



The influence of weather and temperature on pedestrian walking characteristics on the zigzag bridge

Fan Dong¹ · Xiaolian Li² · Qimiao Xie¹ · Rui Ye³ · Shuchao Cao⁴

Received: 9 April 2022 / Accepted: 1 October 2022 / Published online: 18 October 2022
© The Author(s) under exclusive licence to International Society of Biometeorology 2022

Abstract

With the increasing number of tourists in recent years, ensuring the safety of visitors in tourist attractions has become an enormous challenge for safety management. At present, many experiments have been conducted to study pedestrian dynamics, but empirical data on tourists' movement state under different weather conditions are still few. Therefore, a series of field experiments were conducted to analyze the effect of external weather and temperature on pedestrians' movement characteristics. The results show that pedestrians are more concentrated in the middle and inner tracks during the turning process to seek the shortest path on rainy days. Moreover, it is found that pedestrians speed up under the conditions with low (below 10 °C) and high (over 30 °C) temperatures. The average speed of pedestrians is 0.677 m/s as the temperature is below 0 °C, which is much higher than the average speed of pedestrians in other temperature ranges. In addition, the speed of pedestrians changed more dramatically under the low-temperature conditions. It is hoped that this research can provide a reference for crowd control and rational design of pedestrian facilities.

Keywords Pedestrian · Zigzag bridge · Weather · Field observation · Movement speed and density

Introduction

With the rapid development of the modern transportation networks and tourism industry, tourist resorts are generally crowded with many pedestrians. Due to the more and more crowded tourist attractions, its capacity becomes insufficient, which may cause a high risk of stampede accidents. In recent years, there have been many serious stampede accidents around the world, and most of them caused heavy casualties and property losses (i.e., some of them are given in Table 1). Most severe accidents are caused by human factors, such as confusion and out-of-control persons. Therefore,

understanding the characteristics of pedestrians' behavior is essential to prevent congestion and stampede incidents.

Previous research has found that environment and layout affect the behavior of pedestrian flow (Kelly et al. 2011; Guo and Tang 2012; Cambra and Moura 2020). Congestion formation can vary widely in different architectural and geometrical contexts (Shi et al. 2018). Many studies have identified the effects of straight corridors on the pedestrian flow (Ren et al. 2019; Zhao et al. 2020; Zhang et al. 2011; Jin et al. 2021; Heliövaara et al. 2012). However, angled corridors exist in most walkways in public places. Understanding the pedestrian movement state in complex configurations, such as turns, is beneficial to formulate effective evacuation strategies and design solutions for public buildings and urban environments (Dias et al. 2013). Dias and Lovreglio (2018) calibrated two static floor fields for cellular automata models to represent pedestrians' walking behavior around 90° bends. Kirik et al. (2019) simulated pedestrian movement in “L”-shaped, “Z”-shaped, and “U”-shaped corridors. The results showed that the model parameters control the dynamics of the turning region, providing the methods for implementing the shortest path and shortest time strategies.

The development of numerous models enriches pedestrian flow research. However, the actual experimental data are

✉ Xiaolian Li
lixiaolian2018@163.com

¹ College of Ocean Science and Engineering, Shanghai Maritime University, Shanghai 201306, China

² Public Order Department, Fujian Police College, Fuzhou 350007, China

³ Business School, University of Shanghai for Science and Technology, Shanghai 200032, China

⁴ School of Automotive and Traffic Engineering, Jiangsu University, Zhenjiang 212013, China

Table 1 Casualties of major stampede accidents

Time	Place	Consequence
2010	Cambodia Water Festival	465 dead and 755 injured
2012	New Year's Eve in Luanda, Angola	10 dead and 120 injured
2014	Shanghai New Year's Eve	36 dead and 47 injured
2017	Italian Champions League Final	200 injured
2018	Concert in Manila, Philippines	66 dead and 280 injured

needed for the establishment, verification, and calibration of simulation models. Therefore, it is necessary to collect more pedestrian motion movement parameters data in different environments. Gorrini et al. (2013) empirically investigated the impact of angled corridors on orderly crowd egress flows and highlighted the importance of turning movements of a crowd during evacuations. Rahman et al. (2018; 2019) empirically studied the characteristics of pedestrians when walking through different angled corridors. It was found that the dimensional of a corridor (i.e., widths and angles) influence the movement speed of pedestrians. Ye et al. (2019) conducted a series of experiments in a right-angled corridor to investigate the effects of pedestrians' turning at the corners on pedestrian flow in uni- and bi-directional scenarios. Wu (2021) performed a series of unidirectional pedestrian flow experiment in an L-shaped corridor and studied the turning behavior of pedestrians in the L-shaped corridor with obstacles and asymmetry.

So far, there are quite a few studies on angled corridors (Shi et al. 2018). The current studies mainly explore the influences of the number of pedestrians on pedestrian movement behavioral characteristics in corridors with different angles (Rahman et al. 2020; Chen et al. 2019; Hannun et al. 2022). Although scholars have conducted extensive research, the mechanisms regulating human walking are not fully understood. Movement speed is the core parameter of most microscopic simulation models (Liang et al. 2020). For example, the average walking speed of pedestrians is 1.0–1.5 m/s under normal circumstances (Vanumu et al. 2017), and the movement speed of the wheelchair user is 0.61–1.31 m/s when there is no obstacle (Georg et al. 2020). In addition to personal factors, speed changes can also be affected by many environmental factors. Previous studies have shown that pedestrian walking speed and motion characteristics are also susceptible to weather (Walmsley 1989; Rotton et al. 1990). However, there are still few field experiments on how extent temperatures and weather affect pedestrian movement characteristics. Aultman-Hall et al. (2009) found that rainfall and sunshine affect the decision-making process of pedestrians. Kimura et al. (2015) noticed that the walking speed, rhythm, and stride of the elderly in winter were greater than in summer. Liang et al. (2020) studied the relationship between environmental

temperature and walking speed in places with cold winter climates and believed that low temperature may be related to individual behavior. Obuchi et al. (2021) pointed out that walking parameters were closely related to environmental temperature. Walking may be regulated by environmental temperature as well as by the response of the autonomic nervous system to environmental temperature.

In this study, a series of field experiments were conducted on the Zigzag Bridge in Shanghai Yu Garden. Many methods were employed to quantitatively analyze the pedestrians' movement characteristics at different temperatures. The rest of this paper is organized as follows: “**Methodology**” briefly describes the environment of the field experiments and the video-based tracking and extracting method. The differences of pedestrians' trajectories around the corner in different weather and the changes of pedestrians' movement speed under different temperature ranges are presented in “**Result analysis**.” In “**Conclusions**,” some conclusions are reported.

