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EXPERIMENTAL STUDY ON THE EVACUATION BEHAVIOUR OF A CROWD THROUGH BOTTLENECKS

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Abstract

The growth of cities is very fast and is often very difficult for urban development. Pedestrian dynamics in this context are very important when designing a facility in terms of the safety, economics, and level of service to its users. The present study focuses on analysing the effect of density and width of a bottleneck on the behaviour of a crowd under emergency conditions. The inclusion of a buffer space for the dispersion of a crowd through a bottleneck is analysed. A relationship is established between total times, the flow and, a specific flow versus the width of a bottleneck. The formation of a dynamic layer was observed during capacity conditions due to the zipper effect. Among the five types of distributions, a semi-random distribution was the better fit for the headway data observed. It was observed that capacity increases in a stepwise manner as the width of a bottleneck increases, which can be attributed to the formation of dynamic lanes. The distance between these lanes is independent of the width of the bottleneck.

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Key words

- Crowd;
- Total time;
- Time-gap;
- Headway;
- Dynamic lanes;
- Speed; Density.

1 INTRODUCTION

A crowd is defined as "a sizeable number of people gathered at a specific location for a measurable time period, with common goals and displaying common behaviours". Generally, crowd behaviour can be divided into two categories: normal behaviour and abnormal behaviour. With normal behaviour, everyone tries to reach their goal as fast as possible, spending the least amount of energy and time, whereas with abnormal behaviour, each person in a crowd will tend to show some kind of panicky or aggressive behaviour. Crowd scenes are divided into two categories based on their motions i.e., structured or unstructured. With a structured crowd, the crowd moves in an organised manner, and the path does not vary frequently. Whereas, with an unstructured crowd, people move in random directions and the path changes frequently.

Crowd analysis is performed in three ways: counting people, tracking them, and understanding crowd behaviour models. In public locations, a crowd density estimating is very important for the safety of people. Generally, crowd density estimation methods are mainly classified into two categories: direct and indirect methods. In direct methods, crowd density is estimated in a crowd by using some classifiers to directly detect, segment and count each human body in the crowds. In indirect methods, the crowd density can be obtained using three different methods: pixel-based, texture-based and object-based methods. Pixel-based analysis is based on background subtraction or edge detection models to determine the density of the crowd. Texture based analysis mostly used to estimate people count rather than density and it requires the analysis of image patches. Object-level analysis tries to identify individual objects in a scene, but identifying individuals in

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a single image or a video sequence is mostly feasible in lower density crowds. Tracking in crowd scenes can be done using three techniques, namely, point tracking, kernel-based tracking and silhouette-based tracking. Understanding crowd behaviour models are based on two approaches: an object-based approach and a holistic-based approach. With an object-based method, crowd behavior is analyzed through detecting individuals. This method can fail in a higher density crowd because tracking each person in the crowd is very difficult. This method is valid for a low and medium density crowd. In the holistic-based method, a crowd is considered a single unit and the crowd flows can be calculated. This method is mostly applicable to densely crowded scenes.

There are two main types of models for simulating the movement of a crowd i.e., macroscopic and microscopic models. Macroscopic level models deal with collective observable behaviours emerging from the crowd by considering the crowd as a whole. Fluid dynamic models and the crowd continuum approach are examples of macroscopic models. Microscopic level models are based on the individual behaviour, actions, and decisions within a crowd and their interactions with other people in the crowd. Cellular automata, social force models and, agent-based models are some examples of microscopic models.

Most pedestrian facilities operate under conditions of extreme crowding i.e., shopping malls, sports stadiums, railway terminals, movie theatres, and exhibitions. Persons using these facilities show different kinds of behaviors based on their familiarity with the facility. Over the last few years, disastrous stampede accidents have occurred in which a number of fatalities and injuries have been reported (http://www.crowddynamics.co.uk/). Most of these accidents occur when persons want to evacuate the facility as soon as possible, which leads to panicky behavior. The objective of this study is to assess a pedestrian facility by measuring the time required to evacuate a facility while ensuring the safety of all the pedestrians. In order to achieve this, variations in the flow behavior of crowd with reference to widths of bottlenecks at different densities, both with and without a buffer space are studied and evaluated.

2 LITERATURE REVIEW

Several experiments have been conducted in the past to understand the flow of pedestrains through botttlenecks. Most of these experiments were performed under well-controlled laboratory conditions in which the participants were asked to move normally. The Society of Fire Protection Engineers (SFPE), Predtechenskii and Milinskii (1978), and the guidelines of Weidmann (1993) assume a linear dependence between a location's capacity and thw width of a bottleneck. Hoogendoorn et al. (2003) observed however that capacity increases in a stepwise manner. They observed that when a crowd enters a bottleneck, the formation of dynamic lanes occurs inside the bottleneck due to the zipper effect. They reported that the distance between these lanes is independent of the bottlenecks width. The "zipper effect" is a self-organizing phenomenon leading to the optimization of an available space and the velocity inside the bottleneck. The capacity only increases when an additional lane can develop which generally occurs in a stepwise manner with an increasing width. Weidmann (1993) studied the walking behaviour of pedestrians and observed that many factors such as the personal characteristics of pedestrians, characteristics of the trip, properties of the infrastructure, and finally, environmental characteristics affect the walking speeds of pedestrians. Tajima et al. (2001) investigated a pedestrian channel flow at a bottleneck under open boundaries by using the lattice-gas model of biased random walkers. They showed that a dynamic phase transition from a free flow to a choking flow occurs at a critical density.

Hoogendoorn et al. (2005) observed the speeds of pedestrians obtained from previous studies in uncongested corridors and determined the average speed to be 1.34 m/s with a standard deviation of 0.37 m/s. It was observed that age-related factors are also influential in the study of walking behaviour in addition to the age of the pedestrian itself. Movement conditions affecting the pedestrian's speed include the purpose of the trip, the presence of attractions, the length of trip, weather conditions, the type of infrastructure, and surface conditions.

Lee (2005) a real life video of crowd stampedes and data related to panicking ants was used to develop a simulation model showing the potential problems and consequences of turning movements during collective dynamics. Nirajan et al. (2011) developed evacuation strategies and design solutions that can prevent stampedes. Panicking ant data and simulated crowd dynamics model data were used to describe how right-angled egress paths work ineffectively compared with straight egress paths during a collective panic egress. Dias et al. (2012) the total egress behavior of a crowd was influenced by their choice of exit choice. A discrete choice model was proposed to represent pedestrian exit choice decisions during an evacuation (Duives and Mahamassani 2012). Dias et al. (2014) conducted a series of experiments in angled corridors to understand the walking characteristics of individuals at different speeds.

