Experimental study of bidirectional pedestrian flow in a corridor with certain height constraint

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Abstract. Bidirectional flow is believed to be the main cause of trampling disaster in mass gathering events. To control such kind of disasters, deeper insights into the pedestrian movement features could help. However, bidirectional pedestrians flow of stoop walking has barely been studied. Such form of movement can usually be found when firefighters entered the building to rescue the evacuees who escaped from dangerous zone. Therefore, a series of bidirectional flow experiments with a constraint height of 1.4 m were conducted in order to investigate this movement features. The lanes formation, relationship between speed and density, specific flow and density were analyzed. Results indicated that the numbers of lanes gradually increase with the global density increase. In speed-density relation, when the density is less than 0.8 ped/m^{-2}, the free speeds of bidirectional pedestrian flow is larger when compared with unidirectional pedestrian flow. In specific flow and density relationship, the specific flow of unidirectional pedestrian flow is larger than that bidirectional pedestrian flow when the density is more than 0.6 ped/m^{-2}.

Keywords: Height constraints, bidirectional pedestrian flow, Fundamental diagrams

1 Introduction

In recent years, fire accidents in building induced in serious deaths and injuries. Analyzing these accidents, we can find that bidirectional pedestrian flow is a common form of movement. As one typical scenario, bidirectional pedestrian flow movement can be observed when firefighters entered the building to rescue the evacuees who are escaping from dangerous zone. Under this kind of condition, it is of critical importance to study the mutual interaction between firefighters and evacuees.

The impact of fire conditions on the efficiency of pedestrian evacuation is mainly manifested in two aspects. One aspect is that the effect of smoke on pedestrians' visibility, and it would further reduce the pedestrians' motion speed. The other aspect is that

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smoke will change pedestrians' movement behavior in the process of smoke spreading from top to bottom in vertical direction, and as a consequence, pedestrians' vertical movement space becomes smaller and smaller [1]. Considering the impact of smoke on pedestrians' movement behavior, previous researches can be classified into mathematical modeling research and experimental research. In terms of controllable experiments, some researchers have studied the influence of different height constraints on pedestrian movement characteristics by designing a height-adjustable experimental device. For example, Ma *et al* [2,3], Chen *et al* [4], Li *et al* [5] studied the influence of height constraints on pedestrians' movement characteristics through a series of controllable single-file experiment and unidirectional pedestrian flow experiment. Li *et al* [6] studied effects of restricted walking height and bottleneck width on the unidirectional pedestrian flow through bottlenecks. In terms of mathematical model, the microscopic model of pedestrian evacuation dynamics mainly includes cellular automata model [7,8] and social force model [9,10]. Guo *et al* [11] proposed an improved heuristic-based model and the pedestrians' shape is represented by multiple connected circles, which is used to imitate crawler. Zheng *et al* [12] proposed an extended Floor-Field model to study the pedestrian evacuation dynamics with the influence of the fire and the smoke spreading, each pedestrian occupy a number of cells and the pedestrian's movement behavior can be described in a detailed way.

Summarizing the current literatures on this topic, it can be found that experimental data of bidirectional pedestrian flow under height constraints is still lack. Therefore, we conducted a controlled bidirectional pedestrian flow experiment to study the movement characteristics of pedestrians at certain height constraints. The rest of the article will be organized as follows: Section 2 describes the experimental setup. In section 3, the experimental results will be analyzed. Section 4 presents the conclusions of this paper.

2 Experiment setup

Our experiments were designed to study the movement characteristic in the certain constraint height for unidirectional and bidirectional pedestrian flow. The experiments were performed at Southwest Jiaotong University in June 2021. A total of 63 volunteers from the university campus were recruited to take part in this experiment, including 32 males and 31 females. The other basic individual information could be found in Ref. [4].

The experiment is performed in a circular channel, which consist of an inner wall with radius of 1.0 m and an outer wall with radius of 2.8 m, as shown in Fig. 1(a). In bidirectional pedestrian flow experiment, the pedestrians located in inner side of the channel spontaneously walked along counter-clockwise direction, the others were clockwise walking direction lied in outer channel. When smoke presents, smoke layer would change pedestrians' walking posture due to fire smoke spreads from top to bottom. To construct the experimental scenarios of bidirectional pedestrian flow under different height constraints, as shown in Fig. 1(b), a height-adjustable transparent protective net roof is designed and installed the 2.0 m high steel-frame structure. The experimental detail of unidirectional pedestrian flow has been shown in Ref. [4]. We only considered scenarios with a constraint height of 1.4 m in this study, four experimental runs were performed to obtain different global density. At the beginning of each experimental run, the participants were uniformly distributed in the experimental channel. Meanwhile, the periodic boundary condition is considered in order to obtain continuous circulating flow.