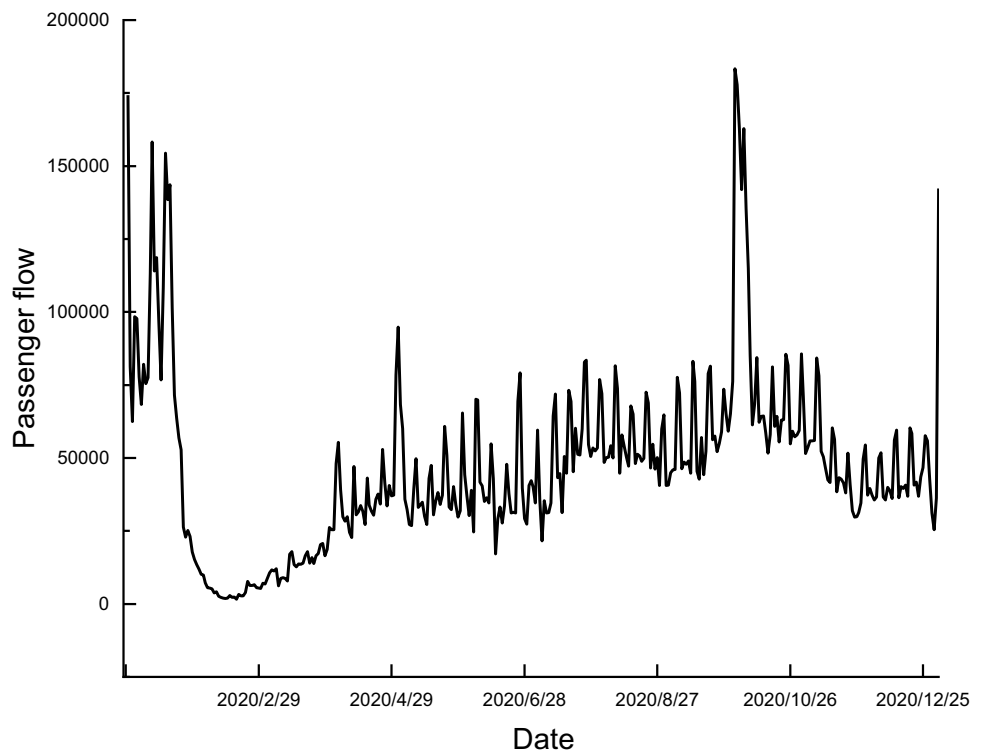
Methodology

Data collection

Yuyuan Garden is one of the top ten famous gardens in China, located in the north of Huangpu District, Shanghai. In 1982, it was listed as a national critical protection unit of cultural relics by the State Council of China. Because of its unique architecture and design style, it attracts many tourists every year. Figure 1 shows the number of tourists in the Yuyuan Garden business district in 2020. Passenger flow reached 183,302 *ped* on October 1. Yuyuan Garden belongs to the Yu Garden business district. To enter the Yu Garden, tourists have to pass the Zigzag Bridge. The passenger flow of the Yuyuan Garden business district reflects the passenger flow through the Zigzag Bridge to a certain extent. The whole bridge is 2.45 m wide and 97 m long with 15 continuous corners. Zigzag Bridge has a complex structure outdoors, which has enough samples for experimental studies. Thus, it is considered an excellent study site for our investigation.

Field observation was conducted to obtain the law of pedestrians' dynamics. There was no communication and exchange of information between the observed and the observer. As shown in Fig. 2, a video surveillance camera with a resolution of 1920 × 1080 pixels and a frame rate of 30 fps was installed on the outer wall of the third floor of the Yixiu Building. The data is recorded after pedestrians enter L1, and the recording ends when they leave L2; the actual measurement area is made up of a right-angled corridor in area I (2.45 × 2.45 m²) and a straight corridor in area II (2.45 × 2.4 m²). The video data is stored in the mobile hard disk in mp4 format. The pedestrians' movement and

Fig. 1 Passenger flow of Yuyuan Garden business district



behavior can be obtained by dealing with the video data in the target environment. This method is simple to work with low risk and cost.

To record pedestrians' movement at different temperatures, the observations were recorded by the camera from 9 a.m. to 5 p.m. throughout 2020. Moreover, the relevant weather data obtained from the National Meteorological Information Center are shown in Table 2. The observation time of the camera is about 2920 h, which leads to difficulties in the data processing. Therefore, stratified sampling is adopted for the video data according to the collected meteorological data. Due to the influence of COVID-19, data for the first half year of 2020 was not used.

Data extraction and processing method

Tracker, a software tool for video analysis and trajectory tracking, is adopted to extract pedestrians' trajectories (Claessens 2017). The tracker software establishes the movement tracking in two-dimensional plane coordinates and calibrates the video data with the actual size. The software has been widely used in video data processing and analysis research (Aghabayk et al. 2020). First, feature points are marked in the first frame of each pedestrian entering L1, which is marked on the pedestrian's head, and a tracker is constructed by using this frame. Then, the most likely next frame region is tracked based on the marked features, marking the same pedestrian again. This

process continues until the pedestrian leaves L2. In addition, Tracker pauses when a never-before-seen instance appears in the upcoming frame due to visual errors and pedestrians' occlusion. The trajectory of some pedestrians would deviate, and it is necessary to manually extract the position information of the research area frame by frame. When it rains, the umbrellas will affect the path tracking of pedestrians. However, the number of pedestrians is small on rainy days, which can be conveniently tracked. The locating point is placed at the umbrella cap.

In this study, the video frame rate is 30 fps, that is, the camera can capture 30 frames in 1 s. Each frame is a picture, and by concatenating these frames in chronological order, the dynamic continuous coordinates of pedestrians are obtained.

Based on the collected pedestrians' trajectory data, we calculate the movement speed of each pedestrian. The average speed of pedestrians can be analyzed under different weather and temperature conditions. The calculation method of the instantaneous speed $v_i(t)$ of pedestrian i at time t is presented in Eq. (1).

$$v_i(t) = \frac{x_i\left(t + \frac{\Delta t}{2}\right) - x_i\left(t - \frac{\Delta t}{2}\right)}{\Delta t} \quad (1)$$

where $x_i(t)$ represents the position coordinates of pedestrian i at time t , and Δt is the time interval used to calculate the

