly adopts the control strategy of Centralized Traffic Control and is equipped with the CTCS-2 or CTCS-3

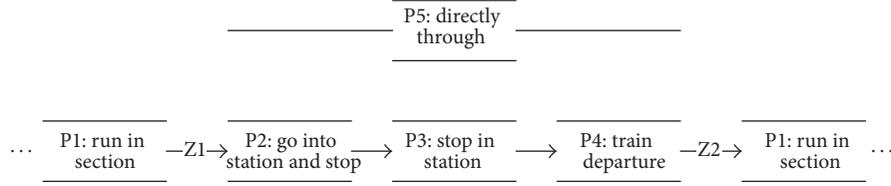


FIGURE 1: Train operation process.

level train control system. In this case, the train operation is controlled by the continuous speed mode curve. To this end, it is necessary to analyze the tracking interval time of high speed trains.

Tracking interval time of high speed trains (I) refers to the minimum interval time of two trains running in the same direction in automatic block section, using Centralized Traffic Control (CTC) mode and the CTCS-2/CTCS-3 level train control system, and it is the maximum of the section tracking interval time, departure tracking interval time, arrival tracking interval time, and passing tracking interval time. Train tracking interval time is an important component of the train running diagram and the main basis for calculating the carrying capacity, and it is an important index to reflect the level of railway transport capacity.

(1) *Section Tracking Interval Time*. In order to ensure the safety of train running in the sections, the distance between the adjacent trains must be large enough, so that we can ensure the minimum distance running time of trains. According to the relevant literature [30], the minimum interval time for the normal operation of the train is as follows:

$$I_t = 3.6 \times \frac{L_b + L_p + L_{bp} + L_t}{v_s} + t_a, \quad (1)$$

where I_t expresses section tracking interval time and the unit is s; L_b expresses the braking distance of the train control equipment and the unit is m; L_p expresses safety braking distance and the unit is m; L_{bp} expresses the length of the block partition and the unit is m; L_t expresses the length of the train and the unit is m; v_s expresses the average speed of the train running in section and the unit is km/h; t_a expresses braking additional time of the train running in section and the unit is s; 3.6 expresses unit conversion factor in a representation.

(2) *Departure Tracking Interval Time*. The operation and organization of high speed train are controlled by CTCS-2 or CTCS-3 mode in China. For the two consecutive trains from the same station, when the leading train starts to leave, departure of other trains can be handled. Therefore, the departure tracking interval time of high speed railway in China can be expressed as follows:

$$I_d = 3.6 \times \frac{L_s + L_{bp} + L_t}{v_d} + t_d, \quad (2)$$

where I_d expresses departure tracking interval time of train and the unit is s; L_s expresses the distance between the train

stop signal and starting signal and the unit is m; v_d expresses the running speed of the train from the station and the unit is km/h; t_d expresses train departure operation time and the unit is s.

(3) *Arrival Tracking Interval Time*. For each station, when it is in the condition of arrival, the front train completely enters into the arrival-departure track; the speed is gradually reduced and eventually stopped.

Centralized Traffic Control (CTC) automatically prepares receiving route for following train. The arrival tracking interval time can be expressed as follows:

$$I_a = 3.6 \times \frac{L_b + L_p + L_a + L_t}{v_a} + t_a, \quad (3)$$

where I_a expresses arrival tracking interval time of train in station and the unit is s; L_a expresses the distance between entry signal and reverse starting signal and the unit is m; v_a expresses the running speed of arrival train and the unit is km/h; t_a expresses train arrival operation time and the unit is s.

3.2.2. *Calculation of Braking Distance of the Train*. According to [31], by the TDEO model, the maximum braking distance of the train can be expressed as follows:

$$L_{\text{TDEO}} = \sum_{i=1}^6 \frac{v_i^2 - v_{i+1}^2}{2a_i}, \quad (4)$$

where v_i and v_{i+1} , respectively, express initial and final speed of speed section. a_i expresses constant deceleration of speed section.

