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Effect of Right-Hand Traffic Rules on Evacuation Through Multiple Parallel Bottlenecks

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Abstract. In a transportation hub complex (THC) in China, ticket entrance gates and station exits are common bottlenecks. Although road traffic in China follows right-hand traffic rules, the influence of right-hand traffic rules on the movement characteristics of pedestrians passing through such facility bottlenecks have been investigated rarely. In this article, simulation experiments are conducted to investigate the effect of THC bottle-necks on pedestrian movement characteristics given the existence of right-hand road traffic rules. Based on the use of a combination of histograms of oriented gradients and support vector machine algorithms, the movement behavior of pedestrians passing through multiple parallel bottlenecks are extracted. A total of 21 scenarios are considered in this simulation experiment, consisting of two-opening and three-opening parallel bottlenecks, where the width of each opening and width of the barriers between adjacent openings are varied. This study provides fundamental data for pedestrian flow passing through multiple parallel bottlenecks, data that can help identify important parameters for the design and improvement of many kinds of pedestrian flow management facilities. Results from the study also will be useful for the development and verification of evacuation models.

Keywords: Pedestrian dynamic, Traffic rules, Transportation hub complex, Video image processing, Evacuation, Evacuation bottlenecks

1. Introduction

Efficient pedestrian traffic and effective pedestrian evacuation in an emergency such as a fire is an important challenge for large-scale, crowded places such as a transportation hub complex (THC). The THC is a railway station that allows for passengers to conveniently transfer among a variety of transport modes, while allowing for the integration of shopping, entertainment, leisure and other

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functions. According to the Medium- and Long-Term Railway Network Planning Program of China, 42 high-speed passenger-dedicated lines are to be completed by the end of 2012. The operating railway mileage of passenger dedicated lines will be more than 16,000 km by the end of 2020. Therefore, a large number of railway stations are being built or are under construction. Most of the newly constructed and designed railway stations are of the THC type. Therefore, optimization of pedestrian flow lanes and the management of crowd evacuation routes are essential.

Currently, about 66.1% of the world's population lives in countries that follow the right-hand traffic rule. Furthermore, about 72% of the world's total roadway carries traffic following this rule [1]. The term right-hand or left-hand traffic rule in this article refers to regulations for all bidirectional vehicle traffic to stay on the right- or left-hand side of the road, respectively [2]. China is an example of a country following the right-hand traffic rule. Although Chinese law has no regulations and restrictions to require pedestrians to travel on the right or left side, pedestrian traffic is affected by the traffic rules for vehicles. According to a comparison of experimental results, Ma et al. [3] found that the preference in Chinese pedestrians for right-side travel in traffic is more obvious than that in French pedestrians.

Due to a large population, public transportation facilities are usually crowded in China. In order to avoid congestion in pedestrian traffic, people are conditioned to move in accordance with the right-hand traffic rules of the road. Thus, they choose to walk on the right side and as a mass, rather than as individuals. However, the movement characteristics of evacuating individuals for a predominantly right-handed traffic rule population, passing through multiple parallel bottlenecks such as ticket entrance gates and station exits, have rarely been investigated. The simulation experiments in this study therefore focus on this problem.

Extraction of pedestrian movement behavior from video images is an effective approach to investigate and quantify the movement characteristics of pedestrian flow. However, there are two different ways of analyzing the video images: artificial statistics and automatic extraction with video image processing technology. The first is the derivation of artificial statistics or more abstract relationship data quantifying the pedestrian movement behavior. The second is an analysis of the fundamental data automatically extracted from video images.

Extraction and analysis with artificial statistics is a traditional method. A variety of simulation experiments for different typical scenarios have been conducted during recent years based on this method. Fang et al. [4] conducted research of the crowd movement in an exit tunnel of a main railway station in Wuhan City during the rush hours of Chinese Spring Festival. Gwynne et al. [5] extracted the micro-movement characteristics of pedestrians who entered an arena and explored the nonlinear relationship between doorway width and pedestrian flow rate. Isobe et al. [6] performed some experiments to investigate the pedestrian counter flow in a channel with open boundaries. Helbing et al. [7] studied the process of evacuation from a classroom. In addition, some simulation experiments for special scenarios or special populations have also been carried out. Nagai et al. [8] investigated the counterflow of students crawling, or going on all fours, to simulate evacuation from a smoke-filled room through a corridor with low ceiling or when an earthquake takes place. Furukawa et al. [9] reproduced the group evacuation behavior of elderly individuals using average age people wearing an elderly simulator. Tsuchiya and Hasemi [10] studied the evacuation characteristics of a group of individuals who were wheel chair users.

Automatic extraction is a relatively more recent and advanced method compared to artificial statistics. This approach allows for pedestrian movement behavior parameter identification and analysis of typical pedestrian flow characteristics with video image processing technology. Seyfried et al. [11] and Song and Liu et al. [12–14] investigated the micro-movement characteristics of pedestrians, such as individual velocity, density and individual time gap, in building bottlenecks and single-file pedestrian movement scenarios. The characteristics of pedestrian lane formation, pedestrian movement behavior in the same lane, change of velocity and distance between two successive pedestrians were discussed in their research. Hoogendoorn et al. [15–18] conducted a series of walking experiments to study the condition of over-saturated bottleneck pedestrian flow and also bi-directional and crossing pedestrian flows.

The approach using automatic extraction of the pedestrian movement behavior parameters with video image processing technology is more suitable for huge transportation facilities with large pedestrian flows, complex flow directions and uneven distribution of passenger load. It is well known that collecting pedestrian movement behavior parameters in real pedestrian flow is the best method for research on movement characteristics of pedestrians. However, some factors are not controllable in the acquisition of behavior parameters in real pedestrian flow. Moreover, the large-scale simulation experiments of real scene pedestrian flow are difficult to organize and bring a risk of accidental injury for volunteers involved in the simulation experiment. Therefore, at present, small-scale pedestrian flow experiments to simulate typical pedestrian flow is a commonly used method in research on movement characteristics of pedestrians. Although there are some differences in pedestrian behavior between a small-scale simulation experiment and real pedestrian flow, small-scale experiments can be applied to observe some basic patterns and characteristic phenomena of pedestrian movement.

