European Transport \ Trasporti Europei (2022) Issue 89, Paper n° 8, ISSN 1825-3997

https://doi.org/10.48295/ET.2022.89.8

Studies on Pedestrian Flow through Open Corridors with Geometric Variations

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Abstract

Pedestrians are important part of transportation system. Understanding pedestrian motion is a difficult task as it involves a lot of complexity at various level of studies. This study is based on pedestrian flow along the corridor highlighting the impact of geometric variations along the corridor. The impact of geometric variation (basic, symmetric, asymmetric) on pedestrian flow is studied in terms of lateral and longitudinal variations in densities and longitudinal variations in speed. The result shows (i) Corridor edges have a significant impact on the use of corridor (ii) Disturbance to pedestrian flow is significant in the case of narrowing (asymmetric) as compared to narrowing (symmetric) (iii) Effect of constriction is felt at both upstream and downstream side of the narrowed section. In a nutshell, the study provides a platform to understand pattern of pedestrian flow moving through an open corridor with and without constrictions.

Keywords: Pedestrian motion, geometric variations, mesoscopic study, corridor.

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1. Introduction

The role of physical activities in present day world cannot be ignored. One of the important part of physical activities is walking. Walking is the elementary mode of transportation. But with urbanization and industrialization, the vehicular mode of transportation has taken over as the major mode of transportation. As a result of which, a lot of research and innovation are carried out for the development of vehicular mode of transportation; at the same time development for the pedestrian flow has taken over the back seat. Keeping in mind the benefits of pedestrian movement to the environment and society, pedestrian flow should be given an equal importance as vehicular mode. Pedestrian movement can be categorized as movement along an open corridor and movement within an enclosed space with few entry and exit points. This paper focusses on understanding pedestrian motion along the corridors.

Experimentally, pedestrian motion can be studied at three levels. At macroscopic level, one can understand basic flow parameters (speed, density) for the pedestrian flow. At microscopic level one may follow an individual pedestrian to understand the psychology of that pedestrian and to analyze the factors affecting pedestrian movement along the corridor. At mesoscopic level one can study the pedestrian motion in space (laterally and longitudinally) and with time along the corridor. Such studies enrich the understanding on pedestrian flow and help in simplifying the complexity of the

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pedestrian motion. In this paper mesoscopic level studies along the corridor of various geometries have been studied.

This paper is divided into five sections of which this is the first. Second part involves reviews of literature consisting of empirical studies related to concerned topic. Third part explains the experimental set-up and the methodology. Fourth part provides the results from the study and final part is conclusion and important findings.

2. Literature Review

In spite of many studies conducted to understand the importance of pedestrian motion in shopping malls, terminals, sidewalks etc. along with some isolated studies; coordinated and continuous effort to understand and analyze the behavior of pedestrian started only after 1990.

A lot of studies have been conducted in corridor to analyze the fundamental relationship (like speed, density) of pedestrian motion under different circumstances (Fruin (1971), Hankin and Wright (1958), Isobe et al. (2004), Mori and Tsukaguchi (1987), Navin and Wheeler (1969), O'Flaherty and Parkinson (1972), Older (1968), Seyfried et al. (2005), Lam et al. (2002), Seyfried et al. (2007), Polus et al. (1983), Chattaraj et al. (2009)). As in case of vehicular motion, speed decreases monotonically with increase in density, similar observation can be seen in the case of pedestrian motion. Lam et al. (2002) and Seyfried et al. (2007) have focussed their studies to understand issues related to capacity, while Polus et al. (1983) have addresses the issues related to level of service. Chattaraj et al. (2009) have focussed their study on understanding the impact of cultural differences on speed-density relationship. Various other researchers have studied the impact of age, gender, level of crowd, nature of pedestrian facilities and many other factors (Henderson and Lyons (1972), Lee and Lam (2006), Smith (1995), Tanaboriboorn et al. (1986), Tanaboriboorn and Guyano (1991), Young (1999)). Also some researchers have studied different phenomena related to pedestrian motion along the corridor. Kretz et al. (2006) and Hoogendoorn and Daamen (2004) have studied the phenomena of formation of lanes especially in bidirectional flow. Hoogendoorn and Daamen (2005) have observed the 'zipper effect' in case of bottleneck condition. Helbeing et al. (2005a) have observed alternate passing and stopping during bottleneck condition in case of counter flow. Helbeing et al. (2005b) in another study of unidirectional flow have observe stop and go shockwaves in case of high density condition.