Kretz et al. (2006) experimented with crowd flow through bottlenecks and presented the results in the form of time gaps, total times, fluxes, and specific fluxes. A continuing decline of a specific flux was observed with an increasing bottleneck width as long as only one person could pass at a time, and specific flux is constant value for larger bottleneck widths. Nagai et al. (2006) investigated the corridor evacuation processes of pedestrians, and crawlers by experimentation and simulation. For the simulation, lattice gas simulation was used, where a biased random walker simulates each pedestrian. It was found that the experimental results are consistent with the simulation results. Liddle et al. (2009) investigated the effect of the width of the bottleneck on the specific flow and observed that the specific flow through the bottleneck is approximately 1.9 Pad/m/s in a normal situation, and is independent of its widths, ranging from 0.6m to 2.5m. Seyfried et al. (2009) performed an experimental study on crowd behaviour at bottlenecks and observed that a continuous flow depends on the width of the bottleneck. Furthermore, in certain ranges of width w, the dependence is considered to be linear. However, the actual slope of the dependence is highly influenced by the crowd's density, the motivation of people to pass, and the type of bottleneck. Saboia & Goldenstein (2012) studied crowd behaviour at bottlenecks and observed that a faster-is-slower pattern leads to clogging at locations close to the exit. The average speed of pedestrians leaving an exit decreases when they attempt to walk faster and consequently the egress time increases.

Sharifi et al. (2016) developed a time headway model between the individual types using a mixed distribution model. They also estimated the capacities for passage ways and identified that the persons with disabilities impact on capacity estimation. A minimum reduction in capacity was observed for visually impaired persons and persons using non-motorized wheel chairs, while a maximum reduction of capacity was observed for persons using motorized wheel chairs. Shiwakoti (2016) explored the difference between experimental data on pedestrian crowd egress and emergency egresses at a bottleneck and tested them using force-based crowd simulation model. The force-based simulation model was able to replicate normal as well as panic egress situations. Bode and Coding (2015) presented a framework of statistical models to analyse microscopic pedestrian behaviour in front of bottlenecks. This approach established mechanistic similarities and the differences between simulated and real microscopic pedestrian behaviour.

To summarize, the literature addresses the capacity of a bottleneck with respect to the effective width of the bottleneck. It was observed that capacity values varied widely for the same bottleneck width in different studies. Thus it is necessary to analyse the actual capacity values for the study area selected and compare it with the past literature. In the present study, an attempt is made to understand crowd flow behaviour at varying bottleneck widths, their composition, and the impact of the presence or absence of buffer space.

3 DATA COLLECTION AND EXTRACTION

The experimental study area chosen is 10 m by 5 m. A digital camera was fixed at the top of the building covering the entire study area. In order to study the influence of overtaking within a crowd during evacuation, a buffer space was considered in the study area. This study is divided into two cases: the presence of a buffer space and the absence of a buffer space. The study area for both cases is divided accordingly as shown in Figure 1. The waiting areas ensure the same initial density of the crowd for each run. The height and length of the bottleneck were constant. Five different widths of bottlenecks were examined i.e., 80, 100, 120, 140, and 160 centimetres. Thirty and Fifty individuals were involved in the two different densities. The groups were heterogeneous and consisted of men and women.

Pixel based-level analysis was used for estimating the crowd density. The first step in the density estimation was the conversion of video into frames (one frame per second); the next step was to divide the entire area into an equal number of grids having grid size of (0.5 × 1 meter). The next step was to manually count the number of persons in each grid in each frame and then average the values of the densities for all the frames in each grid. The whole study area was divided into grids in order to calculate the density in each grid because it was not uniform throughout the study area. This also gives us an idea of the path/ route of the evacuation chosen by most individuals while evacuating.

The second step in crowd analysis was to track the people. To track a person is to identify the position of the person in a sequence of frames. For this exercise, TRACKER software was used; it is a free open source software and tracks a person semi-automatically. For extracting the speed, the video has to be converted into frames. The video therefore was imported into the TRACKER software. Then, the coordinate axis of the frames needed to be fixed. The lower left corner of the video image was selected to fix the origin coordinates. The next step of the analysis was to create and assign a separate point mass for each and every person. This assigned point mass can be used to store and display the characteristics (coordinates, speed, acceleration) of a person. Due to the camera angle which was not set up perpendicular to the ground, the pixel coordinates obtained could not represent a person's movements in a real scenario. To get the actual coordinates, conversion of the pixel coordinates is required. To convert the pixel coordinates, (Wolf & Dewitt 2000) a linear conversion algorithm was developed to minimize the effect of differences in swaying and heights. The conversion equations are as follows (Eqs. 1 & 2):