Recent research on evacuation simulation models is mainly focused on the social force model [19, 20], lattice model [7, 21] and cellular automata model [22, 23]. These models predict pedestrian behavior based on real-life observations and the collection of movement characteristic parameters. The results of small-scale simulation experiments can provide fundamental data for these models.

Based on the above discussion, a series of simulation experiments were conducted in this study. The automatic extraction method for pedestrian movement behavior parameters with video image processing technology was used. In these experiments, twelve scenarios with two openings and nine scenarios with three openings were considered to investigate the influence of the traffic rules. In addition, the width of the opening and width of the barriers between adjacent openings were also considered in this study. Using custom software, characteristic parameters such as the distribution of pedestrian number, pedestrian time interval between two successive pedestrians, flow rate and specific flow rate were extracted and analyzed.

2. Experiment

2.1. Experimental Scenarios

Based on the results of field research at the Nanjing South and the Hefei railway stations, as well as the Code for Design of Railway Passenger Station Buildings (GB 50226-2007) Clause 6.4.2 (the ticket entrance should adopt flexible or movable railings. The wicket channel should be straight and its net width is not less than 0.75 m) the minimum width of the opening in the simulation experiments was set to 0.75 m. In the scenarios with two and three openings, the width of the opening was increased 0.1 m, from 0.75 m to 0.95 m. At the same time, following THC field research of ticket entrances, exit and fare gates in stations within Hong Kong, Beijing, Shanghai, Nanjing, Hefei and other cities, the minimum distance interval between adjacent openings, or width of the barrier, is set to 0.4 m. The maximum barrier width was set to 0.8 m in the scenarios with two openings and 0.6 m in those with three openings. Therefore, four barrier widths (namely 0.4 m, 0.5 m, 0.6 m and 0.8 m) were investigated in the scenarios with two openings. Three barrier widths (namely 0.4 m, 0.5 m and 0.6 m) were investigated in the scenarios with three openings. A total of 21 simulation experiments were conducted. Referencing the preceding "Code for Design," which requires, "The length of the wicket channel centerline should not be less than 1.5 m," the channel length was set to 1.5 m. In most of the newly constructed THC, an automatic swing gate is used to check the ticket. In normal situations, pedestrians pass through the swing gate by inserting their ticket and taking it out. In an emergency situation, the swing gates stay open. The experimental scenarios studied here represented the situation when the doors stay open in an emergency.

2.2. Experimental Set-up

The simulations were conducted in front of the experimental building in a large space in the State Key Laboratory of Fire Science, University of Science and Technology of China, in November, 2012. A video camera with a 1,440 × 1,080 resolution was used to record pedestrian flow movement while suspended at an angle close to vertical (the angle between camera and ground was greater than 80°) on the fourth floor of the experimental building (approximately 15 m above the ground). The video recordings from this vantage point (angle and position) were conducive to analyzing the movement characteristics of evacuation through multiple parallel bottlenecks.

In the experiments, the narrow channel was created by using both cordon and isolation fence to simulate multiple parallel bottleneck facilities such as ticket entrance, exit and fare gate in a THC. The "passengers" in the experiments were volunteers from the University of Science and Technology of China. The 42 participants, 17 female and 25 male, were all students between 21 years and 29 years. The average age was 23.2 years, with a female average age of 22.9 years and a male average age of 23.3 years. The height of all participants was from 1.55 m to 1.82 m. The average height was 1.688 m, with a female average of 1.615 m and a male average of 1.737 m. All the participants were asked to act and walk as if in a

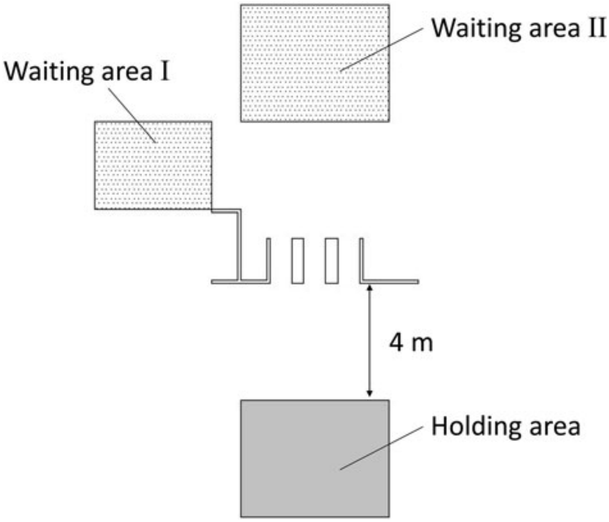

Figure 1. Experimental setup.

transportation facility during the experiments to ensure the experimental results were more realistic.

Figure 1 shows the experimental setup. Here, the scenario with three openings is shown, as an example. At the beginning of each experiment all the participants stood in the holding area. The distance between the holding area and the entrance of openings was 4 m. When the experiment started, all participants walked to the multiple parallel bottlenecks simultaneously. In order to eliminate the interference of the participant location on the selection for openings, the distribution of the participants in the holding area was symmetrical.

There were two separate waiting areas that were used in different experiment scenarios. These were provided in order to investigate the effect of the expectation of turn direction on the choice of opening. Some scenarios required the pedestrians to travel left through the openings to get to Waiting area I and other scenarios required travel straight through the openings to get to Waiting area II.

3. Method

In this study, the method of pedestrian recognition and tracking through video image processing technology was used to investigate a number of movement behaviors. Given the right-hand traffic rules, the pedestrian count through each opening, time interval between successive pedestrians, flow rate of pedestrians and specific flow rate were analyzed. Pedestrian recognition was achieved by the combination of histograms of oriented gradients, HOG, [24] and support vector machine, SVM [25, 26], algorithms. The template matching technique was used for pedestrian tracking.

