Pedestrian Flow Characteristics for Different Pedestrian Facilities and Situations

Rajat Rastogi[1], T. Ilango[2] and Satish Chandra[3*]

[1] *Associate Professor, Department of Civil Engineering, Indian Institute of Technology Roorkee, India*
[2] *Research Scholar, Department of Civil Engineering, Indian Institute of Technology Roorkee, India*
[3]*Professor, Department of Civil Engineering, Indian Institute of Technology Roorkee, Roorkee, India*

Abstract

The pedestrian walking data collected at nineteen locations in five cities of India are analyzed in this paper. Pedestrian facilities are classified based on their width as sidewalk, wide-sidewalk and precincts. The analysis indicates that the pedestrian free flow speed is high on sidewalks (1.576 m/s) and low on precincts (1.340 m/s). The increase in width of the facility resulted in increased space available to a pedestrian, but reduced maximum flow rate and optimum density. It is found that the relationship between speed and density follows Underwood (exponential) model on sidewalk of varying widths and Greenshield's (linear) model on a non-exclusive facility. Bi-directional flow on a facility affects the free flow speed and space available to the pedestrian adversely at high density. Squeezing effect at the centre and follow the predecessor near sides is observed under heavy bidirectional flow. The presence of a bottleneck reduces the free flow speed and maximum flow substantially. Pedestrians moved in layers at high density. Maximum flow rate is observed to be higher on the carriageway (2.067 ped/s) as compared to an exclusive pedestrian facility (1.493 ped/s).

Keywords: Pedestrian, sidewalk, Flow characteristics, directional flow, bottleneck

1. Introduction

Walking has been a traditional mode of movement between places, irrespective of cities and countries. People walk with different purposes and in large numbers especially in developing countries. This necessitates the provision of exclusive walking facilities. The width of these facilities is generally governed by the pedestrian volume. In situations where these facilities are either encroached or occupied by vendors and hawkers, or are poorly maintained, the pedestrians are forced to walk on a portion of the carriageway, side-buffers or shoulders. Parking of vehicles in these areas further pushes the pedestrians on to the carriageway, thus increasing their interaction with vehicles, and thus their risk. The behaviour of the pedestrians observed across the cities or countries

[*] Corresponding author: Satish Chandra (satisfce@iitr.ernet.in)

is affected by the culture of the place. This paper examines the pedestrians' movements and flow characteristics on different types of facilities and under varying prevailing conditions like uni- and bi-directional flows, bottlenecks and walking on the carriageway. Findings are compared with those reported in literature to ascertain the cultural effects. In view of the above, important research works are discussed in the next section. It is followed by the section on methodology adopted for this research, flow relationships and characteristics, flow characteristics under varying conditions and finally the conclusions.

2. Review of Earlier Studies

Researchers have studied the pedestrian flows in different countries under varying conditions ranging from indoor to outdoor walkway, sidewalks, movements in central business district (CBD) areas, movements under unidirectional or bidirectional pedestrian flows or under mixed traffic conditions. Pedestrian flow relationships have been developed by many researchers in the context of the study undertaken. Most of these models are based on a linear speed-density relation, except those given by Virkler and Elayadath (1994), Weidmann (1993) (as quoted in Daamen 2004) and Kotkar et al. (2010). The relation between speed and density becomes exponential under heavy pedestrian flow. Polus et al. (1983) developed single and three regime linear speed-density models for pedestrian flows on sidewalks in CBD of Haifa (Israel). They found that speeds are inversely proportional to densities. In another similar study Al-Masaeid et al. (1993) found that the quadratic polynomial relation fits the speed-flow data the best. Tanaboriboon et al. (1986) developed flow relationships for sidewalks and walkways in Singapore and compared them with those obtained for the United States and the Britain. The relationship between speed and density was found to be linear while flow-density and flow-speed relationships were quadratic. Seyfried et al. (2009) studied the unidirectional pedestrian flow using controlled experiments to measure the relation between density and speed of pedestrians. Contrary to the previous studies a linear relationship was found between the step length and speed even during low speeds of less than 0.5 m/s. It was also found that the space requirement of pedestrians moving at an average speed is less than the average space requirement.
The mean speeds in literature vary from 1.23 m/s to 1.50 m/s on sidewalks/walkways; the variation being from 1.23 m/s to 1.39 m/s in Asian countries (Tanaboriboon et al. 1986, Lam and Cheung 2000, Hongfei et al. 2009, Kotkar et al. 2010); from 1.31 to 1.50 in European countries (Oeding 1963, Older 1968); and from 1.31 to 1.37 m/s in the US (Navin and Wheeler 1969, Fruin 1971). The average mean speed is lower in Asian countries and higher in European countries, which indicates towards the cultural effect on speed. Some researchers have calculated critical speed at maximum flow (capacity). This is found ranging from 0.61 m/s to 0.82 m/s on sidewalk or level walkways (O'Flaherty and Parkinson 1972, Weidmann 1993, Virkler and Elayadath 1994, Sarkar and Janardhan 1997, Lam et al. 2003). Pedestrian walking speeds under mixed traffic are studied by Yu (1993, China), Gerilla (1995, Phillipines) and Kotkar et al. (2010, India). The speed is found lower in China (1.26 m/s) and comparable in Philippines and India (1.38-1.39 m/s). Daamen (2004) found the mean speed of non-constrained pedestrians as 1.406 m/s whereas, that of constrained pedestrians was 1.454 m/s. It is observed from studies that an average speed in European countries is 1.41 m/s, 1.35 m/s in the United States, 1.44 m/s in Australia and 1.24 m/s in Asia. This indicates that

pedestrians in Asian countries walk at slower speed as compared to those in European, US and Australian cities.

Pedestrian density is reported by various researchers either as jam density or as density at capacity. Hongfei et al. (2009) found a very low jam density (1.65 p/m^2) for a corridor in China, whereas, it was 4.83 p/m^2 on a walkway in Singapore (Tanaboriboon et al. 1986). It is found varying between 3.6 p/m^2 and 5.10 p/m^2 under mixed traffic condition, the highest being observed in China (Yu, 1993) and lowest in Philippines (Gerilla, 1995). Kotkar et al., 2010 reported pedestrian density of 4.17 p/m^2 for Indian cities. It is found ranging between 2.7 p/m^2 and 3.99 p/m^2 in Europe and the USA (Navin and Wheeler 1969, Older 1968, Oeding 1963, Friun 1971). Some researchers have indicated a very high value (greater than 4.2 p/m^2) of jam density (Weidmann 1993, Sarkar and Janardhan 1997). The jam density at capacity flow is reported by other researchers also. It is found low (1.3–1.9 p/m^2) for the US and United Kingdom (Virkler and Elayadath 1994, O'Flaherty and Parkinson 1972) and high (2.1 p/m^2) for India (Sarkar and Janardhan 1997). Higher density observed in Asian cities and especially in India indicates accommodating nature of pedestrians who are willing to share the available space with other pedestrians more effectively.

The maximum flow rates are also different in different countries and on different walking facilities. Lower flow rates of 1.03 to 1.2 p/m^2 are observed on sidewalks/walkways (Virkler and Elayadath 1994, Navin and Wheeler 1969) and high of 1.35 p/m^2 on corridor (Fruin 1971) in the US. The maximum flow on sidewalks is relatively low (1.27–1.29 p/ms) in United Kingdom (Older 1968, O'Flaherty and Parkinson 1972) and also in South-East Asian countries (1.12–1.36 p/ms, Lam and Cheung 2000). Very high flow rates of 1.49–1.53 p/ms are observed in Germany, India, Singapore and Hong Kong on sidewalk and walkways (Oeding 1963, Tanaboriboon et al. 1986, Sarkar and Janardhan 1997, Lam et al. 2003). It is observed that irrespective of the flow condition the pedestrian flows in India are quite higher than those observed flows in other countries including from South-East Asia. It is mediocre in mixed traffic conditions of Philippines (Gerilla 1995). This variation may be due to a smaller Asian body buffer zone space. Lam and Cheung (2000) have reported that pedestrians' speed and flow rates on outdoor walkways are greater than those on indoor walkways due to environmental factors like exposure to sun, rain, dust, wind, pollution etc. Similar effect was observed for pedestrians in commercial areas when compared with those in shopping areas.