3.2.3. *Other Parameter Values*

(1) *Train Length L_t* . High groups of trains are selected, with designed speeds of 200–250 km/h and 300–350 km/h, respectively. For the group with 8 cars, L_t is 214 m, and for the group with 16 cars L_t is 403 m.

(2) *Train Braking Distance L_p* . According to (interim technical specification for CTCS-2 level train control equipment), (interim technical specification for CTCS-3 level train control equipment), and (overall technical scheme of CTCS-3 level train control system), maximum value of L_p is set to be 110 m in sections and 60 m in stations.

(3) *Technical Operation Time*. The parameter settings are similar to reference [9].

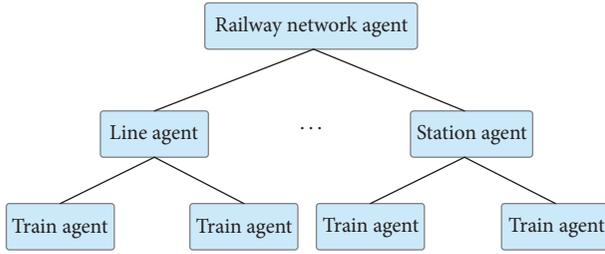


FIGURE 2: Model system of agent.

4. Agent Modeling

4.1. Model System of Agent. If we regard station track and section line as resource and regard train as user, then train operation process can be abstracted as an occupation and reservation process of railway stations and lines by multiuser (train). In the simulation of train operation process based on multiagent, there are two kinds of agents, resource agent (line and station) and user agent (train). Simulation model system of high speed railway operation process based on multiagent is shown in Figure 2.

In the three-layer model of agent, the train agent is the object of the control. The purpose of line agent is to spread the data needed to be centrally processed in each line agent, so balance the burden of the system. Railway network agent is specially used to process the control strategy needed global information. Therefore, railway network agent needs status information of all the line agents, in order to assess the state of the entire network.

Railway network agent only needs to obtain the state information of line agent and does not need to obtain the information of train agent, so that this can significantly reduce data amount which needs to be processed. Because the number of line agents is very small compared with the number of train agents running in whole network, it can meet the needs of real time processing. Railway network agent is in the top layer of the three-layer structure, and it does not interact with train agent directly but indirectly controls the operation of train through line agent. Railway network agent is different from line agent and train agent. Line agent and train agent can have multiple instances, but railway network agent only allows one instance.

Each agent is composed of basic attribute, knowledge base, decision-making unit, sensing unit, and communication unit, as shown in Figure 3. Basic attribute describes the characteristics of the agent. Sensing unit is used to collect the external environment data. Knowledge base stores the historical information that supports the judgment of agent. The decision-making unit analyzes and processes information, and combined with the information extracted from the knowledge base, basic attribute, and sensing unit makes a decision. The communication unit is in charge of communication with other agents and carries on the coordination work with each other.

4.2. Line Agent. The operation of train cannot be separated from the line, and line model is an important part of the

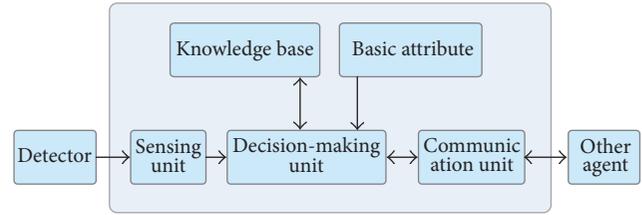


FIGURE 3: Structure diagram of the agent.

multiagent simulation system. The traditional arc and node vector line network model easily expresses the direction and topology of the line, but it is not suitable for discrete space simulation. Line agent model based on multiagent divides line into square grid of equal size; each square grid is a line unit. Several line units combine into one line. Line unit is an object with spatial location and attribute.

When a train enters a line unit, it sends a message to line agent, so following train can know existence of the train. when a train runs in the line, line agent can get the speed, position, and other information of the train in real time. Similarly, when the train agent leaves the line, it should send a message to the line agent to notify line agent to write off the information of this agent.

