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Exploring the effect of turning manoeuvres on macroscopic properties of pedestrian flow

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Abstract

Public infrastructures, such as public transport hubs, are increasingly visited by large crowds for daily commuting purposes as well as during special events. It is important to ensure safety of these crowds and to facilitate efficient movements not only during emergency situations but also in day-to-day activities. In order to achieve such broad objectives, fundamental properties, i.e., fundamental relationships, of crowd movements in various complex situations should be properly understood.

Previous studies have investigated fundamental relationships for various complex pedestrian movements associated with complex geometrical settings such as crossing and merging configurations. Regarding turning configurations, no significant studies have investigated the effect of the angle of the bend on pedestrian fundamental relationships. Considering this knowledge gap, the main objective of this paper is to quantify the effect of turning angle on pedestrian speed-density and flow-density relationships under normal walking conditions. Trajectory data collected through a controlled human trial experiments for different angled bends (i.e. 0° or straight, 45°, 90°, and 180°) are utilized in this study.

Findings of this study could be beneficial in estimating level of service at locations where complex crowd movements are expected. Further, databases for calibration and validation of pedestrian simulation models could also be enhanced.

1. Introduction

With rapid urbanization, major public infrastructures are increasingly visited and utilized by large crowds during peak hours for daily commuting purposes and during special events. Interactions between these crowds and complex architectural features at those public spaces can considerably hinder the movements of crowds. Further, crowd interactions with different geometrical settings may be different. As a result, bottleneck effect and congestion mechanism of different complex geometrical settings could be considerably different. Thus, it is important to understand the fundamentals of pedestrian crowd flows associated with complex geometrical and architectural settings in order to plan and design public infrastructures for day-to-day activities as well as for emergency evacuations. This understanding is essential to locate bottlenecks and to ensure safety and efficiency of crowd movements by optimizing architectural designs at planning and design stages. Further, such information could be useful for predicting crowd flows and proper management of crowds during special events at public buildings when larger crowds are expected.

Various complex behavioural phenomena, such as crossing, merging and turning behaviours, have been experimentally as well as theoretically verified by previous authors. Microscopic and macroscopic behaviours of crowds have been described through those studies. Table 1 summarizes previous studies which reported fundamental relationships (flow-density and speed-density relationships) for crowd movements associated with common indoor geometrical settings with data collected through laboratory experiments.

Table 1: Previous studies that explored fundamental diagrams with experiment data

Scenario	Authors (year)	Remarks
Straight (unidirectional)	Daamen and Hoogendoorn (2003)	Straight corridor/bottleneck of 1 m wide
	Seyfried et al. (2005)	Single-file movement
	Chattaraj et al. (2009)	Single-file movement
	Jelić et al. (2012)	Single-file movement
	Zhang et al. (2012a)	Straight corridors of 1.8 m, 2.4 m, 3.0 m wide
	Ziemer et al. (2016)	Single-file movement
Crossing	Asano et al. (2007)	45°, 90°, 135°, 180°*
	Wong et al. (2010)	45°, 90°, 135°, 180°*
	Plaue et al. (2011)	90°
	Zhang et al. (2012b)	180°*
	Zhang and Seyfried (2014)	90°, 180°*
Merging	Zhang et al. (2011, 2012c)	90° symmetrical T junction
	Shi et al. (2015)	60°, 90° symmetrical Y junction 90° symmetrical T junction 90° asymmetrical T junction
Turning (unidirectional)	Zhang et al. (2012c)	90°
	Hoskins and Milke (2012)	Stairways (180°)
	Burghardt et al. (2013)	Stairways (180°)

* 180° crossing means straight bidirectional flows

Based on the summary presented in Table 1 it is evident that fundamental relationships for straight and crossing scenarios have been adequately explored by previous authors. Regarding merging flows, although limited, there are several attempts to investigate the fundamental relationships for merging configurations with various merging angles and different merging approaches or directions. For turning configuration, very limited research are available that studied fundamental relationships. That is, fundamental relationships only for 90° corridors and 180° stairways have been explored so far in previous studies. As experimentally verified in previous studies, turning corridors or bends are inefficient for crowd movements and can become bottlenecks under emergency as well as normal conditions (Dias et al. 2014a). Therefore, attention should be given for locations with bends when planning and designing crowd gathering places. Thus, investigating the effect of turning angle on pedestrian fundamental relationships could be beneficial in many ways. For example, output of such investigations could be directly used in planning and design guidelines. Further, such investigation can enhance the database that would be useful for calibrating and validating crowd simulation models. Considering these, this study aims at quantifying the effect of turning angle of the bend on pedestrian fundamental relationships. For this study, data were collected through comprehensive controlled experiments and this paper discusses some findings related to pedestrian fundamental diagram for turning movements. This paper is structured as follows. The next section provides a brief description on the experiments and methods. This is followed by the discussion on obtained results. Finally, conclusions and further research are presented.

