EXPERIMENTAL STUDY ON PEDESTRIAN FLOW CHARATERISTICS AT CROSSWALKS UNDER RAINY CONDITIONS

S.Q. Xie[a], Y.C. Li[a], S.C. Wong[a] and William H.K. Lam[b]
[a] *Department of Civil Engineering, The University of Hong Kong, China*
Corresponding Author: S.Q. Xie Email: seakay@connect.hku.hk
[b] *Department of Civil and Environmental Engineering,*
The Hong Kong Polytechnic University, China

ABSTRACT

Walking is highly encouraged as a sustainable transportation mode. Unlike motorized transportation modes, pedestrians are often exposed to outdoor environments, and hence walking movements are affected by weather conditions. In rainy weather in particular, the use of umbrellas appears to have considerable conflicting effects on crowd movements. Therefore, the influence of rainy weather on pedestrian flow raises concerns regarding the efficiency and safety of the traffic facilities associated with intensive pedestrian movements.

This study investigated pedestrian movements at crosswalks under rainy conditions by conducting controlled experiments. The experiments were designed to cover wide ranges of experimental variables, including rainfall intensity, crosswalk width, pedestrian density, total number of pedestrians, umbrella usage proportion, and the split ratio of bidirectional pedestrian flow. Ninety-seven testing scenarios with different variable combinations were adopted in the controlled experiments, and three runs were performed for each scenario. The experiments were video recorded, and pedestrian walking trajectories were extracted for further analysis with the aid of computer programs. The characteristics of bidirectional pedestrian flow under rainy conditions were identified while accounting for proportions of umbrella usage and rainfall intensity, which permitted estimation of the influence of rainy weather on bidirectional pedestrian flows. Fundamental diagrams of the testing scenarios with and without rain are presented to illustrate how pedestrian movements were affected by conflicts between umbrellas and an increase in rainfall intensity. Possible temporary traffic arrangement measures are proposed to alleviate the influence of rainy weather and maintain traffic efficiency at crosswalks and intersections.

Keywords: Pedestrian flow, experimental study, bidirectional pedestrian movements, rainy weather, crosswalk.

1. INTRODUCTION

Walking is an environmentally friendly and flexible mode of transport that has received increasing attention in recent years. Since 2000, the Hong Kong Transport Department has implemented various kinds of pedestrian schemes for Hong Kong. As the majority of these pedestrian schemes/facilities are located in open or semi-open areas, adverse weather conditions directly affect pedestrians' travel behavior (e.g., walking speeds and route choices) and thus the level of service of these schemes/facilities. Due to the subtropical climate in Hong Kong, the average number of annual rainy days is about 100 days/year (Hong Kong Observatory, 2017); that is, nearly one third of the year exhibits rainy weather. Pedestrian crosswalks are among the most common types of outdoor pedestrian facilities in Hong Kong. Hence, a study of pedestrian movements at crosswalks under rainy weather conditions would be beneficial for improving the efficiency of traffic intersections and enhancing the walkability and safety of current pedestrian crosswalks.

2. CONTROLLED EXPERIMENT

In this study, 97 testing scenarios with different variable combinations were considered in controlled experiments, and 3 runs were performed for each scenario. The experiments were video recorded, and pedestrian walking trajectories were extracted for further analysis with the aid of computer programs.

2.1 Setup of the Controlled Experiment

2.1.1 General procedures

The purpose of this experiment was to measure the flow characteristics of pedestrians at crosswalks, such as their speed, flow, and density, under different proportions of umbrella usage. One hundred and eight participants were recruited for the experiment, which was conducted in the pavement laboratory at Hong Kong Polytechnic University over 3 separate days. Participants wearing windbreakers (with/without umbrellas) were asked to walk in designed directions, designated as Stream A (in green) and Stream B (in red), to model the bidirectional pedestrian stream under a controlled environment.