Another important aspect related to pedestrian movements is the space occupied by a pedestrian and the minimum space required for comfortable walking. The minimum area of an average pedestrian (without bulky clothes and baggage) is about 0.085 m^2. As pedestrian body shape is taken as an ellipse, they cannot fill completely a specific area, which leads to a pedestrian area of 0.11 m^2, and a maximum density of 9.09p/ m^2. In practice, a density between 2.0 and 2.9 p/m^2 is achieved for waiting pedestrians (Weidmann 1993, as quoted in Daamen 2004). Pushkarev and Zupan (1975) noted that pedestrians prefer a body buffer zone space of 0.27-0.84 m^2 including the space needed to make a step. Physical contacts may be avoided at densities of 3.0-3.5 p/m^2 (Weidmann 1993, as quoted in Daamen 2004). The data from India clearly indicates that physical contact between pedestrians at higher density is not avoidable. Hall (1990) has examined the effect of culture on the distances maintained in human interactions and found that different cultures use spaces differently and this includes sitting, standing, talking and walking.

At times, pedestrian facilities are encroached leading to a reduced walk through space for the pedestrians. This creates a bottleneck condition with wider space available before and after the constrained location. Tajima et al. (2001) examined the pedestrian flow through a bottleneck at varying pedestrian densities and found that the saturation occurs due to choking of pedestrians at bottlenecks. Daamen (2004) has conducted experiments by varying length and width of the area and found that the mean free speed increases by 10.57% if the size of the area becomes 5.0 × 0.75 m. In case of wide and narrow bottlenecks, the mean free speed is found to be 1.24 m/s and 0.815 m/s respectively. Daamen and Hoogendoorn (2003), Hoogendoorn and Daamen (2005a, b), and Kertz et al. (2006a) have conducted controlled experiments on pedestrian movements through bottlenecks. It was observed that pedestrian form two layers at narrow bottlenecks and four to five layers at wider bottlenecks. Shi et al. (2005) reported that the pedestrians wait till a group is formed and then move disregarding the flow from opposite direction. Under heavy flow they follow their predecessors. The behaviour of pedestrians at bottlenecks in India has not been studied so far.

A real time aspect is the use of a facility by pedestrians walking in opposite directions. Most of the studies discussed above have focused only on unidirectional flows. Hughes (2002, 2003) pointed out the importance of considering bidirectional flows to capture realistic interactions of pedestrians. Studies conducted by Lam and Cheung (1997), Lam et al. (2002, 2003) and Lee et al. (2005) in Hong Kong found reduction in walkway capacity and at-capacity walking speeds in minor flow direction. The free flow walking speed is however, not affected by the bidirectional flow. Helbing et al. (2001) also conducted controlled experiments and found that under bi-directional flow, pedestrians' density was an important factor affecting the pedestrian flow and under very high pedestrian densities, interactions between pedestrians increase at bottlenecks leading to block formation. Kertz et al. (2006b) found that in case of bidirectional flow, the pedestrian flow depends on the directional ratio. For a given density, as counter flow increases, the capacity losses decrease and total flow therefore increases (Navin and Wheeler 1969). Wong et al. (2010) studies bidirectional pedestrian streams with an oblique intersecting angle to capture the crossing effects on a pedestrian facility. They found maximum speed of 1.675 m/s and minimum of 0.280 m/s with an average speed as 0.819 m/s (SD 0.207 m/s). Jian et al. (2005) studied pedestrian bidirectional flow in a corridor and inferred that they are affected by interaction with other pedestrians and friction from surrounding environment.

The overview of the works done by various researchers indicates that mostly pedestrian flow characteristics and their relationships for exclusive pedestrian facilities are studied under controlled environment using observed data. The relative change in the flow characteristics of pedestrians when walking on exclusive pedestrian facilities of different widths has not been studied so far in the conditions prevailing in developing countries. Similarly, the flow characteristics of pedestrians walking in a large open area or on a carriageway are not fully studied. Teknomo et al. (2000) have highlighted that pedestrian flow characteristics are different for different countries and their walking speeds vary depending upon the nature of the work. Similar observation is made by Morrall et al. (1991) after comparing the walking speed and flow characteristics of pedestrians in Calgary with those in European and Asian countries. They opined that pedestrian planning should be based on the local pedestrian characteristics. This paper examines the changes in the pedestrians' flow characteristics due to an increase in the width of the pedestrian facility, as well as, due to the bidirectional pedestrian flows on a facility and formation of bottlenecks due to encroachment of a facility. It also compares the results with those reported in literature to bring out with the differences in pedestrian behaviour. The findings of the study will be useful in the evaluation of the level of service on walking facilities. These can also be used as important inputs for the development of dynamic continuum models to describe the pedestrian movements in the spatio-temporal domain. Some of the recent works in this area are of Hughes (2002), Hoodendoorn et al. (2003) and Huang et al. (2009).

3. Methodology

Five cities, two in North India (Delhi, and Chandigarh) and three in South India (Chennai, Coimbatore, and Erode) were selected for the collection of pedestrian flow data. Out of these, Delhi and Chennai are the mega-metropolitan cities. Delhi has a population of 19 million (2011 census) and density of 12812 persons/km^2. Chennai has 4.68 million population (2011 census) and density of 26896 persons/km^2. Chandigarh and Coimbatore are class-I cities of India. Chandigarh has population of 1.05 million and density of 9210 persons/km^2 and Coimbatore has 1.96 million population with density as 7396 persons/km^2 (census 2011). Erode is also a class-I city but with population of 0.50 million and density of 6757 persons/km^2. The cities selected have cultural, historical and manufacturing background, represent different population groups and supports substantial pedestrian activity. 19 study locations were selected within these cities for on-site data collection. To understand the general behavior of the pedestrians while walking, the locations were selected such that they represent varied land use around the facility, change in facility by width, and the effective width of the facility available for pedestrians to walk on. Some locations have uni-/bi-directional pedestrian flows and some are constrained in width available to the pedestrians. These allow to study and examine the pedestrian behavior under varying flow conditions on facilities. The classification of selected locations based on the above criteria is given in Table 1. The sample locations are shown in Figure 1.

