Experimental study of pedestrian flow mixed with wheelchair users through funnel-shaped bottlenecks

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Abstract. With the aging of the world’s population and the resulting increase of disabilities, the characteristics of pedestrian flow mixed with wheelchair users has been paid more and more attention. In this study, experiments in funnel-shaped bottlenecks were performed to study the impact of the bottleneck shape and the ratio of wheelchair users on the crowd dynamics. It is found that the increase in wheelchairs in the crowd leads to lower moving efficiency and greater congestion impacting the escape time, time-space relationship and time headway. Under low mixing ratios (<2.35\%), less congestion occurred in the 45° bottleneck among the four tested angles (0°, 15°, 30°, 45°). The average speeds of the wheelchair users are the fastest in 45° bottleneck (0.310 ± 0.097 m s\(^{-1}\)) until the mixing ratio becomes 7.05\%. However, the advantage of the angle disappears when the mixing ratio gets higher. The findings in this study are meaningful for the guidance of pedestrian evacuation through bottlenecks with the presence of wheelchair users.

Keywords: traffic and crowd dynamics

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1. Introduction

Nowadays, the numbers of the elderly and the disabled are increasing due to the aging of population all over the world. According to the second national sampling survey on disabled people, 6.34% of people (82.96 million) in China have various physical impairments [1]. In addition, the number of people with impaired mobility has increased significantly compared with the first national sampling survey in China [2]. Therefore, the travel safety of this group has been paid increasing attention. For the purpose of safe evacuation and barrier-free facilities design, it is of great importance to study the characteristics of pedestrian flows including wheelchair users.

Many experimental studies on heterogeneous pedestrian flows consider limited characteristics such as age, gender, emotion (competition, selfish attitude) [3–6] or disabilities including visual, physical and other types of impairments [7–11]. Recently, some studies have focused on the characteristics of the pedestrian flows by considering physical disabilities, especially the wheelchair users [12–16]. Sharifi et al summarized the individual speeds of wheelchair users under different congestion levels and
environments [12, 13]. It is found that the maximum walking speed in a passageway can be reached at low congestion levels. The average speed of wheelchair users with an aid in the experimental scenarios of passageways is 1.06 m s$^{-1}$, which is slower and barely influenced by gender [14]. Miyazaki et al [15] experimentally studied the overtaking behavior of able-bodied participants in a flow including one wheelchair user. According to the experiments by Geoerg et al, the average walking speeds of pedestrians are 0.35 ± 0.23 m s$^{-1}$ (participants with an average age of 37 ± 16 mixed with wheelchair users) and 0.37 ± 0.23 m s$^{-1}$ (participants with an average age of 32 ± 16 without wheelchair users) in a symmetrical bottleneck with the width of 0.9 m and length of 2.4 m [16].

To gain more insight into the traffic efficiency of pedestrian flows including wheelchair users, Shimada et al [17] analyzed the impact of different mixing ratios of wheelchair users on pedestrian flow. The experimental results show that the traffic efficiency decreases with the increase of the mixing ratio while the width of bottleneck has less impact. Besides, the bottleneck width shows linear relations to the flow [18–21] and the evacuation efficiency of the bottlenecks is higher in the circumstances of the funnel angle between 46° and 65° [22, 23]. However, these studies are less concentrated on the influence of bottleneck of angles between 0° and 45° and wheelchair users. Based on the time-space diagrams of pedestrian flow with different populations (namely with and without wheelchair users), Geoerg et al [16, 24] found that the jams occur more frequently in the presence of wheelchair users. Another effective factor utilized to reflect the congestion of the crowd is time headway, which has been adopted both in animal experiments and pedestrian flows. Garcimartín et al [25] calculated the time headway of sheep herding and adopted power law distribution to quantify the clogging. Referring to pedestrian flows, less congestion is found in the scenario where the exit was in the corner instead of the middle [26]. However, it is not clear how the congestion is at different mixing ratios of wheelchair users or bottleneck angles.

Based on these considerations, we conducted a series of controlled experiments to explore the effect of the ratios of wheelchair users on pedestrian flows through funnel shaped bottlenecks with different angles. The paper is organized as follows: section 1 introduces the background and the state of the art on pedestrian flows including wheelchair users through bottlenecks. Section 2 describes the setup of the controlled pedestrian experiment. Section 3 analyzes the experimental data and discusses the result. Finally, section 4 contains the conclusions of this study and recommendations of future research.