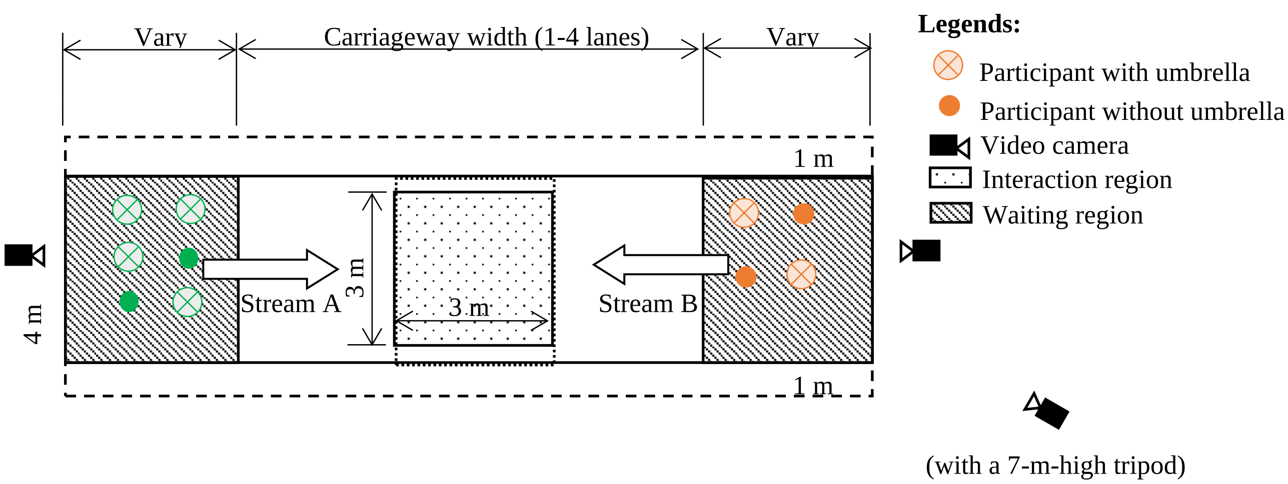

Figure 1. Setup of the controlled experiment

In this controlled experiment, we referenced the following standards to design the experimental parameters (see Tables 1 and 2).

Table 1 Rainfall intensity

Level	Rainfall intensity (mm/hr)
Light	1 – 2.5
Moderate	2.5 – 5
Heavy	> 5

Table 2 Expected pedestrian density and space at waiting region (Wong et al., 2010)

Level	Pedestrian density (ped/m^2)	Pedestrian space (m^2/ped)	No. of pedestrians required (ped)	Area at waiting region (m^2) for different proportions of umbrella usage (Width×Length)			
				0	1/3	2/3	1
Low density	~1	~1	16	4×4	---	---	---
			12	---	4×4	---	---
			10	---	---	4×4	---
			8	---	---	---	4×4
Moderate density	2.5	0.4	30	4×3	---	---	---
			23	---	4×3	---	---
			18	---	---	4×3	---
			15	---	---	---	4×3
High density	4.0	0.25	48	4×3	---	---	---
			36	---	4×3	---	---
			29	---	---	4×3	---
			24	---	---	---	4×3
"Jam" density	6.0	0.17	54	3×3	---	---	---
			41	---	3×3	---	---
			32	---	---	3×3	---
			27	---	---	---	3×3

* Interaction area (Width × Length) = 3×3 = 9 m^2.

** Pedestrian body ellipse = 0.5×0.6 m^2 (National Research Council, 2010). Umbrella radius = 0.55 m. Additional area for pedestrian with umbrella = $0.55^2 \div (0.5 \times 0.6 \div 2) = 2$ m^2.

2.1.2 Experimental parameters

To simulate the effects of pedestrian performance under different advanced weather conditions, a number of controlled variables were changed, such as the proportion of bidirectional flow of Streams A and B (5 levels), rainfall intensity (4 levels), pedestrian density at the waiting region (4 levels), proportion of umbrella usage (4 levels), proportion of two persons using one umbrella (2 levels), and number of lanes (4 levels).