To begin with, the pedestrian samples are extracted to calculate the HOG descriptor and input to SVM for training. Then the HOG descriptor of the region where a pedestrian had occurred in each frame of video sequence was calculated and input into the SVM for detection. The frames of video were evaluated to count and time pedestrian traffic flow using a comparison matching algorithm. If a pedestrian was detected in the current frame which matched the information for the pedestrian saved in the previous frame, then the pedestrian count was unchanged. If it did not match, then the pedestrian count was incremented by one. If no pedestrian was detected in the current frame, it continued to the next frame.

Since the contour and color of a pedestrian in the video changed insignificantly between the two adjacent frames in our experiments, these features were used for pedestrian recognition. Using contour and color features can maintain the accuracy of pedestrian recognition. In addition, HOG descriptors have better robustness to illumination changes and shadows, which can diminish the influence of illumination light changes and shadows. The experiments were carried out during the afternoon time from 15:00 to 17:30. Therefore, there were some differences in illumination and shadow among those scenarios. It was found in this study that the algorithm used here could effectively solve the interference of illumination and shadow changes for pedestrian detection.

4. Results and Discussion

4.1. Pedestrian Count

To begin with, the pedestrian counts for each opening in the multiple parallel bottlenecks were analyzed. Figure 2 shows the pedestrian count for the scenarios with two openings. Three opening widths (namely 0.75 m, 0.85 m and 0.95 m) and four different barrier widths between openings (namely 0.4 m, 0.5 m, 0.6 m and 0.8 m) were considered in the experiments. In this study, the width of a single opening is represented by w. The barrier width is represented by D. Figure 2 shows that, in most scenarios with two openings, the majority of pedestrians chose the opening on the right side. In order to investigate the effect of the expectation of turn direction on the choice of opening, the participants were required to turn left into the waiting area I (see Figure 1) after passing through multiple parallel bottlenecks in the four scenarios, which are shown in Figure 2a. In the scenarios that are shown in Figure 2b, c, the pedestrians were required to walk straight ahead into waiting area II after passing through multiple parallel bottlenecks. From Figure 2a it can be seen that, despite the expectation to turn left after passing through the openings, the majority of pedestrians in two of the four scenarios chose the right-side opening. In those scenarios where pedestrians are required to walk straight ahead, it is obvious that the majority of pedestrian chose the right-side opening due to the effect of the traffic rules.

In the scenarios with three openings, the majority of pedestrians in most scenarios chose the right opening. Of the nine scenarios with three openings, only two scenarios resulted in more pedestrians choosing the center opening than those choosing the right opening, as is shown in Figure 3. According to the results of all

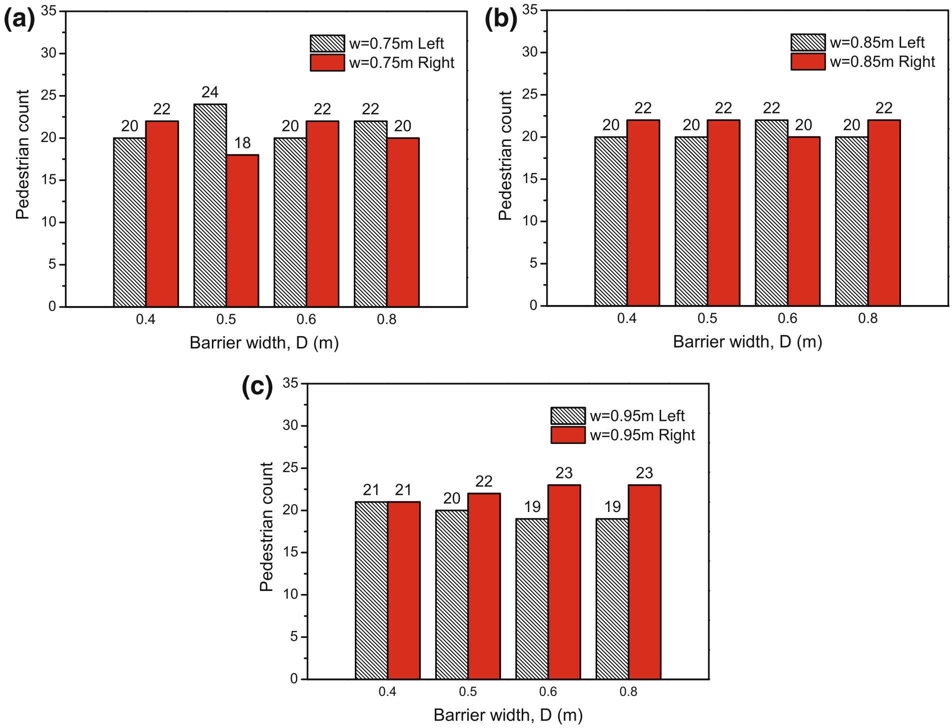

Figure 2. Pedestrian count in scenarios with two openings where (a) $w = 0.75$ m and pedestrians turned left; (b) $w = 0.85$ m and (c) $w = 0.95$ m and pedestrians travel straight through.

the scenario experiments, it can clearly be seen that the pedestrian choice of openings is influenced by traffic rules in the scenarios with two and three openings.

4.2. Time Interval Between Successive Pedestrians

The time interval between two successive pedestrians was analyzed in this study in order to further investigate the difference of the micro-movement characteristics of pedestrians choosing right or left openings. The entrance and exit of the channel were chosen as the start and finish lines for recording the time interval. By investigating the time interval, further progress was made on analyzing the effect of traffic rules on micro-movement characteristics of pedestrians.