2. Experiment

The purpose of the experiment is to study the influence of ratios of wheelchair users and angles of the funnel-shaped bottlenecks on pedestrian flows. The design of the experiment was inspired from the previous studies [17, 22, 23], which explored evacuation efficiency by adding a funnel-shaped buffer zone in front of a bottleneck [22, 23] and changing the mixing rate of wheelchair users [17]. Two variables are considered in the experiment setup:

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2.1. Experimental setup

As shown in figure 1(a), the experiment was conducted on November, 10, 2018 in front of a teaching building where the space was large enough and the ground is flat. The weather conditions were the appropriate temperature and the humidity was comfortable for participants. Figure 1(b) shows the sketch of the experiment setup. The scenario of the experiment is a bottleneck with a dimension of 4.8 m $\times$ 3.5 m $\times$ 1.8 m (length, width, height) surrounded by the boards with a height of 1.8 m and width of 0.8 m. In this study the angle of the bottleneck is defined as the angle between the dotted line and the vertical line of the bottleneck entrance (namely $\theta$ in figure 1(b)) and set to 0°, 15°, 30°, 45° separately by moving the boards around the bottleneck entrance in the experiment.

2.2. Participants

In total 85 able-bodied participants (40 females and 45 males) with an average height of 169 $\pm$ 7.6 cm and an average age of 22 $\pm$ 2.1 years were recruited from universities. Six were selected to represent wheelchair users and their assistants. The three assistants were trained to push the wheelchairs and to avoid collisions with others before the experiment. The wheelchairs used in this experiment were Hubang manual wheelchair

Figure 1. (a) A snapshot of the experiment (b) sketch of the experiment setup. The scenario of bottleneck is consists of two parts: one is from the starting line to the bottleneck entrance with a dimension of 4.8 m (length) $\times$ 3.5 m (width) and another is from the bottleneck entrance to the exit with the size of 1.6 m (length) $\times$ 1.2 m (width). The blue shaded area with the length of 3 m and width of 3.5 m shows the measurement area adopted in our analysis. Only the front and middle of the team are shown in the waiting area, while the others are represented by the blue dots. The schematic diagram of two wheelchair users is shown here. The angle between the dotted line and the vertical line of the bottleneck entrance is defined as the bottleneck angle $\theta$ and set to 0°, 15°, 30°, 45° separately by moving the boards around the bottleneck entrance in the experiment.

1) Mixing ratio: namely the mixing ratio of wheelchair users and assistants. It is defined as the ratio of the number of wheelchair users and assistants to the number of the total pedestrians.
2) Bottleneck angle: the change of the angles in the outer margin of the bottleneck entrance, which is shown in figure 1.
model HBL33, which are made by Hubang medical devices company in Shanghai and comply with the relevant national standards. The specifications of the wheelchairs are shown in figure 2.

2.3. Experimental procedure
The experiment scenarios include four symmetrical bottlenecks with different angles (0°, 15°, 30° and 45°). Meanwhile, four trials with a different number of wheelchair users (0, 1, 2, 3) were performed in each bottleneck scenario. Table 1 shows the details of the experimental scenarios. Considering the width of the waiting area and the discipline management of the procedure, the participants were asked to stand in seven columns facing the bottleneck in the waiting area before the start of each trial. The wheelchair users and their assistants pushing the wheelchairs were spaced evenly in the middle of the whole team given that the location of the wheelchairs is not researched in this study. The crowd stood in the waiting area as shown in figure 1(b) and began to move towards the exit upon hearing the signal of start. After finishing several trials, the participants were allowed to have a rest for 10 min.

2.4. Data extraction
The whole experiment was recorded by high definition digital cameras installed vertically 12 m from the ground with the frame rate of 25 fps. The trajectories of the participants were automatically extracted from the video footages using the pedestrian tracking software PeTrack [27]. The trajectories were manually examined and corrected after the automatic extraction from the software in order to get precise tracking data, which are shown in figure 3. Afterwards, the variables on pedestrian movement including speed, escape time can be calculated from those trajectories.

3. Results and discussion
The movement of pedestrians in a bottleneck is considered as low velocity and clogged [28]. In order to gain insight into the characteristics of motion and congestion, we adopt the following factors including walking speed, escape time, time-space relation  

![Figure 2. The specifications of Hubang manual wheelchair HBL33.](image)
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Table 1. Parameters of the experiment scenarios.

| Index | Scenario | Angle of bottleneck | Mixing ratio of wheelchair users and assistants |
|-------|----------|---------------------|------------------------------------------------|
| 1     | BW-0-0   | 0°                  | 0                                               |
| 2     | BW-0-1   |                     | 2.35%                                           |
| 3     | BW-0-2   |                     | 4.70%                                           |
| 4     | BW-0-3   |                     | 7.05%                                           |
| 5     | BW-15-0  | 15°                 | 0                                               |
| 6     | BW-15-1  |                     | 2.35%                                           |
| 7     | BW-15-2  |                     | 4.70%                                           |
| 8     | BW-15-3  |                     | 7.05%                                           |
| 9     | BW-30-0  | 30°                 | 0                                               |
| 10    | BW-30-1  |                     | 2.35%                                           |
| 11    | BW-30-2  |                     | 4.70%                                           |
| 12    | BW-30-3  |                     | 7.05%                                           |
| 13    | BW-45-0  | 45°                 | 0                                               |
| 14    | BW-45-1  |                     | 2.35%                                           |
| 15    | BW-45-2  |                     | 4.70%                                           |
| 16    | BW-45-3  |                     | 7.05%                                           |

Figure 3. The trajectories of the participants in the bottleneck experiment with mixing ratio of 2.35% (namely one wheelchair user and one assistant). Those in other scenarios are shown in appendix A. The grey lines represent the trajectories of the able-bodied participants, while the red one shows the trajectories of the wheelchair user and the green one that of the assistant.
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and time headway. These factors can reflect the sporting abilities, efficiency of the movement in the crowd, stop and go waves during the motion and the congestion of crowd in the bottleneck entrance separately.