Although various level of studies are conducted along the corridor to understand the pedestrian motion but very few studies are conducted at mesoscopic level to study spatial (laterally and longitudinally) and temporal (transient) variation in speed and density of pedestrian due to various geometric variations. Comprehensive studies on this aspect will aid in understanding the impact of various geometric conditions on pedestrian flow. This paper focusses on studying such impacts in pedestrian flow for different corridor conditions.

3. Experiments

As a part of this study, several experiments are conducted to examine the temporal and spatial impact of various corridor geometries on pedestrian flow. In this part, the various parameters observed, procedure conducted and experimental set-up are outlined in detail.

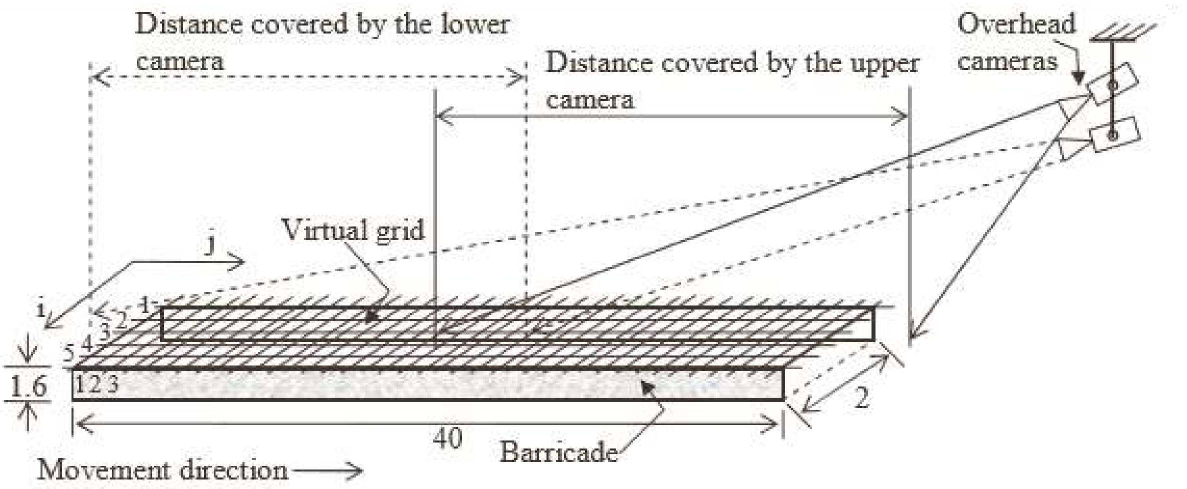
3.1 *Experimental Set-up and procedure*

A corridor of dimension 40 m × 2 m was developed by putting metal barricades (height ~ 1.6 m) on a paved surface with enough passage area for free movement of pedestrian. Figure 1(a) shows the experimental set-up. From the extended center line of the corridor, two video cameras of high resolutions (640 × 480 pixels) were fixed at an elevation of almost 10 m and at a distance of nearly 10 m from the edge of the corridor. The purpose for the use of two high resolution cameras is to allow one of them to zoom in on about half the length of the corridor and the other the remaining half to have a top notch quality during video recording. To determine the positon of pedestrian along the corridor, a grid (0.4 m × 0.4 m) was constructed. The grid was made of thin but viewable wires at a height of 1.65 m (a value which is approximately equal to height of average Indian people (Brennan et al. (1995)) from the paved surface. Once the grid construction was completed it was recorded by the fixed cameras and there after grid was removed before the initiation of the experiments. The angle and position of cameras were maintained fixed throughout the period of all experiments. The recorded video are projected on a 53 inch television screen. Before the process of extracting data from the video camera begins, the grid was very carefully recreated by marking each line of the grid on the television screen by the use of removable marker. This lines act as a virtual grid on which recorded videos of pedestrian motions are played back. It is to mention here that the concept of gridding is obtained from the understanding of Cellular Automata (more details on which can be obtained from Das and Chattaraj (2019)). Experiment starts randomly but gradually uniform distribution is observed. The time of start of data collection is subjective and depends upon when the experimenter feels the impact of starting time have finished. Time period for data collection for each experiment is nearly 5 minutes.