A digital camera, which resolution is 1920 × 1080 and video capture frame rate is 25 per second, was positioned on 14 m above the ground to record the pedestrians' movement inside experimental area. Meanwhile, for convenience of facilitating data processing, as shown in Fig. 1(b), each participant was required to wear a small red cap with a white dot in the center. The pedestrian trajectories were automatically tracking from the experimental video by using software *PeTrack* [13]. The direct linear transformation (DLT) algorithm is adopted to transform the trajectories from pixel coordinates of image to physical coordinates of real space [14]. Base on above experimental data, we plotted the pedestrians' trajectory diagrams, as shown in Fig. 2.

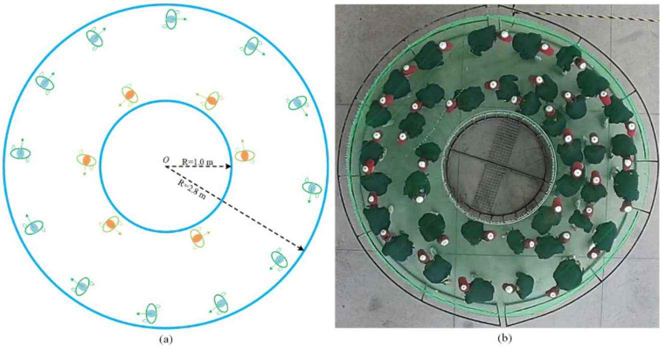

Fig. 1. Experiment setup. (a) Sketch of the experimental corridor. (b) A snapshot of bidirectional pedestrian motion for the experimental run of $H = 1.4$ m and $N = 39$.

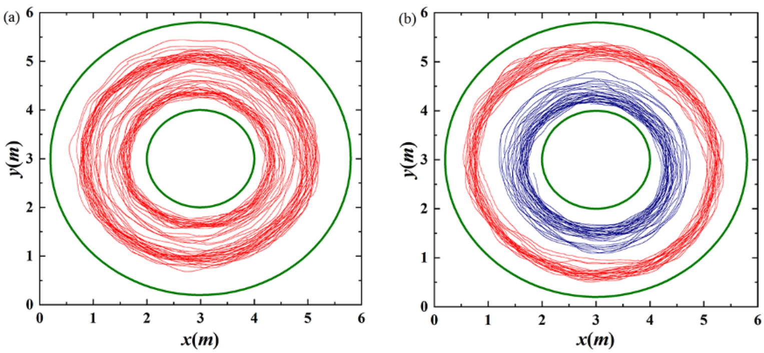

Fig. 2. Trajectory diagrams for different global densities in certain constraint height. (a) denotes unidirectional pedestrian motion. (b) presents bidirectional pedestrian motion.

3 Results

3.1 Lane formation

Lane formation is a typical self-organizing phenomenon, which could minimize conflicts and collisions among pedestrians moving in the opposing direction and increase the passing efficiency by following pedestrians moving in the same direction. From a qualitative point of view, as shown in Fig. 3, the position distribution in polar coordinates for each pedestrian has been plotted for a certain frame. The different color-shaded rectangles roughly represent the lanes formed. It should be noticed that 2 lanes formed in low density scenarios. With the increase of pedestrian density, 3 lanes could be observed. Meanwhile, the other related characteristics can be found that the lane formation in bidirectional pedestrian flow is more distinctly than that in unidirectional pedestrian flow. This interesting phenomenon is consistent with the finding from Fig 2.