Table 1: Details of study locations

By width of the facility			*By effective width of the facility*	
Classification	*Number of locations*	*Width of facility, m*	*Facility width, m*	*Effective Width, %*
Sidewalk	12	1.6 – 4.0	7.3	42
Wide sidewalk	4	> 4.0, ≤ 9.0	6.1	48
Precinct	2	> 9.0		
Carriageway	1	5.3*		

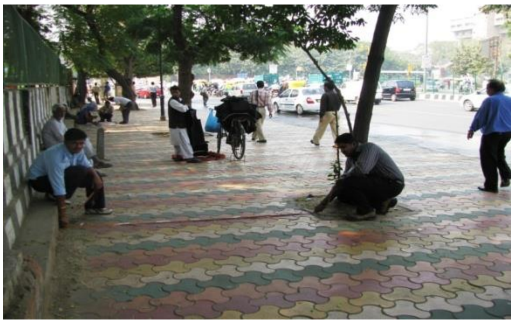
* Used by pedestrians, total width of the road is 10.5 m per direction separated by a median

(a) Sidewalk

(b) Wide-sidewalk

(c) Precinct

(d) Non-exclusive Facility



(e) Restricted Facility

(f) Highly Restricted Facility

(g) Bidirectional Flow

(i) Unidirectional Flow

Figure 1: Flow Conditions observed under study

Video-graphic technique was employed for collecting the pedestrian data. A trap of known length was marked on the pedestrian facility using a self-adhesive white tape for measuring the pedestrian speed and flow. The video camera was kept at an elevated point so as to cover the pedestrian movement on the entire trap. The movements of pedestrians were recorded during the morning and evening peak periods (8.00 – 9.30 A.M, and 5.00 – 6.30 P.M) on a working day at each of the study locations. The required pedestrian data were later extracted from the recorded videos. Looking at the continuous flow of pedestrians entering the trap the flow data was extracted on one minute basis though under fluctuating flows lower value of time interval would be more appropriate. The time taken by each pedestrian to cross the trap length was noted to an accuracy of 0.01s to determine pedestrian speed. Based on the pedestrian flow, pedestrian density per square meter is calculated. The inverse of pedestrian density yielded the area module. These were found for the entire study duration. The sample size for the classified 19 study locations is given in Table 2. As the minimum sample size is also quite high it makes the inferences drawn from the analysis sound and reliable.

4. Pedestrian Flow Relations and Characteristics

Before estimating various flow characteristics for pedestrians at different selected locations, the locations which are found similar (based on pedestrian flow conditions and width of the facility) have been clubbed together. In this regard, a sidewalk study location in Chandigarh is excluded from the analysis. This is the only location which has divided sidewalk with unidirectional flow. Bottleneck conditions prevailing on two of the wide-sidewalks are also excluded. Data from rest of the locations are combined under the heads sidewalk, wide-sidewalk, precinct and carriageway and the flow characteristics like pedestrian flow, speed, density and area module are estimated.

Table 2: Sample size for classified conditions

Classification	*Sample size, pedestrians*
Sidewalk	674
Wide-sidewalk	2227
Precinct	1883
Unidirectional	1058
Bidirectional	1710
Exclusive	1673
Non-exclusive	1768
Restrained	2639
Normal	1959

A single-regime approach is used to ascertain the relationship between speed and density due to constraints of the data points. Various distributions like linear, logarithmic, power, polynomial, exponential, etc. are considered to arrive at the best fit distribution. Once this is ascertained, the mutual relationships between flow, density and speed are derived theoretically and their goodness of fit is examined based on data plot and statistical parameters like R^2, standard error and Chi-squared test. The goodness-of-fit statistics are calculated for the observed range of the data. In the case of sidewalks, wide-sidewalks and precincts, a negative exponential relationship is found fitting pedestrian speed and density data the best. The theoretical relationship between pedestrian flow and density, as well as, pedestrian flow and area module is exponential; and is logarithmic between pedestrian flow and speed. The developed relationships are given in Table 3. In general, the goodness-of-fit defined by various statistics is found between satisfactory and good (based on R^2 value, >0.70), leaving speed-density relationship for wide-sidewalks for which it is quite low (<0.50), and is fair (>0.50 and <0.70) for flow-speed relationship of sidewalks and speed-density relationship of precincts. The data points are found to be highly scattered around the best fit curve in these cases. The flow relationships developed in the present study are similar to those reported for Hong Kong (Lam et al. 1995) and United States (Virkler and Elayadath 1994) for heavy density pedestrian back flow.

Table 3: Relationships between pedestrian flow characteristics

Facility	*Relation*	*Model equation*	*R^2 value*	*SE*	*Chi test**
Sidewalks	Speed-Density	$v = 1.576 \times e^{-k/3.03}$	0.817	13.50	9.25
	Flow-density	$q = 1.576 \times k\, e^{-k/3.03}$	0.726	23.63	10.68
	Flow-speed	$q = -3.03 \times v \times \ln(v/1.576)$	0.641	12.05	13.53
	Flow-space	$q = (1.576/M) \times e^{-1/3.03M}$	0.857	5.17	8.94
Wide-sidewalks	Speed-Density	$v = 1.492 \times e^{-k/2.857}$	0.364	41.25	19.21
	Flow-density	$q = 1.492 \times k\, e^{-k/2.857}$	0.911	37.19	6.17
	Flow-speed	$q = -2.86 \times v \times \ln(v/2.857)$	0.791	16.48	11.23
	Flow-space	$q = (2.857/M) \times e^{-1/2.857M}$	0.842	32.42	9.14
Precincts	Speed-Density	$v = 1.340 \times e^{-k/2.564}$	0.566	17.28	15.66
	Flow-density	$q = 1.340 \times k\, e^{-k/2.564}$	0.939	25.89	4.93
	Flow-speed	$q = -2.56 \times v \times \ln(v/1.340)$	0.861	4.79	8.78
	Flow-space	$q = (1.340/M) \times e^{-1/2.564M}$	0.959	21.09	5.71

Units: k [p/m^2], q [p/ms], u [m/s], * Significant at 95 percent confidence level

The flow relationships developed for different types of pedestrian facilities are shown in Figure 2.