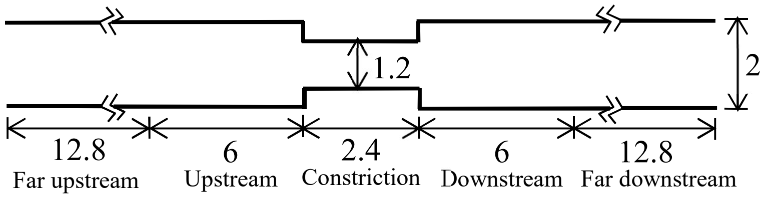
Pedestrians used in this study are male and their body stature is healthy (height of about 1.55 m to 1.75 m and weight is about 50 kg to 70 kg). The age group selected is between 20 to 30 years. The participants for the experimental procedure are a mix of engineering volunteers and paid civilian persons of high school level education. The participants selected are uninformed with other participants and they didn’t carry any item with them. The only piece of instruction given to them were once they exit from the given space they should return back to the entry position through the open space available along the corridor and maintain the same process as if they are present in a loop and continue till they are asked to stop. However as each pedestrian moves through the created space at most thrice, the impact of “learning” on pedestrian behaviour was minimal.

The main focus of this paper is to observe the impact of various corridor geometry on the basic flow parameters of pedestrian. For the study it was felt that, if the density of the corridor will be high then pedestrian behavior will be affected, not only by corridor geometry but also due to crowding. At the same time if the density is too low then the impact of corridor geometry on pedestrian behavior will be hard to observe and analyze. For that reason the density at which the study needed to be conducted is chosen very cautiously. In this study a density of approximately 0.6 persons/m^2 (speed-density diagrams indicate at this value the density is neither in “forced flow regime” nor in “free flow regime”) is chosen and at any given instant there are approximately 50 persons inside the corridor.

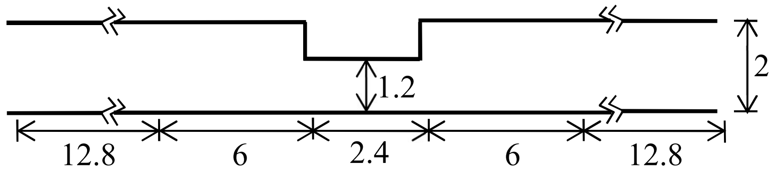
In order to understand the impact of various corridor geometry, three different plans were developed. Figure 1(a) shows the basic (40 m × 2 m) corridor dimension. Figure 1(b) shows a symmetrically narrowed corridor dimension and figure 1(c) shows an asymmetrically narrowed corridor dimension. In the constriction zone, in both the narrowed cases, the width is reduced 60% of the basic corridor width. Figures 2(a), 2(b) and 2(c) show the snapshots of the experimental set-up of the three respective corridors.



(a) Basic Corridor



(b) Narrowed Corridor (Symmetric)



(c) Narrowed Corridor (Asymmetric)

Figure 1: Schematic Diagram showing the Experimental set-up (all dimensions are in ‘m’)

(a) Basic Corridor (b) Narrowed Corridor (Symmetric)

(c) Narrowed Corridor (Asymmetric)

Figure 2: Snapshots showing the Experimental set-up

3.2 *Observed and Computed Parameters*

Figure 1(a) shows the (i, j) axes and their corresponding values on which one can observe the position and location of pedestrians. Figure 1(b) and 1(c) show the various zones within a section; these are discussed in later part. Following are the types of data recorded from the experiments:

Variable $O_{i,j}^{t}$ is defined as

$$O_{i,j}^{t} = \begin{cases} 1\ if\ cell\ (i,j) is\ occupied\ at\ time\ t \\ 0\ otherwise \end{cases}$$

An assumption is that a cell (i, j) which in this case is (0.4 m × 0.4 m) cannot have more than one person at a time. This tacit assumption is justified in early studies (Schadschneider et al. (2009)) on wide corridor and indicated that highest density possible is around 6.25 persons/m^2 (or minimum space occupied per person is 0.16 m^2).

For almost 25% of the pedestrians the time at which they reached j = 8, 16, 24, 32, 40, 44, 48, 52, 56, 60, 68, 76, 84 and 92 are also recorded. The data collected through this can be employed to get an overall idea on longitudinal speed profile of the pedestrians.

For the collection of relevant information regarding pedestrian motion, the data needed to be examined at an aggregate level. As a result two spatial units at an aggregate level are established. These are discussed as follow:

(i) *Lane* l:

This spatial unit consists of all cells (i, j) for which i = l. It is to mention that physically there are no lanes. This allows one to focus attention towards lateral change in flow parameters along the width of the corridor and also it aids in visualizing the given data more minutely. For this study, five lanes are considered (as shown in figure 1(a)).