2. Methods

2.1. Data

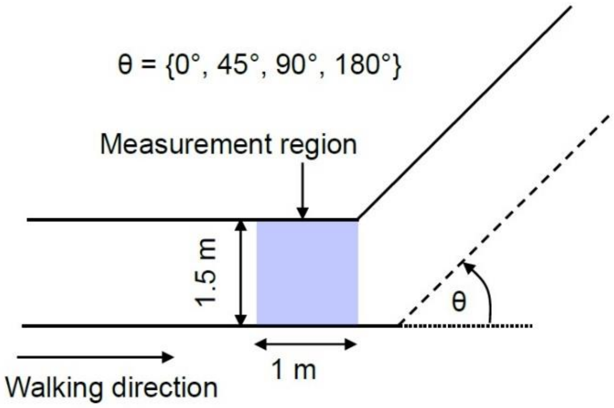
Data were collected through an experiment conducted at Monash University in October 2013 in accordance with the guidelines by the human research ethics committee of Monash University (ethics grant no.: CF11/2592-2011001519). Trajectory data for walking through a straight (0°) and different angled (45°, 90°, 135° and 180°) corridors (corridor width = 1.5 m) were collected under two different conditions (normal speed walking and slow speed running). Around 55 individuals participated in this experiment and each experiment scenario was repeated 3 times. Initial conditions were kept similar for all these experiments. I.e., individuals were instructed to gather in front of the beginning of the corridor before instructing them to walk or run through the corridor. Data for straight, 45°, 90° and 180° corridors under normal walking speeds were utilized in this paper and the estimated average walking speed for normal condition was 1.07 m/s (± 0.16 SD). The positions of each pedestrian's heads were manually tracked at 0.12 second intervals from video recordings. Snapshots taken during several of these experiment runs are shown in Figure 1. A detailed description regarding the experiment setup and collected trajectory data can be found in Dias et al. (2015).

Figure 1: Snapshots during experiments; (a)-Straight, (b)-45° turning, (c)-90° turning, (d)-180° turning scenarios

2.2. Density, speed and flow estimation

Density and speed were estimated for individuals within a region in the vicinity of the corner for each turning case. To maintain the consistency an equivalent location was considered for straight corridor as well. Location and dimensions of the measurement region is shown in Figure 2. This region can be identified as a critical region associated with turning configurations due to reasons like blocked vision and blocked (self-organized) inner pedestrian lanes. Thus, frequent congestion as well as dangerous blockages could be resulted within and around this region. Further, this measurement region is the upstream portion of the "turning region", where speed reduction is occurred when an individual making a turning movement, as defined in Dias et al. (2014b).

Figure 2: Location and dimensions of the measurement region



Density and speed within the measurement region were determined based on a method (Method B) described in Zhang et al. (2011), which calculates the average density and speed over space and time, as follows:

$$\langle k \rangle = \frac{1}{t_{out} - t_{in}} \int_{t_{in}}^{t_{out}} \frac{N(t)}{A} dt \quad (1)$$

$$\langle v \rangle = \frac{\Delta x}{t_{out} - t_{in}} \quad (2)$$

Where;

$\langle k \rangle$ = Density

$\langle v \rangle$ = Speed

t_{in} = The time a person enters the measurement region

t_{out} = The time a person exits the measurement region

$N(t)$ = The number of persons in the measurement region at time *t*

$A = b\ \Delta x$ = Area of the measurement region

b = Width of the corridor

Δx = Length of the measurement region

Pedestrian flow at a given time ($\langle q \rangle_t$) within the measuring region was determined with the following equation:

