

Research Article

Exploring Boarding Strategies for High-Speed Railway

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In light of the increasing demand for passenger transportation on high-speed railway (HSR), the pedestrian flow at HSR stations has become quite crowded in many countries, which has attracted researchers to study the HSR boarding behavior. In this paper, we propose three boarding strategies based on the features of the boarding behavior at an origin HSR station; we then use a cellular automaton (CA) model to study the impacts of boarding strategies on each passenger's motion during the boarding process at HSR station. The simulation results indicate that some of the three strategies can optimize some passengers' boarding time and relieve the congestion degree, and the positive impacts on the boarding process are the most prominent when the three strategies are used simultaneously. The results can help administrators to effectively organize the boarding process at the origin HSR station.

1. Introduction

High-speed railway (HSR) has been adopted in many countries across the globe. In China, for example, the HSR track length reached 19000 km in 2015 [1]. The quantity of HSR passengers exceeded 1.4 billion in 2016 after sharp increase in past years [2]. Hence, the HSR has become a hot topic and attracted researchers to explore various related traffic phenomena [3–9]. The enormous and rapidly increasing demand for passenger transportation has made the HSR station more crowded than ever. The pedestrian facilities at the HSR stations have not been able to accommodate the great number of passengers, which may have great effects on the boarding efficiency and the passengers' comfort, as well as the public safety. However, it will take several years to improve the infrastructures to provide more supply. Therefore, optimizing management and enhancing operational efficiency at the HSR stations offer more cost-effective ways to solve these problems.

Research into pedestrian management has been conducted for decades. For example, Okazaki and Matsushita [10] proposed a simulation model for pedestrian flow in architectural and urban space and used the simulation

examples of queuing behaviors at the conventional railway station to testify the effectiveness of the model. Daamen et al. [11] proposed a model to study the pedestrian flow in transfer stations, which can be used to facilitate railway station planning and design. Helbing et al. [12] developed some methods to increase the efficiency and safety of public place (e.g., railway station), which included optimizing intersecting flow, increasing diameters of egress route, and zigzag-sharp geometry and column. Bauer et al. [13] used crowd control facilities, such as temporary access restrictions, to keep the crowd density in specific areas below a certain limit. Zhang et al. [14] tested a dynamic evaluation indicator of crowd management in four scenes of intermodal transfer stations and pointed out that the indicator can display the level of crowd management. Molyneaux et al. [15] developed some control strategies to guide pedestrian motion in hubs and improve the flow dynamics, where the strategies considered “hard” strategies (e.g., barriers) and “soft” strategies (e.g., information, advertisements). The above studies focused on studying pedestrian management strategies in general/specific situations, but they did not evaluate the boarding process.

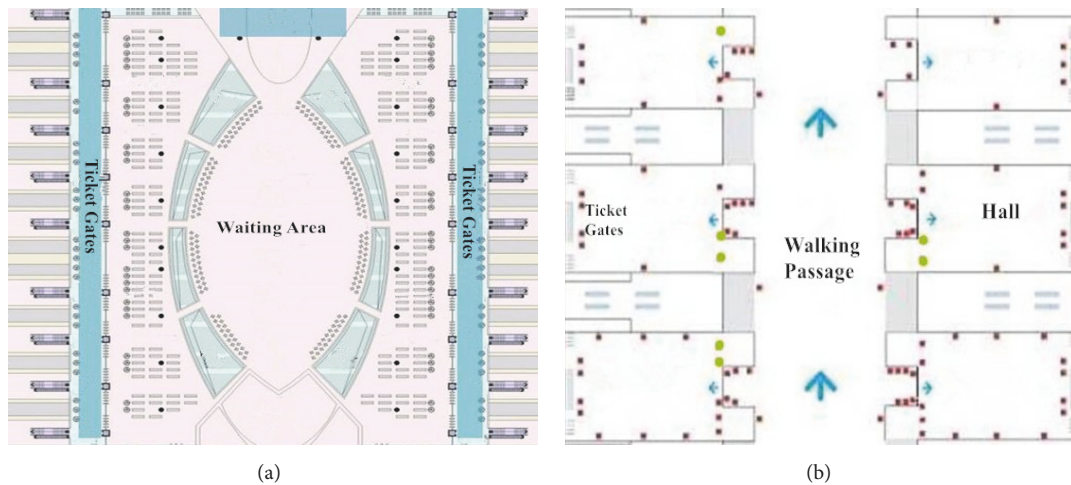


FIGURE 1: The sketches of the waiting hall, where (a) is the HSR waiting hall and (b) is the conventional railway waiting hall.

Few researchers studied the pedestrian management strategies during the boarding/alighting process at railway/metro station. To study this topic, Daamen et al. [16] carried out some laboratory experiments using video cameras to study the boarding/alighting behavior in the railway station and testified the effects of physical environment, population, flow composition, and prevailing traffic conditions on the boarding/alighting behavior. Zhang et al. [17] found that the controlling group size had some impacts on the alighting and boarding preference at metro stations. Seriani and Fernandez [18] studied the impacts of pedestrian management on each pedestrian's boarding/alighting time at the metro station and found that the management had significant effects on some indicators. Van den Heuvel [19] testified the solution of adjusting the train's stopping position along the platform to improve the railway capacity and pointed out that one slight adjustment of the stopping position resulted in a 20% decrease in the station's dwell time during the peak demand. Ahn et al. [20] developed a method to forecast the pedestrian flow pattern within a railway station and pointed out that the congestion on the current platform was alleviated if one new platform were placed, but the connecting passages to the new platform may become more congested.

In fact, the pedestrian dynamics at the HSR station and railway/metro station have some common properties (e.g., boarding behavior, congestion). Hence, the existing studies [17–20] can provide useful guidance to explore the HSR boarding process. However, pedestrian motion at the HSR stations differs from those at other stations in the following aspects.