Table 3 Experimental parameters for the controlled experiment

Level	Proportion of bidirectional flow (Stream A:B)	Rainfall intensity	Pedestrian density at waiting region	Proportion of umbrella usage	No. of lanes (3.5 m per lane)	Proportion of two persons using one umbrella
1	0	No rain	Low	0	1	0
2	0.5	Light	Moderate	1/3	2	1/2
3	0.7	Moderate	High	2/3	3	---
4	0.9	Heavy	"Jam"	1	4	---
5	1	---	---	---	---	---

An interaction region of 3×3 m^2 was set to observe the pedestrian flow characteristics, such as pedestrian density and speed, using a video capture approach. Overall, 97 combinations (17 control and 80 main tests) of testing scenarios were proposed. Each testing scenario lasted for about 6 minutes (3 minutes for preparation and 1 minute for the experiment × 3). On Day 1, 28 testing scenarios were conducted, where the number of participants was limited to 30 participants. On Day 2, another 28 testing scenarios were conducted, where the number of participants was limited to 60 participants. We then finished the remaining 41 testing scenarios, where a maximum of 108 participants were involved in the experiment. The proposed pedestrian arrangements for different scenarios are shown in Figure 2.

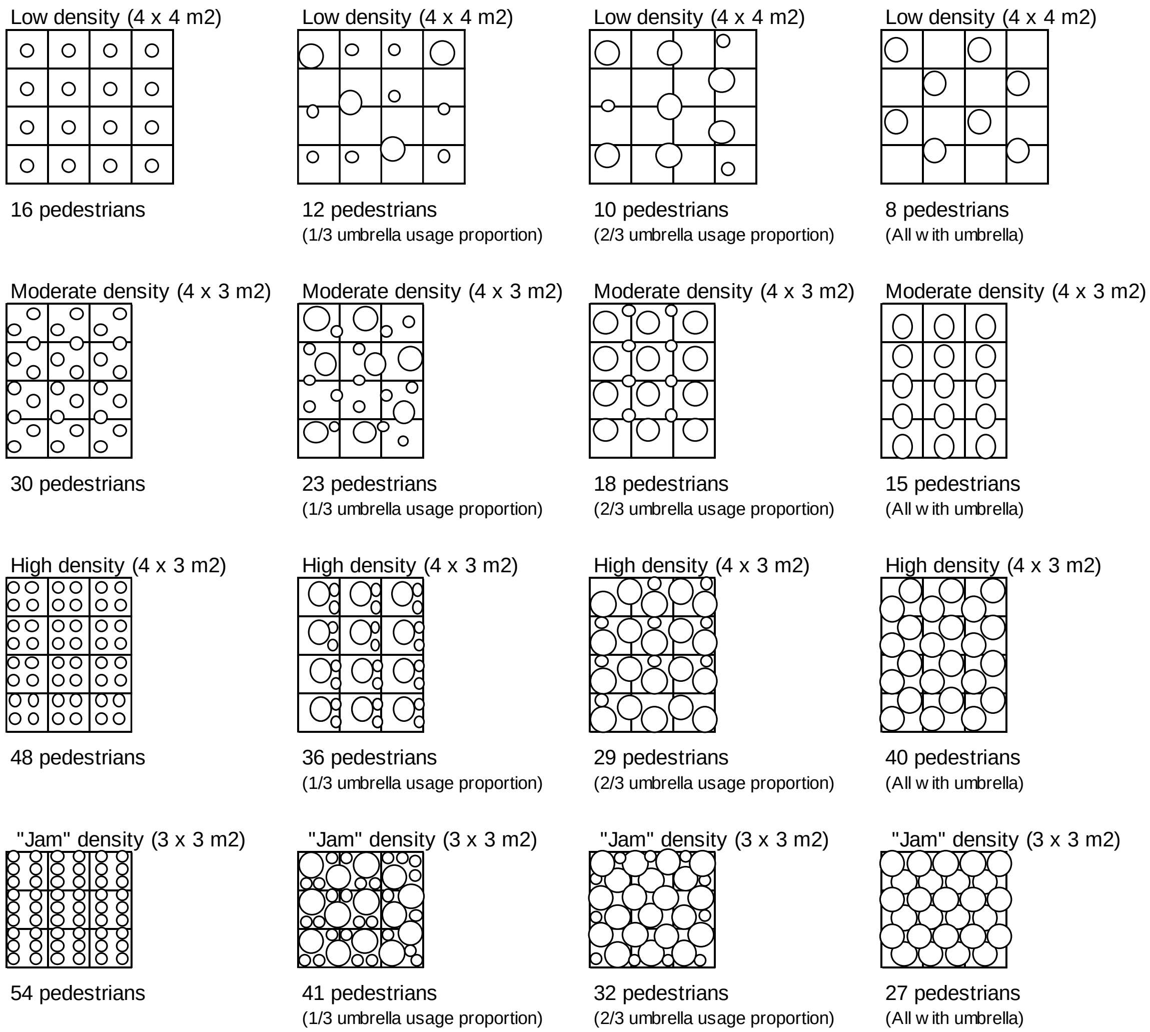

Figure 2. Arrangements of pedestrians in different scenarios

2.2 Data

In the preliminary study presented in this paper, 23 scenarios were investigated. The experimental parameters are shown in Table 4. In processing the video data, a 5-second period in the middle of each run was extracted to capture pedestrian movements when the two streams had fully mixed at the 3×3 m^2 region of interest. The pedestrian movements were tracked every 0.5 second. Therefore, the trajectory of each pedestrian consisted of 10 positions. Ultimately, 1,455 trajectories were extracted. The average speed was 0.94 m/s, and the average density was 0.88 ped/m^2 (Table 5). Although the pedestrian density in a few scenarios reached as high as 5-6 ped/m^2 at the waiting area, pedestrians adjusted themselves during their walk across the site and kept the density below 2 ped/m^2.