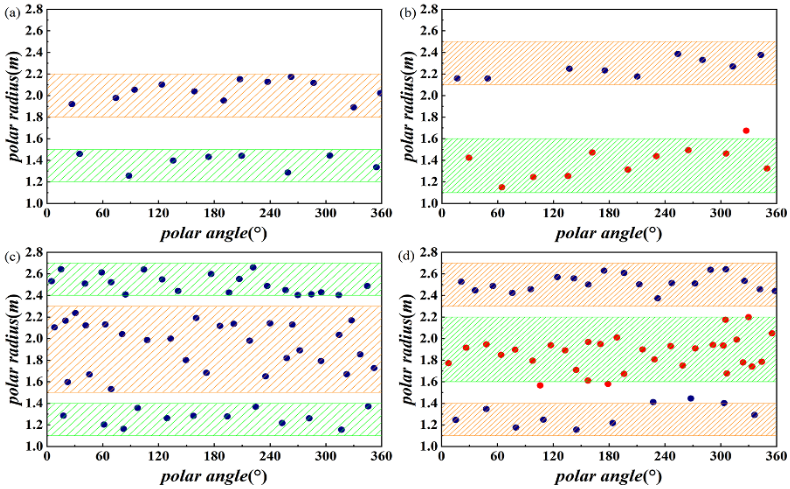

Fig. 3. Pedestrian positions in polar coordinates for height constraint of 1.4 m in a certain frame, where color-shaded rectangles roughly represent the lanes formed. (a) and (c) indicate the unidirectional pedestrian flow. (b) and (d) signify the bidirectional pedestrian flow.

To quantify the numbers of lane, some analytical methods such as order parameter, clustering method, velocity profile based Voronoi method, order entropy method have been proposed. Here in this paper, a novel clustering-based method where a weight density f_w has been introduced to identify and quantify the lane formation has been selected. It can be calculated by the following equation [15],

$$f_w(D_r) = \sum_i e^{-\phi|D_i - D_r|} \tag{1}$$

where D_i is the polar radial distance from pedestrian i to the corridor center, D_r is the polar radial distance from location r to the corridor center, parameter ϕ is set to be

0.2 in the present study, and the summation index stands for the cluster of pedestrians in the radial direction.

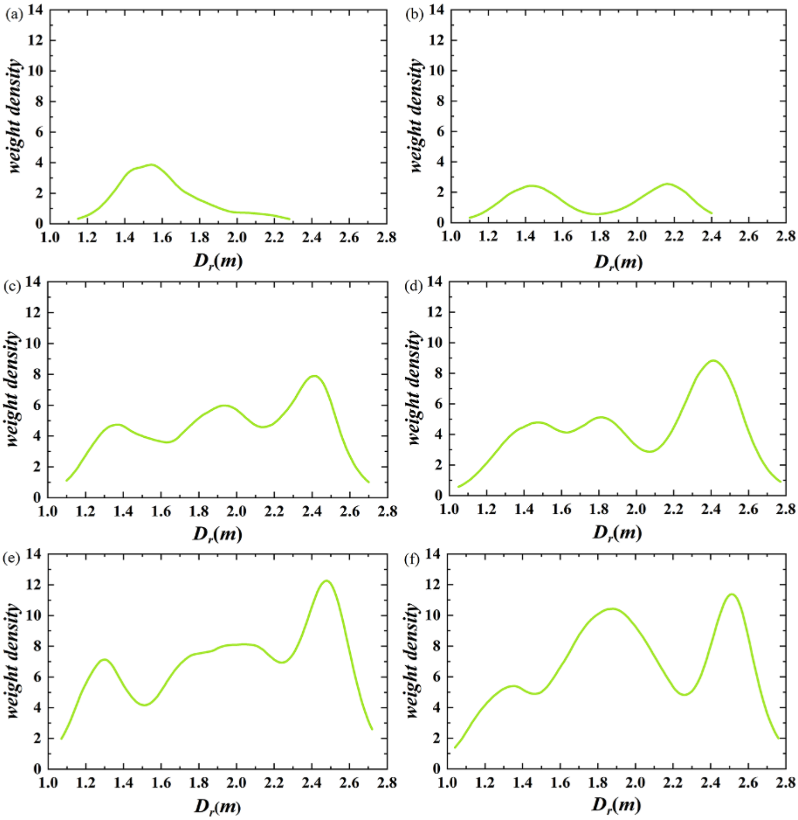

Fig. 4. Weight density in the polar radial direction in certain height. (a), (c) and (e) denote the unidirectional pedestrian flow. (b), (d) and (f) signify the bidirectional pedestrian flow.

The weight density is plotted for experimental runs in unidirectional and bidirectional pedestrian flow, as shown in Fig. 4. According to the implication of the weight density function, the number of peaks in the figure can be regarded as the number of lanes in the polar radial direction. From Fig. 4 it can be found that the numbers of lanes gradually increase with the global density increase. In low density, 1 lane is observed and the lane is wide in unidirectional pedestrian flow, however, 2 lanes are distinctly distributed in the channel for bidirectional pedestrian flow, as shown in Fig. 4(a) and (b). In medium density, 3 lanes can be observed in Fig. 4(c) and (d). Further increasing the global density to high values, it can also be found 3 lanes in Fig. 4(e) and (f), while 1 flat peak presents in unidirectional pedestrian flow, the 3 distinct peaks can be observed in bidirectional pedestrian flow, indicating that the distance between lanes is greater in bidirectional pedestrian flow to reduce the collision conflicts.