(1) Passenger motion at the waiting hall: a typical waiting hall of HSR station in China is an open area including some ticket gates (see Figure 1(a)). The queuing in front of ticket barriers should be required and enforced, and the passengers' tickets are checked at the ticket gates by the automatic fare collection or manual fare collection. On the other hand, one typical waiting hall of conventional railway station in China is often a single waiting room (see Figure 1(b)). The passengers usually have their tickets checked manually. Furthermore, the metro station generally is not equipped

with a waiting hall. Therefore, the passenger's motion in the HSR station, conventional railway station, and metro station has differences due to the waiting hall layout and ticket-checking patterns.

(2) Passenger motion at the platform: each HSR platform is equipped with two entrances, which can be regarded as two obstacles for pedestrians who move along the platform. Passenger seats are preassigned; therefore, the destination carriage is automatically determined. When passengers are boarding the train at an origin HSR station platform, the pedestrian flow is obviously unidirectional.

(3) Passenger entrance choice behavior: during the boarding process, the passengers' behaviors include queuing and having their ticket checked at the hall, passing through the corridors that connect the hall and platform, and entering the platform from the platform entrances. Each HSR platform is equipped with two entrances and the passengers' seats and carriages are beforehand assigned, but the HSR platform is different from a conventional railway station platform and a metro station. Each ticket gate at the hall of the HSR station corresponds to an entrance at the platform. Each passenger chooses one ticket gate at the hall to enter the platform and is told to check in at the ticket gate closer to his/her carriage, so he/she will choose a proper ticket gate and entrance. For simplicity, we here assume that no passenger selects the improper ticket gate and entrance.

However, the existing studies cannot be used to evaluate the boarding process at the HSR station. During the HSR boarding process, the waiting hall and platform are the two most important scenarios due to the complex self-organized phenomena and high-density pedestrian flow, where heavy congestion and self-organized pedestrian dynamics often occur. To explore the scenario, Tang et al. [21] proposed a cellular automaton (CA) model to explore the passenger flow at the waiting hall of HSR stations during the check-in process and found that the passengers' arrival rate at the waiting hall and the service efficiency of ticket barriers have significant effects on the passenger dynamics at the waiting hall. The platform is worth studying since the boarding/alighting behaviors also exist. Many studies [14, 17, 18, 20, 22] have

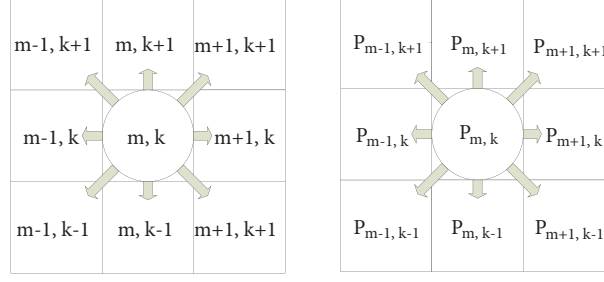


FIGURE 2: The scheme of Moore neighborhood.

explored the pedestrian dynamics at the platforms, but only a few have considered the platform at the HSR station. Tang et al. [22] proposed a CA model to study each passenger's boarding behavior at the HSR platforms and found that the passenger inflow rate and entrance choice behavior have great effects on boarding efficiency at the platform.

In this paper, we design three strategies to study the boarding behavior at an origin HSR station. This paper is organized as follows: the CA model is developed in Section 2; three strategies and eight cases are proposed to study the boarding efficiency in Section 3; some numerical tests are carried out to explore the influences of each strategy on the boarding efficiency in Section 4; and some conclusions are summarized in Section 5.

2. Model

Pedestrian flow models can roughly be divided into macro-models and micromodels, where the macromodels mainly explore the macrofeatures of pedestrian flow (e.g., speed, density, flow) and the micromodels mainly study each pedestrian's motion that considers the effects of self-motivation, intersections with each other, and intersections with surroundings. One of the most famous macromodels is the fluid dynamic model [23, 24], where the pedestrians' collective motions are displayed and qualitatively accordant with those observed in real situations [23]. Well-known micromodels are the social force model [25–27], the lattice-gas model [28–30], and the CA model [31–39]. In the CA model, the space is equally divided into cells and each pedestrian moves to neighboring cells based on his/her potential. Many pedestrian phenomena were studied with the CA model, including the bidirection pedestrian flow [36], the exit and route choice behaviors [33, 34, 37], and the competitive/cooperative behaviors [35, 38].

Next, we propose a CA model to describe each passenger's motion at the waiting hall and the platform of an HSR station. Due to the features of the scenario, this model is modified to be suitable for pedestrian motion at the HSR station. The floor is equally divided into cells of $0.4m \times 0.4m$. The Moore neighborhood is used to realize pedestrian position update in certain rules. Each pedestrian at cell m, k has nine options to move to the neighbor cell or keep still according to the transition probabilities (see Figure 2).

We use the logit model to define the transition probability. $P_{m,k}^{i,j}$ is the transition probability such that the passenger

at cell m, k chooses cell i, j . $N_{i,j}$ is the potential of cell i, j and relevant to the weight sum of the static floor field potential and the dynamic potential of cell i, j . $E_{i,j}$ is one 0-1 variable. $S_{i,j}$ is the static floor field potential which reflects the destination attraction of the obstacle repulsion. $L_{i,j}$ is the geometry distance between cell i, j and the destination, which can reflect the effects of the destination attraction on cell i, j . $O_{i,j}$ is the obstacle repulsion on the pedestrian's motion at cell i, j and is set as the number of cells that are not obstacle cells among the eight neighboring cells of cell i, j . $D_{i,j}$ is the number of empty cells among the eight neighboring cells of cell i, j , which can reflect the congestion degree around cell i, j . $k_s, k_D, k_L, k_O, k_1, k_2, k_3$ are seven influence factors, where k_s is one sensitivity of the static floor field potential to the passenger's motion benefit, k_D, k_3 are two sensitivities of the dynamic floor field potential to the passenger's motion benefit, k_L, k_1 are two sensitivities of the geometry distance to the passenger's motion benefit, and k_O, k_2 are two sensitivities of the obstacle repulsion to the passenger's motion benefit.