Line agent plays a connecting role in the whole network structure. Its role is not just a carrier that the train gets information from; it also includes submitting the train situation about this section to its upper layer, that is, network agent, and providing status of global network for its lower layer, that is, train agent. Line agent records the status information of the train running on this section and display status of various control facilities (such as signal light) on this section and summarizes this information and sends it to the upper layer for the judgment of the whole network state.

4.3. Train Agent. The station agent is used for connecting each line agent; it is the center of railway transportation network, and it is mainly responsible for the transfer and control of the intelligent body from one line to another. Attribute of station agent mainly includes center coordinate, connected line, station track number, and track occupation number.

When the train arrives at the station, it determines whether to stop according to the stop station list. If it needs to stop and at the same time there is a remaining track available the train pulls in.

4.4. Railway Network Agent. Different from train agent and line agent, railway network agent is an abstract concept, and there is no corresponding entity in the real network. Due to the setting of the line agent, the massive data in the network which needs to be centralized processing is distributed in each line agent. It can balance the burden of the system, but because there is no agent that can grasp the overall information of the railway network, the whole network control cannot be implemented. So an abstract railway network agent is presented to grasp the global information. From this point

of view, the railway network agent is similar to the railway dispatching command center.

4.5. Train Agent. Train is the main element of the railway transportation system. For microscopic simulation of railway transportation system, the most basic issue is to describe the running state of the train accurately and rapidly. So the train agent is the most important one in the simulation system. Train agent is subject with high degree of autonomy, it can automatically obtain the information of the external environment, it has own knowledge and complex decision-making ability to judge, and it can adjust their own behavior according to the surrounding traffic conditions in real time.

The main components of the train agent include the following parts:

- (1) train attribute: train number, train level, maximum speed, acceleration, minimum tracking interval time, length of the train, and safety braking distance;
- (2) operation plan: starting point, end point, stop station, stop time, and train schedule;
- (3) operation state: position, speed, and distance between the current train and the front train;
- (4) train behavior
 - (i) acceleration: when the distance between the train and the front train is more than the minimum tracking interval time and the train speed is less than the maximum speed, the train accelerates in accordance with the set of acceleration.
 - (ii) following: when the distance between the train and the preceding train is equal to the minimum tracking interval time, the train follows the preceding train with the speed of the preceding one.
 - (iii) arrival: when the train arrives at a station, it should judge whether it is needed to stop; if it is not, the train can directly go through. Otherwise, the train enters into the free track of the station.
 - (iv) avoidance: when the low level train is in the station, if a high level train passes through the station, the low level train must extend stop time to give way and let high level train pass through first.

5. Simulation Experiment

5.1. Simulation Parameter. Based on the proposed model, the train operation process simulation is carried out, and the maximum railway carrying capacity is calculated. Select the actual data of Beijing–Shanghai high speed railway. The parameters are shown in Table 1.

5.2. Simulation Flow. This system is simulated by using the time scanning method, as is shown in Figure 4. After loading

TABLE 1: Parameters of Beijing–Shanghai high speed railway.

Station	Mileage (km)	Number of arrival and departure tracks
Beijing South	0	24
Langfang	59	4
Tianjin South	131	6
Cangzhou West	219	6
Dezhou East	327	13
Jinan West	419	17
Tai'an	462	6
Qufu East	533	6
Tengzhou East	589	4
Zaozhuang	625	6
Xuzhou East	688	15
Suzhou East	767	6
Bengbunan	844	24
Dingyuan	897	4
Chuzhou	959	6
Nanjing South	1018	10
Zhenjiang South	1087	6
Danyang North	1112	4
Changzhou North	1144	6
Wuxi East	1201	6
Suzhou North	1227	6
Shanghai Hongqiao	1302	30

the system parameters and the railway network structure, the system starts a new iterative process [32]. In each iteration, there are mainly the following calculation processes:

Step 1. Determine whether the distance to tail train in train flow is greater than the minimum tracking interval time; if it is, then a new train will be added to the end of the train flow.

Step 2. Determine position of train. If distance to destination is equal to braking distance, then the train begins to decelerate and finally stops.