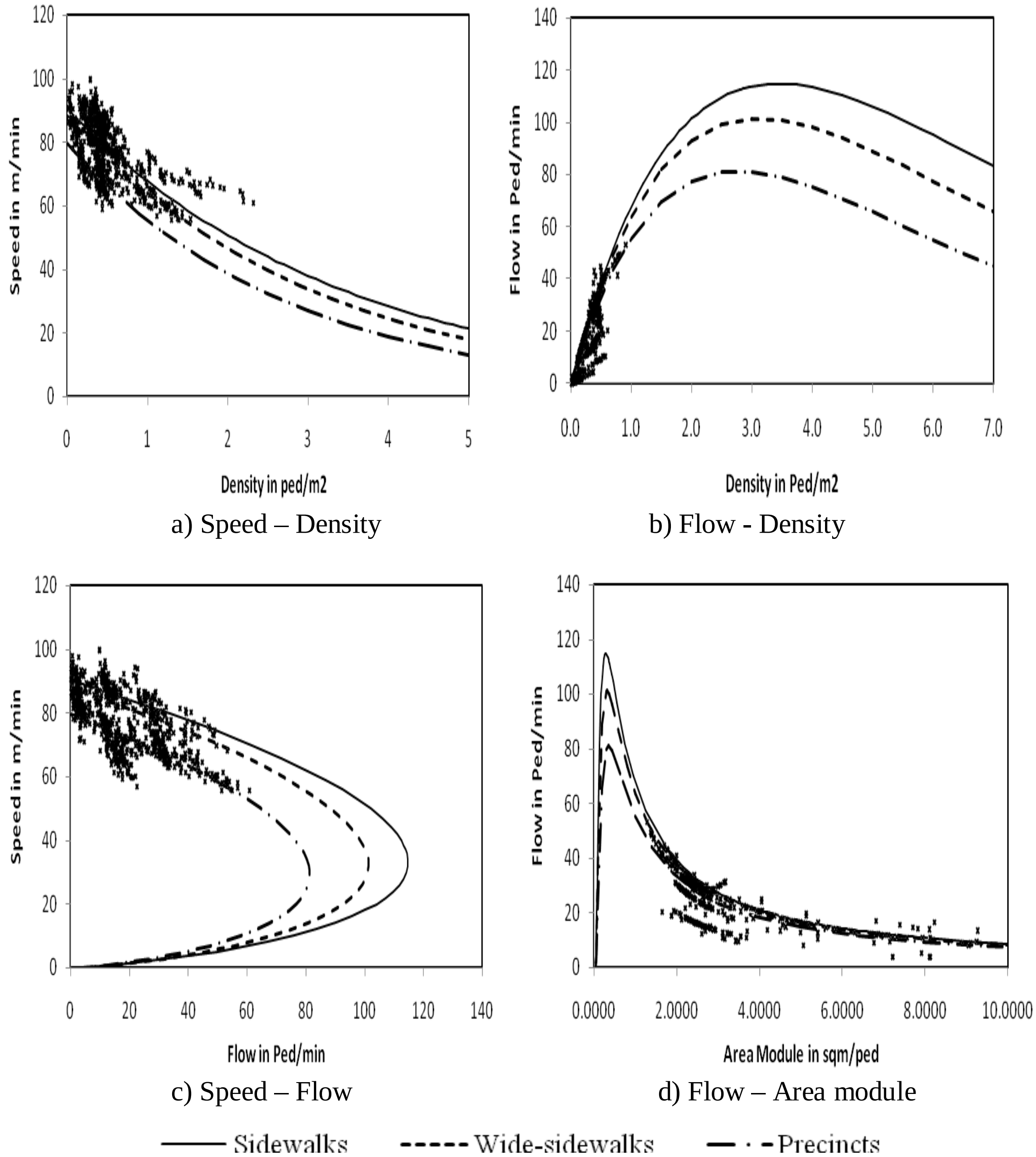


Figure 2: Flow relationships developed for different pedestrian facilities

These relationships clearly indicate the difference in the three types of sidewalk facilities as classified in the present work. Based on the relationship between flow characteristics and characteristics parameter values, the behavior of the pedestrians on sidewalks and wide-sidewalks is found to be more similar than that on precinct. This indicates that as the width of the pedestrian facility increases above 9.0 m a distinct change in the pedestrian behavior is noticeable. The mean free speed of pedestrians decreased from 1.576 m/s on a conventional sidewalk (≤ 4.0 m) to 1.492 m/s on a wide-sidewalk (5.33% reduction) and to 1.339 m/s on a precinct (15.04% reduction). These speeds are in the higher range of 1.23 m/s to 1.50 m/s given in the literature. These are also higher than the mean free speeds estimated in other Asian countries including previous study done in India. This indicates that due to heavy pedestrian flows or density the pedestrians in India are walking slower than their counterparts in other countries but given a chance (i.e. uncongested conditions) they may walk faster than them. The average speed of pedestrians in India is found to be 1.165 m/s (SD 0.204 m/s, Maximum 1.67 m/s, Minimum 0.72 m/s). The speed at capacity is 0.578 m/s on sidewalks, 0.548 m/s on wide-sidewalks and 0.493 m/s on precincts. These speeds are lower than the range (0.61 m/s to 0.82 m/s) reported in literature for sidewalks and level walkways.

Kotkar et al. (2010) has reported that pedestrians in India walk at higher speed during side frictions on the facility. Similar behavior is observed in the present study also. At low densities (< 0.18 p/m^2) and low flow values of up to 20 p/ms the behavior of pedestrians on the three facilities is more or less similar. As the flow increases above 20 p/ms, a higher reduction is observed in the pedestrian speed on precincts as is evident from the steepness of the speed-flow curve (Figure 2). The flow at capacity is found to be 1.757 p/ms on sidewalks, 1.568 p/ms on wide-sidewalks (10.75% low), and 1.263 p/ms on precincts (28.11% low). The reduction in flow rate is almost double the reduction in speed values on the facilities as compared to the normal sidewalk condition. These are much higher than those found on sidewalks/ walkways in USA (1.03 – 1.2 p/ms), UK (1.27 – 1.29 p/ms), and South-East Asian countries including India (1.12 – 1.53 p/ms). The study locations of sidewalks are mostly in commercial or mixed activity areas and this may be the reason for higher flows. The same is reported by Lam and Cheung (2000), as they observed higher flow values in commercial areas as trip characteristics are mainly business oriented. The density at capacity is found to be 3.03 p/m^2 on sidewalks, 2.86 p/m^2 on wide-sidewalks (5.6% reduction) and 2.56 p/m^2 on precincts (15.51% reduction). This is almost similar to the trend observed for speed. The values observed are higher than those reported for USA and UK (1.3 – 1.9 p/m^2). The jam density is expected to be higher than 4.5p/m^2. This is higher than that reported for Europe and USA, but lower than the one reported from China (Yu, 1993) and Saudi Arabia (Al Gadhi et al. 2001).

This is supported by the pedestrian space available on a facility. The pedestrian buffer space (space occupied by a pedestrian along with half of the surrounding clearances between pedestrians) at capacity flow is found to be 0.33 m^2/p on sidewalks, 0.35 m^2/p on wide-sidewalks and 0.39 m^2/p on precincts. The increased space and freedom from boundary restrictions resulted in higher leisure walking behavior of pedestrians on wider facilities. In all the three cases the physical contact between the pedestrians at capacity flow is avoided as suggested by Weidmann (1993, quoted in Daamen 2004).

Various flow characteristics as estimated from Figure 2 for different pedestrian facilities are given in Table 4.

Table 4: Pedestrian flow characteristics under different conditions

Facility / Condition	*Free speed (μ_f), m/s*	*Flow at capacity, p/ms*	*Area module (M) at capacity (m^2/p)*	*At capacity*	
				Speed m/s	*Density p/m^2*
Sidewalks	1.576	1.757	0.33	0.578	3.03
Wide-sidewalks	1.492	1.568	0.35	0.548	2.86
Precincts	1.339	1.263	0.39	0.493	2.56
Unidirectional	1.595	1.333	0.44	0.588	2.27
Bi-directional	1.576	1.768	0.33	0.568	3.13
Unrestrained	1.492	1.568	0.35	0.548	2.86
Restrained	1.212	1.345	0.29	0.413	3.45
Carriageway	1.415	2.067	0.34	0.703	2.92
Exclusive facility	1.502	1.493	0.37	0.553	2.70

5. Flow Characteristics Under Different Conditions

The pedestrian movements are observed at certain locations for studying the effect of directional flows and reduced width of the facility. Three conditions as listed below are evaluated and compared.
1) Unidirectional flow and bidirectional flow
2) Restrained and normal flow condition
3) Exclusive and non-exclusive pedestrian facility

The locations are selected in a way that they provide a comparison of principal effect which is under consideration. The details of the study locations and sample size are given in Table 1 and 2 respectively. The locations with sidewalks of width 2.1 m are considered for the comparison of unidirectional and bidirectional flows. Both type of locations fall in commercial area. Similarly, the wide-sidewalks considered for the effects of restrained conditions existing on the pedestrians facilities like encroachment by vendors or hawkers are 7.3 m and 7.8 m wide. The level of encroachment observed on the facility is high enough as only 42% of the space is left for the pedestrians to walk on. The data for restrained flow condition is taken at the middle of the restrained stretch of the location and the movement / behavior of the pedestrians is observed at the middle and before start of the location. The flow on the facility is bidirectional and this causes the restraint to the flow of fellow pedestrians. The relationships between flow characteristics were developed and the flow parameters are given in Table 4.