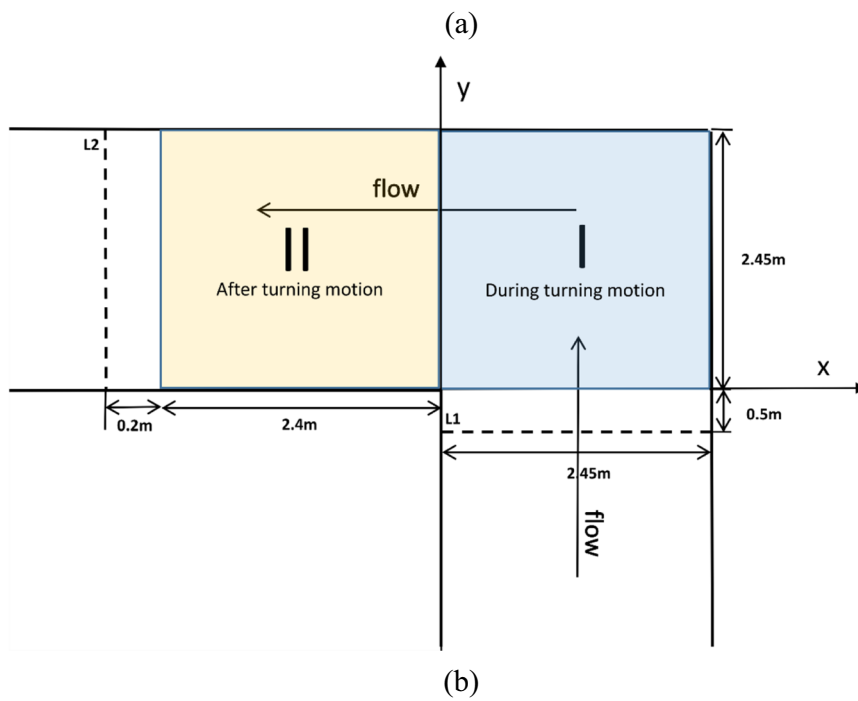
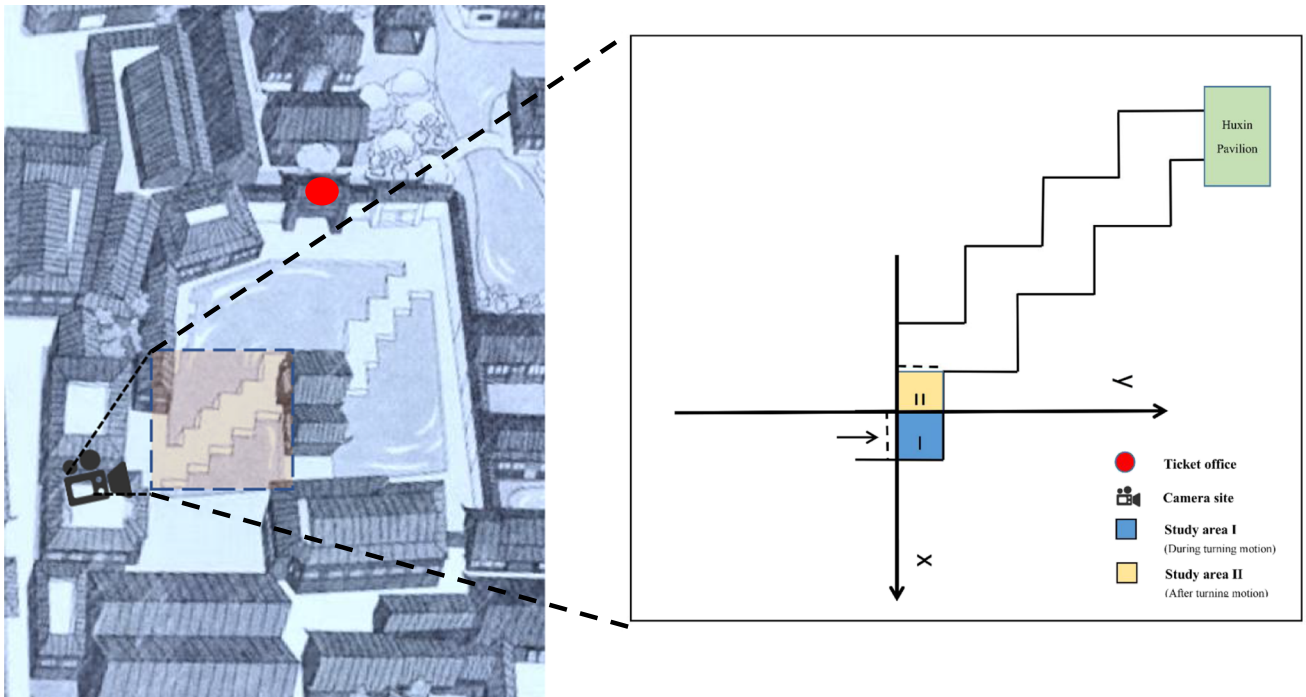


Fig. 2 **a** The scene at the Zigzag Bridge. **b** Partially enlarged schematic diagram

Table 2 Temperature statistics

Date	Week	Weather	Temperature(9 a.m.–5 p.m.)		
			Maximum	Mean	Minimum
2020.07.02	Thur	Rainy	26 °C	25 °C	24 °C
2020.07.15	Wed	Rainy	21 °C	21 °C	21 °C
2020.07.19	Sun	Cloudy	36 °C	34 °C	28 °C
2020.08.12	Wed	Sunny	36 °C	35 °C	32 °C
2020.08.29	Sat	Cloudy	32 °C	31 °C	26 °C
2020.09.05	Sat	Sunny	32 °C	31 °C	29 °C
2020.09.11	Fri	Rainy	27 °C	25 °C	22 °C
2020.09.19	Sat	Cloudy	23 °C	22 °C	21 °C
2020.10.01	Thur	Sunny	27 °C	26 °C	24 °C
2020.10.16	Fri	Rainy	17 °C	17 °C	17 °C
2020.11.08	Sun	Sunny	20 °C	19 °C	17 °C
2020.11.27	Fri	Rainy	14 °C	13 °C	11 °C
2020.12.14	Mon	Cloudy	6 °C	5 °C	2 °C
2020.12.21	Mon	Sunny	10 °C	9 °C	6 °C
2021.01.07	Wed	Cloudy	−3 °C	−3 °C	−4 °C

instantaneous speed; it usually equals to 0.4 s. The average speed of pedestrian flow at the time t is shown in Eq. (2).

$$v(t) = \frac{1}{N(t)} \sum_{i=1}^{N(t)} v_i(t) \tag{2}$$

where $v(t)$ is the average speed at the time t ; $N(t)$ is the total number of pedestrians in the measurement area at the time t . The calculation of pedestrians’ density in the study area at time t is shown in Eq. (3). Among them, A is the area of the

measurement area that includes a 2.45×2.45 m right-angle corridor and a 2.45×2.4 m straight corridor.

$$\rho(t) = \frac{N(t)}{A} \tag{3}$$

Result analysis

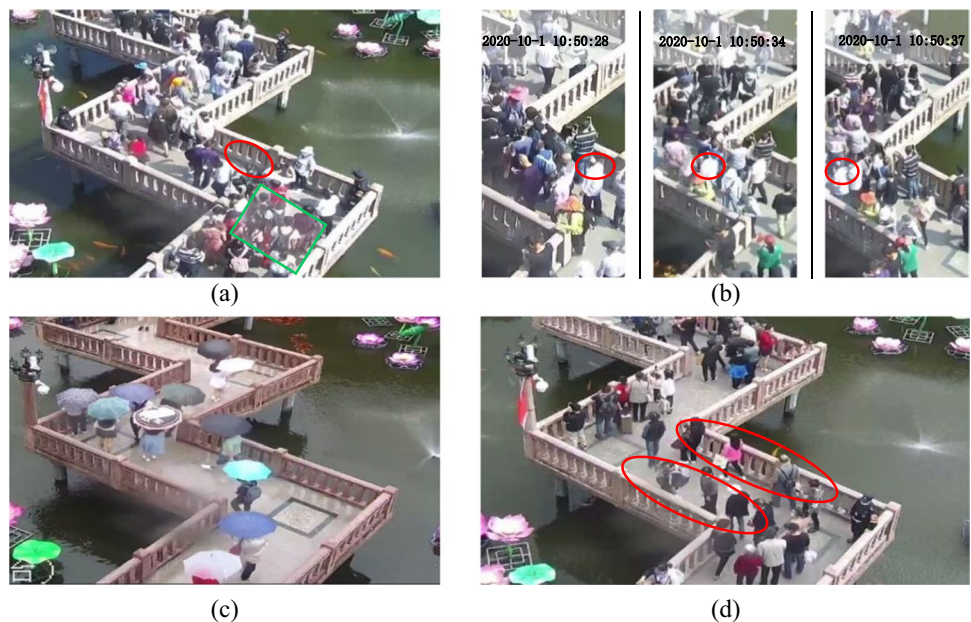
Findings from observations and video footage

As displayed in Fig. 3, some interesting phenomena can be observed in the video footage. From Fig. 3a, tourists stop on the bridge to take pictures, which affect pedestrians moving behind, and there is a gap in the flow of pedestrians in front. In Fig. 3b, there is a blockage ahead, and the blocked pedestrians would detour. From Fig. 3c d, it can be seen that there would be fewer tourists on rainy days than on sunny days. Because of foul weather, most tourists would give up viewing temporarily and choose the shortest path to leave the bridge. From Fig. 3d, it can also be seen that pedestrians have a self-organizing behavior of walking along the railing.