It is worth noticing that the last seven participants who stood in the last row of the crowd fell behind and wandered around the bottleneck. Therefore, their data has been ruled out in the following analysis, which means that only 91.7% (78 participants) of the whole group are considered. The measurement area in the following analysis is an area of 3 m × 3.5 m in front of the exit, which is shown in blue shaded area in figure 1(b).

3.1. Speed

In order to reflect the physical abilities of participants in the bottlenecks, the instantaneous speed of each participant $v_i(t)$ is adopted and calculated by the values of the position $p_i$ in a small time interval $\Delta t'$ around $t$, which is defined as:

$$v_i(t) = \frac{p_i \left(t + \frac{\Delta t'}{2}\right) - p_i \left(t - \frac{\Delta t'}{2}\right)}{\Delta t'}$$

(1)

Based on the equation (1), the average speed of each participant in the measurement area can be obtained by calculating the ratio between the sum of the instantaneous speeds passing through the measurement area and the number of them. As shown in figure 4(a), the ordinate of each point represents the average speed of each participant in the measurement area based on the above method and the abscissa represents the sequence each participant arriving at the bottleneck entrance. The earlier a participant arrives at the bottleneck entrance, the smaller the abscissa of the point is. The sequence, namely the abscissa, of the first one who arrived at the bottleneck entrance is set to one. The evolution of the speeds can be divided into two stages. In the first stage it is found that the average speeds of the participants who arrived early decline quickly. While the speed enters the stationary stage as the sequence of arrival becomes larger (almost more than 40). It is indicated that these pedestrians who arrived at the bottleneck entrance earlier have a larger average speed in the measurement area. The speeds of those who arrived later get slower compared to the pedestrians arriving earlier. The reasons for this phenomenon are as follows: the speed of the participants who arrived at the bottleneck entrance earlier is larger because there are no pedestrians standing in front of them and their movements are close to unimpeded movement especially for the participants at the front of the group. Afterwards the speed of the participants becomes smaller because those participants who arrived earlier than them lead to congestion at the bottleneck. Meanwhile, it is obvious that the speeds of wheelchair users (red scatters in figure 4(a)) are smaller than that of the able-bodied participants whose sequence of arrival is similar to wheelchair users (the black line in figure 4(a)). Moreover, the differences of the speed of wheelchair users throughout the different scenarios are studied by calculating the average speed and the results are shown in figure 4(b). Table 2 lists the average speeds of wheelchair users in different scenarios and the $p$ value (by $T$-test) between angle 0° and other three angles at different mixing ratios. We find that the average speeds of wheelchair users decrease with the increase of the mixing ratios.
Figure 4. (a) The relation between the average speeds of participants passing through the measurement area and their sequence of arrival. (Only scenario BW-0-3 is shown. More diagrams of other scenarios are shown in appendix B). The red scatters represent the average speeds of wheelchair users and the blue ones represent the average speed of each able-bodied pedestrian. The black lines show the average speeds of the group except the wheelchair users. (b) The diagram of the average speeds of the wheelchair users in different scenarios. (c) The relation between the width of the crowd and the corresponding $x$-coordinate position at the mixing ratio of 0% with different bottleneck angles. The results are calculated based on the trajectories of the crowd, which is shown in figure 3.

Table 2. The average speeds of wheelchair users in different scenarios.

| Scenario | BW-0-1  | BW-15-1 | BW-30-1 | BW-45-1 |
|----------|---------|---------|---------|---------|
| Speed (m s$^{-1}$) | 0.282 ± 0.152 | 0.270 ± 0.126 | 0.261 ± 0.134 | 0.310 ± 0.097 |
| p value   | /       | 0.31    | 0.08    | 0.01    |
| Scenario | BW-0-2  | BW-15-2 | BW-30-2 | BW-45-2 |
| Speed (m s$^{-1}$) | 0.218 ± 0.177 | 0.261 ± 0.166 | 0.241 ± 0.136 | 0.286 ± 0.145 |
| p value   | /       | 0       | 0.01    | 0       |
| Scenario | BW-0-3  | BW-15-3 | BW-30-3 | BW-45-3 |
| Speed (m s$^{-1}$) | 0.205 ± 0.122 | 0.227 ± 0.135 | 0.205 ± 0.124 | 0.204 ± 0.138 |
| p value   | /       | 0.98    | 0.93    |         |
The average speeds of wheelchair users in the measurement area is the fastest in angle 45° until the mixing ratio becomes 7.05% ($p$ value < 0.05).