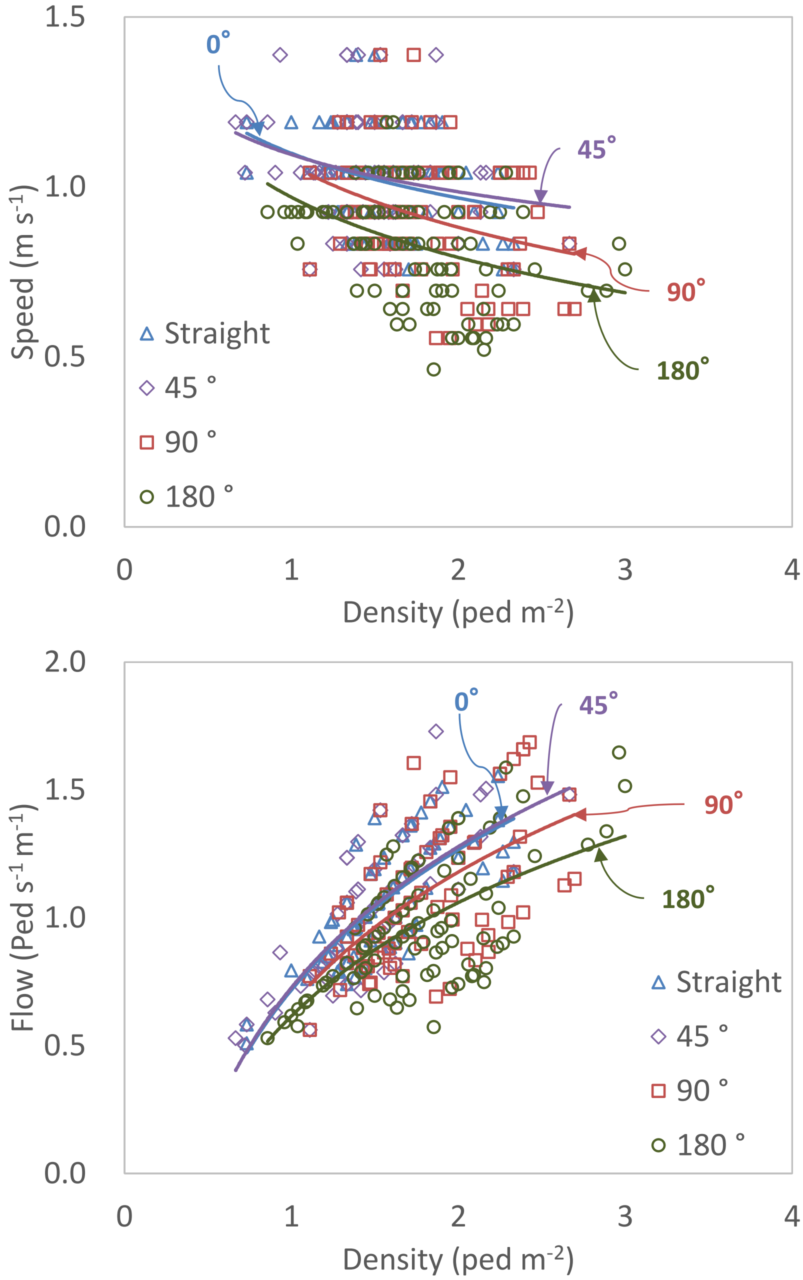
$$\langle q \rangle_t = \langle k \rangle_t * \langle v \rangle_t \tag{3}$$

For these calculations, time was measured at 0.12 second intervals. Fundamental relationships among estimated speed, flow and density within the measurement region was examined with respect to the turning angle as discussed in the next section.

3. Fundamental relationships

Density, average speed and flow rate were determined for straight, 45°, 90° and 180° corridors utilizing data for 2 experiment runs for each case. Figure 3 compares speed-density and flow-density relationships for those different angled corridors within the considered measurement region.

Figure 3: Comparison of speed-density and flow-density relationships for various angled corridors



General trends (i.e., decrease in speed and increase in flow with increasing density) for pedestrian flows below the capacity level can be observable in these scatter plots. Further, as can be understood from logarithmic trend lines in Figure 3, fundamental relationships for different angled corridors can be well distinguished. This indicates that if one relationship is used to describe pedestrian flow characteristics through different angled corridors that may underestimate the bottleneck effect of higher angled corridors. One reason for this observation could be the reduction in individual desired speed when an individual making a turning movement. As explained in Dias et al. (2014b), the speed is significantly decreased for bends with higher angles (greater than 90°) even under free-flow conditions.

For a given density level (which is lower than the critical density) the difference in pedestrian flow between straight and 45° turning was found to be negligible. Walking radius for 45° turning case is relatively high and for such cases there is no or negligible effect on fundamental relationships as described in previous studies as well (Dias et al. 2014a, Ziemer et al. 2016). However, it could be observed that for a given density level the speed is decreased approximately by 10 % and 20 % for 90° and 180° turning cases respectively compared to straight corridors. Percentage average speed difference between 90° and 180° turning cases were 11 %. Under critical conditions (i.e., very high density and panic situations), level of service of walkways with bends could further be reduced as discussed in previous studies (Dias et al. 2013).