The time interval between successive pedestrians fluctuated around a mean value. To facilitate the comparison between different scenarios, the mean values of time interval are used in this discussion. Figure 4 shows the time interval at the entrance of the scenarios with two openings. It can be seen that in most scenarios with two openings, regardless of $w = 0.75$ m, $w = 0.85$ m or $w = 0.95$ m, the time interval at the left opening is greater than that of right opening. The time interval results are consistent with the results of the pedestrian count. Because the

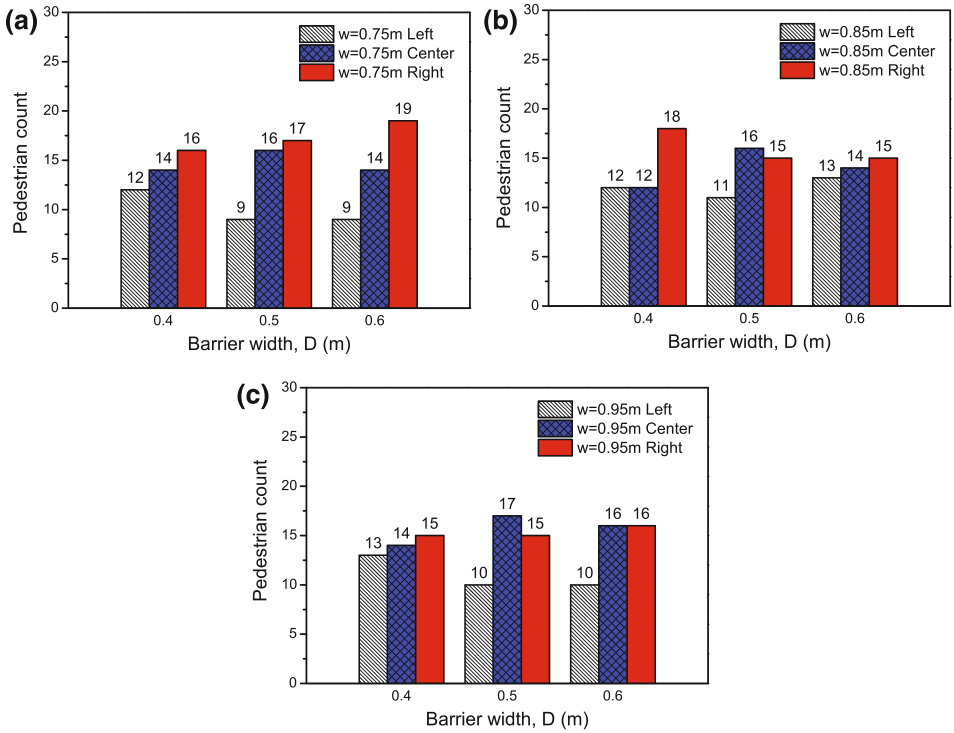

Figure 3. Pedestrian count in scenarios with three openings where (a) *w* = 0.75 m, (b) *w* = 0.85 m and (c) *w* = 0.95 m; pedestrians travel straight through in all (a), (b) and (c) cases.

majority of pedestrians chose the right opening, the degree of congestion outside the right opening was higher than that outside the left opening. Therefore, the mean time interval at the entrance of the right opening is less than that at the left opening. In addition, it was noticed in the video recording that some pedestrians who finally chose the left opening originally intended to pass through the bottleneck by the right side opening. They changed travel lanes due to the congestion outside the right opening. As shown in Figure 5a–c, the pedestrian initially chose the right opening and waited at Location 1. Then he changed his direction at Location 2 due to the congestion outside the right opening. At Location 3, the pedestrian entered the left channel. According to the experimental results, except for the scenario when w = 0.75 m and D = 0.5 m (due to the effect of expectation to turn left), the time interval at the entrance at the left opening was an average value of 7.85% larger than that at the right opening, ranging from 0.48% to 21.2%.

The comparison of the time interval between successive pedestrians at the entrance and the exit will be further discussed in future work. In this article, the main focus is the relationship among the parameters of the right, left and center openings. However, the situation of time interval between successive pedestrians at

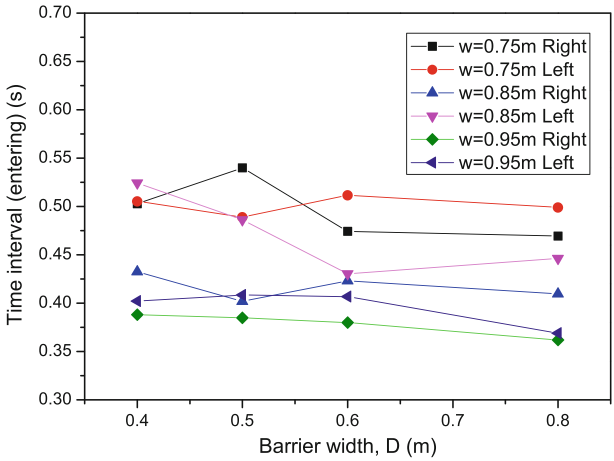

Figure 4. Mean time interval at entrance in scenarios with two openings of *w* = 0.75 m, *w* = 0.85 m and *w* = 0.95 m.

Figure 5. Pedestrian who changed travel lanes due to congestion outside the right-hand opening.

the exit for scenarios with two openings is similar to that at the entrance. Except for the scenario when $w = 0.75$ m and $D = 0.5$ m, the time interval at the exit between pedestrians choosing the left opening had an average value of 8.36% larger than that at the right opening, ranging from 1.48% to 24.4%.

For the scenarios with three openings, the time interval at the entrance and the exit of the right, left and center openings also exhibited certain regularities. At the entrance, the mean time interval at the right opening is relatively close to the mean time interval at the center opening. The mean time interval at the left opening is generally greater than the mean time interval at the right and center openings. The mean time interval at the right, center and left openings with different opening widths is shown in Table 1. The mean time interval between successive pedestrians choosing the left opening is greater than the mean time interval of

Table 1
Mean Time Interval Between Successive Pedestrians Choosing Right, Center or Left Openings with Different Widths of Opening *w*

	Mean time interval at entrance (s)			Mean time interval at exit (s)		
w (m)	Right	Center	Left	Right	Center	Left
0.75	0.492	0.514	0.614	0.517	0.547	0.636
0.85	0.485	0.465	0.527	0.511	0.477	0.543
0.95	0.413	0.411	0.499	0.439	0.439	0.527

choosing the right or center opening from 8.56% to 24.75% and from 13.26% to 21.15%, respectively.