The hall and the platform of an HSR station have different layouts and structures, so $k_s, k_D, k_L, k_O, k_1, k_2, k_3$ are different in the two scenarios. On the one hand, k_1, k_2, k_3 have quantitative effects on the simulation results, but this topic is beyond the scope of this paper; on the other hand, these parameters have no qualitative impacts on the simulation results. $N_{i,j}$ drops with $L_{i,j}$ but increases with $O_{i,j}, D_{i,j}$. For simplicity, we set the parameters as follows: (1) $k_1 = -20, k_2 = 0, k_3 = 1$ at the waiting hall since there are no obstacles and (2) $k_1 = -5, k_2 = 1, k_3 = 1$ at the platform.

Based on the aforementioned discussions, we can define the following equations:

$$P_{m,k}^{i,j} = \frac{N_{i,j}}{\sum_{c=m-1}^{m+1} \sum_{d=k-1}^{k+1} N_{c,d}}, \quad (1)$$

$$i \in [m-1, m+1]; \quad j \in [k-1, k+1],$$

$$N_{i,j} = E_{i,j} \exp(k_s S_{i,j} + k_D D_{i,j}), \quad (2)$$

$$E_{i,j} = \begin{cases} 1, & \text{if the cell is empty} \\ 0, & \text{if the cell is occupied or obstacle,} \end{cases} \quad (3)$$

$$S_{i,j} = k_L L_{i,j} + k_O O_{i,j}, \quad (4)$$

$$N_{i,j} = E_{i,j} \exp(k_1 L_{i,j} + k_2 O_{i,j} + k_3 D_{i,j}). \quad (5)$$

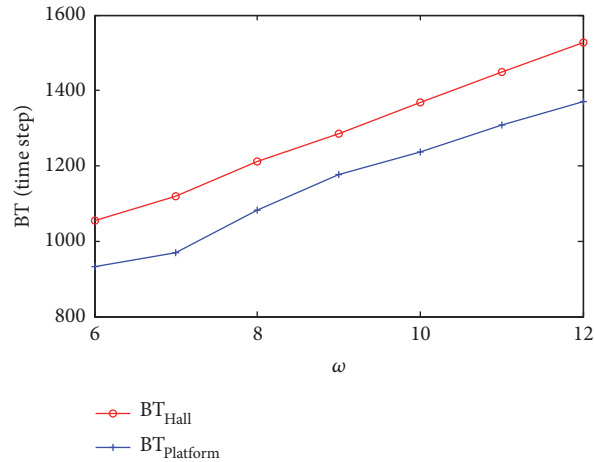


FIGURE 3: The boarding time at the waiting hall and platform.

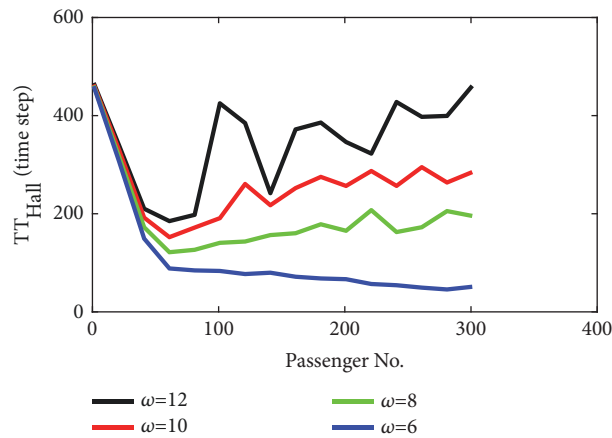


FIGURE 4: The passenger's motion time at the waiting hall during the check-in process under different ω , where the passenger's no. from 1 to 320 shows each passenger's entry order at one entrance of the waiting hall.

3. Boarding Strategies

Management strategies in transportation hubs may cover access gate, platform allocation, flow separation, moving walkway, and floor markings, [15]. In this paper, we design three boarding strategies that are suitable for optimizing the passengers' boarding process at the HSR station.

3.1. Strategies Description. According to the previous studies [21, 22] and the related literature, three boarding strategies that are believed to be effective and suitable to enhance the passengers' boarding process are formulated as follows.

Strategy 1 (enhancing ticket-checking efficiency). The check-in process includes the period that the passengers enter the hall, wait, line up in queues, have their tickets checked, and run across the ticket gates. Tang et al. [21] pointed out that the average time that each passenger runs across the ticket gate at Beijing South Railway Station is 4.77s and that the passengers have their tickets checked by staff and then apply the automatic fare collection machine to run across the ticket barrier. Therefore, the repeated work prolongs the check-in time. Of course, using of a single method (manual or

automatic check-in) is expected to enhance the check-in process. Wu et al. [40] found that the capacity of automatic ticket barriers is 1800ped/h (i.e., the passenger's average check-in time is 2s) while the empirical capacity is about 1500ped/h (i.e., the passenger's average check-in time is about 2.4s). During the real check-in process, the check-in time is longer than the expected time. Thus, it is possible that the passengers save the check-in time by changing the ticket-checking pattern or other available methods.

Tang et al. [21, 22] found that each passenger's check-in time (denoted by ω) affects the boarding efficiency (called the clearance time) at the waiting hall and platform (see Figure 3) and that his/her check-in time affects his/her motion time at the waiting hall during the check-in process (see Figure 4). The outcomes show that the passenger's check-in time is an important factor which determines the ticket-check efficiency. In practice, we can shorten the passenger's check-in time to enhance the ticket-check efficiency by changing the ticket-checking pattern. In this paper, the unit of ω is time step, where the time step is equal to 0.4s.