Paired Mann-Whitney U test was conducted to compare mean speeds for different angled cases and results are shown in Table 2. These tests were conducted categorizing speeds in to two clusters based on the density (i.e., density < 2 ped/m^2 and ≥ 2 ped/m^2) considering the data availability within each density bin. Further, for each angle, the difference in mean speeds for these density levels was significant as confirmed with the Mann-Whitney U test (p < 0.01 for all cases).

Table 2: Results of paired Mann-Whitney U test for average speeds

Pair	Mann-Whitney U test results	
	Density < 2 ped m^{-2}	Density ≥ 2 ped m^{-2}
0° and 45°	p = 0.7039	p = 0.4472
0° and 90°	p = 0.0085 *	p = 0.0021 *
0° and 180°	p << 0.001 *	p << 0.001 *
45° and 90°	p = 0.0046 *	p = 0.0173 *
45° and 180°	p << 0.001 *	p = 0.0002 *
90° and 180°	p = 0.0168 *	p = 0.0173 *

* Significant at 0.05 level

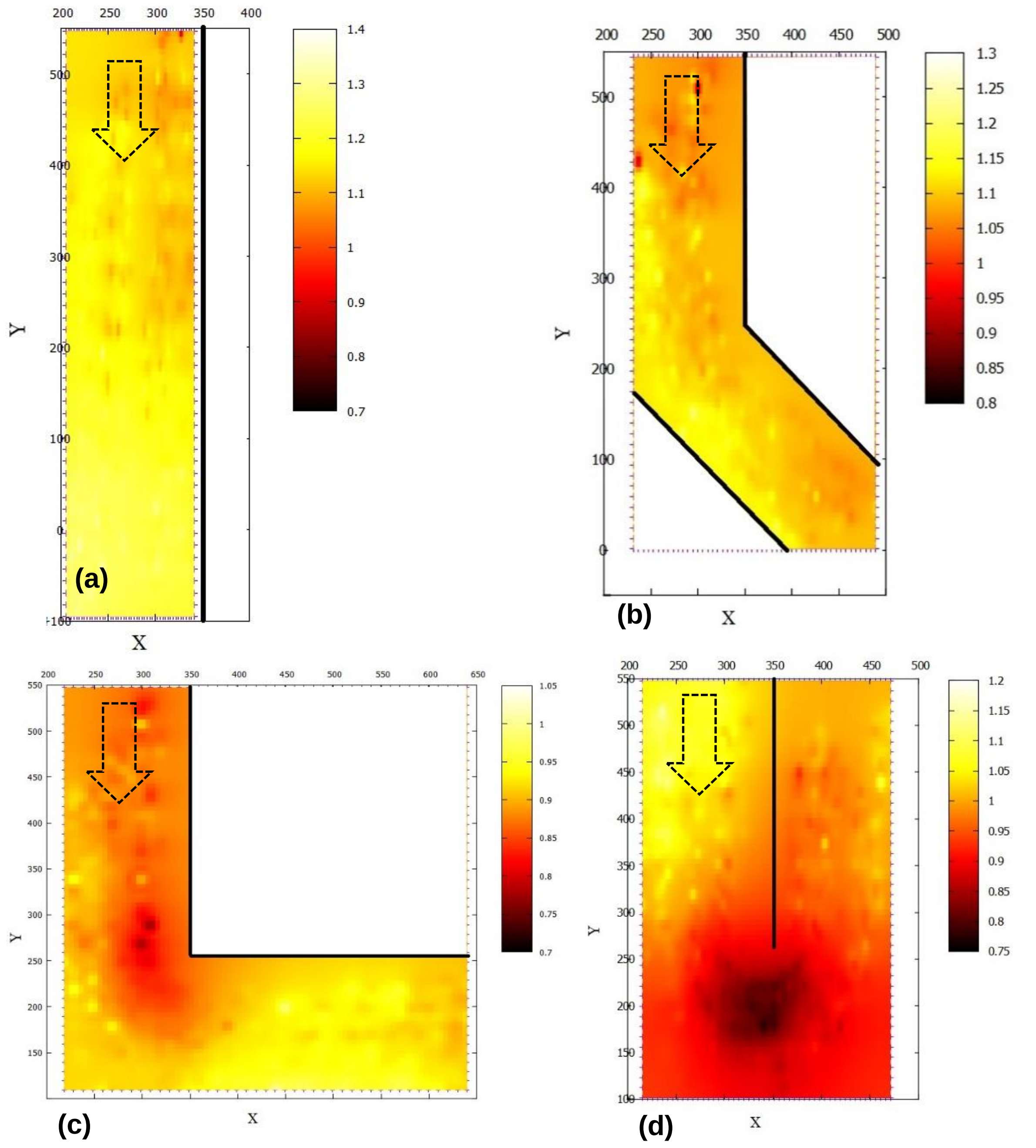
Table 2 explains that except for 0° and 45° pair, differences in mean speeds for other pairs are statistically significant. This finding indicates that a single speed-density relationship may not be suitable to evaluate pedestrian flow conditions at bottlenecks created by complex geometrical settings, such as bends, as a single fundamental relationship may underestimate the effect of higher angled cases.