(ii) *Zone*:

This spatial unit consists of all cells (i. j) for which "j" lies within a specified range. For example, in figure 1(b) for the far upstream (fus) zone j ∈ [1, 32]. Physically there are no zones. However such a creation allows one to focus attention towards longitudinal change in flow parameters along the corridor. For this study, five zones are considered (as shown in figure 1(b) and figure 1(c)). The five zones are far upstream (fus), upstream (us), constriction (c), downstream (ds) and far downstream (fds).

Following are the quantities used for the study of spatial variations in flow parameters:

(i) *Relative Overall Lane Density:*

The term Overall lane density (OLD) for a certain duration of time, say, 'T', for a particular lane, say, Lane "*l*" can be defined as the number of pedestrians occupying that particular lane over the course of period of study. This can be obtained through:

$$\mathrm{OLD}_l = \sum_{t=1}^{T} \sum_{j=1}^{J} O_{l,J}^{t} \tag{1}$$

Where "T" is the total time period of study and "J" is the maximum number of cells along the j direction.

The relative overall lane density for Lane "*l*" (ROLD$_l$) is defined as the ratio of the number of people occupying lane "*l*" and the total number of people occupying the corridor for the entire period of study duration. It is given by:

$$\mathrm{ROLD}_l = \frac{OLDl}{\sum_{l=1}^{L} OLDl} \tag{2}$$

Where, "L" is the maximum number of lanes.

(ii) *Relative Zonal Lane Density:*

The relative zonal lane density (for lane '*l*' and zone 'z'), RZLD$_{lz}$ can be obtained by including cells within a particular zone. Therefore zonal lane density can be obtained by

$$\mathrm{ZLD}_{lz} = \sum_{t=1}^{T} \sum_{j=J_{Lz}}^{J_{Uz}} O_{l,J}^{t} \tag{3}$$

And

$$\mathrm{RZLD}_{lz} = \frac{ZLD\ lz}{\sum_{l=1}^{L} ZLD\ lz} \tag{4}$$

Where,

J_{Lz} and J_{Uz} are lower and upper limits of 'j' for a particular zone 'z'. For example, for the far downstream zone (fds), $J_{Lfds} = 54$ and $J_{Ufds} = 68$.

(iii) *Progression Speed:*

For the determination of speed, the corridor length is divided into 13 subzones. Considering a subzone "s", the mean speed is determined as:

$$\mathrm{PS_s} = \frac{(JUs-J\quad)}{\frac{\sum_{k=1}^{K} t_{\cup s}^{k} - t_{Ls}^{k}}{K}} \tag{9}$$

Where, s is a subzone and K is the number of persons considered for the speed study.

The above defined parameters help in study of spatial variation in density and speed. The parameter ROLD_l helps one to observe the lateral variation in density over the entire corridor width. Whereas, the parameter RZLD_l helps one to observe longitudinal and lateral variations in density for different zones. The parameter $\mathrm{PS_s}$ helps in determining longitudinal variation in speed.

4. Results and Discussions

In this part of study, the obtained results from the experiments are shown. These experiments are conducted under three corridor geometries as discussed earlier.

The value of various assumed parameters are discussed here:

(i) Width of the cell = 0.4 m

(ii) Far upstream zone (fus) = length (0 m to 12.8m); number of cells occupied (0 to 32)

(iii) Upstream zone (us) = length (12.8 m to 18.8m); number of cells occupied (33 to 47)

(iv) Constricted zone (c) = length (18.8 m to 21.2m); number of cells occupied (48 to 53)

(v) Downstream zone (ds) = length (21.2 m to 27.2m); number of cells occupied (54 to 68)

(vi) Far downstream zone (fds) = length (27.2 m to 40m); number of cells occupied (69 to 100)

(vii) Number of male persons used in the experiment is 100 (at any instant of time about 50 persons are within the corridor and the rest are present in open spaces around the corridor).