Trajectory analysis

To understand the movement characteristics of pedestrians under different weather conditions, we extract about 200 pedestrians’ trajectory data on sunny, cloudy, and rainy days, respectively. Trajectories are shown in Fig. 4. Moreover, the instantaneous speeds of pedestrians are depicted in different colors.

Fig. 3 a Pedestrians’ congestion and flow gap, b pedestrians’ detour behavior, c tourists on rainy days, and d self-organization behavior of pedestrians walking along railings.



It is found that pedestrians move faster on rainy days, and the trajectory distribution is more concentrated than that on sunny and cloudy days. An underutilized triangular area appears in the outer corner on rainy days. The actual walking distance of each pedestrian is calculated by summing the distances between adjacent points of each

pedestrians' trajectory. Table 3 shows the average length and time of pedestrian trajectory. The average walking time of pedestrians is only 7.33 s on rainy days, while they are 14.58 s on sunny days and 13.02 s on cloudy days. The average walking distances on sunny, cloudy, and rainy days are 7.45 m, 6.79 m, and 5.59 m respectively, which

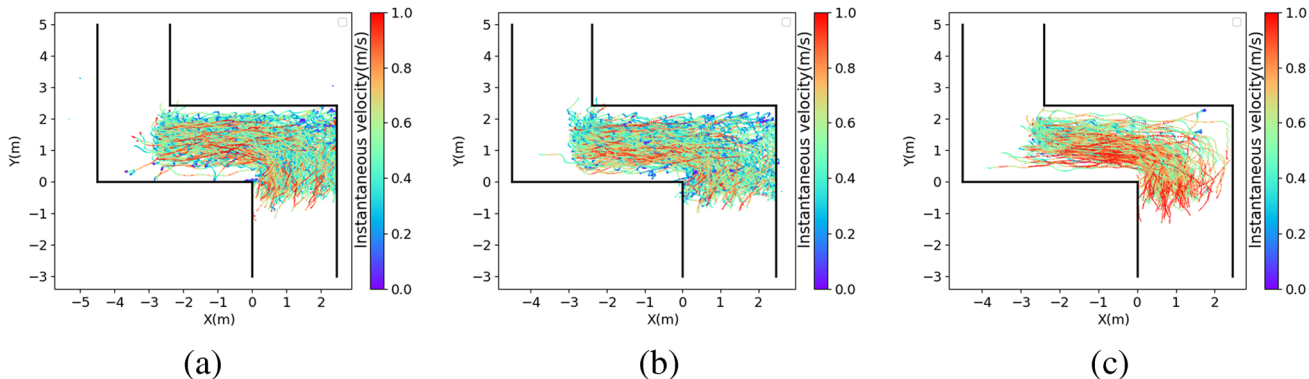
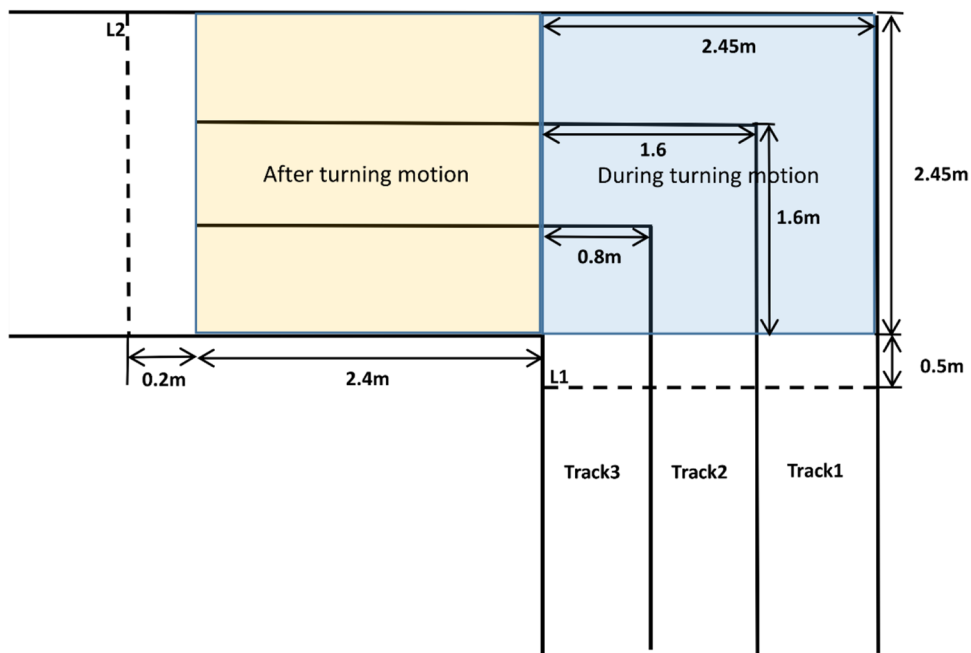


Fig. 4 Pedestrians' trajectory and instantaneous speed in different weather a sunny, b cloudy, and c rainy

Table 3 Average distance and average time of trajectories under different weather conditions

		Mean	Standard deviation	Minimum	Median	Maximum
Sunny	Distance/m	7.44984	2.16827	4.49031	7.0052	21.4227
	Time/s	14.57817	8.43429	4.2	11.96667	53.66667
Cloudy	Distance/m	6.78834	1.80215	4.00646	6.42118	16.96653
	Time/s	13.02307	7.96227	4.24	10.86667	51.96667
Rainy	Distance/m	5.58508	0.93623	3.66424	5.48142	10.78459
	Time/s	7.33067	2.80087	3.73333	6.85	27.06667

Fig. 5 Schematics of track



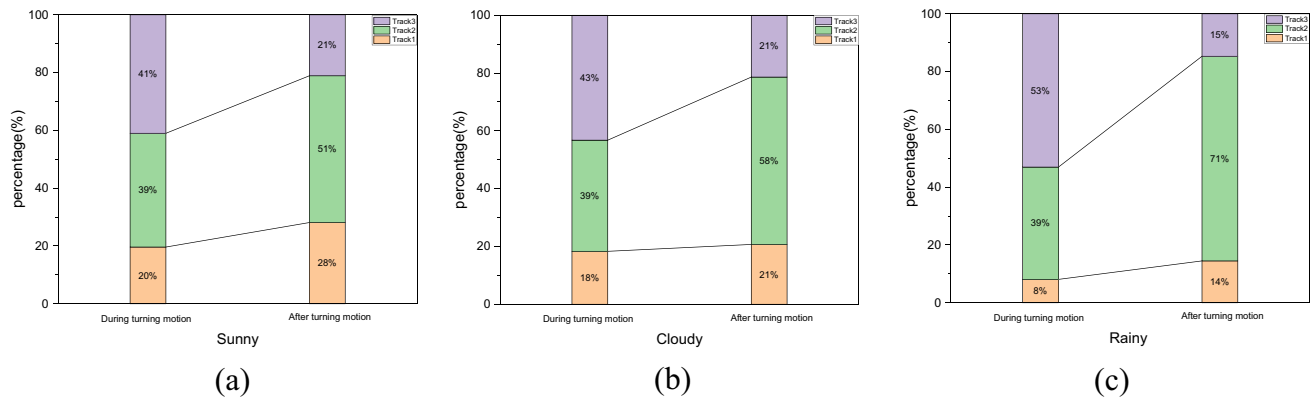


Fig. 6 Pedestrians' distribution on different tracks under different weather conditions: **a** sunny, **b** cloudy, and **c** rainy

demonstrates that rain would prompt pedestrians to give up viewing and leave quickly.