The reasons for the influence of bottleneck angles on the walking speed are explored as follows. When the mixing ratio is relatively small (e.g. 2.35%), the position where the width of the crowd becomes narrow is similar (nearly 4 m in x-coordinate) among angle 0°, 15° and 30°. However the taper position is further back in angle 45° because of the great contraction in the edge of the scene near the bottleneck, which can be found in figures 3 and 4(c). It is supposed that the phenomenon that the taper position of the trajectories is backward in angle 45° decreases the walking distance and makes the pedestrians move more directly towards the exit. Hence, the wheelchair user can move at a relatively high speed in angle 45° due to this positive impact on participants’ movement, while the differences among angle 0°, 15°, 30° are minor ($p$ value > 0.05). When the mixing ratio is relatively large (e.g. 7.05%), the existence of the large amount of wheelchair users with larger occupied area makes the crowd’s movement more clogged, especially in the scenario of angle 45° with less space near the bottleneck. Influenced by the negative impact, the average speed in angle 45° is not the fastest compared to other bottleneck angles at this mixing ratio.

### 3.2. Escape time

The escape time of each trial, including individual time and total time, can indicate the movement efficiency. Here the individual escape time is defined as the period from one participant entering the starting line of the scenario to the departure of the bottleneck exit. The total escape time is the period from the first pedestrian entering the starting line of the scenario to the last one departing the bottleneck exit.

#### 3.2.1. Individual escape time.

According to the definition mentioned above, the time period of each pedestrian passing through the bottleneck and the average value can be obtained. It needs to be noted that there is a significant difference between the speeds of the first 40 participants who arrived at the exit earlier and the other participants arriving later, which can be found in figure 4(a). Hence, instead of considering the whole group, which is used in [22], we calculate the average speeds of the latter group, namely the last 38 participants arriving at the exit. Besides, the variation ratio of a factor variable $VR_i$ which can reflect the gaps between itself $T_i$ and the reference $T_0$ (namely the factor value in angle 0° in this study) is calculated as:

$$VR_i = \frac{T_i - T_0}{T_0} \times 100\%.$$  

Hence, the negative value of $VR_i$ means that the value in the current scenario is smaller than that in angle 0° and vice versa.

Considering figure 5(a), the individual escape time becomes larger with the mixing ratio in the way of quadratic function. The fitting parameters of the quadratic function are shown in table 3. This reveals that the flow efficiency in the bottleneck becomes lower with the increase of mixing ratio from the perspective of individuals. The influence of the mixing ratio results from the lower speeds and larger occupied
areas of wheelchair users. With the increase of wheelchair users, the crowd gets more clogged and the flow efficiency decreases.

Meanwhile, the influence of the bottleneck angles are shown in figure 5(b) and the variation ratios between the individual escape time in angle 0° and that in angle 15°, 30°, 45° respectively are calculated and shown in figure 5(c). Comparing to the
individual escape time in the bottleneck of angle 0°, the value in angle 45° is smaller when the mixing ratio is 0% or 2.35% (the variation ratio are −3.6% and −2.8% respectively), while it becomes larger and the difference is minor at a mixing ratio of 4.70% and 7.05% (the variation ratio are −0.27% and 0.24% respectively). The individual escape time in angle 15° and 30° is larger than that in angle 0° and 45° in most cases. The results show that there is a significant advantage of utilizing the bottleneck of angle 45° at a low mixing ratio (lower than 2.35%) from the perspective of individual characteristics.

The causes for the effect of bottleneck angles are analyzed from the following aspects. We find that the participants need extra walking distance compared to the linear distance between their initial position (namely on the starting line) and ending position (at the exit) because of the deflection of their motion direction. This phenomenon can also be observed from the tapered shape of the trajectories (see figure 3). Therefore, two factors, namely the actual walking distance and average speed of the crowd, are utilized to reflect the flow efficiency. Considering the comprehensive impact of these two factors, the flow efficiency performs better when the actual walking distance of the crowd is smaller and the average speed is larger. We calculate the actual walking distance and average speeds of the pedestrians from the starting line of bottlenecks to the exit. Moreover, considering the apparent decline in the average speed of the first 40 participants arriving at the exit and the minor differences in the last 38 ones, the latter is considered both in the calculation of the two factors, which is the same as the calculation of individual escape time. The results of the actual walking distance and average speed are shown in figure 6.