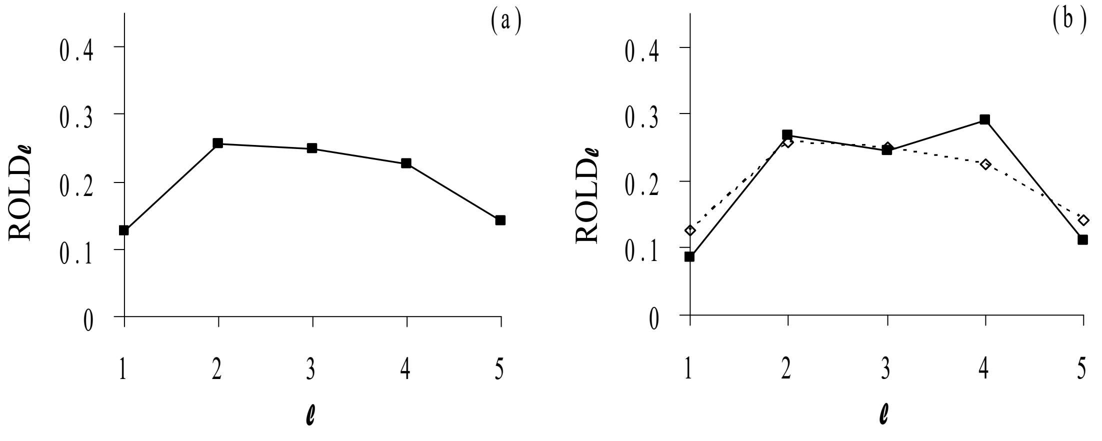
In the results, spatially defined parameters for pedestrian flow are presented in terms of ROLD_l, RZLD_{lz} and $\mathrm{PS_s}$.

Figure 3 shows the relation between ROLD_l, and '*l*' for all the three geometric conditions considered in the case of corridor. Figure 3(a) depicts the case of basic corridor condition in which the impact of corridor edges on the lateral distribution of relative density can be seen. From the graph it can be observed that the interior lanes have much more density as compare to exterior lanes. The value of density in the case of interior lanes are about twice of the exterior lanes. In case of Indian roads/corridors, "keep left" policy is followed. The impact of this policy can be seen in the results obtained as the value of $\mathrm{ROLD}_2 > \mathrm{ROLD}_3 > \mathrm{ROLD}_4$. So there is a little tendency to move left within a section of corridor. From figure 3(a) the influence of boundary (barricade in this case) of the corridor on the efficient utilization of the corridor space can be seen. One can see the difference between the effective width and the actual width of the corridor. The effective width is less than that of actual width of corridor. In this case 60% of corridor width is utilized by about 73% of the people. From which it can be understood that about 82% (1.65 m of the total of 2 m) of the total width is effectively used. These numbers are valid only for a particular density (that is 0.6 persons/m^2) and for the type of barricade used for the purpose of simulation of boundaries. The value will vary with different densities and type of boundary conditions.

Figure 3(b) depicts the case of narrowed corridor (symmetrically) condition in which the impact of corridor edges on the lateral distribution of relative density can be seen. As seen from the figure the values of ROLD_1 and ROLD_5 have reduced down further from the case of basic corridor condition. The dotted line in figure 3(b) is basic lane density variation (BLDV) and is a replica of ROLD_l plot as shown by figure 3(a). The effect of narrowing can be seen by the transfer of people from exterior lanes (lane 1 and lane 5) towards their adjacent lanes (lane 2 and lane 4). People on lane 3 seem to be unaffected due to narrowing condition.

Figure 3(c) depicts the case of narrowed corridor (asymmetrically) condition in which the impact of corridor edges on the lateral distribution of relative density can be seen. As seen from the figure the impact of narrowing is mostly observed in the values of ROLD_1 and ROLD_2 where the value of density have come down. Least effect is seen in the case of lane 3; whereas, the maximum effect is seen in the case of lane 4 and lane 5, where the values of ROLD_4 and ROLD_5 have gone up. This observation does not mean that most people have transferred directly from lane 1 and lane 2 to lane 4 and lane 5; due to redistribution at the end, lane 3 seems to be unaffected by the narrowing. One of the reasons of finding any change in the case of ROLD_3 can be the nearness of lane 3 to the edge of the corridor in the section of narrowed portion and thus the disadvantage of the edge is counteracted by the exodus of pedestrians from lane 1 and lane 2.

To understand the effect of longitudinal and lateral variation along the corridor, the relative zonal lane density is studied. It is studied in five different zones. These zones are shown in figures 1(b) and 1(c). Figure 1(a) shows the basic corridor where zonal relative densities in each of the zones are nearly similar to the total overall lane density.