Enhancing ticket-checking efficiency is an effective and feasible way to enhance the boarding efficiency. We assume

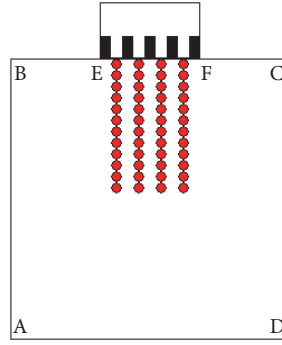


FIGURE 5: The sketch of passengers' boarding at the hall of an HSR station.

that the passenger's average check-in time is 2.4s in an ideal and efficient situation and that it is 4.8s in an inefficient situation. Thus, if Strategy 1 is used, the passenger's average check-in time should be 2.4s; otherwise, the passenger's average check-in time should be 4.8s.

Strategy 2 (check-in in groups at the waiting hall). Under this strategy, we classify the passengers into groups according to their carriage no. (i.e., each passenger should check in in a group). The ticket-check order is organized as follows:

(1) Passengers within the same carriage are sorted into a group.

(2) The greater the distance of the passengers' carriage to the entrance is, the earlier the group of passengers should check in.

This strategy reflects a case of platform allocation and is rarely used in the HSR/railway station, but we think that it will make sense at an origin station.

Strategy 3 (avoiding improper entrance choice at the platform). This strategy is developed for the HSR boarding. As presented in the introduction, each passenger displays entrance choice behavior. Passengers selecting an improper entrance should walk a long way at the platform, and this may prolong the motion time at the platform. Hence, this strategy can enhance the boarding efficiency. Note that this strategy is easily conducted manually or with signage guidance.

3.2. Boarding Management Cases. The three strategies may be useful for optimizing the boarding process at the HSR station, and they can be managed separately or simultaneously and do not have conflicts. Hence, we consider eight combinations of those three strategies. Here, we use XYZ to denote one case, where X, Y, and Z are binary variables, i.e., X, Y, and Z are formulated as follows:

$$X = \begin{cases} 1, & \text{if Strategy 1 is used} \\ 0, & \text{if Strategy 1 is not used,} \end{cases} \quad (6)$$

$$Y = \begin{cases} 1, & \text{if Strategy 2 is used} \\ 0, & \text{if Strategy 2 is not used,} \end{cases} \quad (7)$$

TABLE 1: Definitions and composition of eight cases.

	Strategy 1	Strategy 2	Strategy 3
Case 000	×	×	×
Case 001	×	×	√
Case 010	×	√	×
Case 011	×	√	√
Case 100	√	×	×
Case 101	√	×	√
Case 110	√	√	×
Case 111	√	√	√

Note: √ means the strategy is used; × means the strategy is not used.

$$Z = \begin{cases} 1, & \text{if Strategy 3 is used} \\ 0, & \text{if Strategy 3 is not used.} \end{cases} \quad (8)$$

Thus, we can obtain eight cases (see Table 1).

4. Simulation

In this section, we simulate the boarding efficiency at the HSR station under the above eight cases. The simulations are implemented in Microsoft Visual Studio 2012. To compare the simulation results, we apply the eight cases to respectively simulate each passenger's motion at the hall/platform during the boarding process. In this paper, we assume that each passenger's desired speed is 1 m/s and the time step is 0.4s. In addition, we simplify the scenario and make some basic assumptions.

4.1. Scenario and Assumptions. The first scenario is the waiting hall where passengers wait and check in. Here, we provide the following facts based on the previous study [21] and observations:

(1) The waiting hall of an HSR station during the check-in process is approximately a rectangle, where the size is 12m×10m; no obstacles exist, most passengers enter the hall from the bottom side of the hall (i.e., the line AD in Figure 5), and each passenger leaves the hall from one of the four ticket barriers (see Figure 5).

(2) Each passenger's initial origin is the position where he/she enters the hall, and his/her destination is the ticket

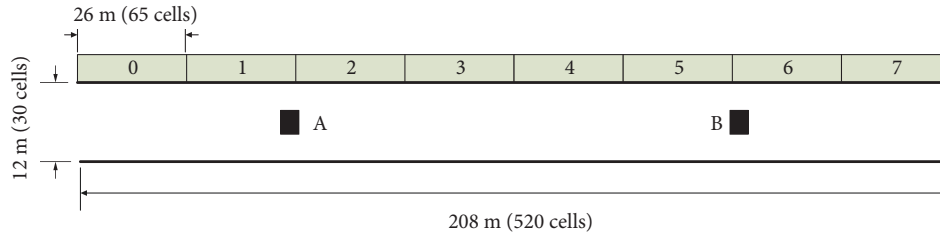


FIGURE 6: The simplified sketch of the HRS platform.

barrier where he/she leaves the hall. Note: each passenger can run across the ticket barrier only after his/her ticket is checked.

(3) All passengers must queue in line to leave the ticket barrier during the check-in process, where one ticket barrier serves only for one queue.

(4) The station is one origin station, the train is loaded to full capacity of 640 passengers, and two ticket gates simultaneously serve passengers of this train.

Thus, we can make the following assumptions:

(1) The waiting hall is equally discretized into 30×25 cells, where the cell size is $0.4\text{m} \times 0.4\text{m}$; the width of each ticket barrier is 0.4m ; i.e., no passengers can run across the ticket barriers side by side.

(2) Each passenger enters the hall from the bottom side and leaves the hall only from one of the four ticket barriers (see Figure 5).

(3) Each queue has 12 passengers before check-in. The first passenger enters the hall three minutes before the check-in starts. Also, each queue's capacity is 12 cells due to the space limitation, that is, when the number of passengers in each queue is 12 while other passengers wait near the queue and do not enter the queue.

(4) Two waiting halls serve 640 passengers who board the same train, where each hall serves 320 passengers. The passenger's No. from 1 to 640 indicates each passenger's entry order at the whole waiting hall.