According to figure 6(a), the actual walking distance in angle 15° and 30° is close to that in angle 0° (p value are 0.52 and 0.67, respectively and larger than 0.05) when the mixing ratio is down to zero. However, the actual walking distance in angle 45° is obviously smaller than that in angle 0° (p value <0.05). Figure 6(b) indicates that the average speed in angle 45° is larger than that in the other three angles. It is supposed that the position where the width of the crowd began to contract is similar amongst the scenarios of angle 0°, 15°, 30°, while the position is further back in angle 45° due to the great contraction in the edge of the scene near the bottleneck. These are shown in figures 3 and 4(c). According to the trajectories of the crowd, three points (two points of them represent the different positions where the width of crowd tapered and the other one represents the terminal point) form a triangle. The earlier the crowd starts to taper, the smaller walking distance will be taken by participants considering the three points and the principle that one side of a triangle is smaller than the sum of the other sides. Therefore, there is a positive effect on making participants moving towards the exit and a better flow efficiency in angle 45° because of its smaller actual walking distance and larger average speed.

When the mixing ratio is larger, e.g. 7.05%, the average speeds decrease in angle 15°, 30° and 45°. We suppose that the contraction in the edge of these scenarios leads to the congestion of the crowd considering the large number of wheelchair user occupying a larger area moving towards the exit where there is less space. The comprehensive effect of the actual walking distance and average speed, which can be represented by the individual escape time, illustrates that the individual flow efficiency in angle 45° falls to a value similar to that in angle 0° when the mixing ratio is larger than 4.70%. From
another perspective, the finding that the advantage of flow efficiency in the bottleneck with an angle of 45° decreases can also be explained as follows. When the mixing ratio is relatively large, each wheelchair user had to change their paths of travel compared with the movement in small mixing ratio (e.g. only one wheelchair user) which is close to a straight line centered in the stream and poses little disruption. Besides the change of travel path, the behavior of negotiating with or even yielding to each other would also result in congestion and a reduction in flow efficiency especially in the bottleneck with angle 45° considering its narrow edge and the larger occupied area of wheelchairs.

3.2.2. Total escape time. In order to reflect the motion efficiency of the crowd at a group level, we utilize $N$–$t$ diagrams to straightforwardly describe the moment when each participant leaves the bottleneck exit and then calculate the total escape time of the crowd in each scenario for quantification. In this study, 91.7% (78 participants) of the whole crowd are considered in order to calculate the total evacuation time. Figure 7(a) describes the relation between the cumulated number of people leaving the bottleneck exit and the corresponding time needed for their departure. In figure 7(a) we observe that the motion efficiency in angle 0° is similar to that in angle 15° and is slightly higher than that in angle 30°. Besides, the efficiency performs better at angle 45° than the other three angles according to the slopes of these lines.

For the purpose of quantitative analysis of the motion efficiency, the total escape time of each trial is calculated (according to its definition or the points of intersection between the black and other lines in figure 7(a)) and plotted in figures 7(b)–(d). Figure 7(b) describes the relation between total escape time and mixing ratio of wheelchair users and assistants in the bottleneck of angle 0°. Meanwhile, the fitting curves are plotted and the value of fitting parameters as well as coefficient of determination ($R^2$) are shown in table 4. It is illustrated that the total escape time increases with the mixing ratio in the form of a quadratic function.

According to figures 7(c) and (d), it can be found that the total escape time from 45° bottleneck is smaller than other three bottlenecks at the mixing ratio of 0% and
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2.35% (the variation in angle 45° are −8.22% and −4.05% respectively), while the value in 45° bottleneck is close to that from 0° bottleneck at the mixing ratio of 4.70% and 7.05% (the variation in angle 45° are 0.72% and 0.28% respectively). The total escape time from 15° and 30° bottlenecks are larger than from 0° and 45° bottlenecks in most cases (except when the mixing ratio is 2.35%). The results indicate that the movement efficiency at the group level performs the best in the bottleneck with angle 45° when

Table 4. Parameters of the fitting curves between the total escape time and mixing ratio.

| Equation Value | Value | $Y = ax^2 + bx + c$ |
|----------------|-------|---------------------|
| Angle 0°       | 0.06  | 0.45  | 36.27 | 0.94 |
| Angle 15°      | 0.14  | 0.10  | 36.37 | 0.99 |
| Angle 30°      | 0.27  | −0.88 | 38.10 | 0.98 |
| Angle 45°      | −0.01 | 1.42  | 31.84 | 0.99 |

Figure 7. (a) The relation between the cumulated number of people leaving the bottleneck exit and the corresponding time needed for the departure. Each line represents the relation in one type angle when the mixing ratio is zero. The relations in other mixing ratios are shown in appendix C. The points of intersection between the black and other lines represent the escape time for 78 participants at different angles. (b) Diagrams of the relationship between total evacuation time and the mixing ratio of wheelchair users and assistants as well as their own fitting curves in the bottlenecks of angle 0° (diagrams in other angles are shown in appendix C). (c) Diagrams of the relation between total evacuation time and bottleneck angles. (d) The diagram of the relation between total evacuation time and bottleneck angles. (d) The diagram of the variation ratio in each trial.
the mixing ratio is lower than 2.35%. However, the advantage of the bottleneck with angle 45° in movement efficiency disappears in the conditions of a relatively high mixing ratio (larger than 4.70%).