3.2 Fundamental diagrams

To study fundamental diagrams of unidirectional and bidirectional pedestrian flow in height constraints, we adopted modified Voronoi diagram method to calculate the pedestrians' density [4,16]. We plotted the scatter diagrams of the relation between speed and density. It can be seen from Fig. 5 that the maximum local densities can reach 6 ped/m^{-2} for unidirectional and bidirectional pedestrian flow, which is same as the results of Ref [4].

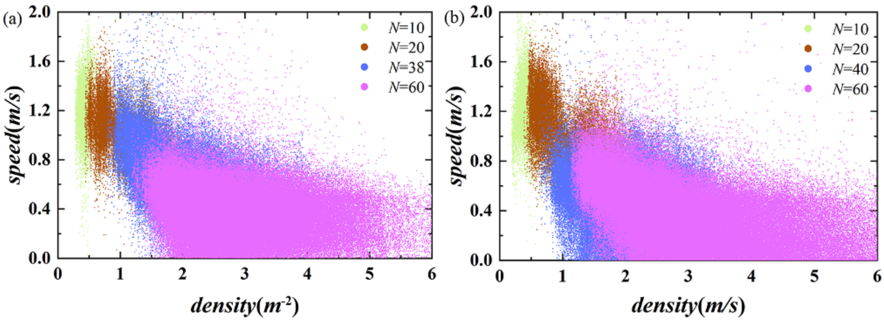

Fig. 5. Scatter diagrams of local density and speed. (a) unidirectional pedestrian flow and (b) bidirectional pedestrian flow.

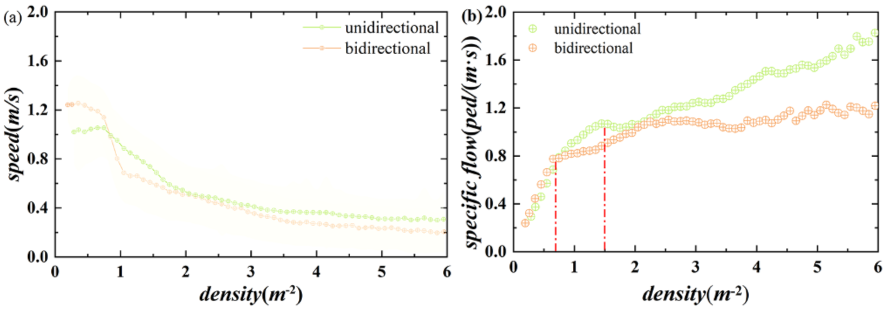

Fig. 6. Comparison of fundamental diagrams for unidirectional and bidirectional pedestrian flow.

For the convenience of better comparison, we used to the binning program to calculate the average value of density and the corresponding speed. Results can be found in Fig. 6. In speed-density relationship, an interesting phenomenon can be observed. When the density is less than 0.8 ped/m^{-2}, the speeds of bidirectional pedestrian flow is distinctly larger than that of unidirectional pedestrian flow. However, the result is inverse when the density is more than 0.8 ped/m^{-2}. In the specific flow-density relationship, it can be found that, at low density, the difference of specific flow for unidirectional and bidirectional pedestrian flow in height constraints is very small when the density is less than 0.6 ped/m^{-2}. However, with the density increase, the specific flow of unidirectional pedestrian flow is significantly larger than that of bidirectional pedestrian flow. The results are similar to findings of Ref [4].

4 Conclusions

A series of bidirectional pedestrian flow experiments under controlled laboratory conditions have been carried out to study movement characteristics of pedestrians under height constraints. The lane formation and fundamental diagrams have been discussed based on pedestrians' trajectories which were extracted from experimental video. On the basis of these discussions, we have the following conclusions. Firstly, the lane formation in bidirectional pedestrian flow is more distinct than that in unidirectional pedestrian flow. Meanwhile, no matter for unidirectional or bidirectional, the number of lanes formed in pedestrian flow always increase with the global density. Secondly, in speed and density relationship, when the density is less than 0.8 ped/m^{-2}, the free speeds of bidirectional pedestrian flow is distinctly larger than that of unidirectional pedestrian flow. In specific flow and density relationship, the specific flow of unidirectional pedestrian flow is significantly larger than that bidirectional pedestrian flow when the density is more than 0.6 ped/m^{-2}.

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