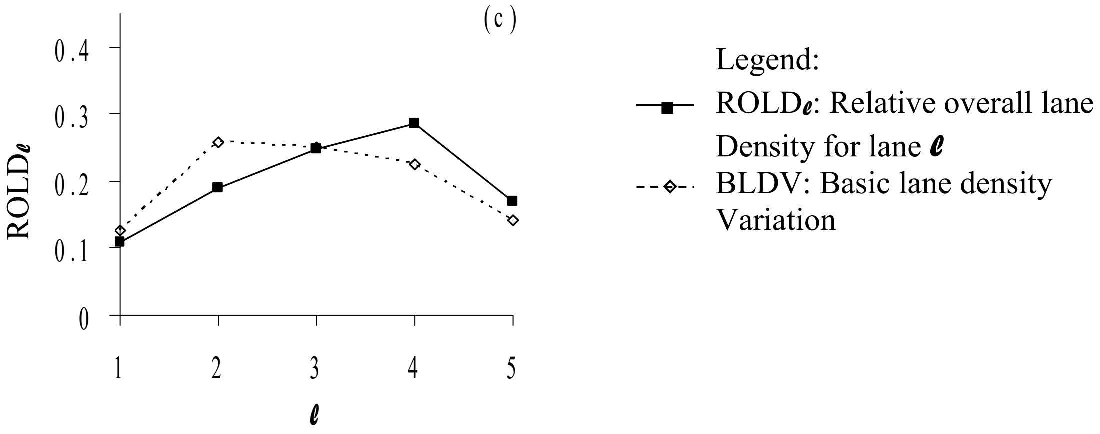


Figure 3: ROLD$_l$ Variations in the case of: (a) Basic Corridor (b) Narrowed corridor (symmetric) (c) Narrowed Corridor (asymmetric)

Figure 4(a) shows the variations of RZLD$_{lz}$ in the five different zones for the case of narrowed corridor (symmetric). The dotted line in each figure represent the RZLD$_{lz}$ vs '*l*' for the basic corridor width. The following important findings can be seen as one moves from far upstream to far downstream:

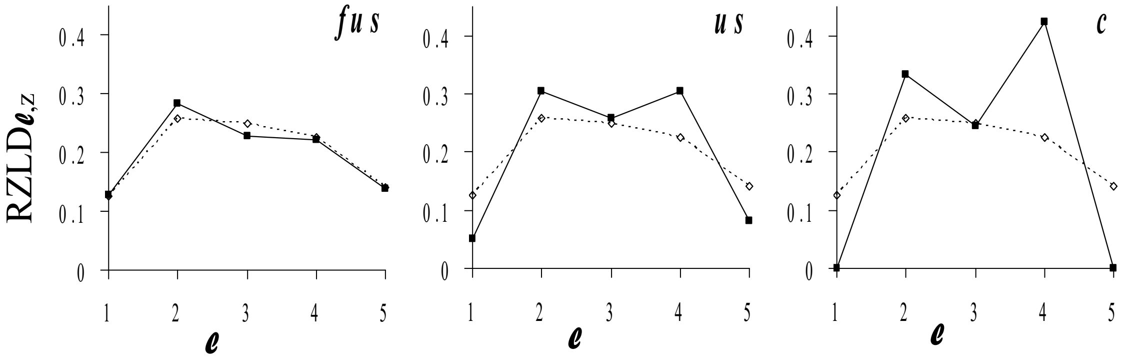
(i) The narrowing of corridor width has little or no effect on far upstream zone (fus). The effect can be seen to be started to affect pedestrian behaviour from upstream zone (us).

(ii) Though the density variations seem to be getting as usual as basic corridor pattern immediately after the constricted zone; there seem to be some exuberance among the people while shifting from lane 4 to other lanes. This may be due to people wanting to increase their speed after decreasing their speed in the constricted zone.

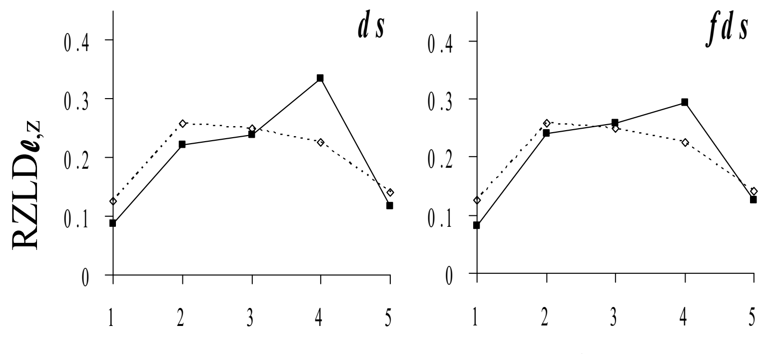
(iii) A constriction length of 2.4 m seems to have an impact over a length of 14 to 20 m.