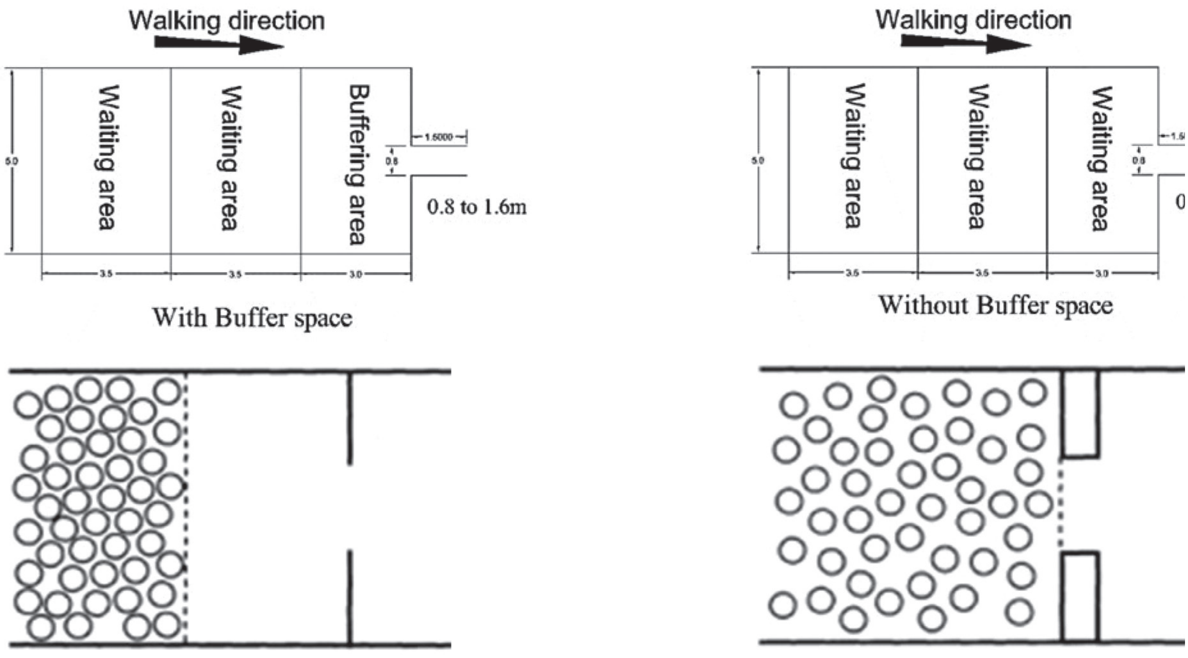

Fig. 1 *Experimental setup*

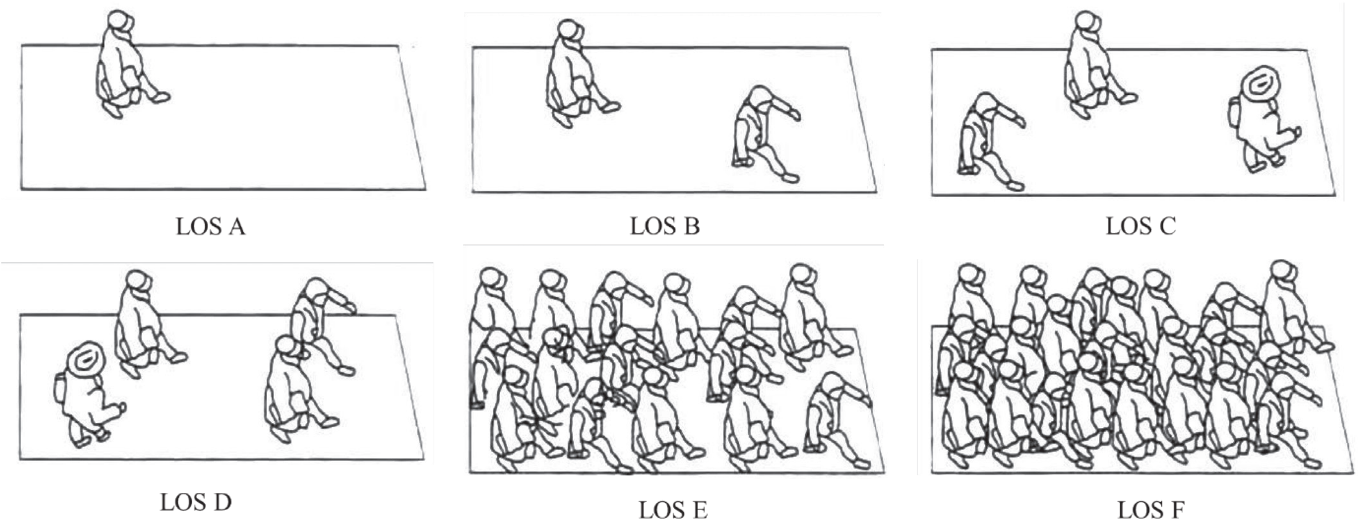

Fig. 2 *Pedestrian LoS according to HCM*

$$u + \frac{l_1 x + l_2 y + l_3}{l_7 x + l_8 y + 1} = 0 \quad (1)$$

$$v + \frac{l_4 x + l_5 y + l_6}{l_7 x + l_8 y + 1} = 0 \quad (2)$$

where (*u, v*) are the pixel coordinates; (x, y) are the real coordinates; and l1–l8 are the transformation coefficients. To convert the pixel coordinates, eight actual reference points were selected; the distances between them using tape in the experiment site were measured before collecting the video. After the collection of the video data, the corresponding pixel coordinates were measured using the TRACKER software while extracting the data. Four points were used to calculate the conversion coefficients using four points; the remaining four points were used to check the errors. The error percentage obtained was less than 5% (3.945).

The pedestrian facilities were analyzed using factors such as the speed and the pedestrian flow and density, culminating with the capacity and Level of Service (LOS) of the various forms of pedestrian facilities. The pedestrian LoS suggested by the Highway Capacity Manual (HCM) based on the space, flow rate, speed, and V/C ratio is tabulated in Table 1. Figure 2 shows the pedestrian LoS according to HCM from A to F.

Tab. 1 *Pedestrian LOS as per HCM*

LOS	Space (ft^2/p)	Flow Rate (P/min/ft)	Speed (ft/s)	V/C ratio
A	>60	≤5	>4.25	≤0.21
B	>40-60	>5-7	>4.17-4.25	>0.21-0.31
C	>24-40	>7-10	>4-4.17	>0.31-0.44
D	>15-24	>10-15	>3.75-4.00	>0.44-0.65
E	>8-15	>15-23	>2.50-3.75	>0.65-1.00
F	≤8	Variable	≤2.50	Variable

4 RESULTS

Total times, time gaps, and densities were extracted from the experimental study. The time duration from the first person crossing the reference line to the last person is defined as the total time. If there are '*n*' persons, the total is the sum of '*n*-1' time gaps. Figure 3 shows the variation of the total time with the bottlenecks width. It was observed that the total time decreased as the bottleneck width increased for both compositions with and without a buffer space. The effect of the buffer space in the reduction of the total evacuation time was more in the case of 50 persons than that in the case of 30 persons.

The flow is the ratio of the total number of persons walking through the bottleneck to the total time to cross the reference line. Figure 4 shows the variation of the flow versus the bottleneck widths. It was observed from this figure that the flow increased as the width of the bottleneck increased and that this increase in flow was due to the formation of dynamic lanes, as some of the researchers mentioned in their studies. When the crowd entered into a bottleneck, the formation of lanes occurred inside the bottleneck as the width increased due to a zipper effect.

A specific flow is the ratio of the flow to the width of the bottleneck. The variation of the specific flow versus the width of the bottleneck is shown in Figure 5. It was observed that specific flow decreases as the width of the bottleneck increases and that specific flows are more without a buffer space as compared to one with a buffer space.

The trajectories of different persons for the different widths for the cases with and without a buffer space is shown in Figure 6. This was plotted in order to track the choice of route of each individual throughout the evacuation period in the study area. It can be seen that the lateral occupancy pedestrians are greater in the case without a buffer space as compared to one with a buffer space for both compositions (i.e., for the number of persons (n = 30 & 50). The observations showed a phenomenon called "arching", which appears when a crowd with a highly desired velocity tries to pass through a bottleneck in less time; the bottleneck gets clogged, and the crowd becomes arc-shaped.

The variation of the density over the entire area for different widths of bottlenecks considering with and without a buffer space is shown in Figure 7. It can be seen that the densities are decreasing as the width of the bottleneck increases. The density values appear to increase if the number of people is 30 when compared to 50 persons for the same width of bottleneck. High densities (i.e., p = 3 to 2.65 pedestrians/meter^2