5.1 Unidirectional Flow and Bidirectional Flow

The relationships between the flow characteristics are shown in Figure 3. The characteristic for the two conditions are given in Table 4. For a flow up to 0.67 p/ms and density 0.425 p/m^2, the pedestrians do not behave differently under the two conditions. The space available to a pedestrian in this condition is 2.35m^2/p. Free speed of pedestrians under unidirectional flow is found to be 1.595 m/s which is marginally higher than that (1.576 m/s) in bidirectional flow. Thus the free speed is not affected by the type of flow. For flow higher than 0.67 p/ms or density higher than 0.425 p/m^2, the speed is higher under bidirectional flow as compared to unidirectional flow. This trend continues up to the flow at capacity and after that speed is low in bidirectional flow condition, probably due to more congestion. While the speed at capacity is same for two conditions, the flow rate is higher for bidirectional flow (1.768 p/ms) than that for unidirectional flow (1.333 p/ms). It is contrary to the observation made by Lam and Cheung (1997), Lam et al. (2002, 2003) and Lee et al. (2005) who found low flow rate at capacity in the case of bidirectional flow. It is mainly due to squeezing of pedestrians in bidirectional flow condition, which is clear from area module at capacity also (refer Figure 3d). The space value has reached the lower limit of non-contact movement of pedestrians on a facility as indicated in the literature. This indicates that pedestrians are more comfortable when walking in unidirectional flow than in bidirectional flow. Further, contrary to the observation made by Hoogendoorn and Daamen (2005a, b), lane formation was observed at both the sides of the facility under unidirectional flow. In the case of bidirectional flow, higher squeezing effect is observed towards the centre of the facility as compared to the sides. Pedestrians who are walking at the sides of the facility are mostly found following their predecessors and thus walk in an orderly manner. Pattern formation is not staggered and persisted for a long time contrary to that observed by Hoogendoorn and Daamen (2005a, b). Pattern of following their predecessor under high pedestrian flow was observed by Shi et al. (2005) also. This phenomenon suggests that pedestrians walking on sides prefer to walk in a manner that minimizes their interaction with other pedestrians. The directional ratio is not being taken into account for this analysis as in real time situation the fluctuation in the directional ratios changes quite fast and therefore, what matters is the overall flow.

5.2 Restrained and Normal Flow Condition

The pedestrian behavior on a bidirectional wide-sidewalk with space restraints (reducing effective width by more than 50%) is compared with that on an unconstrained facility which is free from hawkers, vendors, encroachment and obstructions, and supports the bidirectional pedestrian flow. The flow relations are shown in Figure 4 and corresponding parameters are given in Table 4. The free speed of pedestrians walking under restrained condition (1.212 m/s) is substantially lower (by 18.76%) than that under normal condition (1.492 m/s). Daamen (2004) reported 10.57 percent reduction in free speed due to space constraints. For a density higher than 4.70 p/m^2, the speeds of pedestrians in both the conditions are similar. This represents the congested condition on both types of facilities. Beyond this density, the flow under a restrained condition is found to be relatively higher (refer Figure 4b). The speed at capacity under unrestrained condition (0.548 m/s) is found higher by 24.63 % than that under restrained condition (0.413 m/s). It is further observed that as the friction increases the pedestrians start walking faster so as to get out of the situation as early as possible. Similar point is highlighted by Kotkar et al. (2010) also. It is noted that the restrained condition causes higher reduction in speed than in flow at capacity. The flow at capacity reduces from 1.568 p/ms to 1.345 p/ms, showing a reduction of 14.22%. The density at capacity is found to be higher for restrained condition (3.45 p/m^2) as compared to unrestrained condition (2.86 p/m^2). This translates into the lower pedestrian space under restrained condition (0.29 m^2/p) as compared to the unrestrained condition (0.35 m^2/p). It indicates that the pedestrian may walk with body contact under the restrained condition if the effective width is reduced by almost 50%. Under the restrained conditions, the pedestrians are reported to move as groups or layers by Hoogendoorn and Daamen (2005) and that the pedestrians follow their predecessors by Shi et al. (2005). However, it is observed in the present study that pedestrians form layers only at high pedestrian flows. Under normal flow conditions, pedestrians are observed to walk in staggered pattern. Pedestrian to pedestrian interactions and frictions increase even at medium flow conditions (0.583 p/ms to 0.783 p/ms) under restrained conditions. When the pedestrian flow is high in one direction, the pedestrians from opposite direction had to wait for 2-4 s at the sides of the restrained location and before walking in a single lane.

5.3 Exclusive and Non-Exclusive Pedestrian Facility

The pedestrians are forced to walk on the carriageway in either of the two cases, one the pedestrian facility is fully encroached and other in the absence of a pedestrian facility. Depending upon the flow, the pedestrians occupy varying width of the carriageway. In case the facility is not provided and the road side margin is encroached by the parked vehicles, the road width used by pedestrians will be more, thus increasing the pedestrian-vehicle interaction. A location with three lanes per direction and a median in between was selected for this analysis. It has no pedestrian facility at the side of the carriageway, but the road margin space was encroached by parked vehicles. Pedestrians are observed using up to 5.3 m width of the carriageway, which is 34% of the total carriageway width in a direction. Also, the presence of a parked bus on the carriageway reduced the effective width to 4.8 m. Therefore, pedestrians walking on carriageway are compared with those walking on an exclusive facility having an effective width of 4.5 m but free from encroachments. The flow relationships are developed for both the conditions as shown in Figure 5 and flow parameters given in Table 4.

Flow characteristics of pedestrians on the two types of facilities are found different. Free speed of pedestrians on non-exclusive facility (1.415 m/s) is found to be lower (by 5.80%) than that on an exclusive pedestrian facility (1.502 m/s). Speeds on two types of facilities are found to be similar at very low (~0.53 p/m^2) or very high density (4.875 p/m^2) and for flow rate of up to 40 p/ms or 80 p/ms, respectively. Under free flow condition the speed ranges between 1.25 – 1.50 m/s and under congested condition it remains below 0.25 m/s. The speed at capacity is 0.703 m/s on an exclusive facility and 0.553 m/s on a non-exclusive facility. Pedestrian flow rate at capacity is found to be higher on a non-exclusive facility (2.067 p/ms) as compared to an exclusive pedestrian facility (1.493 p/ms). The exclusive facility reaches its capacity earlier than a non-exclusive facility which is due to boundary restrictions imposed on the pedestrians at such a facility. Also, the density affects the pedestrian behavior more than the flow at such facilities.