Moreover, the time interval at the exit shares the similar regularities with those at the entrance, see Table 1. At the exit, the mean time interval at the left opening is greater than the mean time interval at the right and center openings from 6.21% to 22.95% and from 13.69% to 19.88%, respectively. This phenomenon indicates that the pedestrian behavior in the process of passing through multiple parallel bottlenecks was significantly affected by traffic rules.

4.3. Flow Rate of Pedestrians

In this study, the pedestrian flow rate is defined as the ratio of the number of pedestrians passing through to the amount of time it took to complete evacuation:

$$J = N/T \tag{1}$$

where ΔN is the pedestrian count and ΔT is the total time for all pedestrians to pass through to the finish line in an experiment scenario. The comparison of the flow rate through the right and left openings in the scenarios with two openings were investigated. Figure 6a shows that for two opening scenarios the flow rate through the right opening is generally greater than that at the left opening. However, there is an outlying data point. It can be seen in Figure 6a that when w = 0.75 m, one data point for flow rate at the right opening is obviously lower than the other data points for flow rate. This data point was shown in Figure 2a above and is the flow rate in the scenario with w = 0.75 m and D = 0.5 m. It corresponds to the scenario where more pedestrians chose the left opening than the right opening.

Figure 6b shows the flow rate at right, left and center openings in scenarios with three openings. Although the scenarios with three openings are more complex than the two openings scenarios, the flow rate also exhibits certain regularities. The flow rate at the left opening is the lowest among the three openings. The flow rate at the right opening is close to that of the center opening. And the flow rate at the center opening is slightly higher.

In order to further investigate the effect of traffic rules on the flow rate at openings, scenarios with opening widths equal to 0.75 m, 0.85 m and 0.95 m were compared. As it is shown in Figure 7, a comparison of flow rate results at right

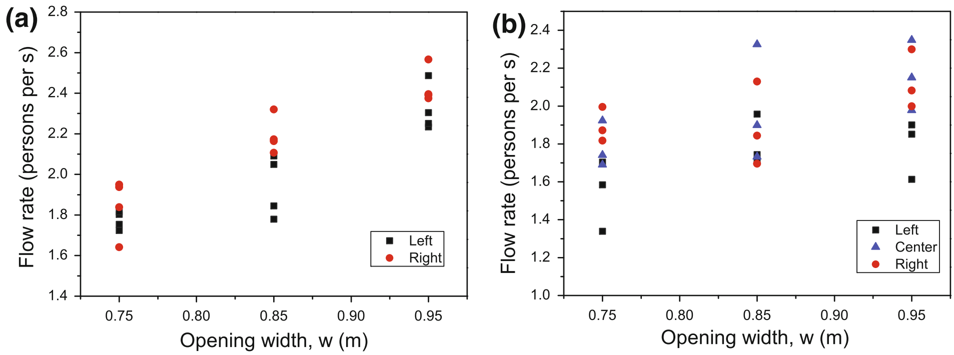

Figure 6. Flow rate in scenarios (a) with two openings and (b) three openings.

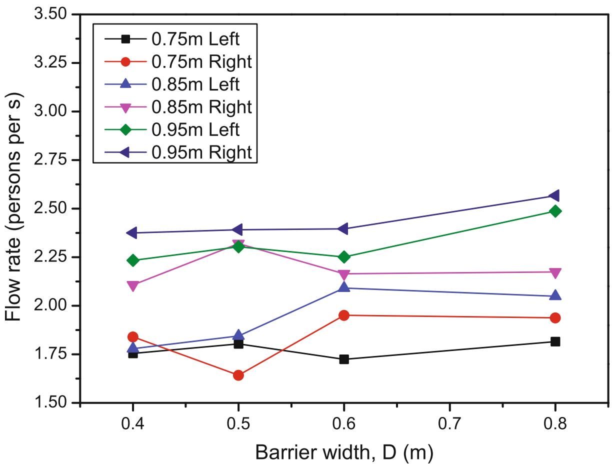

Figure 7. Flow rate in scenarios with two openings; *w* = 0.75 m, *w* = 0.85 m and *w* = 0.95 m.

and left openings indicate a consistent statistical regularity. The flow rate at the right opening is generally greater than that at the left opening.

The flow rate in each scenario with three openings is shown in Figure 8. By analyzing the results of flow rate, it was found that the flow rate at the center opening was 15.5% greater on average than the flow rate at the left opening. The flow rate at the right opening is 15.6% greater on average than that at the left opening. The influence of traffic rules on the choice of openings is significant.

4.4. Specific Flow Rate

The specific flow rate is defined as:

$$J_s = 1/(b \cdot t) \tag{2}$$

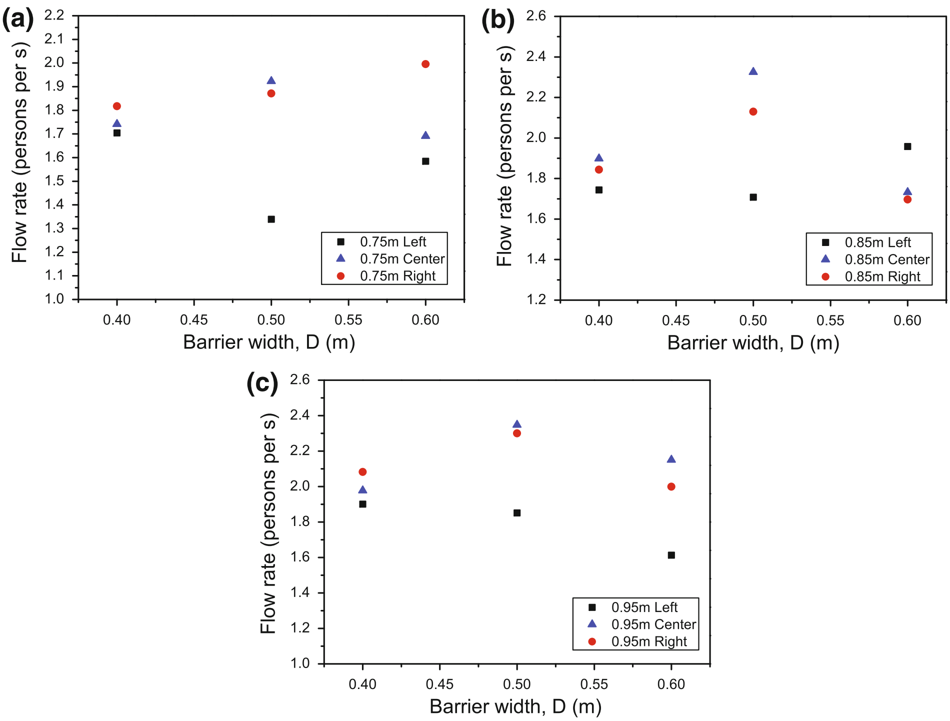

Figure 8. Flow rate in scenarios with three openings; (a) *w* = 0.75 m, (b) *w* = 0.85 m and (c) *w* = 0.95 m.