(iv) The inflow and outflow from lane 3 remain unaffected and balanced.

Figure 4(b) shows the variations in the grey scale, where white portion represents relative density of zero and black portion represents relative density of unity. This figure aids to understand how accumulation and dissipation take place due to constricted region along a corridor.



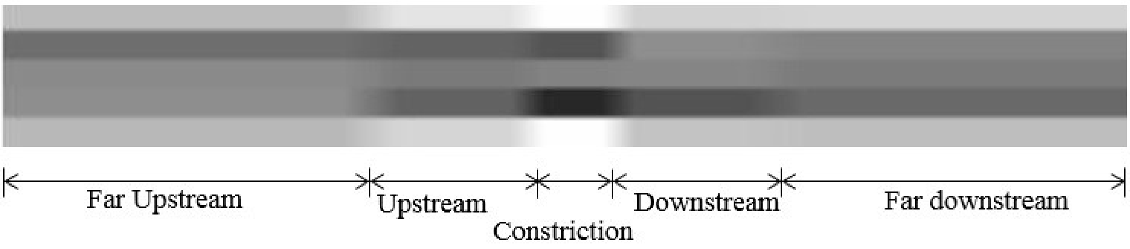
a (i) Far upstream (*fus*) a (ii) Upstream (*us*) a (iii) Constriction (*c*)



a (iv) Downstream (*ds*) a (v) Far downstream (*fds*)

Legend: ─■─ RZLD$_{\ell z}$: Relative zonal lane density for lane ℓ and zone *z*

-◇- BLDV: Basic lane Density Variation



(b)

Figure 4: (a) RZLD$_{lz}$ Variations in the case of narrowed (symmetric) corridor for: (i) Far upstream (*fus*) (ii) Upstream (*us*) (iii) Constriction (*c*) (iv) Downstream (*ds*) (v) Far downstream (*fds*) (b) Grey scale representation of RZLD$_{lz}$ for narrowed (symmetric) corridor

Figure 5(a) shows the variations of RZLD$_{lz}$ in five different zones of the narrowed corridor (asymmetric). The dotted line in the graph represents the same as in the case of narrowed corridor (symmetric).

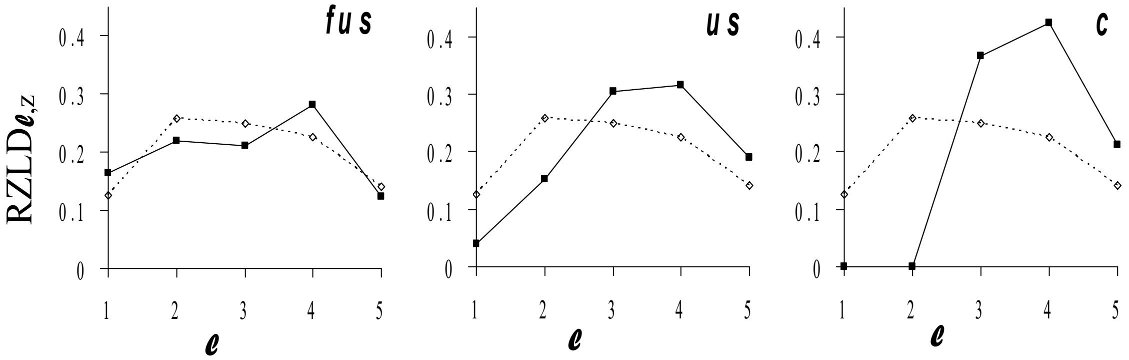
The following important findings can be seen as one moves from far upstream to far downstream:

(i) The effect of narrowing of corridor can be seen to have an impact on far upstream zone (fus) which is not there in the previous case. The effect is quite pronounced in the upstream zone and is totally different from basic corridor case. As almost 40% of the corridor width is blocked and that too from one side seems to have a major impact on peoples' behaviour compared to the case where the corridor is narrowed evenly from both the sides.