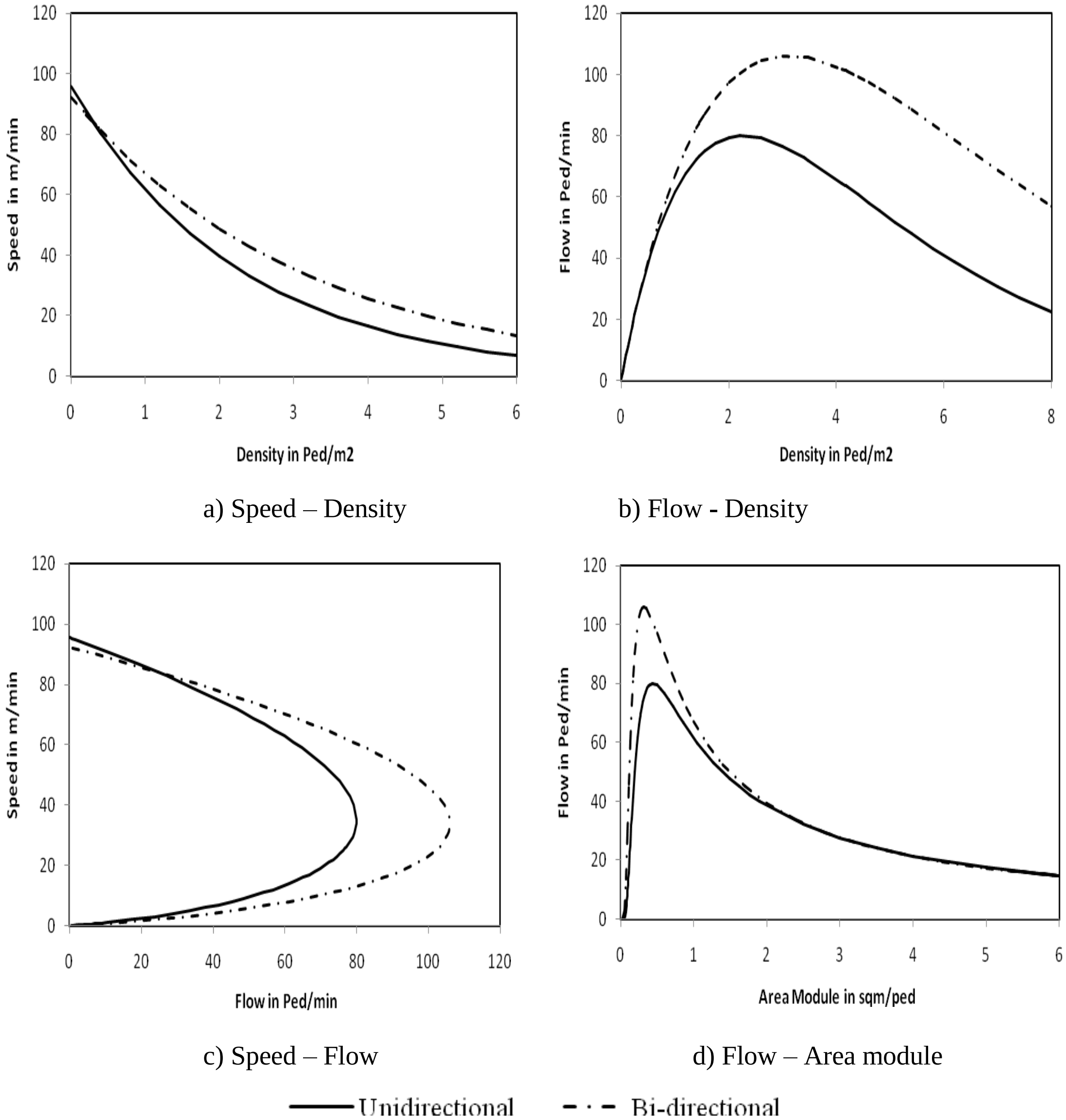


Figure 3: Pedestrian flow characteristics in unidirectional and bidirectional flow

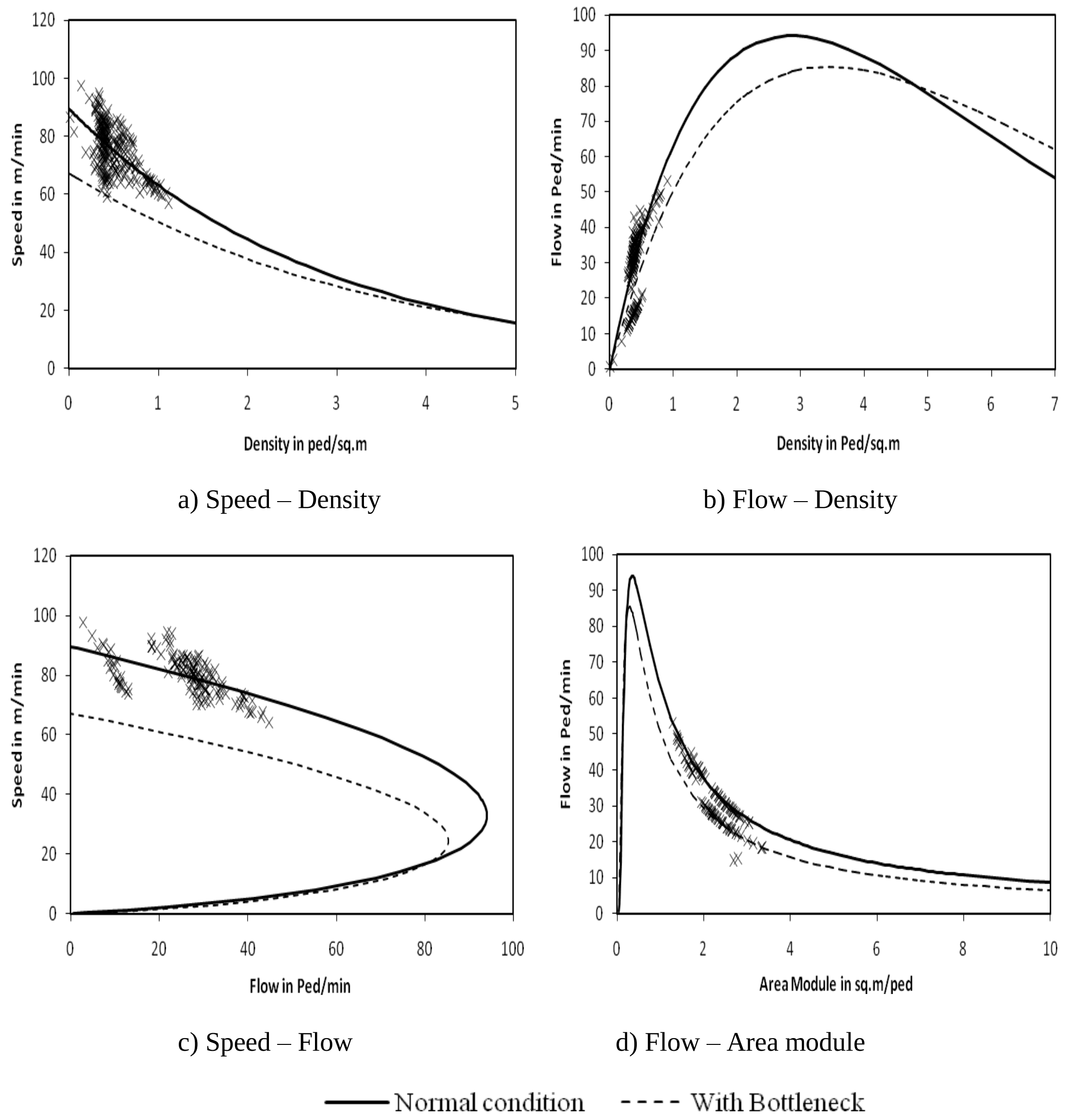


Figure 4: Pedestrian flow characteristics under restrained and unrestrained conditions