Step 3. Determine whether the distance to preceding station is equal to braking distance; if it is, determine whether the preceding station should stop; if it is, check whether the station has spare arrival and departure track; if it is, arrive and stop; otherwise, stop at front of the station and wait.

Step 4. If the preceding station is not the one which should stop, directly go through.

Step 5. If the distance between the train and preceding station is greater than the minimum braking distance, determine whether the distance to preceding train is greater than the minimum track spacing; if it is, judge whether the train speed is less than the maximum speed; if it is, accelerate; otherwise, run in accordance with original speed.

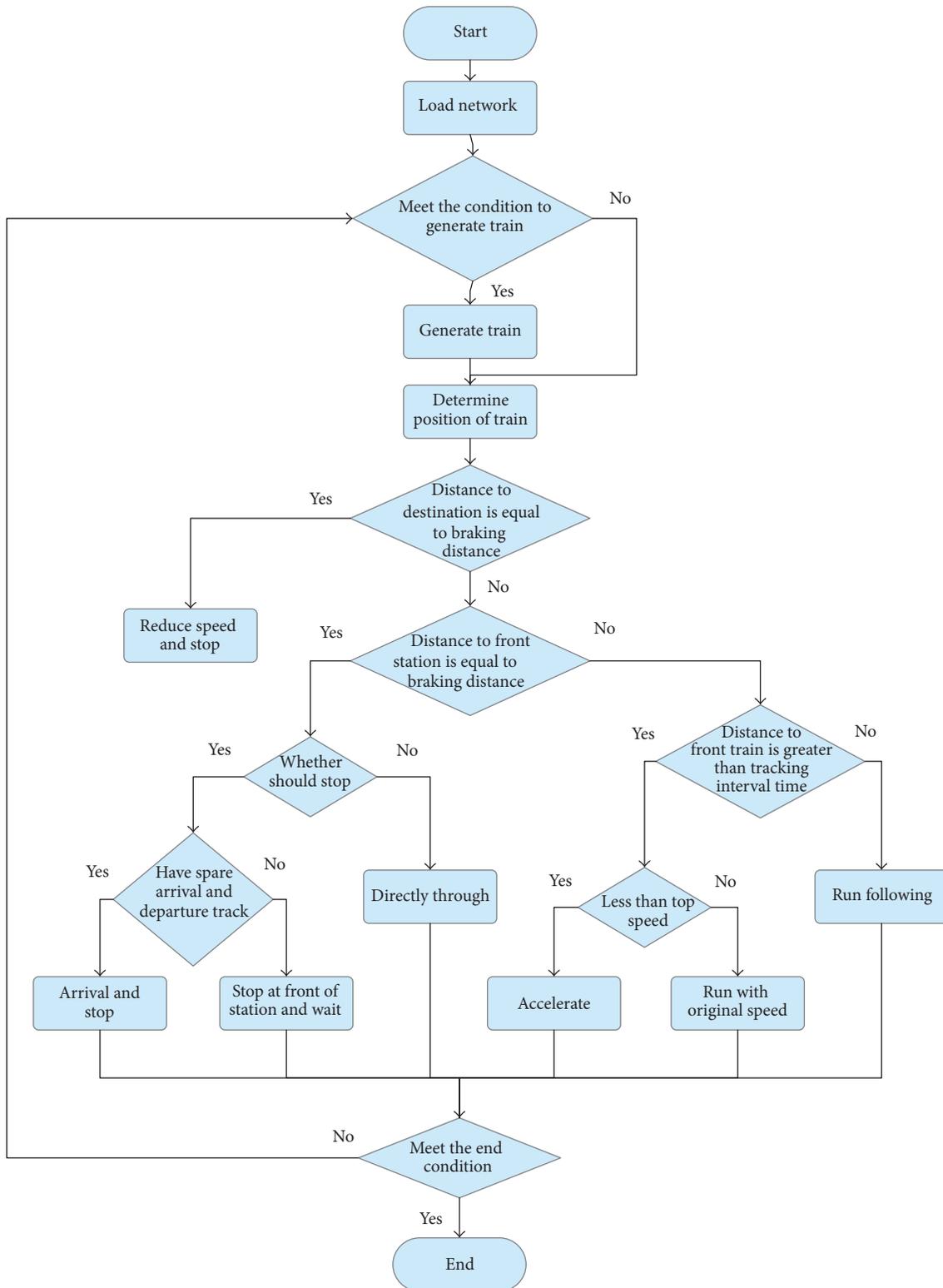


FIGURE 4: Simulation flow.