Overall, the escape time including individual time and total time, indicates that the flow efficiency gets worse with the increase of the mixing ratio because of the increased number of wheelchair users with low ability of motion and large occupied area. Meanwhile, in this study the flow efficiency from the perspective of both individual and group performs best in angle 45° among all bottleneck angles when the mixing ratio of wheelchair users and assistants is lower than 2.35%. However, the advantages over the efficiency in angle 45° gradually disappear with the mixing ratio higher than 4.70%. The reasons can be analyzed from the actual walking distance and the average speed mentioned before.

3.3. Time-space relation

In order to describe the jams or stop-and-go waves in the crowd during participants’ movement, the time-space relation is adopted and defined as the relation between the variation of motion in the direction towards the exit and the time required for the movement. Figure 8 describes the time-space relations in the measurement area of the bottleneck with angle 0°. The red lines represent that the individual velocity is lower than 0.1 m s\(^{-1}\) and are considered in stop stage \([29, 30]\), while the blue ones mean the velocity is higher than 0.1 m s\(^{-1}\). Take the case of the 0° bottleneck, it is found that the red lines appear more frequently with the increase of the mixing ratio. The phenomenon indicates that there are more participants with a speed lower than 0.1 m s\(^{-1}\) (namely the participants considered in stop stage in this study) when the mixing ratio of wheelchair users and assistants increases. In order to describe and quantify the degree of this phenomenon of stopping and jamming during the crowd’s movement, a factor \(R\) is introduced and defined as the ratio between the sums of each pedestrian’s stopping time \(t_i\) and the sum of each one’s moving time \(T_i\) in the measurement area:

\[
R = \frac{\sum_{i=0}^{N} t_i}{\sum_{i=0}^{N} T_i} \times 100\%.
\] (3)

According to figure 9(a), it can be found that the factor \(R\) increases with the mixing ratio, which illustrates that the phenomenon of stopping and jams is more serious in the crowd. It is supposed that the increase of wheelchair users with slower speeds and a larger occupied area has negative impact on the pedestrians’ movement and exacerbates the congestion of the crowd.

With respect to the influence of the angles of bottlenecks, figures 9(a) and (b) show that the factor \(R\) in 45° bottleneck is smaller than in 0° bottleneck when the mixing ratio is lower than 4.70% (the variation ratio in 45° bottleneck are −9.91%, −4.88% and −24.81% respectively). However, when the mixing ratio is up to 7.05%, the factor \(R\) in 45° bottleneck is a little higher than in 0° bottleneck (the variation ratio in angle 45° is 4.91%). Besides, the values in 15°and 30° bottlenecks rise and fall at different mixing ratios compared to the value in angle 0°, while they are mostly higher than the value in 45° bottleneck. Based on the comparison of the factor \(R\) in different bottleneck angles, it is indicated that the degree of stopping and jams during the movement of the
Crowd is relatively small in 45° bottleneck all the time when the mixing ratio is lower than 4.70%. It is supposed that the great contraction of the boundary in 45° bottleneck makes the crowd began to taper early, which is shown in trajectories and leads to a positive impact on making participants move forwards to the exit. However, the advantage of the angle 45° decreases when the mixing ratio is 7.05%. We conjecture that the contraction of the edge of the bottleneck in angle 45° leads to clogging, considering the large amount of wheelchair users with slower speeds and a larger covered area moving towards the exit.

3.4. Time headway and its distribution

For the purpose of reflecting the congestion of the crowd at the bottleneck entrance, time headway, namely time gap is utilized in this study. It is defined as the time interval between two consecutive pedestrians passing through the bottleneck entrance. The time headway is calculated according to the above definition.
The distribution of time headway is often utilized to help study the collective behavior and clogging of the crowd and the power law distribution have successfully explained the phenomenon of jam and congestion. Therefore, we adopt power law distribution to investigate the clogging and jamming of the crowd through bottlenecks in this study. Power laws, one of ‘heavy-tailed’ distribution, are one kind of probability distribution in the form of [31]:

\[ p(x) \propto x^{-\alpha}. \] (4)

Hence, the power law distributions obey a linear relation under the log-log scale coordinates, which can be shown as:

\[ \ln p(x) = -\alpha \ln x + C. \] (5)

It is important to consider the complementary cumulative distribution function (CCDF for short) of a power law distributed variable in many studies [31, 32]. Hence, the CCDF of a random variable (the time headway) was calculated and fitted using power law distributions by the method described in [31]. The goodness-of-fit tests introduced in [32] were conducted and the results in each scenario passed the tests. The scaling parameter \( \alpha \) was estimated from the fitting and shown in figure 10(a), which can describe the severity of the clogging of pedestrian flows in accordance with the rule that the crowd becomes more constricted with the decrease of the scaling parameter \( \alpha \).