Table 5 Summary of data

Total number of trajectories	1,455
Average walking speed (m/s)	0.94
Maximum walking speed (m/s)	2.24
Minimum walking speed (m/s)	0.24
Standard deviation of walking speed (m/s)	0.31
Average density (ped/m^2)	0.88
Maximum density (ped/m^2)	1.78
Minimum density (ped/m^2)	0.22
Standard deviation of density (ped/m^2)	0.32

Table 4 List of scenarios investigated

Scenario	Rainfall intensity	Rainfall intensity (mm/hr)	No. of lanes	Pedestrian density at waiting area	Umbrella usage proportion	Proportion of two persons using one umbrella	Actual No. of pedestrian at waiting area (ped)	
							Stream A	Stream B
C4	No rain	0	$4_{(14.0)}$	$\text{Low}_{(4\times4)}$	0.00	0	16	16
C5	No rain	0	$4_{(14.0)}$	$\text{Moderate}_{(4\times3)}$	0.00	0	0	30
1	No rain	0	$1_{(3.5)}$	$\text{Low}_{(4\times4)}$	0.00	0	0	16
3	No rain	0	$1_{(3.5)}$	$\text{Moderate}_{(4\times3)}$	0.00	0	0	30
4	No rain	0	$2_{(7.0)}$	$\text{Low}_{(4\times4)}$	0.00	0	8	16
17	Moderate	1.92	$3_{(10.5)}$	$\text{Low}_{(4\times4)}$	0.00	0	15	16
25	Heavy	2.51	$4_{(14.0)}$	$\text{Low}_{(4\times4)}$	0.00	0	16	16
27	No rain	0	$3_{(10.5)}$	$\text{High}_{(4\times3)}$	0.00	0	0	48
28	No rain	0	$3_{(10.5)}$	$\text{High}_{(4\times3)}$	0.33	0	18	33
29	No rain	0	$3_{(10.5)}$	$\text{Jam}_{(3\times3)}$	0.33	0.2	0	44
30	No rain	0	$4_{(14.0)}$	$\text{Moderate}_{(4\times3)}$	0.67	0.2	15	20
32	No rain	0	$4_{(14.0)}$	$\text{Moderate}_{(4\times3)}$	1.00	0.2	18	18
33	Light	3.79	$1_{(3.5)}$	$\text{Moderate}_{(4\times3)}$	0.00	0	21	30
35	Light	3.79	$1_{(3.5)}$	$\text{High}_{(4\times3)}$	1.00	0.2	20	29
38	Light	3.79	$4_{(14.0)}$	$\text{High}_{(4\times3)}$	0.00	0	0	48
44	Moderate	4.47	$4_{(14.0)}$	$\text{Moderate}_{(4\times3)}$	0.00	0	21	30
47	Heavy	6.25	$2_{(7.0)}$	$\text{Low}_{(4\times4)}$	0.00	0	14	16
61	Light	1.47	$1_{(3.5)}$	$\text{Jam}_{(3\times3)}$	0.67	0	33	33
66	Light	1.47	$4_{(14.0)}$	$\text{High}_{(4\times3)}$	0.67	0	27	29
T7	Light	1.47	$4_{(14.0)}$	N.A.	1.00	0	42	43
73	Moderate	2.74	$3_{(10.5)}$	$\text{High}_{(4\times3)}$	0.33	0	36	36
74	Heavy	7.72	$1_{(3.5)}$	$\text{High}_{(4\times3)}$	0.33	0	26	36
T9	Heavy	7.72	$4_{(14.0)}$	N.A.	1.00	0	39	41