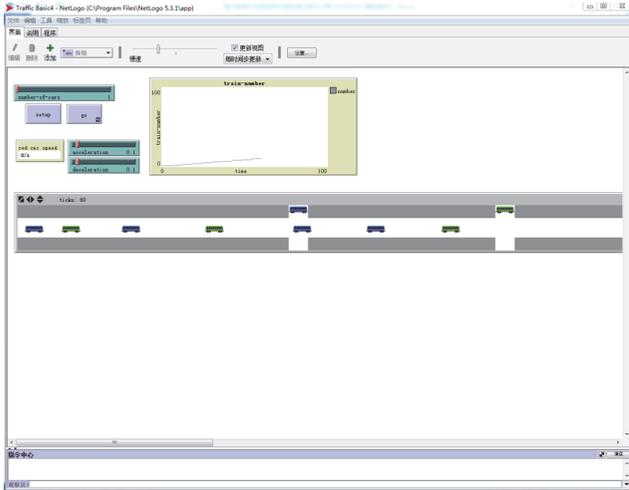


FIGURE 5: Simulation interface of the system.

Step 6. If distance to preceding train is not greater than tracking interval time, the train runs following front train.

Step 7. Check whether terminal condition of simulation is satisfied; if it is, then the simulation program is over; otherwise, enter the next clock.

5.3. Experiment Result. We use NetLogo software to code and simulate the multiagent model designed above. The simulation of the train operation status lasts for 12 hours one day, and then the carrying capacity is calculated. The simulation interface of the system is shown in Figure 5.

5.3.1. Experiment One

(1) The Condition to Generate Train. Two general conditions should be satisfied. First, the distance from departure time of last train should be greater than five minutes; second, the time interval should be larger than the minimum tracking interval time.

(2) Simulation Result

(i) Carrying Capacity. From Beijing South railway station to Shanghai Hongqiao railway station, the carrying capacity is 55 trains.

(ii) Operation Efficiency. The average speed variation against time of the train is shown in Figure 6.

The average speed reaches the maximum value (320 km/h) at the end of the first hour. Then, continuous generation of trains leads to interference between adjacent trains. Average speed falls gradually and reaches the minimum value (165 km/h) at twelfth hour.

The average stop time of trains is shown in Figure 7.

The train is not evenly distributed on the line, which causes the train congestion at stations. The average stop time of trains gradually increases with time and eventually reaches

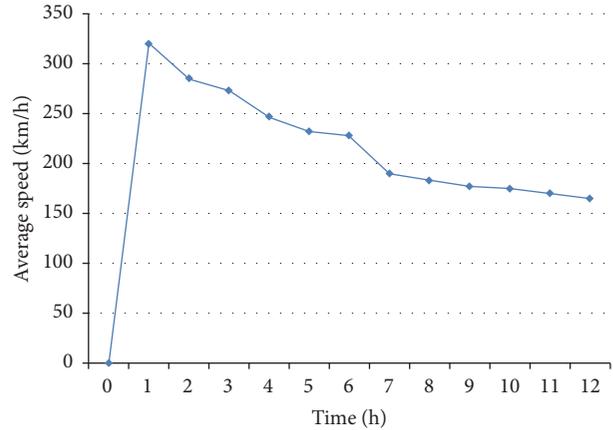


FIGURE 6: Average speed variation against time.