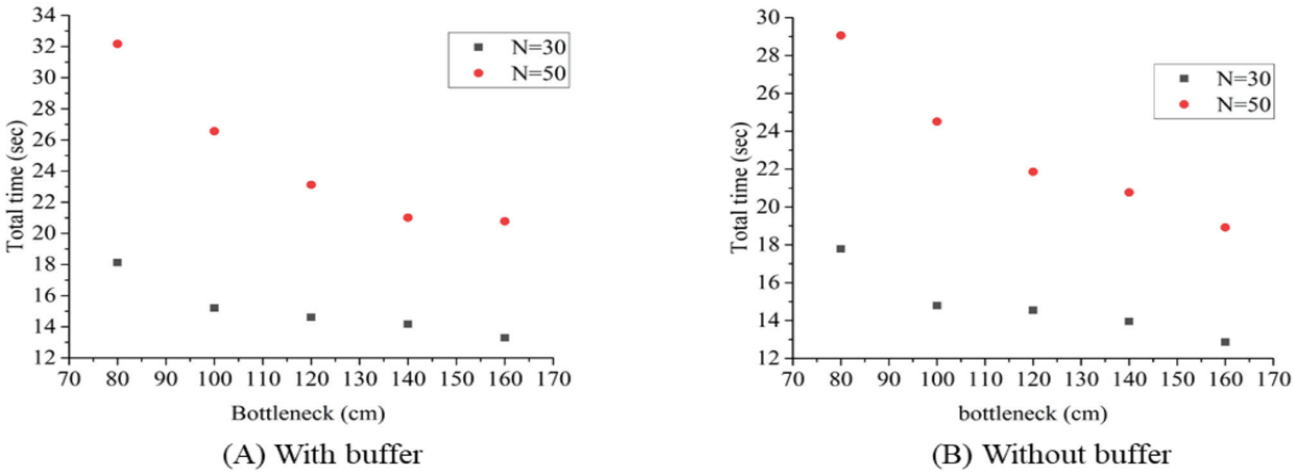

Fig. 3 *Total time versus the width of the bottleneck for different n values*

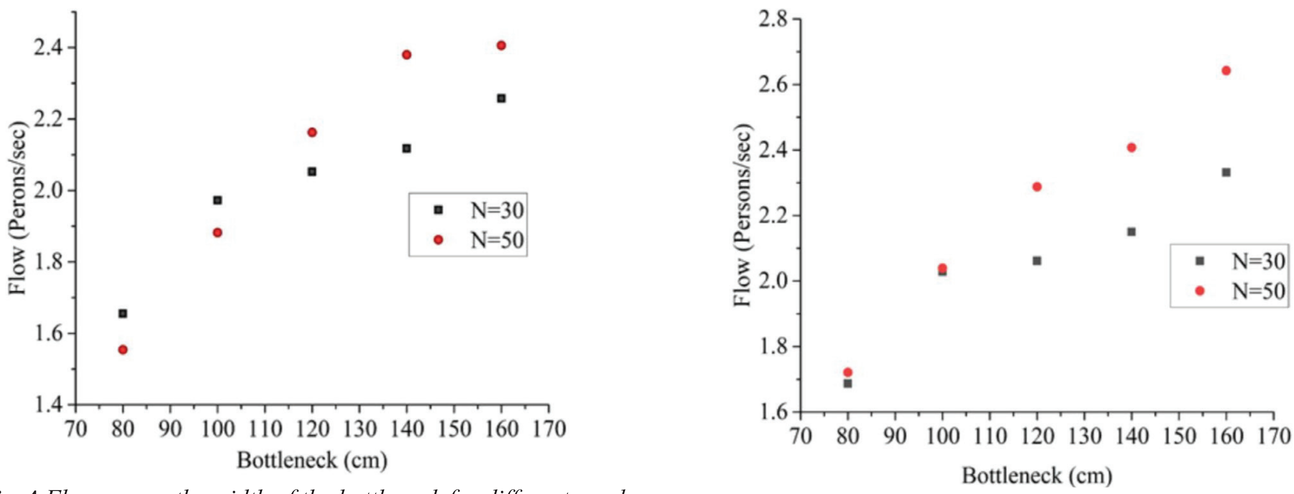

Fig. 4 *Flow versus the width of the bottleneck for different n values*

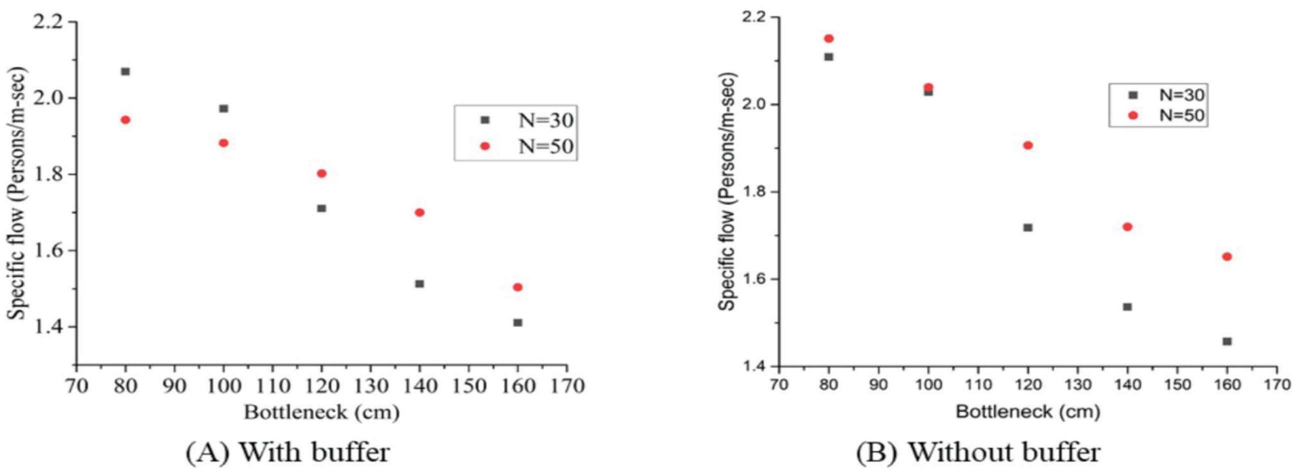

Fig. 5 *Specific flow versus the width of the bottleneck for different n values*

for 30 persons and p = 3.8 to 2.98 pedestrians/meter^2 for 50 persons) were observed near the bottleneck opening; this happens when the incoming flow measured over a surface in front of a bottleneck exceeds the capacity of the bottleneck; hence, jamming occurs in front of the bottleneck.

Figure 8 shows the formation of lanes as the width of the bottleneck increases. From this figure, it can be observed that the flow of the crowd increases as the width of the bottleneck increases; this increase is in a stepwise not in a linear fashion. When the crowd enters into a bottleneck, the formation of lanes occurs inside the bottleneck as the width increases due to a zipper effect. For a width of 80 cm, the formation of lanes is absent. As the width increased from 80 cm to 100 cm, two lanes were formed, and these lanes were continued and later-