In order to further explore the trajectory selection of pedestrians under different weather conditions, Zigzag Bridge is equally divided into three walkways in Fig. 5: outer (Track 1), middle (Track 2), and inner (Track 3). The width of each walkway is 0.8 m.

As shown in Fig. 6, we compared the distribution of pedestrians' trajectories during and after turning motion. Pedestrians who chose the outer track during and after turning motion on sunny, cloudy, and rainy are 20%, 18%, 8%, 28%, 21%, and 14% respectively. It can be found that some pedestrians choose the outer track instead of the inner track. Pedestrians walk along the sides of the fence to get a better view when they pass the corner, in which pedestrians choose the available space for their purpose. Pedestrians during turning motion prefer choosing Tracks 2 and 3, while more pedestrians choose Tracks 1 and 2 after turning motion. Pedestrians tend to change the track from the inner or middle to the middle or outer tracks after turning motion, possibly because the pedestrian is about to enter the next turn in the successive corner. Pedestrians have different track choices in different weather conditions. On sunny and cloudy days, more pedestrians choose Track 1 than that on rainy days during and after turning motion. Because the overall number of tourists is relatively large, Tracks 2 and 3 are fully occupied under these weather conditions. Pedestrians prefer to use the available space to adapt their speed for the purpose of comfort (Rahman et al. 2019), so more pedestrians choose Track 1 to avoid congestion during and after turning motion on sunny and cloudy days. The number of tourists is small, so the aisles would not be congested on rainy days. In addition, pedestrians have less interest in viewing the scenery on rainy days and choose the shortest path to leave as soon as possible. As a result, fewer pedestrians choose Track 1 than that on sunny and cloudy days. This confirms the conclusions of Rahman et al. (2019). Pedestrians do not necessarily choose

the shortest path when walking. The trajectory of pedestrians would change when pedestrians use the walkable space to avoid apparent congestion ahead. It can be concluded that weather affects the walking status of pedestrians, which is consistent with the existing researches (Liang et al. 2020; Obuchi et al. 2021).

Average movement speed on different dates

The distribution of pedestrians' movement speed and density on particular days can be obtained by processing observational test data, as shown in Fig. 7.

In Fig. 7a, the pedestrians' density in the study area is calculated according to Eq. (3). The maximum average density is 1.405 ped/m², and the minimum average density is 0.103 ped/m². Particularly, the average densities are 1.026 ped/m², 1.077 ped/m², 1.406 ped/m², and 1.064 ped/m² on July 19, Sep. 19, Oct. 1, and Nov. 8, 2020, respectively, which are over 1 ped/m². The common feature of these days is that they are holidays. However, the average density is below 0.2 ped/m² within working days. For example, the average densities are 0.153 ped/m², 0.141 ped/m², and 0.143 ped/m² on Aug. 12 and Nov. 27, 2020, and Jan. 7, 2021, respectively, which are much lower than other statistical periods. Whether it is a working day will directly affect the total number of tourists (de Montigny et al. 2011), which may lead to a high density or congestion.

The distributions of the average speed of pedestrians are shown in Fig. 7b. The average speeds are 0.44 m/s, 0.5 m/s, 0.4 m/s, and 0.46 m/s on July 19, Sep. 19, Oct. 1, and Nov. 8, 2020, respectively, within which the range of 0.4–0.5 m/s. On August 12, 2020, November 27, 2020, and January 7, 2021, the average speed was greater than 0.64 m/s. That is, the higher the average density is, the lower the average pedestrians' speed is. Furthermore, as shown in the plot boxes in Fig. 7, the lower the average density is, the more significant the difference between the maximum and