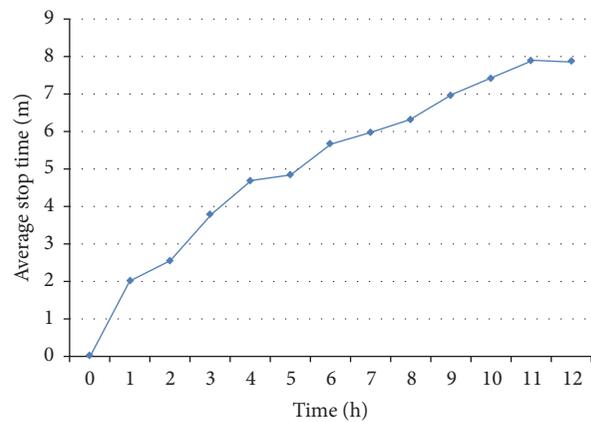


FIGURE 7: Average stop time variation against time.

7.8 minutes. Average train delay time variation against time is shown in Figure 8.

Similarly, due to the congestion of the trains, the delay time gradually increases and eventually reaches 6.3 minutes.

5.3.2. Experiment Two

(1) The Condition to Generate Train. In experiment one, because train departure interval time is too small, it leads to train congestion in station and results in a large area of delay. Not only is the carrying capacity restricted, but also the quality of service declines significantly. So take the adjustment strategy in experiment two. When the average delay time is more than 1.5 m, we gradually increase the departure interval.

(2) Simulation Results

(i) Carrying Capacity. From Beijing South railway station to Shanghai Hongqiao railway station, the carrying capacity is 77 trains.

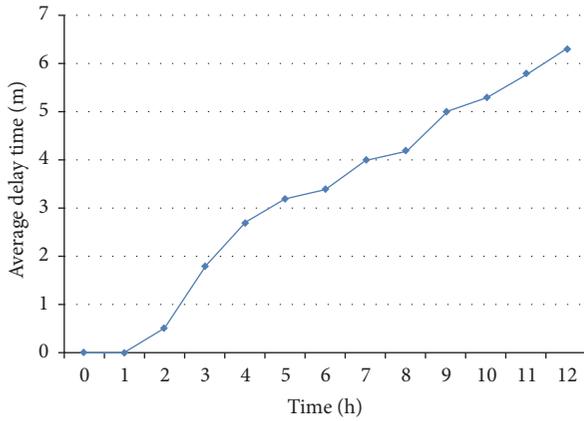


FIGURE 8: Average train delay time variation against time.

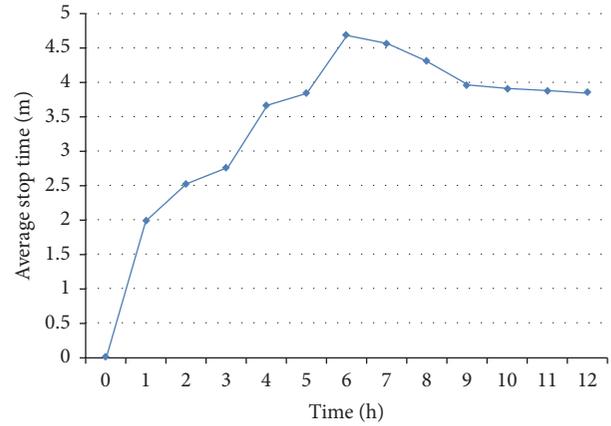


FIGURE 10: Average stop time variation against time.

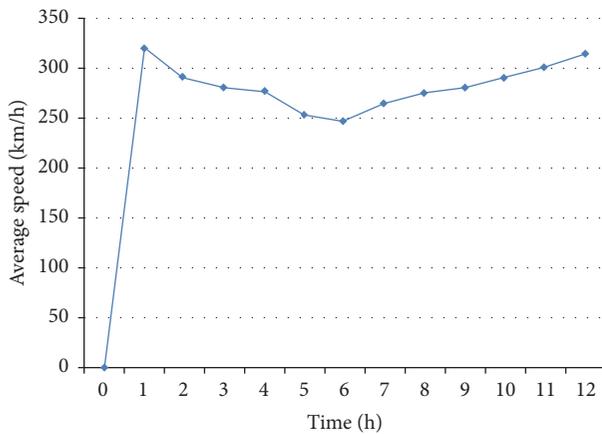


FIGURE 9: Average speed variation against time.