It should be noted that the flow is not regulated in this experiment and therefore a range of flow-density levels could not be obtained. Therefore, the complete information and the shape of the fundamental relationships (particularly the capacity and congested regions) could not be explained. Nevertheless, the trend and the effect of turning angle on fundamental relationships are clear as can be understood from data for a limited range.

4. Spatial variation of speed and density

Variation of walking speeds and densities along the walking path for different angled corridors is depicted in Figure 4 and Figure 5 respectively. Arrowheads on these figures represent the walking direction. For speed plots (Figure 4) instantaneous speed data for one entire experiment for each scenario was utilized. For density plots (Figure 5), densities was estimated in segments along the corridor for each individual at each time step (0.12 seconds in this case), based on Equation 1.

Figure 4: Spatial distribution of speed for; (a)-Straight, (b)-45° turning, (c)-90° turning, (d)-180° turning scenarios (X and Y coordinates are in cm and speed estimates are in m/s)

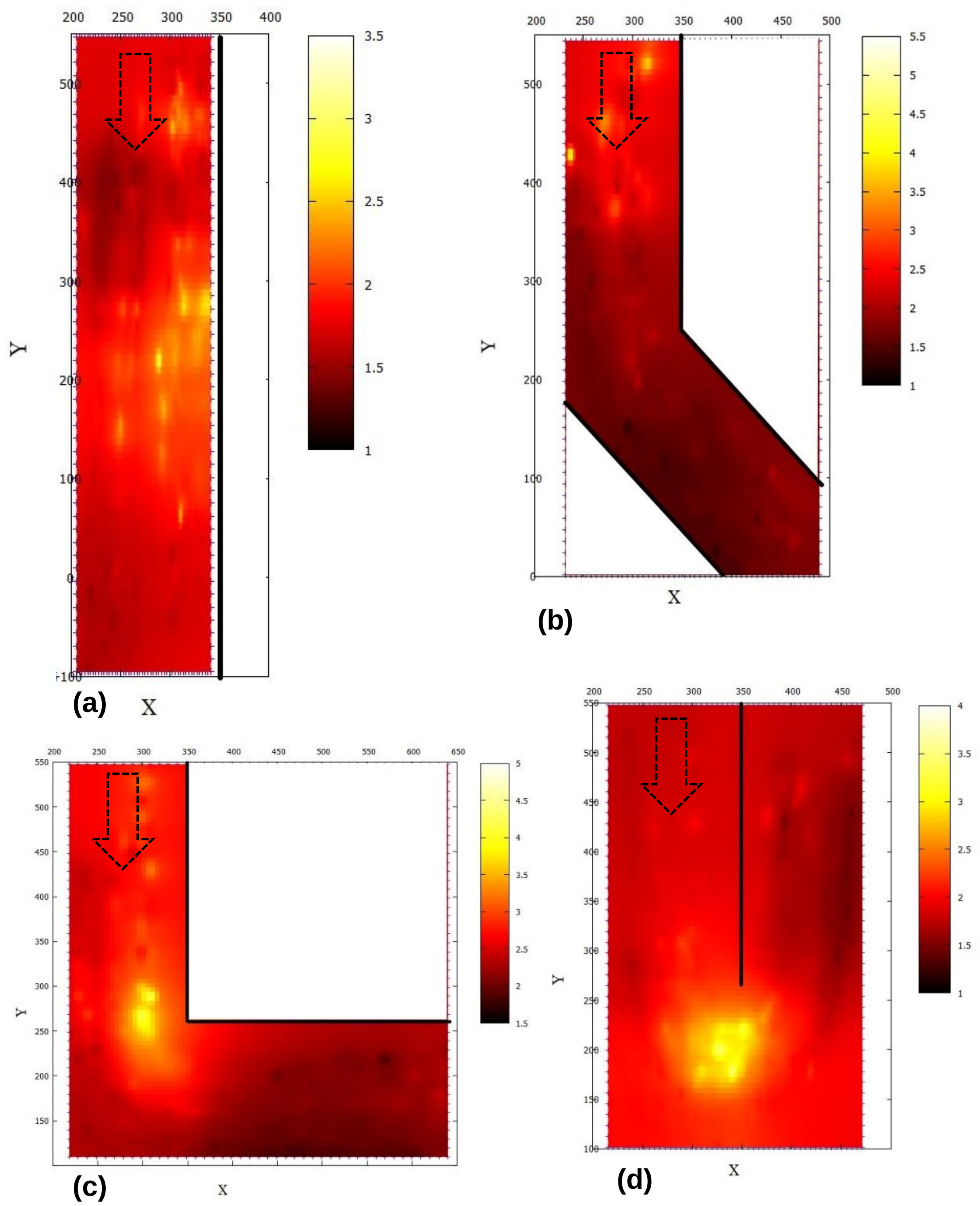


It can be noted that for straight and 45° corridor scenarios walking speeds and densities are almost uniform over the entire walking space. For 90° and 180° corridors, reduction in walking speed (and increase in density) in the vicinity of the bend is clearly observable in

Figures 4 and 5. Bottleneck effect of turning configurations can be clearly visualized in these figures. Further, as can be seen from these plots, the reduction in speed (and increase in density) at turning is magnified when turning angle is increasing.

Closely observing speed distributions (Figure 4) for all turning cases (45°, 90° and 180°), it is understandable that average speeds closer to inner walls is generally lower than average speeds closer to outer walls. This observation is consistent with previous studies based on field observations (Steffen and Seyfried 2009) and controlled experiments (Zhang et al. 2012a), which described that pedestrians prefer to walk in the innermost lanes (shortest path) and inner lanes are blocked by outer lanes.

Figure 5: Spatial distribution of local density for; (a)-Straight, (b)-45° turning, (c)-90° turning, (d)-180° turning scenarios (X and Y coordinates are in cm and density estimates are in ped/m²)