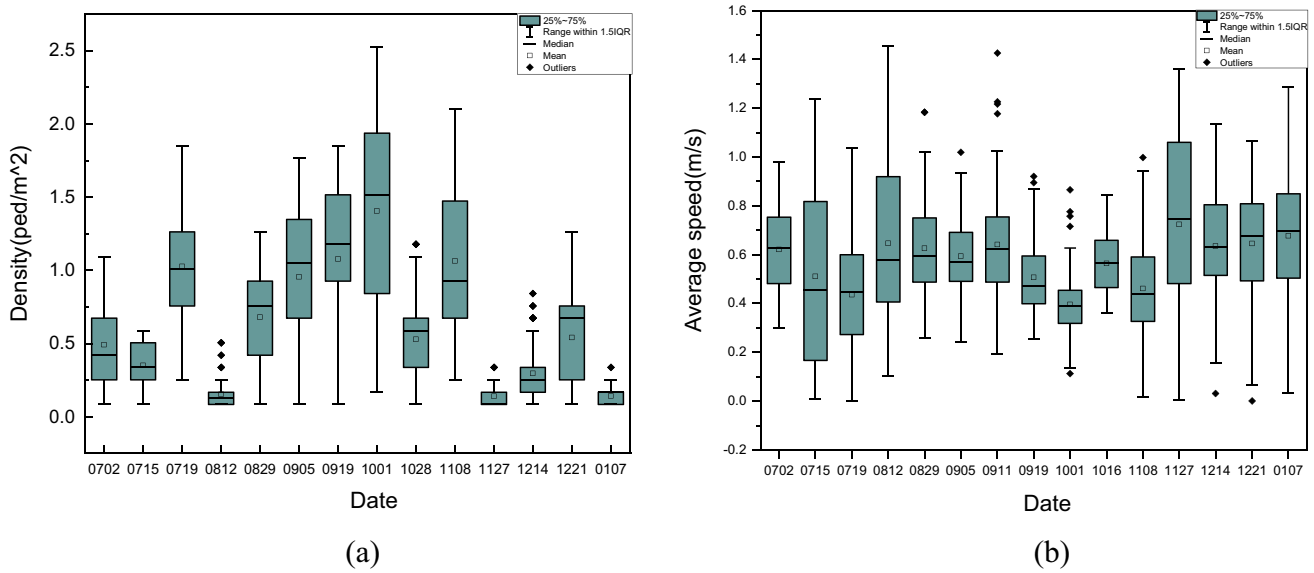


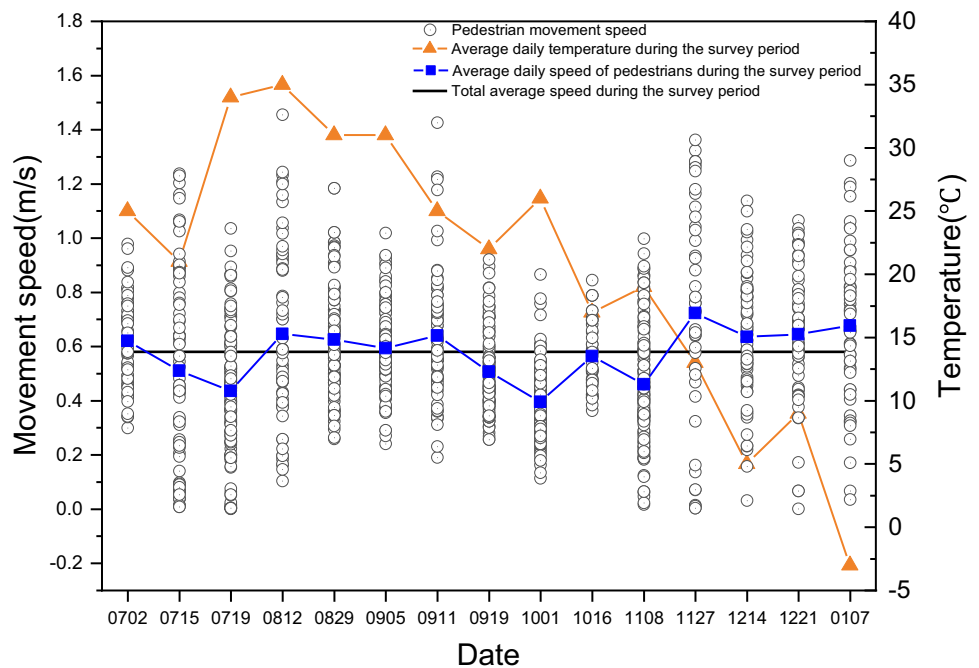
Fig. 7 **a** Density box diagram in the study area and **b** average velocity box diagram in the study area.

minimum average velocities is. When there are many tourists, the pedestrians’ speed is affected by the entire pedestrian flow. However, when the number of tourists is small, tourists can walk freely considering both their purpose and comfort, which may result in significant differences between individual movement speeds.

It is worth noting that the density situation on August 12 is similar to that on November 27, while the average speed on November 27 is 0.72 m/s, which is faster than the average speed on August 12 (0.64 m/s). The most significant difference

between the 2 days is that August 12 is sunny with an average daytime temperature of 35 °C, while November 27 is rainy. The relationships between pedestrians’ movement speed and temperature are presented in Fig. 8. According to Ma et al. (2020), the average speed of pedestrians in normal walking is about 1.2 m/s. But when the density is high, pedestrians are in low-speed walking with the average speed of about 0.5 m/s (Shah et al. 2015). Moreover, a level of perceived naturalness along a route is crucial for decreasing movement speed (Franěk and Režný 2021). The Zigzag Bridge is in an

Fig. 8 The relationship between temperature and movement speed



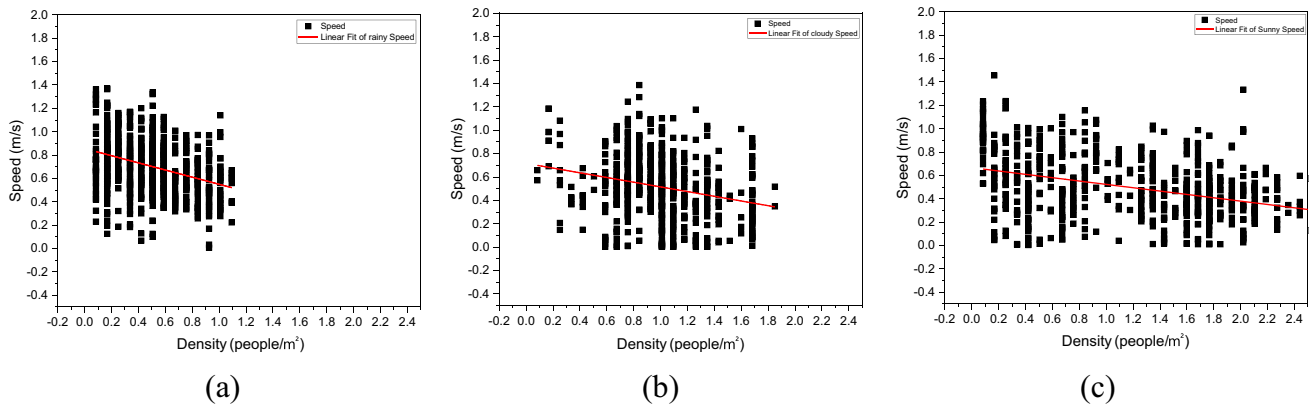


Fig. 9 Density velocity basic diagram in different weather a rainy, b cloudy, and c sunny

Table 4 Density and speed in different weather

	Average density (ped/m ²)	Average speed (m/s)
Sunny	1.32	0.544
Cloudy	0.91	0.574
Rainy	0.31	0.613

environment with greenery and a low level of traffic, so the overall movement speed is slow. Figure 8 shows that the average pedestrians’ movement speed on the Zigzag bridge is 0.58 m/s. However, when the temperature is lower than 15 °C, the average daily speed of pedestrians is above 0.58 m/s, which indicates that the behavior of pedestrians is related to low temperature (Liang et al. 2020).

Average speed for different temperatures and weather

The fundamental diagrams that describe the relationships between density and speed under different weather conditions are obtained. By fitting and analyzing the scatter plot, as shown in Fig. 9, the relationship between pedestrians’ speed and density is shown in formulas (4)–(6). It is found that the average speed of pedestrians decreases with the increase of crowd density. The larger the absolute value of the slope is, the steeper the fitting line is. On rainy days, the average speed is more sensitive to density. As shown in Table 4, the average densities and speeds on sunny, cloudy, and rainy days are 1.32 ped/m², 0.91 ped/m², 0.31 ped/m², 0.544 m/s, 0.574 m/s, and 0.613 m/s, respectively. The density of pedestrians on rainy days is lower than that on sunny and cloudy days. The reason may be that the weather affects people’s non-essential and unconventional travel choices.

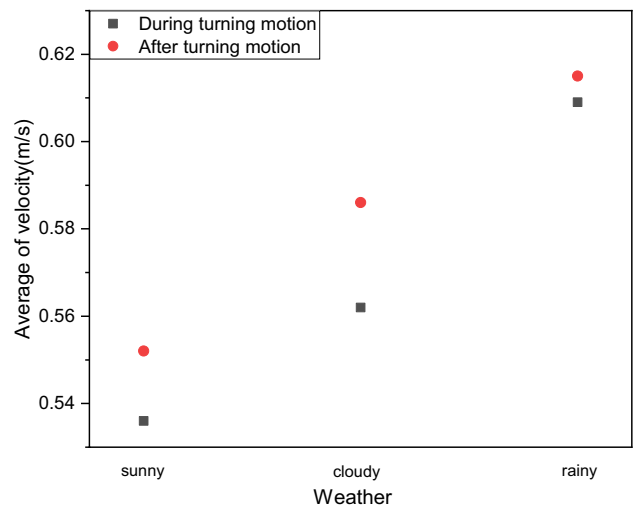


Fig. 10 Average speed during and after turning motion in different weather

$$y = 0.30552 \times +0.8555 \tag{4}$$

$$y = 0.20106 \times +0.71619 \tag{5}$$

$$y = 0.14328 \times +0.66675 \tag{6}$$

The average speeds during and after turning motion are shown in Fig. 10. The average speeds of pedestrians during and after turning motion on sunny, cloudy, and rainy days are 0.539 m/s, 0.562 m/s, 0.609 m/s, 0.552 m/s, 0.586 m/s, and 0.615 m/s, respectively. The speed of the pedestrians after turning motion is slightly higher than during turning motion. The result is consistent with the findings of Wu (2021) and Kirrik et al. (2019) that pedestrians speed up after turning. In addition, on rainy days, the difference in average speed between during and after turning motion is