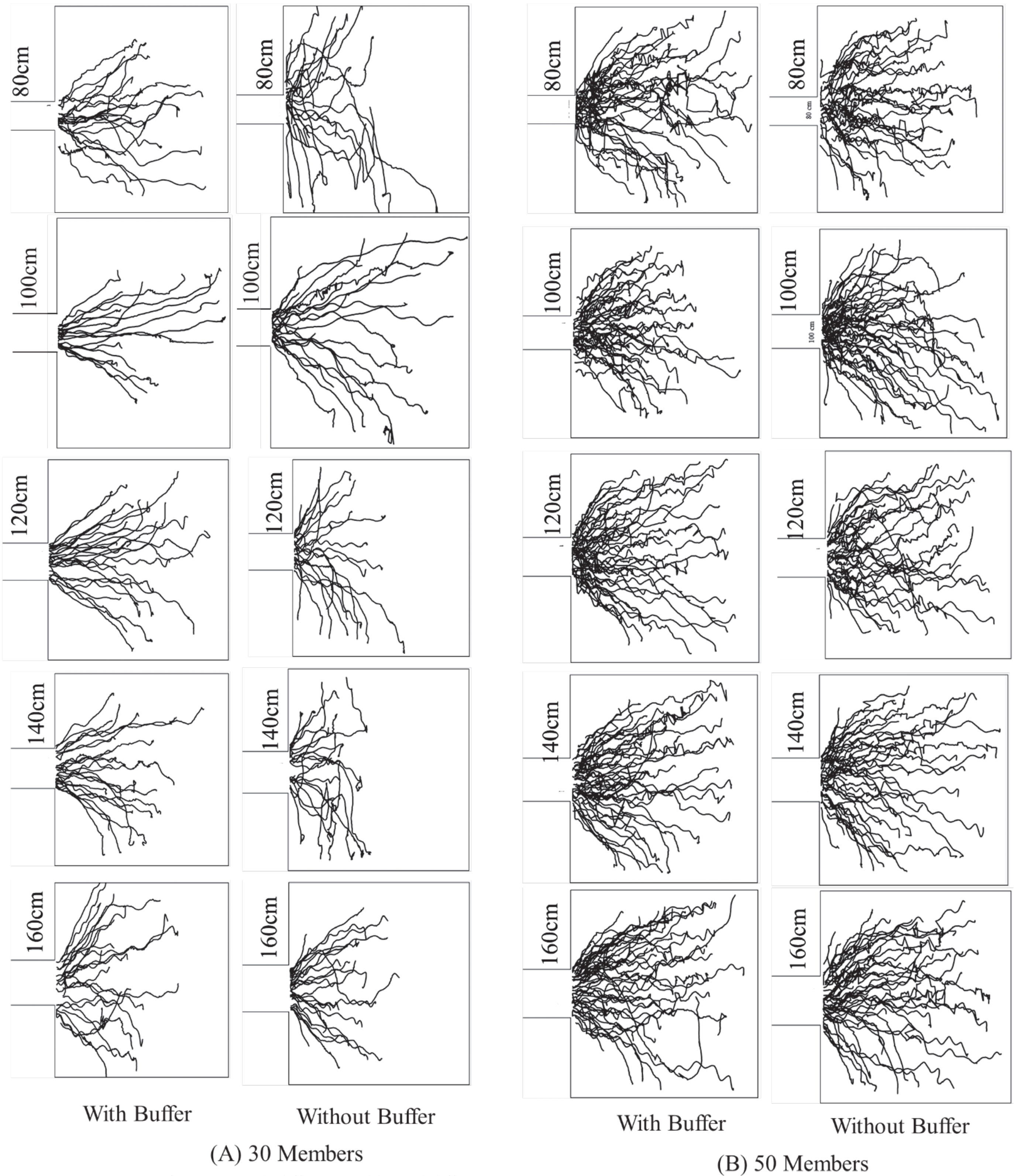

Fig. 6 *Trajectories of persons with different widths and different composition*

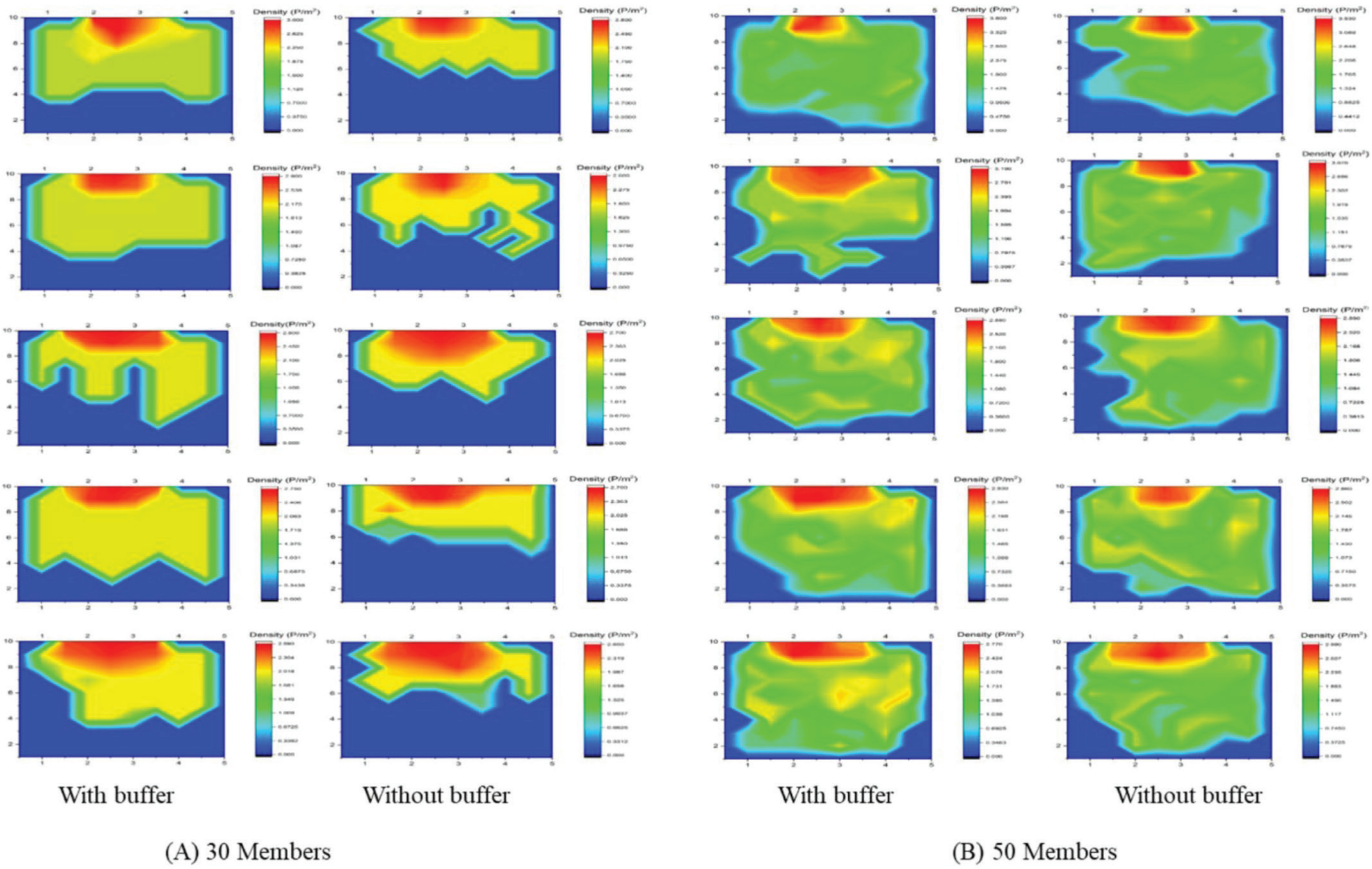

Fig. 7 *Density variations for different bottleneck widths, considering with and without a buffer space*