(5) The passenger's average arrival interval at the waiting hall is equal to 0.8s; the check-in time is 4.8s or 2.4s, which determined whether each passenger uses Strategy 1 or not.

The second scenario is the platform, where the passengers move from the waiting hall to their carriages. Various attributes about the platform and the passengers' motions at the platform can be summarized as follows:

(1) The platform is set as a rectangle of $208\text{m} \times 12\text{m}$ (see Figure 6).

(2) Each carriage's capacity is 80 passengers.

(3) Each passenger's initial position lies at the right hand of square A or the left hand of square B (A and B represent two entrances) (see Figure 6).

To make the simulation executable, assumptions are also needed.

(1) The platform is divided into 520×30 cells, where the cell size is $0.4\text{m} \times 0.4\text{m}$ and the entrance size is 10×10 cells; the carriage length is 65 cells and the width of the carriage door is 1 cell; i.e., two passengers cannot enter the carriage side by side.

(2) To model passengers' entrance choice behavior, it is assumed that 90% of passengers select the entrance closer to their target carriage and 10% select the entrance away from their target carriage.

(3) In order to simplify the boarding process, each passenger's motion in the corridor connecting the ticket gates and the platform is ignored. The passengers who run across the ticket gate at the waiting hall will soon enter the linked entrance at the platform.

4.2. Simulation Results. First, we simulate the boarding time under the above eight cases. The boarding time under the eight cases is shown in Figure 7, where BT_{Hall} is the boarding time at the hall and BT_{Platform} is the boarding time at the platform. Note: $BT_{\text{Hall}}/BT_{\text{Platform}}$ is defined as the difference between the time that the first passenger enters the hall/platform and the time that the last passenger leaves the hall/platform. From Figure 7, we have the following:

(1) BT_{Hall} is approximately equal under cases 000, 010, 001, and 011; similarly, BT_{Platform} is approximately equal under cases 100, 110, 101, and 111. BT_{Hall} under cases 000, 010, 001, and 011 is prominently greater than those under cases 100, 110, 101, and 111. The results indicate that Strategy 1 is a key factor that influences BT_{Hall} and can prominently reduce BT_{Hall} .

(2) By comparison of cases 000, 010, 011, and 111, we can see that if one strategy is added to the current case, the reduction of BT_{Platform} will be more prominent and each strategy can reduce BT_{Platform} . By comparison of cases 010, 001, and 100, we can see that BT_{Platform} is the shortest under case 100 and the longest under case 010, which shows that Strategy 1 is the best for reducing BT_{Platform} while Strategy 2 is the worst for reducing BT_{Platform} .

Next, we study the passenger's individual indicator. Each passenger's motion time is an important indicator that evaluates the boarding efficiency. Each passenger's motion time will often be prolonged if congestion occurs. Since congestion occurs at the hall of the HSR station during the check-in process, we explore the passenger's motion time under the eight cases (see Figure 8), where TT_{Hall} is each passenger's motion time at the waiting hall of the HSR station during the boarding process. From Figure 8, we have the following:

(1) TT_{Hall} under cases 000, 010, 001, and 011 is similar, but TT_{Hall} of the late arrivals is relatively high. TT_{Hall} has the following features. (a) If the passenger No. is not larger than 96, TT_{Hall} linearly decreases with the passenger No., where the reason is that the 96 passengers can quickly finish check-in because no congestion occurs and the check-in time (i.e.,

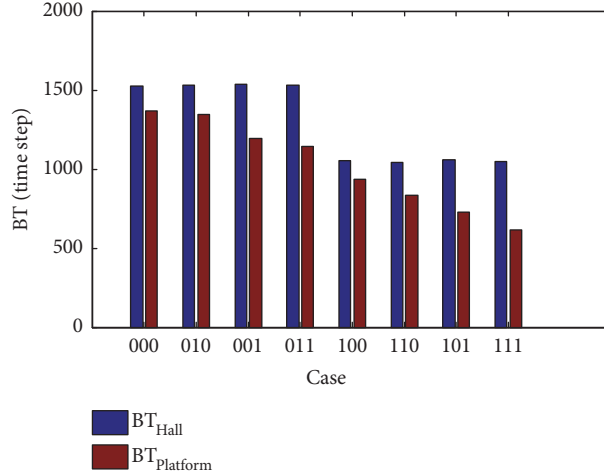


FIGURE 7: BT_{Hall} and $BT_{Platform}$ under the eight cases.

4.8s) is larger than the time gap of two adjacent passengers' arrival time (i.e., 0.8s). Thus, the earlier each passenger enters the hall, the longer is his/her motion time. (b) If the passenger's No. is greater than 96, his/her motion time will gradually grow with his/her No., but this tendency is not stable, where the reason is that all passengers meet congestion and must enter the queues to run across the ticket gate. When the congestion degree increases, some late arrivals cannot immediately enter the queues and the heavy congestion may break the rule of first-in-and-first-out. Therefore, the curve has oscillating phenomena.

(2) TT_{Hall} under cases 100, 110, 101, and 111 is similar, and TT_{Hall} of late arrivals is relatively small. The curves can be sorted into two parts and the drop rates differ, where the reason is that using Strategy 1 enhances the ticket-check efficiency and eliminates congestion. For the passengers who queue in advance, their motion time satisfies the following rules: the earlier the passenger enters the hall, the longer the motion time. For the passengers who arrive late at the waiting hall, their boarding process strictly obeys the rule of first-in-and-first-out.

The passenger's motion at the platform is similar to the free flow since no congestion occurs, but the distribution of each passenger's motion time at the platform is interesting. Next, we study $TT_{Platform}$ under the eight cases (see Figure 9), where $TT_{Platform}$ is each passenger's motion time at the platform of the HSR station during the boarding process. From Figure 9, we have the following:

(1) If Strategies 2 and 3 are not used (see cases 000 and 100), there are no obvious relationships between each passenger's motion time and his/her No.