Table 5 Average speed at different temperature intervals

Temperature	Mean (m/s)	Min (m/s)	Max (m/s)
– 10 to 0 °C	0.67706	0.035	1.386
0 to 10 °C	0.62079	0.001	1.137
10 to 20 °C	0.56251	0.001	1.362
20 to 30 °C	0.54909	0.001	1.238
Over 30 °C	0.59602	0.103	1.455

relatively minor than that in other weather conditions. As a result, it can be deduced that weather affects pedestrian movement characteristics.

The temperature range is divided into five categories: – 10 °C to 0 °C, 0 °C to 10 °C, 10 °C to 20 °C, 20 °C to 30 °C, and over 30 °C. Some limiting measures would be taken to control pedestrian flow on holidays. Thus, to guarantee the accuracy of analysis, the weekday data are chosen in this study. The statistical results of corresponding speeds are shown in Table 5.

From Table 5, it can be seen that the lowest speed is 0.001 m/s within the temperature of 0–30 °C, which indicates that tourists would stop to enjoy the scenery under this comfortable temperature. In contrast, the minimum values of movement speed are 0.035 m/s and 0.103 m/s when the temperatures are below 0 °C and over 30 °C respectively. Moreover, the maximum values of movement speed are 1.386 m/s and 1.455 m/s under these circumstances, which is higher than that within the temperature of 0–30 °C. Thus, the extreme high and low-temperature environment will reduce the desire of tourists to enjoy the scenery.

The average speeds in the ranges of 10–20 °C, 20–30 °C, and over 30 °C are 0.563 m/s, 0.549 m/s, and 0.596 m/s, respectively, which are all lower than the total average speed of all observed data (0.6 m/s). In a low-temperature environment, i.e., below 10 °C, the movement speed will increase under this circumstance. This is consistent with the findings obtained on rainy days. That is, the lower the temperature is, the greater the average speed is. As a consequence, pedestrians are more stimulated by low temperatures. Furthermore, Obuchi et al. (2021) also came to the similar conclusion that movement speed and rhythm are higher in winter (average maximum temperature of 10.2 °C) than that in summer (average maximum temperature of 29.8 °C).

Conclusions

In this paper, a series of field observation of the zigzag bridge from January 2020 to January 2021 were conducted to analyze the effect of weather condition on the movement characteristics of pedestrians during and after the turning motion. A total of 600 pedestrians' trajectories were

extracted from the video data based on the Tracker software. Moreover, the weather conditions and temperature in relation to the observation period are collected to understand the walking status of pedestrians when passing through the corner in different weather conditions. The results indicate that pedestrians have different walking characteristics when passing through the zigzag bridge under the motivation of different weather conditions and temperature. Some conclusions are summarized as follows.

Based on the qualitative analysis of the field observations, some phenomena and characteristics can be captured under different weather conditions. The self-organized behavior is found when pedestrians walk along the railings on both sides of the Zigzag Bridge. For instance, pedestrians stop for a short time to take pictures or stand on both sides of the corridor for a long time, then they block the road and affect the movement flow of people behind. On rainy days, due to the influence of the weather, there are few pedestrians taking pictures or staying at the railings for a long time. Pedestrians tend to choose the inner track to reach their destinations quickly. On sunny and cloudy days, the number of pedestrians is larger than that on rainy days; thus, there is competition or detour behavior during walking when the inner track is occupied by pedestrians. In order to avoid congestion, the remaining pedestrians choose other tracks to maintain the comfort of walking. As a result, weather affects pedestrians' track choices.

Based on the quantitative analysis of trajectories of pedestrian movement on zigzag bridge, the weather has a significant impact on pedestrian's movement characteristics. The average speed of pedestrians (0.613 m/s) on rainy days is larger than that on sunny days (0.544 m/s) and cloudy days (0.574 m/s). Moreover, the temperature is also considered as a main factor to affect the movement characteristics of pedestrians in this study. When the temperature is over 30 °C, the average speed of pedestrians is 0.596 m/s, while the average speed of pedestrians is 0.677 m/s with the temperature below 0 °C. Low temperature is more irritative to pedestrians than high temperature. It may be prone to cause congestion or safety accidents in a high-temperature environment with a large number of tourists and a fast movement speed. Consequently, it is necessary to strengthen the guidance of pedestrians and reduce the time consumption in the middle of the bridge under this circumstance. In addition, the road surface is slick on rainy days or under low-temperature situations, and walkers are more likely to fall when walking quickly. Thus, setting up safety signs and cleaning road timely are conducive to guarantee the pedestrians' safety.

The findings in this work lay the groundwork for a better understanding of microscopic walking characteristics under various weather conditions. Furthermore, relevant research findings can be used to improve pedestrian models, allowing

them to imitate pedestrian walking behaviors connected with turning movements more accurately. It also provides some design insights for urban planners and architectural designers. Weather elements should be taken into account to improve the experience of tourists during the design of outside landscape architecture.

The advantage of this study is that it collected data over a long period, which may include various pedestrian behaviors. Temperature and weather are considered as the main factors that have an impact on pedestrian walking characteristics in this study. However, it is non-negligible that gender, age, height, and other factors may influence the respond of people in reality. In future work, it is necessary to incorporate different factors and conduct more in-depth and comprehensive research in multiple perspectives and fields.

Funding This work was supported by the Young Scientists Fund of the National Natural Science Foundation of China (Grant No.52004158, 72001095, 71503166), China Postdoctoral Science Foundation (2020M681507).