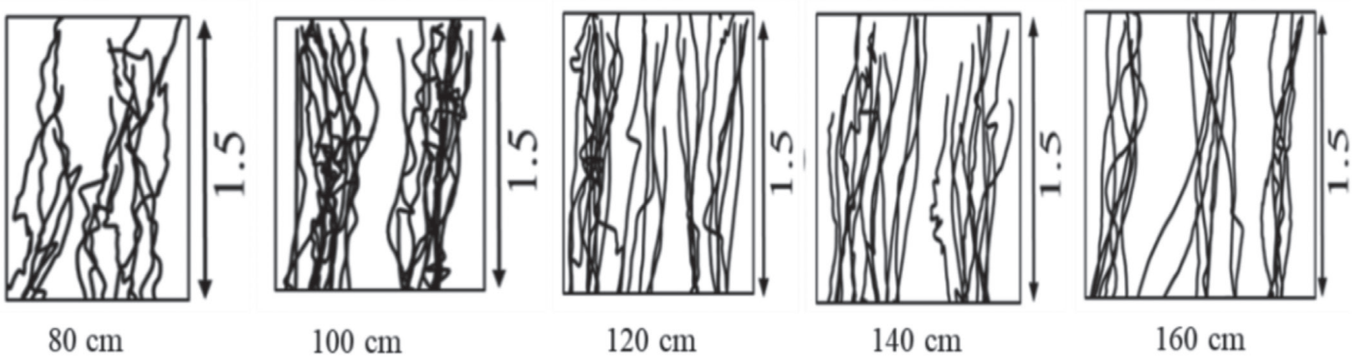

Fig. 8 *Formation of dynamic layers for different bottleneck widths (i.e., 80, 100, 120, 140, and 160 cm).*

ally expanded up to a width of 140 cm. For a width of 160 cm, it can be clearly observed that three lanes were formed. It can also be observed that the distance between these lanes does not depend on the width of the bottleneck (B).

The time elapsed between the arrivals of pairs of pedestrians is called the "time headway". The shape of the time headway distribution varies considerably as the pedestrian flow rate increases. For example, under very low flow conditions, there is very little interaction between the pedestrians, and the time headways appear to be somewhat random. As the flow of pedestrians increases, there are increasing interactions between pedestrians. Generally, headways are classified into three types: a random headway, intermediate headway, and constant headway. The negative exponential distribution and displaced negative exponential distributions are the mathematical distributions that represent the distribution of random intervals such as time headways. For time headways to be truly random, the arrival of one pedestrian at a point in time does not affect the arrival time of any other pedestrian. The constant headway occurs when the flow reaches its capacity. The constant headway can best be appropriately represented using a normal distribution. The intermediate headway lies between the two boundary conditions, i.e., some pedestrians are travelling independent of one another, while other pedestrians are interacting. The Gamma and displaced Gamma or Pearson type III distribution are the mathematical distributions that best represent the distribution of intermediate headways. Buckley (1968) proposed a semi-random model for pedestrian headways. According to Buckley's semi-random model, headways are divided into two categories; one is a "free" headway and the other is a "constrained" headway. "Free" headways are headways of pedestrians experiencing

Tab. 2 *Headway distribution table*

Distribution type	Abbreviation	Probability density function	Population moments
Negative exponential	NE	$\frac{1}{\beta}e^{-\frac{x}{\beta}}$	$\mu_1' = \beta$
Displaced negative exponential	DNE	$\frac{1}{\beta}e^{-\frac{x-\alpha}{\beta}}$	$\mu_1' = \alpha + \beta$ $\mu_2' = \alpha^2 + 2\alpha\beta + 2\beta^2$
Gamma	G	$\frac{1}{\beta\Gamma(k)}\left(\frac{x}{\beta}\right)^{k-1} e^{-\frac{x}{\beta}}$	$\mu_1' = \beta k$ $\mu_2' = \beta^2 k(k+1)$
Pearson type III	DG	$\frac{1}{\beta\Gamma(k)}\left(\frac{x-\alpha}{\beta}\right)^{k-1} e^{-\frac{x-\alpha}{\beta}}$	$\mu_1' = \alpha + \beta k$ $\mu_2' = \alpha^2 + 2\alpha\beta k + \beta^2 k(k+1)$ $\mu_3' = \alpha^3 + 3\alpha^2\beta k + 3\alpha\beta^2 k(k+1) + \beta^3 k(k+1)(k+2)$
Semi-random (Buckley) Note:	SR	$\frac{\phi}{\sqrt{2\pi\sigma^2}}e^{-\frac{(x-\theta)^2}{2\sigma^2}} + (1-\phi)e^{\theta\lambda-0.5\sigma^2\lambda^2}\lambda e^{-\lambda x}\int_{-\infty}^{x}\frac{1}{\sqrt{2\pi\sigma^2}}e^{-\frac{(t-\theta)^2}{2\sigma^2}}dt$	$\mu_1' = \phi\theta + (1-\phi)(\epsilon + \frac{1}{\lambda})$ $\mu_2' = \phi(\theta^2 + \lambda^2) + (1-\phi)(\varepsilon^2 + \sigma^2 + \frac{2\epsilon}{\lambda} + \frac{2}{\lambda^2})$ $\mu_3' = \phi(\theta^3 + 3\sigma^2\theta) + (1-\phi)(\varepsilon^3 + 3\sigma^2\epsilon + \frac{3}{\lambda}\varepsilon^2 + \frac{3}{\lambda}\sigma^2 + \frac{6}{\lambda^2}\varepsilon + \frac{6}{\lambda^3})$ $\mu_4' = \phi(\theta^4 + 6\theta^2\sigma^2 + 3\sigma^4) + (1-\phi)(\varepsilon^4 + 6\varepsilon^2\sigma^2 + 3\sigma^4 + \frac{4}{\lambda}(\varepsilon^3 + 3\sigma^2\epsilon) + \frac{12}{\lambda^2}(\varepsilon^2+\sigma^2) + \frac{24}{\epsilon}\lambda^3 + \frac{24}{\lambda^4})$

no hindrance from other pedestrians, and who are thus able to walk at a free flow speed. "Constrained" headways are headways of pedestrians following pedestrians in front, because no direct overtaking opportunity exists, thereby forcing constrained walking. The headway will fluctuate around the desired minimum headway (the so-called "empty zone"). In the present study, five types of distributions were tested to cover the random, intermediate, and composite headways. The probability density functions and population moments of these distributions are presented in Table 2.

In the above table are the population moments that were obtained using the following equations.

$$\mu_1' = \frac{\sum fd}{N} * I \quad (3)$$

$$\mu_2' = \frac{\sum fd^2}{N} * I^2 \quad (4)$$

$$\mu_3' = \frac{\sum fd^3}{N} * I^3 \quad (5)$$

$$\mu_4' = \frac{\sum fd^4}{N} * I^4 \quad (6)$$

where '*f*' is the frequency; '*d*' is the deviation; '*n*' is the total number of samples; and '*I*' denotes the width of the class interval. The time headways for different widths considering with and without a buffer space were extracted, and five number summaries (i.e., the minimum, maximum, range, and class interval, mean) were calculated, and the observed frequencies were obtained using the frequency function in MS Excel. To get the predicted frequencies, the population moments were calculated using the formulas as mentioned earlier, and different parameters were estimated. The probability density functions for different types of distributions were estimated with the help of the values of the parameters obtained. The predicted frequencies were obtained by multiplying the probability density function values with the sample size. Figure 9 shows the headway versus the frequency. The five types of distributions mentioned above have been compared with the data observed and tested with the goodness of fit (χ^2 **test**). It was determined that among the five types of distributions, the semi-random (SR) distribution was observed to be the best fit for the data observed. The percentage of constrained headways (observed in the case of 50 persons is more than that of 30 persons. This implies that the free flow decreases with an increase in density for the study area.