where b is the width of evacuation facilities which is investigated and Δt is the mean time interval between successive pedestrians in a scenario. The specific flow rate comprehensively reflects the capacity for pedestrian flow of evacuation gates or station exit facilities. When the investigation of specific flow rate is conducted on a single opening, the value of b is equal to w. If the specific flow rate of a bottleneck with multiple openings is discussed, then b represents the sum of the width of all openings of multiple parallel bottlenecks in a scenario. Because of the influence of traffic rules on specific flow rate, as shown in Figure 9, the specific flow rate at the right opening is generally greater than that at the left opening in scenarios with two openings. In the scenarios with three openings, the specific flow rate at the right opening is close to that of the center opening. The specific flow rate at the center opening is slightly larger than that of the right opening. However, the specific flow rate at the left opening is significantly less than that of the right and center openings.

A similar analysis to that mentioned above is conducted on the specific flow rate of openings. It can be seen from Figure 10 that the statistical regularities of specific flow rate in the scenarios with two openings is similar to the regularities of flow rate. The specific flow rate indicates the capacity for pedestrian flow of an opening. Therefore, comparison of the specific flow rates can better reflect the

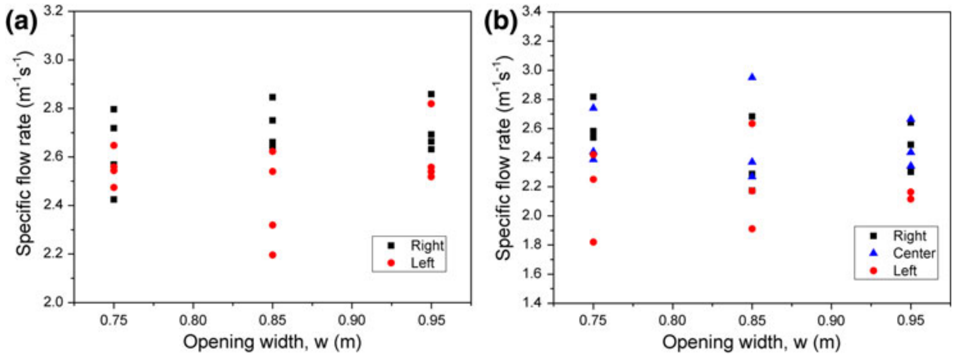

Figure 9. Specific flow rate in scenarios (a) with two openings and (b) three openings.

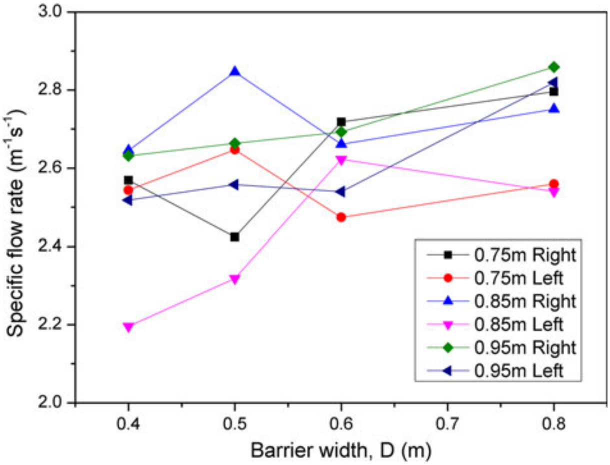

Figure 10. Specific flow rate in scenarios with two openings; *w* = 0.75 m, *w* = 0.85 m and *w* = 0.95 m.

effect of traffic rules on opening choices by pedestrians in an evacuation through multiple parallel bottlenecks. The results of the experiments indicated that in the scenarios with two openings, except the scenario with $w = 0.75$ m and $D = 0.5$ m, the specific flow rate at the right opening is an average of 8.11% greater than that at the left opening, and ranges from 0.99% to 22.8%. Figure 11 shows the results of the scenarios with three openings. By further analysis, it was found that the specific flow rate at the center opening is 18.8% greater on average than the specific flow rate at the left opening. The specific flow rate at the right opening is 17.9% greater on average than that at the left opening. These regularities reflected by the specific flow rate are consistent with those of pedestrian count, time interval and flow rate.

4.5. Extrapolation of Results to Higher Pedestrian Counts

In order to make these experimental results more useful for predicting real pedestrian behavior in scenarios including passing through bottlenecks, an extrapolation was conducted to a sizable number of people evacuating a railway station. The evacuation time of four experiment scenarios with single openings are shown in Figure 12, where Et in the equations stands for evacuation time, and P stands for pedestrian count. It can be seen that the evacuation time increases linearly with increasing pedestrian count. Therefore, a linear best-fit was applied to the experiment results. The equations of the best-fitting lines for the relationship between evacuation time and pedestrian count are shown in the legend of Figure 12. The slope of this line decreases with increasing opening width.

Applying the best-fit linear equations from the results of the simulation experiments with different opening widths, w, the evacuation time was obtained for scenarios with a sizable number of people evacuating. The extrapolation results of the evacuation time for 50, 100, 200, 500 and 1000 pedestrians are shown in Table 2.