Examining density distributions for 90° and 180° cases (Figures 5 (c) and (d)), one can observe that propagation of congestion in the upstream direction of the corner is partially captured. Further, the remarkable drop in the density of the immediate downstream of the bend is also visible. This observation indicates that when the pedestrian volume (approaching to the bend) is further increased, upstream of bends of higher angles (over 90°) can be further congested creating substantial bottleneck conditions. Such detailed observations, i.e., gradual progression of congestion with gradually increasing pedestrian flow could be better visualized with data collected through similar experiment setups with regulated flows.

It should be noted that the initial conditions (number of people, starting location of the crowd) were kept similar for all cases. Despite such similar initial conditions, the combined effect of turning angle and interpersonal interactions on the pedestrian flow through different turning configurations is notable particularly in the vicinity of the inner corner of the bend.

5. Conclusions and further research

Turning configurations can form critical bottlenecks in major crowd gathering places both under normal and emergency situations. However, very limited studies have examined impact of turning angle on macroscopic pedestrian flow properties with empirical data. An attempt is made in this study to address that gap by evaluating the macroscopic variables (speed, flow and density) with respect to turning angle of corridors with bends. Results indicated that the performance (or level of service) of turning corridors of 45° or less will not be significantly different from the performance of straight corridors of the same width. However, flow conditions of higher angled (over 90°) turning corridors could be underestimated if the fundamental relationships for straight corridors were used.

In these experiments, flow of pedestrians through corridors was not regulated and therefore only a portion of the fundamental diagram for each case could be obtained. Nevertheless, the results highlighted that crowd interactions with complex architectural configurations, such as bends, should be properly considered when planning and designing public infrastructures. Further, these studies could possibly be applied to predict level of service at specific locations where complex pedestrian movements can be expected at crowd gathering places.

Under future studies these experiments could be performed under regulated flow conditions to obtain complete information for fundamental relationships for different turning configurations. Further, other variables, such as corridor width, initial conditions, composition of the crowd, may also be considered.

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