In order to estimate the capacity of the bottleneck (C), the constant headway model was used. The capacities of dynamic lanes can be found using an empty zone, i.e., by assuming saturated conditions. The C (in pedestrians/metre/second) equals the inverse of the mean empty zone.

$$C = \frac{1}{E(T)} \quad (7)$$

where, E (T) is the mean of the empty zone, which is calculated using the Wasielewski (1979) method. The following equation is used to calculate the capacity per lane C_1 (in pedestrians/second/lane).

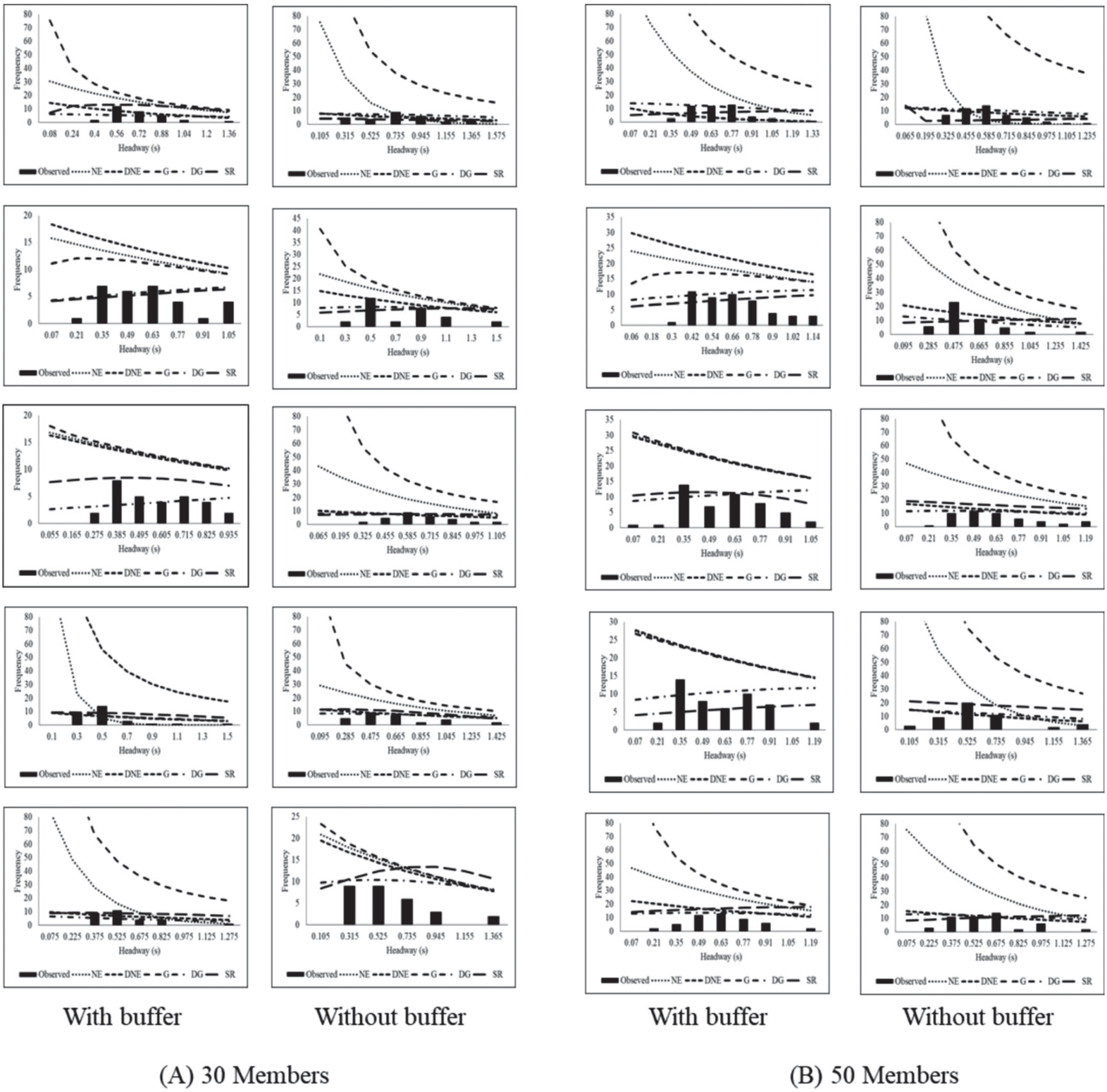

Fig. 9 *Frequency versus headway for different bottleneck widths considered with and without a buffer space.*

$$C_1 = \frac{1}{2aE(T)} \quad (8)$$

where 2a denotes the average lane width; here, the average layer width is equal to 50 cm, because the minimum effective width of a bottleneck must encompass at least one lane; hence, it must be greater than or equal to the expected maximum shoulder width of a pedestrian (i.e., 50 cm). Tables 3 and 4 below show the capacity variations for the different bottleneck widths. It can be observed from these tables that the capacity of a bottleneck increases as the width of the bottleneck increases and that this increase in capacity is because of the formation of dynamic lanes due to the zipper effect. It can also be seen that a bottleneck capacity with a “buffer space” is more compared to one “without buffer space”.

Tab. 3 *Capacity estimation for various bottleneck widths for 30 members*

No of lanes	Bottleneck width(m)	Mean empty zone		Capacity (Pedestrian/meter/second)		Capacity (Pedestrian/lane/second)	
		With a buffer space	Without a buffer space	With a buffer space	Without a buffer space	With a buffer space	Without a buffer space
1	0.8	0.7	0.795	1.43	1.26	2.86	2.52
2	1.0	0.61	0.77	1.64	1.30	3.28	2.60
2	1.2	0.57	0.65	1.75	1.54	3.51	3.08
2	1.4	0.52	0.63	1.92	1.59	3.85	3.17
3	1.6	0.5	0.61	1.96	1.64	4.00	3.28

Tab. 4 *Capacity estimation for various bottleneck widths for 50 members*

No of lanes	Bottleneck width(m)	Mean empty zone		Capacity (Pedestrian/meter/second)		Capacity (Pedestrian/lane/second)	
		With a buffer space	Without a buffer space	With a buffer space	Without a buffer space	With a buffer space	Without a buffer space
1	0.8	0.68	0.71	1.47	1.42	2.94	2.84
2	1.0	0.60	0.65	1.67	1.54	3.33	3.08
2	1.2	0.58	0.62	1.72	1.61	3.45	3.23
2	1.4	0.57	0.60	1.75	1.67	3.51	3.33
3	1.6	0.52	0.56	1.92	1.79	3.85	3.57

The capacities obtained were compared with the capacities from different experimental studies done relating to pedestrian flows at bottlenecks. Table 5 compares the capacities of the present study with previous literature. For the comparison, Kretz and Muller (1981) were considered because of its similarity with this study. The capacities obtained in this study were less than that of the capacities obtained from Kretz and Muller. The reason behind the reduction in capacities was that Kretz and Muller did not consider the formation of dynamic lanes; hence the effective utilization of a width concept was absent there by resulting into the larger capacities.