The results shown in figure 10(a) indicate that the scaling parameter \( \alpha \) becomes smaller with the increase of the mixing ratio. Hence, the congestion of the crowd at the entrance of the bottleneck becomes worse with the increase of the mixing ratio due to the slow movement and large area of wheelchair users. According to figure 10(b), it is illustrated that the scaling parameter \( \alpha \) in 45° bottleneck is smaller than other three angles (0°, 15°, 30°) when the mixing ratio is lower than 2.35%, which indicated less congestion in 45° bottleneck. However, the scaling parameter \( \alpha \) for 45° gets close to that of 0° at the mixing ratio of 4.7% and 7.05% (the variation ratio in 45° bottleneck are 1.49% and −0.53% respectively), while the bottleneck of angle 15° and 30° both have a lower value of \( \alpha \) all the time. Hence, the bottleneck of angle 45° tends to be a
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4. Conclusions

It is of great importance to study the characteristics of the movement of pedestrian flows including wheelchair users, as there has been an increase in the number of the elderly and disabled people in China. For the purpose of improving the efficiency and safety of pedestrians’ motion and evacuation in bottlenecked areas where congestion and stampedes can often occur, controlled pedestrian experiments in the bottleneck including wheelchair users were conducted in this study. Moreover, we arranged different numbers of wheelchair users with assistants to stand evenly in a row in the middle of the crowd and changed the outer margin of the bottleneck in the controlled experiments. The factors such as speed, escape time, stopping time and time headway are analyzed to explore the impact of wheelchair user mixing ratios and bottleneck angles on the ability, efficiency and congestion of pedestrian flows. According to the results of these experiments, conclusions are summarized as follows based on the arrangement of the wheelchair users and the bottleneck in this study:

1. The speeds of wheelchair users, which can reflect the movement abilities of them, become slower with the increase of the mixing ratio. Additionally, the average speeds of wheelchair users in the bottleneck is the fastest in 45° bottleneck (0.310 ± 0.097 m s⁻¹) until the mixing ratio arrives at 7.05%.

2. The presence of wheelchair users leads to worse efficiency of traffic and congestion in the bottleneck and the degree of impact increases with the mixing ratio of wheelchair users and assistants. Moreover, the variation of the escape time on the mixing ratio coincides with the quadratic function in this study.
(3) The bottleneck of angle 45° reflects a better efficiency of movement and lower degree of stopping and congestion (2.8%–9.9% according to the variation ratios of the factors in section 3) in the pedestrian flows under the circumstance of a low mixing ratio (<2.35%) compared to other three angles (0°, 15°, 30°). However, the advantages of the angle 45° disappear in the condition of a high mixing ratio as the factors are close to that in angle 0°.

The findings in this study are meaningful for the guidance of adding specific facilities for evacuation in the bottlenecks considering the presence of wheelchair users. On the one hand, the relationship between the traffic efficiency or clogging and the mixing ratio indicates the worse evacuation in the presence of a large number of wheelchair users and reminds people to pay more attention to safety in such a situation. On the other hand, it is effective to add a funnel shaped zone with angle 45° under the circumstance of no wheelchair users or where the mixing ratio is relatively small (2.35% in this study). However, in this study we only represented a limited number of wheelchair users (by able-bodied participants) and arranged them to stand evenly in a row in the middle of the crowd through the specific dimension of the bottleneck. Our study only contains four different angles of bottleneck without repeated experiments. The explanation for the impacts of bottleneck angles needs further experimental verification. Further research including different dimensions of the bottlenecks and the increase of the mixing ratio as well as different distribution of wheelchair users are necessary in future studies.

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Appendix A

Diagrams of the trajectories of each scenario. The grey lines represent the trajectories of the able-bodied participants, while the red one shows the trajectories of the wheelchair user and the green one that of the assistant.
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Appendix B

Diagrams of the relation between the average speeds of participants passing through the measurement area and their sequence of arrival. The red scatters mean the average speeds of wheelchair users and the blue ones represent the average speed of each able-bodied pedestrian. The black lines are the average speeds of the group aside from the wheelchair users.
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BW-30-1

BW-30-2

BW-30-3

BW-45-1

BW-45-2

BW-45-3
Appendix C

(1) Diagrams of the relation between the individual evacuation time and the mixing ratio of wheelchair users and assistants at different bottleneck angles.
Diagrams of the relation between the cumulated number of people leaving the bottleneck exit and the corresponding time needed for the departure.
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(3) Diagrams of the relation between total escape time and the mixing ratio of wheelchair users and assistants at different bottleneck angles

Angle 0°  
Angle 15°  
Angle 30°  
Angle 45°
Appendix D

Diagrams of the relation between the exit-oriented movements and the time required for the motion under different mixing ratio of wheelchair users and assistants.
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References