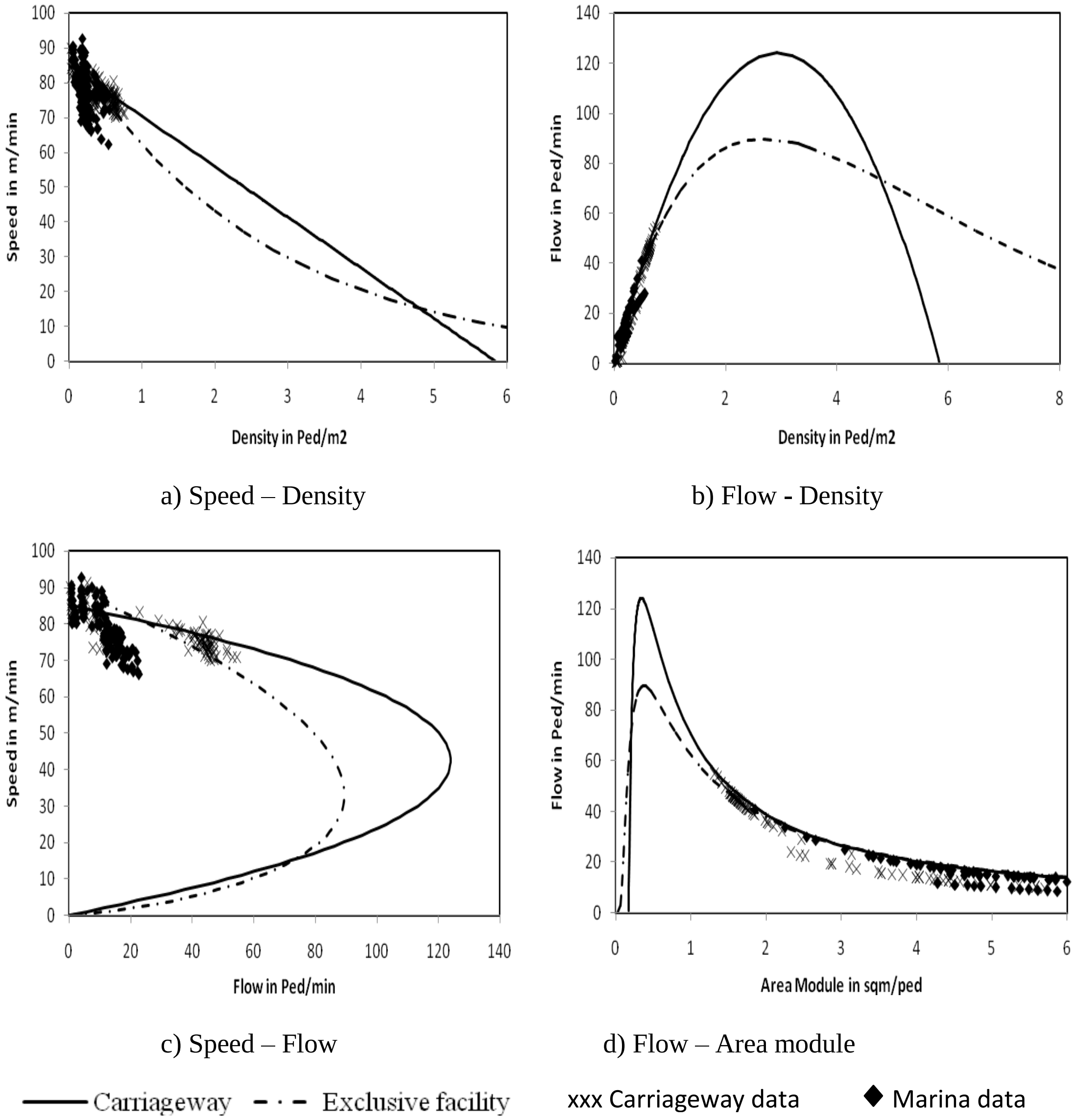


Figure 5: Pedestrian flow characteristics on different facilities

The area module at capacity is found to be lower on a non-exclusive facility (0.34 m^2/p) than on an exclusive pedestrian facility (0.37 m^2/p). This is controlled by the availability of effective space on the non-exclusive facility. The presence of parked vehicle at side pushes the pedestrians farther away on the carriageway. To minimize their interaction with vehicular traffic, the pedestrians walk closer to each other which affect their area module. The average speed of the pedestrians walking closer to the parked vehicle (1.113 m/s) is found lower than that towards centre of the carriageway (1.235 m/s). This suggests that speed of pedestrians increases under friction conditions. In mixed traffic conditions, it is found that the free speeds are greater than those reported by Yu (1993) for China but comparable to those reported in Philippines by Gerilla (1995). The flow at capacity is higher than that reported for China (Yu, 1993), Philippines (Gerilla, 1995), and India (Kotkar et al. 2010). It is observed that even under heavy flows pedestrians in India walk faster on a non-exclusive facility than pedestrians in China (Yu, 1993). The pedestrian space available at capacity is lower than that reported for China and Philippines (Yu, 1993 and Gerilla, 1995).

6. Conclusions

The present is carried out in different cities of India to examine the behavior of pedestrians walking on different type of facilities and under varying flow conditions. The pedestrians are studied on sidewalks categorized by the width of the facility, and under conditions like bidirectional or unidirectional flow, reduction in the effective width of the facility and the absence of an exclusive pedestrian facility at a location. The flow relationships are developed and characteristic values are found out. It is observed that the speed-density relationship follows exponential form on sidewalk of varying widths and linear form on a non-exclusive facility like side of a carriageway. Pedestrians behave similarly to each other within a close band of flow characteristics, up to a width of 9.0 m and beyond this the behavior changes drastically. The variance in the speed reduces with the increase in the width of the facility. The pedestrians behave similarly at very low density (or flow) irrespective of the type of a facility but behavior is different at higher densities. The flow characteristics are found different from those observed in USA, UK, China and South-East Asia indicating a cultural effect. The free speeds in India on sidewalks are found higher than that in most of the Asian countries, though the average speeds are lower. This indicates that due to heavy pedestrian flows and limitation imposed by width of the facility pedestrians in India walk slower but given an ideal condition they may walk faster than their counterparts in other countries. The pedestrians are found to maintain higher buffer space on wider facilities resulting in relaxed walking. Even at very high density, the pedestrians adjust the space available without causing body-to-body contact as indicated by area module at capacity flow. It infers that the width of a facility along with density governs the pedestrian behavior.

The free speed on a sidewalk is not affected by the bidirectional flow as long as the flow is low. As the flow increases, the speed under bidirectional flow is found to be higher than that in unidirectional flow. Opposite behavior is observed under congested conditions or at high density values. The pedestrians under bidirectional flow show adjusting behavior accommodating the fellow pedestrians within the space available but without body-to-body contact was visualized. Two behavioral phenomena are observed, one at centre of the facility termed as ‘squeezing effect’, and other at sides of the facility termed as ‘follow the predecessor rule’. In case pedestrian encounters a high level of restricted condition their speed reduces sharply at lower density. At higher density, it becomes same under restricted and unrestricted condition. This indicates that the boundary conditions and restrictions play a role in controlling the pedestrian behavior along with the density. Pedestrian form layers only at high density otherwise they move in staggered manner. Pedestrian in minor stream wait to build their group and then crosses the restricted stretch by ‘follow the predecessor’ rule. They come closer to each other under risk conditions like, that prevailing on a carriageway, and increase their speed to reduce the risk.

The findings suggest to adopt different flow characteristics for facilities of varying width or operating under varying conditions. The results of this study can be used as input to the development of dynamic continuum models which can help in understanding the pedestrian movements and behavior in spatio-temporal domain. It also indicates towards certain unsymmetrical behavior of the pedestrians especially under bidirectional flow, as well as, under restricted conditions.

References

Al-Masaeid, H.R., Al-Suleiman, T.I. and Nelson, D.C.(1993) “Pedestrian Speed Flow Relationship for Central Business Areas in Developing Countries”, *Transportation Research Record 1396*, National Research Council, Washington, , 69-74.

Daamen, W. (2004) “Modelling passenger flows in public transport facilities,” *Doctoral thesis submitted to Department of Transport and Planning*, Delft University of Technology, Delft, The Netherlands, ISBN 90-407-2521-7.

Daamen, W., and Hoogendoorn, S. P. (2003). “Experimental research of pedestrian walking behaviour,” *Proceedings of Annual Meeting of Transportation Research Board*, CD-ROM, National Academy Press, Washington, D.C.

Fruin, J.J., (1971) “Pedestrian Planning and Design”, Metropolitan Association of Urban Designers and Environmental Planners, New York.

Gerilla, G. P. (1995) “Proposed Level of Service Standards for Walkways in Metro Manila,” *Journal of the Eastern Asia Society for Transportation Studies*, 1(3), Autumn 1995.