Tab. 5 *Comparison of the capacities of the present study with other studies*

Width (meter)	Capacity (C) (Pad/m/s)										
	Estimation				Measurement						
	SFPE [5]	PM [15]	WM [23]	HG [7]	Kretz [9]	Nagai [13]	Muller [12]	This study			
								n = 30		n = 50	
								With out Buffer	With Buffer	With out Buffer	With Buffer
0.8	1.04	1.28	0.98		1.43	2.58		1.43	1.26	1.47	1.42
1.0	1.30	1.60	1.23	0.78	1.85			1.64	1.30	1.67	1.54
1.2	1.56	1.92	1.47	0.78	2.15	3.27	2.75	1.75	1.54	1.72	1.61
1.4	1.95	2.40	1.84	1.56			3.59	1.92	1.59	1.75	1.67
1.6	2.08	2.56	1.96	1.56		3.86		1.96	1.64	1.92	1.79

5 CONCLUSIONS

This study mainly focuses on analysing the effect of density and obstacles (bottlenecks) with varying widths on the behaviour of a crowd flow. The data was collected using digital videos, and extraction of the data was carried out with the help of TRACKER software. Parameters such as the total times, time gaps, densities, and speeds were extracted and analysed in terms of various relations such as the total evacuation times versus bottleneck width, the flow versus the bottleneck width, and the specific flow versus the bottleneck width. The crowd trajectories, density plots, and dynamic lane formations were drawn. The total evacuation times decreased as the width of the bottleneck increased for the cases with and without a buffer space. The effect of the buffer space in the reduction of the total time was more in case of 50 persons than that of 30 persons. The specific flow decreased as the width of the bottleneck increased and the specific flows are greater without a buffer space when compared to one with a buffer space where the number of persons are fifty. Observations from the trajectories showed a phenomenon called “arching”, which appears when a crowd with a highly desired velocity tries to pass through a bottleneck and become clogged. Five types of distribution were tested to fit the observed data. From the headway study, it was observed that among the five types of distributions, a semi-random distribution is the best fit for the headway data observed. The capacities were estimated and a comparison of the capacities obtained with other studies was performed. The capacities increase as the width of the bottleneck increases because of the dynamic lane formation (due to the zipper effect) and this increase is in a stepwise, not linear increase. It can also be observed that the distance between these lanes is independent of the width of the bottleneck. Kretz and Muller were similar to this study but the only difference is that the formation of dynamic lanes was not considered in their study, which led to a larger capacity prediction.

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REFERENCES

Bode, N.W., and Codling E.A. (2016). Statistical models for pedestrian behavior in front of bottlenecks. *In Traffic and granular flow*, 15, pp.81-88.

Buckley. J. (1968). A semi Poisson model of traffic flow. *Journal of Transportation Science*, vol. 2, No. 2.

Dias, C., Ejtemai, O., Sarvi, M., and Nirajan, S. (2014). Pedestrian Walking Characteristics through Angled Corridors: An Experimental Study. *Transportation Research Record: Journal of the Transportation Research Board*, pp. 41–50.

Dias, C., Sarvi, M., Nirajan, S., and Burd, M. (2012). Turning Angle Effect on Emergency Egress Experimental Evidence and Pedestrian Crowd Simulation. *Transportation Research Record: Journal of the Transportation Research Board*, pp. 120–127.

DiNenno, P.J. (2008). SFPE Handbook of Fire Protection Engineering, 3rd ed. National Fire Protection Association, Quincy, MA, USA.

Duives, D.C., and Mahmassani, H.S. (2012). Exit Choice Decisions during Pedestrian Evacuations of Buildings. *Transportation Research Record: Journal of the Transportation Research Board*, pp. 84–94.

Hoogendoorn, S.P., and Daamen, W. (2005). Pedestrian Behavior at Bottlenecks. Journal of Transportation Science, Vol. 39, No. 2, pp. 147-159.

Hoogendoorn, S.P., Daamen, W., and Bovy, P.H.L. (2003). Microscopic pedestrian traffic data collection and analysis by walking experiments: Behaviour at bottlenecks. E. R. Galea, ed. Pedestrian and Evacuation Dynamics, 89-100.

Kretz, T., Grunebohm, A., and Schreckenberg, M. (2006). Experimental study of pedestrian flow through a bottleneck. Journal of Statistical Mechanics Theory and Experiment Vol. 2006 No. 10.

Lee, Y. (2005). Pedestrian Walking and Choice Behaviour on Stairways and Escalators in Public. Delft University of Technology, the Netherlands.

Liddle, J., Seyfried, A., Klingsch, W., Rupprecht, T., Schadschneider, A. and Winkens, A. (2009). An experimental study of pedestrian congestions: Influence of bottleneck width and length, in Traffic and Granular Flow.

Muller, K. (1981). Zur Gestaltung und Bemessung von Fluchtwe gen fur die Evakuierung von Personen aus Bauwerken auf der Grundlage von Modellversuchen. Ph.D. thesis, Technische Hochschule Magdeburg.

Nagai, R., Fukamachi, M. and Nagatani, T. (2006). Evacuation of crawlers and walkers from corridor through an exit. Physica A, 367, 449-460.

Nirajan, S., Sarvi, M., Rose, G., and Burd, M. (2011). Consequence of Turning Movements in Pedestrian Crowds during mergency Egress. *Transportation Research Record: Journal of the Transportation Research Board*, pp. 97–104.

Predtechenskii, V.M., and Milinskii, A.I., (1978). Planning for Foot Traffic Flow in Buildings. Amerind Publishing.

Saboia, P., and Goldenstein, S. (2012). Crowd simulation: applying mobile grids to the social force model. The Visual Computer, 28(10), pp.1039–1048.

Seyfried, A., Passon, O., Steffen, B., Boltes, M., Rupprecht, T., and Klingsch, W. (2009). New Insights into Pedestrian Flow through Bottlenecks. Journal of Transportation Science, Vol. 43, No. 3, pp. 395-406.

Sharifi, M.S., Stuart, D., Christensen, K., and Chen, A. (2016). Time headway modelling and capacity analysis of pedestrian facilities involving with disabilities. *Transportation Research Record*, 2553(1), pp.41-51.

Shiwakoti, N. (2016). Understanding differences in emergency escape and experimental pedestrian crowd egress through quantitative comparison. *International Journal of Disaster Risk Reduction*, 20, pp.129-137.

Tajima, Y., Nagatani, T., and Adler, J. (2001). Scaling behavior of crowd flow outside a hall. Physica A: Statistical Mechanics and its Applications, 292(1-4), pp.545–554.

Tracker- Video Analysis and Modelling Tool, https://physlets.org/tracker/.

Wasieiewski, P. (1979). Car following headways on freeways interpreted by the semi-Poisson headway distribution mode. *Transportation Science*, 13, 36--55.

Weidmann, U. (1993). Transporttechnik der Fufiganger. Schriftenreihe des IVT 90, ETH Zurich.

Wolf, P.R., and Dewitt, B.A. (2000). Elements of photogrammetry with applications in GIS, Third ed. McGraw Hill.