3. PRELIMINARY RESULTS AND DISCUSSIONS

3.1 Effect of Rainfall

The average walking speed of pedestrians not holding umbrellas was 0.95 m/s under normal conditions and 0.94 m/s under light rainfall intensity (Table 6). The light rainfall intensity had little effect on the pedestrians' walking speed. However, the pedestrians' walking speed increased to 1 m/s under moderate rainfall intensity and further to 1.15 m/s under heavy rainfall intensity. Pedestrians appeared to intend to pass the crosswalk as fast as possible to minimize the amount of time they were exposed to rainfall and hence avoid getting too wet.

Table 6 Average walking speed without umbrella under different rainfall intensities

Rainfall intensity (mm/hr)	Average walking speed without umbrella (m/s)
No rain	0.95
Light (1 – 2.5 mm/hr)	0.94
Moderate (2.5 – 5 mm/hr)	1.00
Heavy (>5 mm/hr)	1.15

3.2 Effect of Holding Umbrella

It has commonly been observed that the average walking speed of a pedestrian flow decreases as its density increases. However, in this study, holding umbrellas in crowds also made the average walking speed decrease. As shown in Table 7, the average walking speed decreased from 0.98 m/s to 0.89 m/s when one third of the pedestrians held umbrellas, and decreased further to 0.83 m/s and 0.76 m/s when the proportion of umbrella usage increased to two thirds and to one, respectively. The more pedestrians held umbrellas in the crowds, the more the umbrellas interacted, the harder the pedestrians had to try to overcome interlocking mishaps and conflicts, and thus the lower their average walking speed. While the radius of a human body is about 0.25 m (National Research Council, 2010), the radius of the umbrella used in the controlled experiment was 0.55 m. Hence, the proportion of umbrella usage heavily affected the average density of the pedestrian flow, as it increased the average area occupied by each pedestrian. As shown in Table 7, the average density was 0.94 ped/m^2 with nobody holding umbrellas and decreased more than 40% to 0.57 ped/m^2 when all of the pedestrians held umbrellas in their hands. As such, holding umbrellas in crowds dramatically decreased the pedestrian flow rates and made the crosswalks inefficient under rainy weather conditions.

Table 7 Average walking speed with different proportions of umbrella usage

Umbrella usage proportion	Average walking speed (m/s)	Average density (ped/m^2)
0	0.98	0.94
0.33	0.89	0.83
0.67	0.83	0.78
1	0.76	0.57

4. PRELIMINARY FINDINGS

Rainfall intensity and holding umbrellas are the two major factors introduced by rainy weather conditions. Pedestrians are inclined to remain as dry as possible, and thus may speed up and be aggressive when walking across a crosswalk without an umbrella. However, holding an umbrella considerably increases the area occupied by each pedestrian and results in longer queues and slower speeds. It may be necessary to modify the pedestrian phase of traffic signals and other relevant walking facilities to accommodate pedestrian movements under rainy weather conditions at crosswalks.

5. ACKNOWLEDGMENTS

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