Hall. E. T. (1990) “The Hidden Dimension”, *Anchor Books Edition*, New York, USA.

Helbing, D., Molnar, P., Farkas, I.J. and Bolay, K., (2001) “Self-organizing pedestrian movement,” *Environment and Planning B: Planning and Design*, 28, 361 – 383.

Hoogendoorn, S.P, and Daamen, W., (2005a) “Pedestrian Behaviour at Bottlenecks,” *Transportation Science*, Informs, 39(2), 147-159.

Hoogendoorn, S.P, and Daamen, W., (2005b) “Self-organization in Pedestrian Flow,” *Traffic and Granular Flow '03,* Springer-Verlag Heidelberg, Berlin, 373 – 382.

Hoogendoorn, S.P., Bovy, P.H.L., Daamen, W., (2003) “Walking Infrastructure Design Assessment by Continuous Space Dynamic Assignment Modelling”; *Journal of Advanced Transportation,* 38 (1), 69–92.

Honggei, JIA, Yang, L, and Ming, T. (2009) “Pedestrian Flow Characteristics Analysis and Model Parameter Calibration in Comprehensive Transport Terminal,” *Journal of Transportation Systems Engineering and Information Technology*, 9 (5), 117-123.

Huang, L., Wong, S. C., Zhang, M., Shu, Chi-Wang, and Lam, W. H. K. (2009) "Revisiting Hughes: Dynamic Continuum Model for Pedestrian Flow and the Development of An Efficient Solution Algorithm," *Transportation Research – B*, 43 (1), 127-141.

Hughes, R. L. (2002) "A Continuum Theory for the Flow of Pedestrians." *Transportation Research Part-B*, 36(6), 507–535.

Hughes, R. L. (2003). "The flow of human crowds." Annual. Rev. Fluid Mech., 35, 169–182.

Jian, L., Lizhong, Y. and Daoliang, Z. (2005) "Simulation of Bi-direction Pedestrian Movement in Corridor', Physica A, Elsevier, 354, 619-628.

Kotkar, K. L., Rastogi, R. and Chandra, S. (2010) "Pedestrian Flow Characteristics in Mixed Flow conditions," *Journal of Urban Planning and Development, ASCE*, 136 (3), 23-33.

Kretz, T., Grünebohm, A., and Schreckenberg, M. (2006a) "Experimental study of pedestrian flow through a bottleneck." *Journal of Statistical Mechanics*, 10014.

Kretz, T., Grünebohm, A., Kaufman, M., Mazur, F., and Schreckenberg, M. (2006b) "Experimental Study of Pedestrian Counter Flow in a Corridor." *Journal of Statistical Mechanics: Theory and Experiments*, 10001.

Lam, W. H. K., and Cheung, C. Y. (1997). "A study of the bi-directional pedestrian flow characteristics in Hong Kong Mass Transit Railway stations." J. East. Asia Soc. Transp. Stud., 2, 1607–1620.

Lam, W.H.K. and Cheung, C., (2000) "Pedestrian Speed/Flow Relationships for Walking Facilities in Hong Kong, *Journal of Transportation Engineering*, ASCE, 126 (4), 343–349.

Lam, W.H.K., Morrall, J.F., and Ho, H., (1995), "Pedestrian Flow Characteristics in Hong Kong', *Transportation Research Record 1487*, TRB, National Research Council, 56-62.

Lam, W. H. K., Lee, J. Y. S., and Cheung, C. Y. (2002) "A Study of the Bi-directional Pedestrian Flow Characteristics at Hong Kong Signalized Crosswalk Facilities," Transportation, 29(2), 169–192.

Lam, W. H. K., Lee, J. Y. S., Lee, K. S., and Goh, P. K. (2003) "A Generalised Function for Modelling Bi-directional Flow Effects on Indoor Walkways in Hong Kong." *Transportation Research Part A: Policy Practice*, 37(9), 789–810.

Lee, J. Y. S., Goh, P. K., and Lam, W. H. K. (2005). "New level-ofservice standard for signalized crosswalks with bi-directional pedestrian flows." *Journal of Transportation Engineering*, 131(12), 957–960.

May, A. D. (1990), Traffic Flow Fundamentals. *Prentice Hall*, Inc., New Jersey.

Morrall, J. F., Ratnayake, L. L. and Seneviratne, P. N. (1991) "Comparison of central business district pedestrian characteristics in Canada and SiriLanka," *Transportation Research Record* 1294, TRB, National Research Council, 57-61.

Navin, F. P. D., and Wheeler R. J. (1969), "Pedestrian flow characteristics", *Traffic Engineering and Control*, 39(9), 30-36.

Oeding, D. (1963) "Verkehrsbelastung und Dimensionierung von Gehwegen und anderen Anlagen des Fussgangerverkehrs", Strassenbau und Stasserverkehrstechnik, Heft 22, Bonn.

O'Flaherty, C.A. & M.H. Parkinson (1972) "Movement on a city centre footway," *Traffic Engineering and Control* 13, 434–438.

Older, S. J. (1968) "Movement of pedestrians on footways in shopping streets," *Traffic Engineering and Control*, 10(4), 160-163.

Pauls, J. (1987) "Calculating evacuation times for tall buildings." *Fire Safety Journal,* 12 (3), 213-236.

Polus, A., Schofer, J. L. and Ushpiz, A. (1983) "Pedestrian flow and level of service," *Journal of Transportation Engineering*, ASCE, 109(1), 46-56.

Pushkarev, B. and J. Zupan (1975) "Urban Space for Pedestrians," *MIT Press*, Cambridge.

Sarkar, A.K. and K.S.V.S. Janardhan (1997) "A study on pedestrian flow characteristics," In CD-ROM with Proceedings, *Transportation Research Board*, Washington.

Seyfried, A., Passon, O., Steffen, B., Boltes, M., Rupprecht, T. and Klingsch, W. (2009) "New Insights into Pedestrian Flow through Bottlenecks," *Transportation Science*, 23, Elsevier, 395-406.

Shi, J, Chen, Y, Rong, J and Ren, F (2005) "Research on pedestrian crowd characteristics and behaviours in peak-time on Chinese campus," *Pedestrian and Evacuation Dynamics*, Springer-Verlag Heidelberg, Berlin, 79 – 90.

Tajima, Y., Takimoto, K. and Nagatani, T., (2001) "Scaling of pedestrian channel flow with a bottleneck," Physica A, Elsevier, 294, 257 – 268.

Tanariboon, Y. & J.A. Guyano (1989) "Level-of-service standards for pedestrian facilities in Bangkok: A case study, *ITE Journal* 59(11).
Tanaboriboon, Y., Hwa, S.S. and Chor, C.H. (1986) "Pedestrian characteristics study in Singapore," *Journal of Transportation Engineering*,ASCE, 112(3), 229-235.

Teknomo, K., Takeyama, Y. and Inamura, H. (2000) "Determination of pedestrian flow performance based on Video tracking and microscopic simulations", *Proceedings of Infrastructure Planning Conference* 23(1), Ahikaga, Japan, November, 639-642.

Virkler, M.R. and Elayadath, S. (1994) "Pedestrian Speed-Flow-Density Relationships" *Transportation Research Record* 1438, 51-58.

Wong, S. C., Leung, W. L., Chan, S. H., Lam, W. H. K., Yung, N. H. C., Liu, C. Y. and Zhang, P. (2010) "Bidirectional Pedestrian Stream model with oblique intersecting angle" *Journal of transportation Engineering*, 136 (3), 234-242.

Yu, Min Fang (1993) "Level of Service Design Standards for Non-motorized Transport in Shanghai," China, AIT Thesis no GT 93-35, Asian Institute of Technology, Bangkok.