(2) If Strategy 3 is used while Strategy 2 is not used (see cases 001 and 101), the positive impacts of avoiding the improper entrance choice at the platform are relatively prominent. Comparing case 000 with case 100, we find that no passengers will encounter an extremely large motion time; that is, Strategy 3 can effectively prevent passengers from entering the platform from the improper entrance. As a result, this strategy can avoid the needless waste of motion time.

(3) If Strategy 2 is used while Strategy 3 is not used (see cases 010 and 110), the positive impacts of check-in in groups are quite prominent. For the passengers who late enter the platform (i.e., their Nos. are relatively large), their motion time is shorter.

(4) If Strategies 2 and 3 are applied (see cases 011 and 111), the curve indicates that the passenger's motion at the platform is efficient and in good order. The extremely high-value scattered points do not occur and all points converge to a narrow range.

Finally, we study the congestion degree under the eight cases. Density is often used to evaluate the congestion degree. Calculating the pedestrian density requires discretizing the space. However, the discretization scheme influences the numerical results [15]. Here, we use the number of block-ups to explore the congestion degree under the eight cases. The definition is as follows: when a pedestrian's neighborhood cells in the eight directions are occupied, this situation is regarded as a block-up. This definition can be explained from the following two perspectives:

(i) Each passenger's number of block-ups during the boarding process is the total time steps when the passenger is blocked up.

(ii) At each time step, the number of block-ups is set as the number of blocked-up pedestrians.

Thus, we study the number of block-ups during the boarding process. No congestion occurs at the platform, so we need only study the block-ups at the waiting hall under the eight cases (see Figure 10), where $N_{Hall}^{Block-up}$ is the number of block-ups at the waiting hall. From Figure 10, we have the following:

(1) $N_{Hall}^{Block-up}$ under cases 000, 010, 001, and 011 is similar, where the values are prominently larger than the ones under cases 100, 110, 101, and 111. The reason is that Strategy 1 can relieve waiting and congestion at the waiting hall.

(2) If Strategy 1 is not applied, $N_{Hall}^{Block-up}$ will gradually increase before the peak and then will drop to 0. This indicates that the congestion becomes heavier with continuous arrivals

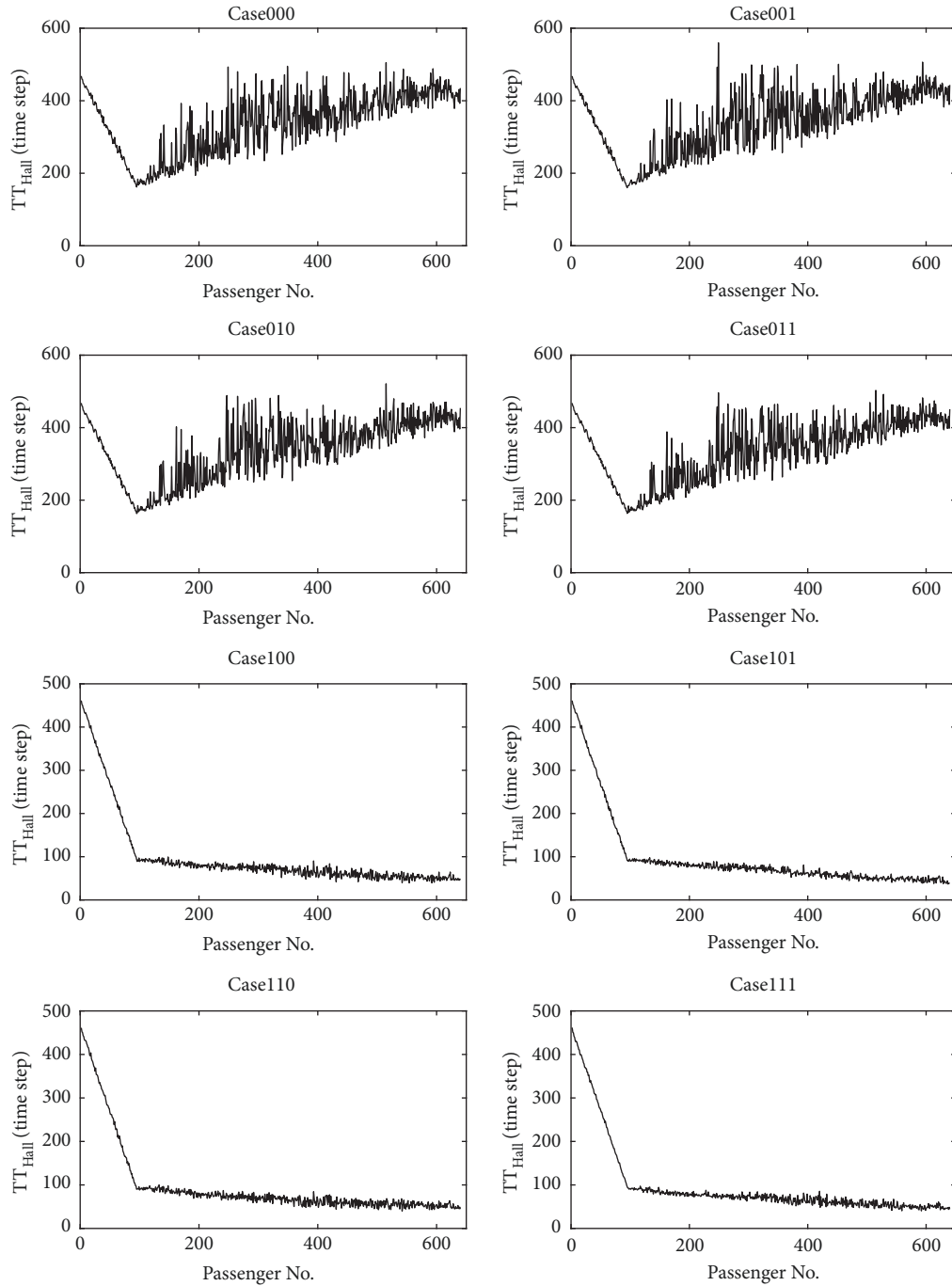


FIGURE 8: TT_{Hall} under the eight cases.

entering the hall, but when all passengers enter the hall, the congestion gradually diminishes.