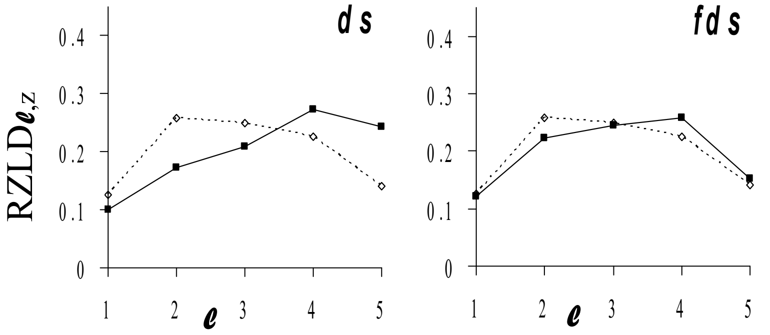
(ii) The recovery follows the same trend as previous; the variation in density more or less the same as in basic corridor case. Though the exuberance can be seen in people shifting from lane 4.

(iii) A constriction length of 2.4 m seems to have a longer and deeper impact as compared to symmetric case and can be seen to be over a length of around 30 m.

Figure 5(b) shows the variations in grey scale which depicts the accumulation and dissipation taking place due to constricted region along a corridor.



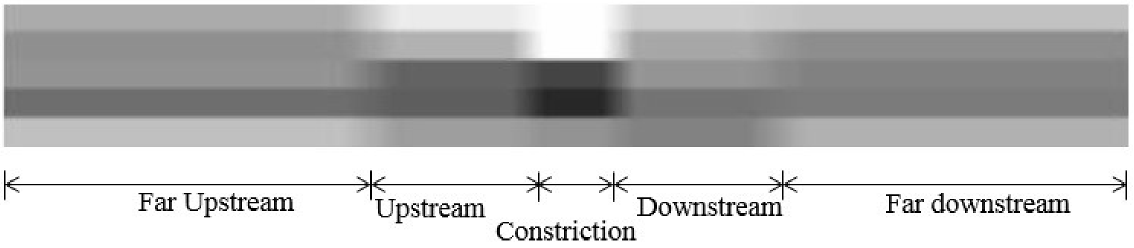
a (i) Far upstream (*fus*) a (ii) Upstream (*us*) a (iii) Constriction (*c*)



a (iv) Downstream (*ds*) a (v) Far downstream (*fds*)

Legend: —■— RZLD$_{\ell z}$: Relative zonal lane density for lane ℓ and zone z

-◇- BLDV: Basic lane Density Variation



(b)

Figure 5: (a) RZLD$_{\ell z}$ Variations in the case of narrowed (Asymmetric) corridor for: (i) Far upstream (*fus*) (ii) Upstream (*us*) (iii) Constriction (*c*) (iv) Downstream (*ds*) (v) Far downstream (*fds*) (b) Grey scale representation of RZLD$_{\ell z}$ for narrowed (Asymmetric) corridor

The information regarding longitudinal speed was also obtained. The following observations can be made based on the collected information (Due to unavailability of space the diagrams were not included):

(i) In the case of basic corridor, the speed remains more or less the same throughout the length of the corridor with mean and standard deviation of about 1.4 m/s and 0.23 m/s.

(ii) When narrowing is considered there is drop in mean speed along the corridor. In both symmetric and asymmetric cases the mean speed is about 1.3 m/s and standard deviation of about 0.2 m/s. The drop is about 7% and is statistically significant as confirmed through one tailed t-test (with 129 degrees of freedom) on the difference of means.

(iii) The speed in the constricted zone as expected is minimum with minimum occurring just upstream of the constricted zone; this is in an agreement with the general understanding that congestion is expected to be maximum at just upstream of bottleneck; the minimum speed in both the narrowed cases is about 20% lower than that of basic corridor average speed (i.e. minimum mean speed ~ 1.1 m/s with standard deviation ~ 0.1 m/s). This decrease is statistically significant as per one tailed t-test (with 20 degrees of freedom) on differences of means. On an average the speed in the constricted zone for both the cases are 14% and 18% lower than 1.4 m/s; confirmed through the statistical tests with the differences being significant.

5. Conclusions

The findings of the study is based on the consideration of:

(i) Lateral and longitudinal variation in densities due to various corridor geometrics.

(ii) Longitudinal variation in speed due to various corridor geometrics.

The results show that the:

(i) Corridor edges have a significant impact on the use of corridor.

(ii) Disturbance to flow of pedestrian is significant in the case of narrowing (asymmetric) as compared to narrowing (symmetric) both for the cases of density and speed.

(iii) Effect of constriction is felt at both upstream and downstream side of the narrowed section.

In a nutshell, basic corridor provides the best condition for the movement of pedestrians; if due to obligatory reason reduction in width is required then it must be symmetric.

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