[1] Chuan-Sheng J, Shuang-Zhong Z and Fei S E Y 2009 Current status and trends of evacuation safety research on the disables China Saf. Sci. J. 3 032
[2] Tian B, Zhang Y and Qiu Z Y 2007 Comparison and analysis of data obtained in two national sampling surveys of disability Chin. J. Spec. Educ. 86 54–6
[3] Bowman B L and Vecellio R L 1994 Pedestrian walking speeds and conflicts at urban median locations J. Transp. Res. Rec. 1438 67–73
[4] Barton B K and Schwebel D C 2007 The roles of age, gender, inhibitory control, and parental supervision in children’s pedestrian safety J. Pediatr Psychol. 32 517–26
[5] Muir H C, Bottomley D M and Morrison C 1996 Effects of motivation and cabin configuration on emergency aircraft evacuation behavior and rates of egress Int. J. Aviat. Psychol. 6 57–77
[6] Nicolas A, Bouzet S and Kuperman M N 2017 Pedestrian flows through a narrow doorway: effect of individual behaviours on the global flow and microscopic dynamics Transp. Res. B 99 30–43
[7] Sharifi M S et al 2015 Traffic flow characteristics of heterogeneous pedestrian stream involving individuals with disabilities Transp. Res. Rec. 2537 111–25
[8] Sharifi M S et al 2015 Analysis of walking speeds involving individuals with disabilities in different indoor walking environments J. Urban Plan. Dev. 142 04015010
[9] Koo J et al 2013 A comparative study of evacuation strategies for people with disabilities in high-rise building evacuation Exp. Syst. Appl. 40 408–17
[10] Daamen W and Hoogendoorn S P 2012 Emergency door capacity: influence of door width, population composition and stress level Fire Technol. 48 55–71
[11] Gaire N et al 2018 Exit choice behavior of pedestrians involving individuals with disabilities during building evacuations Transp. Res. Rec. 2672 22–9
[12] Sharifi M S et al 2015 Exploring traffic flow characteristics and walking speeds of heterogeneous pedestrian stream involving individuals with disabilities in different walking environments Proc. of the Annual Meeting of the Transportation Research Board (Washington, DC)
[13] Sharifi M S et al 2017 A large-scale controlled experiment on pedestrian walking behavior involving individuals with disabilities Travel Behav. Soc. 8 14–25
[14] Tsuchiya S, Hasemi Y and Furukawa Y 2007 Evacuation characteristics of group with wheelchair users Fire Saf. Sci. 7 117
[15] Miyazaki K et al 2004 Behaviors of pedestrian group overtaking wheelchair user National Maritime Research Institute (NMRI)(Report 181-0004) Shinkawa Mitakashi, Tokyo, Japan
[16] Georrg P et al 2018 The influence of physical and mental constraints to a stream of people through a bottleneck (arXiv:1812.03697)
[17] Shimada T and Naai H 2006 An experimental study on the evacuation flow of crowd including wheelchair users Fire Sci. Technol. 25 1–14
[18] Hoogendoorn S P and Daamen W 2005 Pedestrian behavior at bottlenecks Transp. Sci. 39 147–59
[19] Liso W et al 2014 Experimental study on pedestrian flow through wide bottleneck Transp. Res. Procedia 2 26–33
[20] Song W, Lv W and Fang Z 2013 Experiment and modeling of microscopic movement characteristic of pedestrians Procedia Eng. 62 56–70
[21] Liu X, Song W and Lv W 2014 Empirical data for pedestrian counterflow through bottlenecks in the channel Transp. Res. Procedia 2 34–42
[22] Sun L et al 2017 A comparative study of funnel shape bottlenecks in subway stations Transp. Res. A 98 14–27
[23] Oh H et al 2014 Validation of evacuation dynamics in bottleneck with various exit angles Transp. Res. Procedia 2 752–9
[24] Georrg P et al 2019 The influence of wheelchair users on movement in a bottleneck and a corridor J. Adv. Transp. 2019 1–17
[25] Garcimartin S et al 2016 Flow and clogging of a sheep herd passing through a bottleneck Phys. Rev. E 91 022808
[26] Shi X et al 2019 Examining effect of architectural adjustment on pedestrian crowd flow at bottleneck Physica A 522 350–64

https://doi.org/10.1088/1742-5468/ab6b1c
Experimental study of pedestrian flow mixed with wheelchair users through funnel-shaped bottlenecks

[27] Boltes M et al 2010 Automatic extraction of pedestrian trajectories from video recordings Pedestrian and Evacuation Dynamics 2008 (Berlin: Springer) pp 43–54
[28] Pastor J M et al 2015 Experimental proof of faster-is-slower in systems of frictional particles flowing through constrictions Phys. Rev. E 92 062817
[29] Cao S et al 2016 Pedestrian dynamics in single-file movement of crowd with different age compositions Phys. Rev. E 94 012312
[30] Zeng G et al 2018 Experimental and modeling study on relation of pedestrian step length and frequency under different headways Physica A 500 237–48
[31] Alstott J, Bullmore E and Plenz D 2014 Powerlaw: a Python package for analysis of heavy-tailed distributions PLoS One 9 e85777
[32] Clauset A, Shalizi C R and Newman M E J 2009 Power-law distributions in empirical data SIAM Rev. 51 661–703