Finally, we explore the relationship between $N_{Hall}^{Block-up}$ and time under the eight cases (see Figure 11). From Figure 11, we have the following:

- (1) Almost all block-ups occur in the mid time of boarding.
- (2) When congestion is heavy, all the block-ups occur from the 500th time step to the 1400th time step (see

Figure 11(a)), which is the main part of the boarding process; when no congestion occurs, the block-ups occur from the 500th time step to the 1000th time step (see Figure 11(b)).

5. Conclusion

In this paper, we propose a CA model and three strategies to optimize the passengers' motions at the waiting hall and platform of the HSR station during the boarding process. To

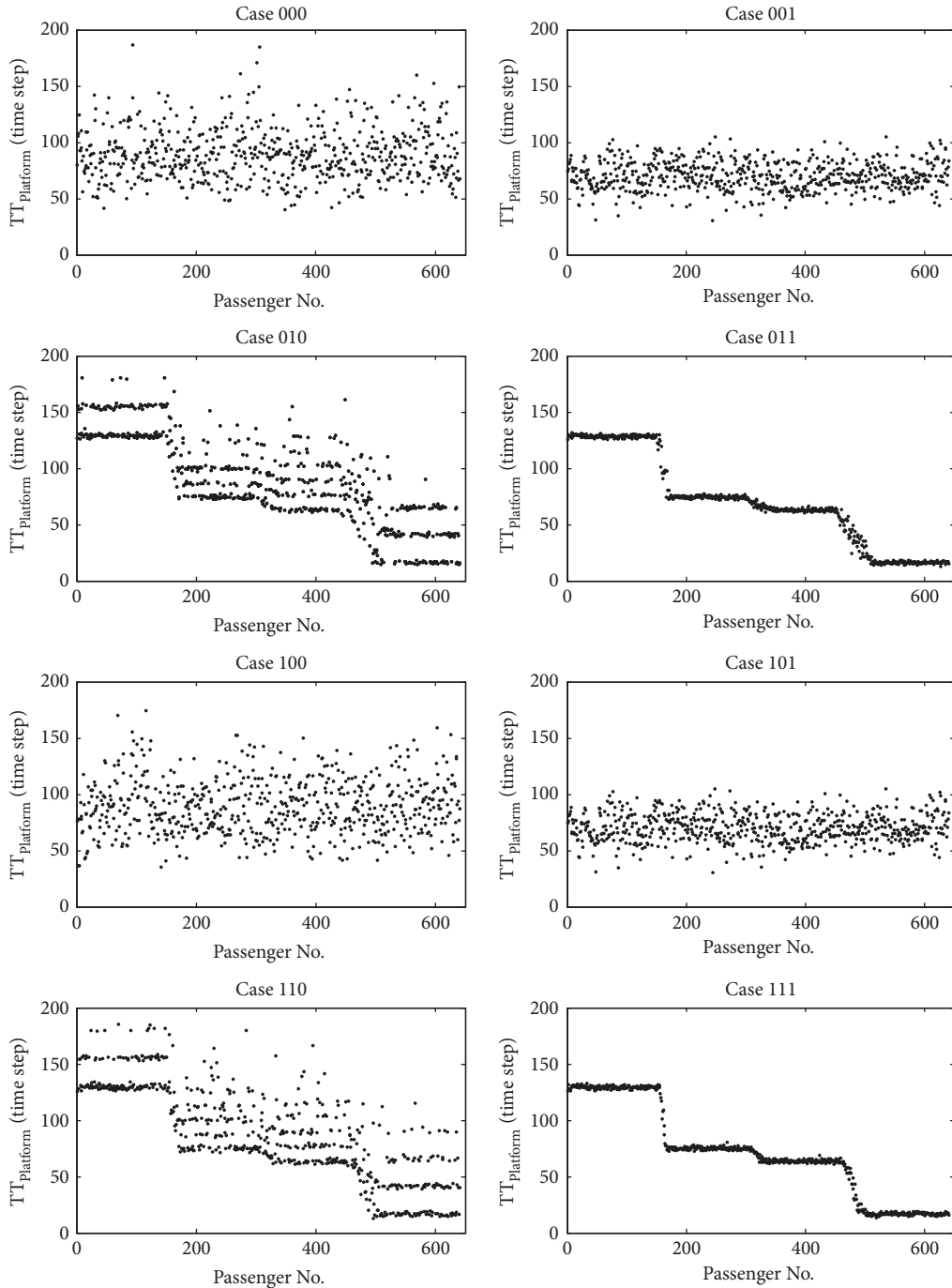


FIGURE 9: TT_{platform} under the eight cases.

evaluate the three boarding strategies (i.e., enhancing ticket-checking efficiency, checking in in groups at the waiting hall and avoiding improper entrance choice at the platform), we apply eight cases in combinations of three strategies to explore the impacts of the three strategies on the boarding time, motion time, and the number of block-ups. The numerical results indicate that those three strategies can streamline the boarding process, with the improvement being most

prominent when those three strategies are simultaneously used. Specifically, Strategy 1 can reduce each passenger's travel time at the waiting hall. Strategies 2 and 3 can both distribute each passenger's motion time in good order; only Strategy 1 can reduce the number of block-ups at the waiting hall.

However, this paper has the following limitations:

(1) The simulation results are not tested with experimental/empirical data.