References

- Aghabayk K, Radmehr K, Shiwakoti N (2020) Effect of intersecting angle on pedestrian crowd flow under normal and evacuation conditions. *Sustainability* 12 (4). <https://doi.org/10.3390/su12041301>
- Aultman-Hall L, Lane D, Lambert RR (2009) Assessing impact of weather and season on pedestrian traffic volumes Transportation Research Record. *J Transp Res Board* 2140(1):35–43. <https://doi.org/10.3141/2140-04>
- Cambra P, Moura F (2020) How does walkability change relate to walking behavior change? Effects of a street improvement in pedestrian volumes and walking experience. *J Transp Health* 16:100797. <https://doi.org/10.1016/j.jth.2019.100797>
- Chen S, Fu L, Fang J, Yang P (2019) The effect of obstacle layouts on pedestrian flow in corridors: an experimental study. *Physica A* 534:122333. <https://doi.org/10.1016/j.physa.2019.122333>
- Claessens T (2017) Analyzing virtual physics simulations with tracker. *The Physics Teacher* 55(9):558–560. <https://doi.org/10.1119/1.5011834>
- de Montigny L, Ling R, Zacharias J (2011) The effects of weather on walking rates in nine cities. *Environ Behav* 44(6):821–840. <https://doi.org/10.1177/0013916511409033>
- Dias C, Sarvi M, Shiwakoti N, Ejtemai O, Burd M (2013) Investigating collective escape behaviours in complex situations. *Saf Sci* 60:87–94. <https://doi.org/10.1016/j.ssci.2013.07.005>
- Dias C, Lovreglio R (2018) Calibrating cellular automaton models for pedestrians walking through corners. *Phys Lett A* 382(19):1255–1261. <https://doi.org/10.1016/j.physleta.2018.03.022>
- Franěk M, Režný L (2021) Environmental features influence walking speed: the effect of urban greenery. *Land* 10(5):459
- Gorrini A, Bandini S, Sarvi M, Dias C, Shiwakoti N (2013) An empirical study on crowd and pedestrian dynamics: the impact of different angle paths and grouping, vol 41.
- Geoerg P, Schumann J, Holl S, Boltes M, Hofmann A (2020) The influence of individual impairments in crowd dynamics. *Fire and Materials* 2020. <https://doi.org/10.1002/fam.2789>
- Guo RY, Tang TQ (2012) A simulation model for pedestrian flow through walkways with corners. *Simul Model Pract Theory* 21(1):103–113. <https://doi.org/10.1016/j.simpat.2011.10.007>
- Hannun J, Dias C, Taha A, Almutairi A, Alhadjyaseen W, Sarvi M, Al-Bosta S (2022) Pedestrian flow characteristics through different angled bends: exploring the spatial variation of velocity. *PLoS ONE* 17:e0264635. <https://doi.org/10.1371/journal.pone.0264635>
- Heliövaara S, Kuusinen JM, Rinne T, Korhonen T, Ehtamo H (2012) Pedestrian behavior and exit selection in evacuation of a corridor – an experimental study. *Saf Sci* 50(2):221–227. <https://doi.org/10.1016/j.ssci.2011.08.020>
- Jin CJ, Jiang R, Liu T, Li D, Wang H, Liu X (2021) Pedestrian dynamics with different corridor widths: investigation on a series of uni-directional and bi-directional experiments. *Physica A* 581:126229. <https://doi.org/10.1016/j.physa.2021.126229>
- Kelly CE, Tight MR, Hodgson FC, Page MW (2011) A comparison of three methods for assessing the walkability of the pedestrian environment. *J Transp Geogr* 19(6):1500–1508. <https://doi.org/10.1016/j.jtrangeo.2010.08.001>
- Kirik E, Vitova T, Malyshev A (2019) Turns of different angles and discrete-continuous pedestrian dynamics model. *Natural Computing* 18. <https://doi.org/10.1007/s11047-019-09764-4>
- Kimura T, Kobayashi H, Nakayama E, Kakihana W (2015) Seasonality in physical activity and walking of healthy older adults. *Journal of Physiological Anthropology* 34. <https://doi.org/10.1186/s40101-015-0071-5>
- Liang S, Leng H, Yuan Q, Wang B, Yuan C (2020) How does weather and climate affect pedestrian walking speed during cool and cold seasons in severely cold areas? *Build Environ* 175:106811. <https://doi.org/10.1016/j.buildenv.2020.106811>
- Ma J, Song WG, Fang ZM, Lo SM, Liao G-X (2010) Experimental study on microscopic moving characteristics of pedestrians in built corridor based on digital image processing. *Build Environ* 45(10):2160–2169. <https://doi.org/10.1016/j.buildenv.2010.03.015>
- Obuchi SP, Kawai H, Garbalosa JC, Nishida K, Murakawa K (2021) Walking is regulated by environmental temperature. *Sci Rep* 11(1):12136. <https://doi.org/10.1038/s41598-021-91633-1>
- Rahman NA, Adenan SHM, Alias NA, Kasehyani NH, Sukor NSA, Halim H, Katman HY (2018) Experimental study and computational analysis on pedestrians behaviour walking through angled-corridor. In *AIP Conference Proceedings* 2030(1):020247
- Rahman NA, Alias NA, Sukor NSA, Halim H, Gotoh H, Hassan FH (2019) Trajectories and walking velocity of pedestrian walking through angled-corridors: a unidirectional scenario. *IOP Conference Series: Mater Sci Eng* 572:012114. <https://doi.org/10.1088/1757-899x/572/1/012114>
- Rahman NA, Alias N, Abdul Sukor NS, Halim H, Gotoh H, Hassan F (2020) Simulation of pedestrian walking through angled-corridors for evacuation behaviour study. *IOP Conference Series: Mater Sci Eng* 877:012061. <https://doi.org/10.1088/1757-899x/877/1/012061>
- Ren X, Zhang J, Song W (2019) Cao S (2019) The fundamental diagrams of elderly pedestrian flow in straight corridors under different densities. *J Stat Mech: Theory Exp* 2:023403. <https://doi.org/10.1088/1742-5468/aafa7b>
- Rotton J, Shats M, Standers R (1990) Temperature and pedestrian tempo: walking without awareness. *Environ Behav* 22(5):650–674
- Shah J, Joshi G, Parida P, Arkatkar S (2015) Impact of train schedule on pedestrian movement on stairway at suburban rail transit station in Mumbai, India. *Advances in Civil Engineering* 2015:1–9. <https://doi.org/10.1155/2015/297807>
- Shi X, Zhirui Y, Shiwakoti N, Grembek O (2018) A state-of-the-art review on empirical data collection for external governed pedestrians complex movement. *J Adv Transp* 2018:1–42. <https://doi.org/10.1155/2018/1063043>

- Vanumu L, Rao KR, Tiwari G (2017) Fundamental diagrams of pedestrian flow characteristics: a review. *European Transport Research Review* 9. <https://doi.org/10.1007/s12544-017-0264-6>
- Walmsley DJ (1989) The pace of pedestrian flows in cities. *Environment and Behavior* 21 (2):123–150. <https://doi.org/10.1177/0013916589212001>
- Wu X (2021) Experimental analysis and simulation study on turning behavior of pedestrians in L-shaped corridor. *Acta Physica Sinica -Chinese Edition-*. <https://doi.org/10.7498/aps.70.20210055>
- Xu L, Wang HY, Song ZG (2015) A literature review on observation of the pedestrian step forces. *Appl Mech Mater* 730:43–49. <https://doi.org/10.4028/www.scientific.net/AMM.730.43>
- Ye R, Chraibi M, Liu C, Lian L, Zeng Y, Zhang J (2019) Song W (2019) Experimental study of pedestrian flow through right-angled corridor: uni- and bidirectional scenarios. *J Stat Mech: Theory Exp* 4:043401. <https://doi.org/10.1088/1742-5468/ab0c13>
- Zhang J, Klingsch W, Schadschneider A, Seyfried A (2011) Transitions in pedestrian fundamental diagrams of straight corridors and T-junctions. *J Stat Mech-Theory Exp*:17. <https://doi.org/10.1088/1742-5468/2011/06/p06004>
- Zhao X, Xia L, Zhang J, Song W (2020) Artificial neural network based modeling on unidirectional and bidirectional pedestrian flow at straight corridors. *Physica A* 547:123825. <https://doi.org/10.1016/j.physa.2019.123825>

Springer Nature or its licensor holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.