For the scenarios with two openings, the same fitting method was used. The evacuation time of twelve experiment scenarios with two openings are shown in Figure 13. Only the slope of the lines was considered due to the fact that the

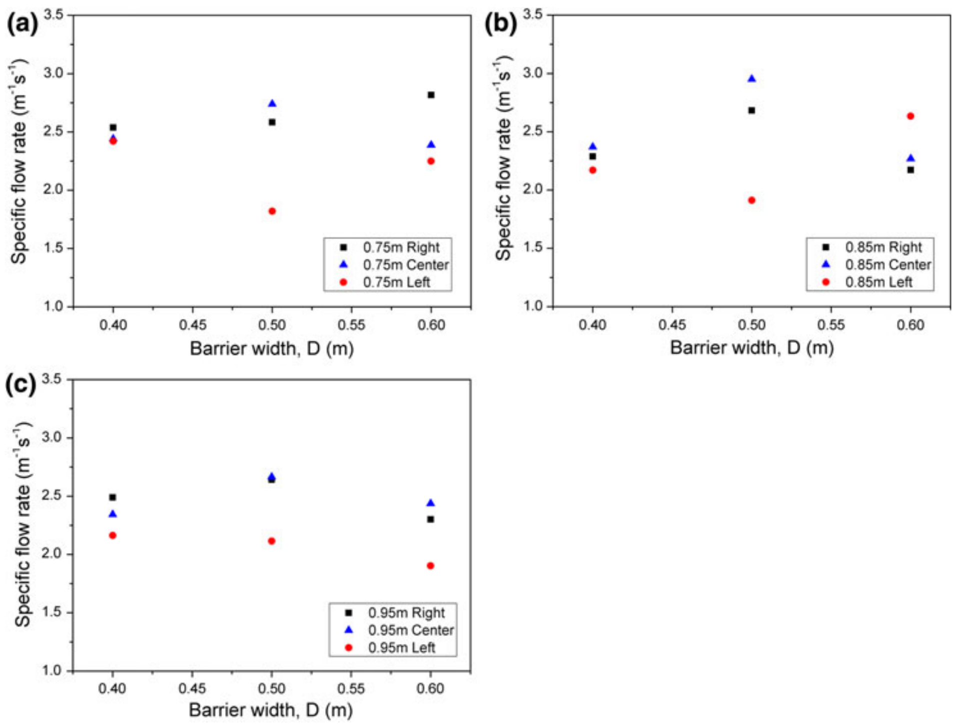

Figure 11. Specific flow rate in scenarios with three openings; (a) $w = 0.75$ m, (b) $w = 0.85$ m and (c) $w = 0.95$ m.

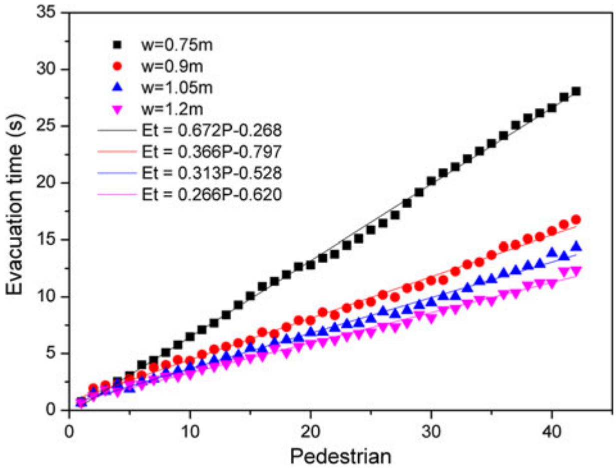

Figure 12. Evacuation time versus pedestrian count in single-opening scenarios.

Table 2
Extrapolation of Evacuation Time to a Higher Pedestrian Count in One Opening Scenarios

	Evacuation time (s)			
Pedestrian count	$w = 0.75$ m	$w = 0.9$ m	$w = 1.05$ m	$w = 1.2$ m
50	33.3	19.1	16.2	13.9
100	66.9	37.4	31.9	27.2
200	134.1	73.9	63.2	53.9
500	335.8	183.7	157.2	133.7
1,000	671.8	366.5	313.9	266.8

intercept of the fitting line equations has little effect on the relationship between the evacuation time and pedestrian count. The slope of lines in scenarios with two openings is from 0.181 to 0.265. The scenarios with the lowest slope and the highest slope are the scenarios with opening widths, w, and barrier widths, D, of $w = 0.95$ m, $D = 0.8$ m and $w = 0.75$ m $D = 0.4$ m, respectively. The extrapolation results for evacuation time in the case of these two scenarios are shown in Table 3.

The evacuation time for nine experiment scenarios with three openings are shown in Figure 14 and linearly fitted. The slope in these nine scenarios is from 0.148 to 0.193. The scenarios with the lowest slope and the highest slope are the scenarios with $w = 0.95$ m, $D = 0.5$ m and $w = 0.75$ m, $D = 0.6$ m, respectively. The extrapolation results for evacuation time in the case of these two scenarios are shown in Table 4. Although the slope of the line, in general, characterizing the trend in evacuation time with increasing pedestrian count is greater for scenarios with three openings than with two openings, there is a dis-

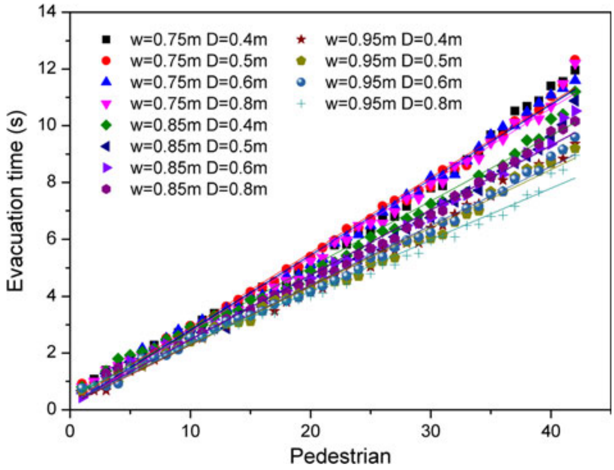

Figure 13. Evacuation time versus pedestrian count in two-opening scenarios.