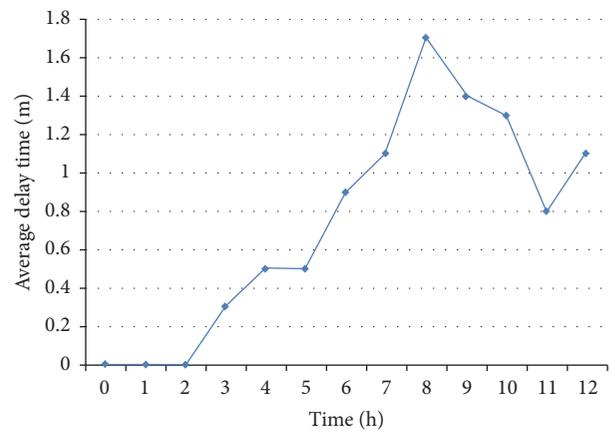


FIGURE 11: Average train delay time variation against time.

(ii) *Operation Efficiency.* The average speed variation against time of the train is shown in Figure 9.

The average speed reaches the maximum value (320 km/h) at the end of the first hour. Then, because of interference among trains, average speed falls gradually and reaches the minimum value (250 km/h) at the sixth hour. Finally, due to the application of adjusting starting strategy, that is, increasing the departure interval, the average speed of the train gradually increases and reaches 165 km/h at twelfth hour.

The average stop time of trains is shown in Figure 10.

The average stop time of trains gradually increases with time and reaches the maximum value (4.6 minutes) at the sixth hour. Then, due to the increase of departure interval, train density is reduced, and average stop time gradually decreases till to 3.8 m.

Average train delay time variation against time is shown in Figure 11.

With the increase of train number, train congestion occurs gradually. Delay time gradually increases and at the eighth hour reaches 1.7 minutes. Because of adjusting starting strategy, that is, increasing the departure interval, we can control the average delay time very well, and the average delay time decreases to 1.1 minutes.

5.3.3. *Actual Data.* According to actual train schedule of Beijing–Shanghai high speed railway, from seven a.m. to seven p.m., there are 43 high speed trains running from Beijing South railway station to Shanghai Hongqiao railway station. In addition, due to the increasing number of trains, including those departing from intermediate stations and importing from other railway lines, the number of trains increases to 52 when the railway stretches from Beijing South station to Jinan West station, and the number further reaches 70 when the railway stretches to Xuzhou East station. In all, the real carrying capacity of the whole line can approach nearly 80 trains.

Accordingly, the maximum value obtained in experiment 2 (i.e., the 77 trains total carrying capacity of Beijing–Shanghai high speed railway) is approximately consistent with the actual data. It reveals that it is feasible to calculate the carrying capacity of high speed railway based on multiagent model, which has certain theoretical and practical guiding significance.

6. Conclusions

It is a multiobjective mixed integer programming problem that calculates the carrying capacity calculation of high

speed railway based on mathematical model method. The model is complex and difficult to solve, and it is difficult to comprehensively consider the influence of various factors on the train operation. Compared with the traditional mathematical methods, computer simulation technology has the advantages of good repeatability, high adaptability, strong controllability, good economy, and so on, and it has become an effective method to calculate the carrying capacity of high speed railway.

In this work, the train operation process is analyzed, and the operation parameters are designed. Based on the multiagent theory, the three-layer agent model for operation simulation of high speed railway is proposed. In this model, railway network agent, line agent, station agent, and train agent are designed, respectively. By using NetLogo software, the multiagent model is programmed and realized. Based on actual operation parameters of Beijing-Shanghai high speed railway, railway carrying capacity is obtained by simulations.

Lots of experiments are performed to obtain the best results. Through flexibly adjustment of departure interval time, the variations of such factors as average speed, average stop time, and average delay time are, respectively, analyzed. Accordingly, the maximum railway carrying capacity with best service quality can be obtained. The conclusion of the experiment is consistent with the actual data, which shows that it is feasible to calculate the passing capacity of high speed railway based on multiagent model, and it has certain theoretical and practical significance.

Competing Interests

The authors declare that there are no competing interests regarding the publication of this paper.

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