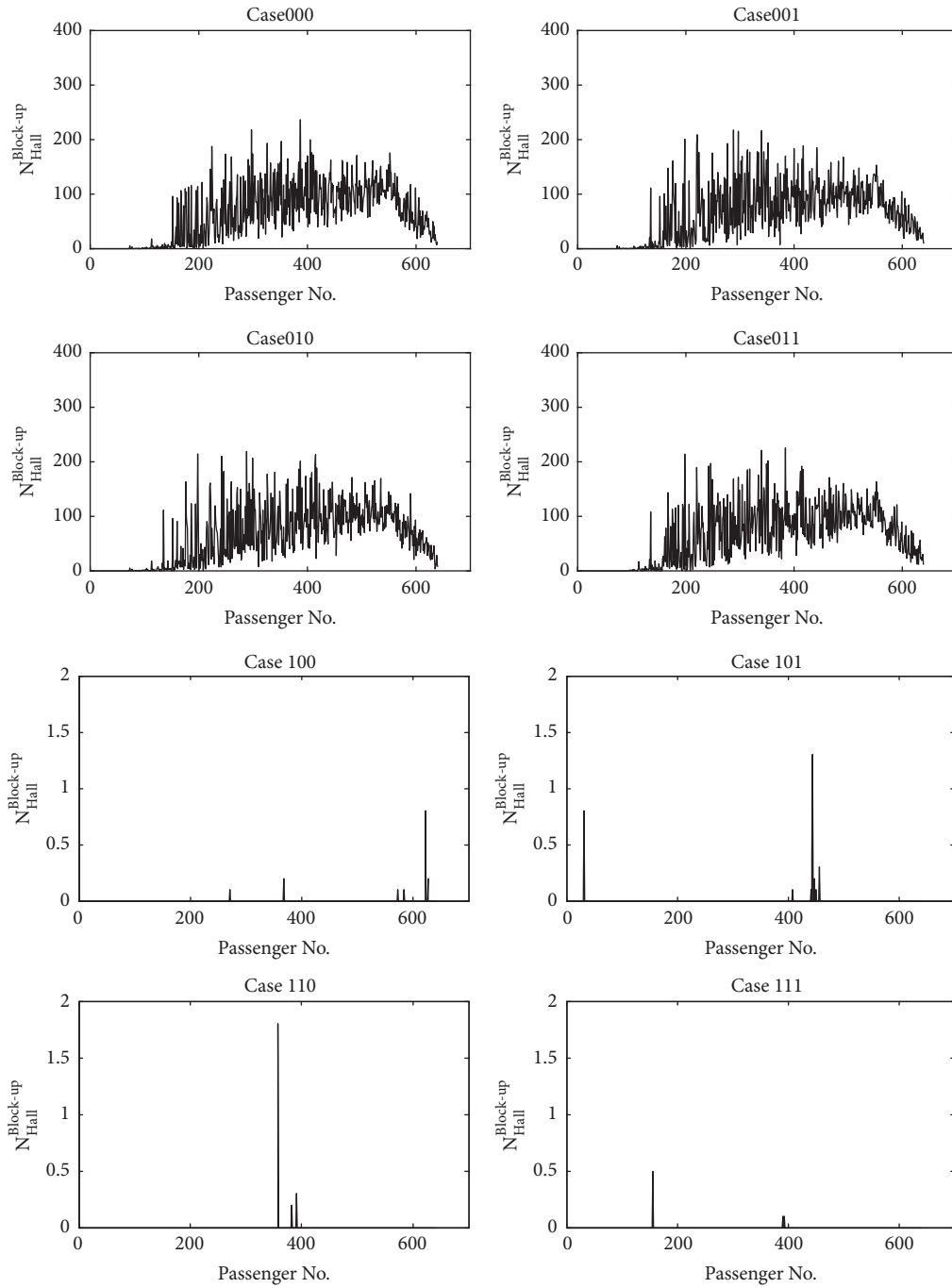


FIGURE 10: $N_{Hall}^{Block-up}$ under the eight cases.

(2) This study does not consider the microattributions of pedestrians (e.g., velocity, luggage).

Therefore, we will use experimental/empirical data to propose a more realistic model/strategy to study the HSR boarding process in the future.

Data Availability

The original codes of the numerical tests used to support the findings of this study are available from the corresponding author upon request.

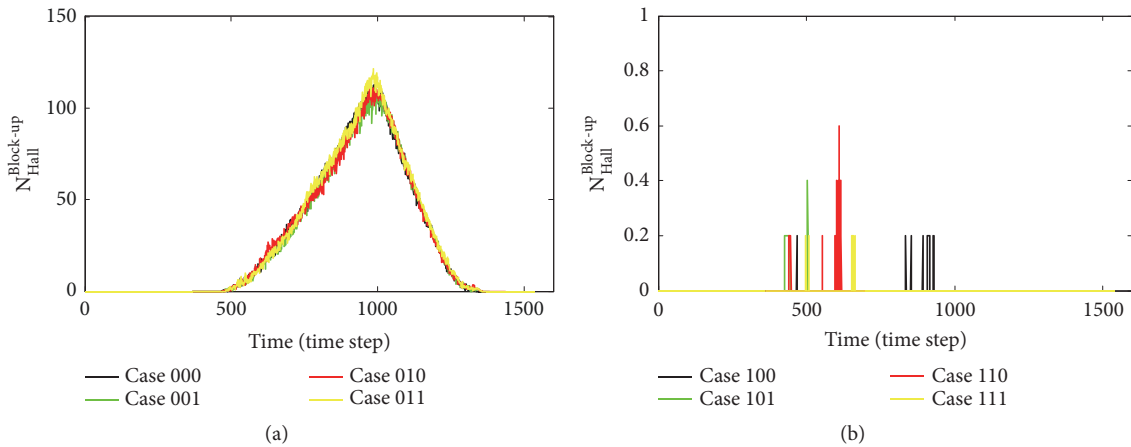


FIGURE 11: Relationship between $N_{Hall}^{Block-up}$ and time under the eight cases.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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