Table 3
Extrapolation of Evacuation Time to a Higher Pedestrian Count in Two-Opening Scenarios

Pedestrian count	Evacuation time (s)	
	$w = 0.75$ m $D = 0.4$ m	$w = 0.95$ m $D = 0.8$ m
50	13.4	9.6
100	26.7	18.7
200	53.2	36.8
500	132.9	91.1
1,000	265.6	181.7

crepancy when it comes to scenarios for evacuation time with three openings of $w = 0.75$ m. In these scenarios, there is a longer evacuation time for bottlenecks with three openings than for those with two openings.

Upon careful inspection of Figure 14, one can see that, especially for higher pedestrian counts, pedestrian behavior in scenarios with two and three openings is more complex than in scenarios with single openings. This would seem to indicate that the relationship between evacuation time and pedestrian count is determined by a variety of factors. This is somewhat true for Figure 13, as well, where the number of openings in the bottleneck is only two. Therefore, the behavior of higher numbers of pedestrians and different exit opening combinations needs to be investigated further. However, results of this study can be used to improve evacuation simulation models. Using the modified evacuation simulation model, as well as more large-scale experiments of pedestrian evacuation, the problem of the evacuation behavior in a sizable number of people evacuating a railway station, say 500 or 1000 people, will be investigated further.

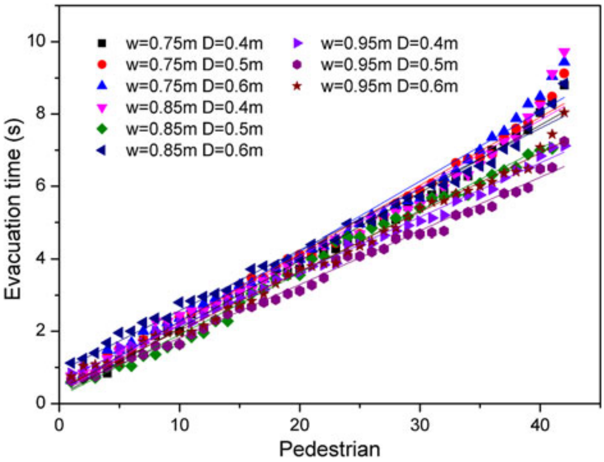

Figure 14. Evacuation time versus pedestrian count in three-opening scenarios.

Table 4
Extrapolation of Evacuation Time to a Higher Pedestrian Count in Three-Opening Scenarios

	Evacuation time (s)	
Pedestrian count	$w = 0.75$ m $D = 0.6$ m	$w = 0.95$ m $D = 0.5$ m
50	10.0	7.7
100	19.7	15.1
200	39.0	29.9
500	97.0	74.2
1,000	193.7	148.1

5. Summary and Conclusions

In this article, a series of simulation experiments were conducted to investigate the effect of right-hand traffic rules on the movement characteristic of evacuation passing through multiple parallel bottlenecks. The HOG and SVM algorithms were applied to pedestrian recognition. Information on pedestrian count was obtained. The movement behavior parameters of pedestrians passing through multiple bottlenecks, such as time interval between two successive pedestrians and flow rate of pedestrians, were extracted based on video image processing technology. Twelve scenarios with two openings and nine scenarios with three openings were considered in these simulation experiments.

The results of this study indicate that the influence of traffic rules on the pedestrian's choice of openings at multiple parallel bottlenecks is significant. In the scenarios with two openings and opening widths of 0.75 m, the participants were asked to turn left into the Waiting area I (see Figure 3) after passing through the multiple parallel bottlenecks. Despite the expectation to turn left after passing through the openings, the majority of pedestrians in two of the four scenarios chose the right-side opening. As for the other scenarios with two openings, it is very obvious that the majority of pedestrians chose the right-side opening. The experimental results of the time interval between successive pedestrians, flow rate of pedestrians and specific flow rate also clearly demonstrated the influence of traffic rules in the movement characteristics of pedestrians evacuating through multiple parallel bottlenecks.

The analysis of pedestrian count, time interval between successive pedestrians, flow rate of pedestrians and specific flow rate were also conducted on the scenarios with three openings. Because the scenarios with three openings offer more choices for pedestrian travel than those with two openings, the influence of traffic rules on the choice of openings and the movement characteristics of evacuation is complex. It was found that, in all nine scenarios with three openings, there were seven scenarios in which the majority of pedestrians chose the right openings. In one scenario, the pedestrian count for choosing the right opening is tied with the count for the center opening. For the flow rate of pedestrians and the specific flow rate, the center opening and right opening were significantly greater than the rates for the left opening. However, it was found that the rates for the center opening were generally greater than that for the right opening, which was inconsistent with the findings for pedestrian count.

All the results indicate that pedestrians show an obvious preference for right-hand openings and the traffic rules have a significant impact on the movement characteristics of evacuation through the multiple parallel bottlenecks. Additionally, all the scenarios of this study were further extrapolated to determine evacuation time for a higher numbers of pedestrians. Linear best-fit equations were calculated in order to quantify the relationship between evacuation time and pedestrian count for scenarios with single openings. Also, the slope of the corresponding lines for scenarios with two openings ranged from 0.181 to 0.265 and with three openings ranged from 0.148 to 0.193.

The fundamental data and analysis of those experimental scenarios will be useful for the development and verification of evacuation models and may help define important parameters for the design of some kinds of pedestrian management and evacuation facilities. In a THC, the number of evacuating people would likely be far greater than the number of participants in this experiment. The apparent preference for right-hand openings in real-life bottlenecks will lead to more serious congestion than in this experiment. Therefore, emergency openings should be designed for the right side of multiple parallel bottlenecks in China. Moreover, multiple parallel bottlenecks should be located in the position of the center-right where they are required and located at the end of the pedestrian exit tunnel. This would likely be necessary because the majority of pedestrians prefer to walk on the right side before they reach the multiple parallel bottlenecks at the end of the pedestrian tunnel.

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