Estimation of free speed of pedestrian flow on stairways at busy suburb rail transit station in India

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Free speed, the key parameter in the modelling of pedestrian flow, is the speed that a pedestrian desires to walk at. In this study free speed of pedestrians considering characteristics such as age, gender, and with or without luggage in ascending and descending stairways located on platforms in suburban and intercity railway stations was examined. Due to difficulty in observing free speed directly, an approach for developing distributions of speeds at varying levels of pedestrian density is proposed to estimate free speed precisely. The outcome of this study may be useful for planning, design and operation of the pedestrian facility.

Keywords: Free speed, pedestrian flow, rail transit station, stairway.

WALKING speed is an important factor in pedestrian studies, which helps in determining the comfort level for the given facility. Many researchers agree that pedestrian speed differs among pedestrians[1–3]. This is because of the characteristics of pedestrians, the direction of movement, and characteristics of pedestrian facility (type and physical characteristics such as length, width, height, slope, number of steps in a single flight and dimension of steps in case of a stairway), weather and other external conditions. However, these factors do not influence in the case of high dense flow, where pedestrians are walking closely. Free speed is a speed at which pedestrians walk when not hindered by other pedestrians or by external factors[3]. Hence, free speed is an important criterion to understand individual behaviour. However, it is difficult to measure free speed of a pedestrian from the data since an enumerator does not identify whether a pedestrian walks at his/her free speed. Free speed and its distributions are an important input for many traffic flow models, such as developing a speed-flow plot.

Free speeds are also an important aspect from the viewpoint of design of walking facilities and the corresponding schedule of public transport services, which affect directly the overall efficiency of the system. Many researchers have studied the performance of pedestrian walking speed at different facilities. However, very few studies have been undertaken at transit stations, where pedestrian flow dynamics depend largely on the schedule of the train. This becomes imperative particularly during peak periods as there can be a large number of passengers in a short time interval. Generally, it is expected that arrival of trains is likely to make the gathering and dispersion of pedestrians efficient. It also facilitates easy transfer of pedestrians on other platforms, for catching the next train, through good transfer facilities. As discussed, many factors make a significant contribution to deciding free-flow movements of a pedestrian. These factors include age, gender, the baggage carried by a pedestrian and the walkability of a facility[4], the gradient or roughness of surface[5], time of day[6] and type of walking facility[2]. The most important factor governing pedestrian movement on a public transport facility is the presence or absence of other pedestrians[5]. However, passengers' entry and exit at platform and transfer to another facility are possible only through critical elements like stairways and can have a significant effect on the overall performance of transit service, particularly when flow is high in both directions at an undivided stairway.

In view of the growing concerns for the safety of transit users and its quality of service, it is pertinent to understand the maximum walking speed of pedestrians keeping in view immediate scheduled activity. However, individuals' speed is largely influenced due to the presence of surrounding pedestrians. Higher walking speed downstairs than upstairs and reduction in walking speed with increase in pedestrian density have been observed[1,2,7,8]. Outdoor stairs are reported to offer more speed than indoor stairs[9]. Small variation (0.01 m) in the riser height can cause +7% variation in the speed at upstairs and +1% at downstairs[2]. Walking speed depends on the start-up time of the pedestrian and it plays a vital role in design[10]. Smallest variation in walking speed has been observed[11], when pedestrian flow approached at capacity. The direction of flow and arrival time of train also impact average horizontal speed. However, other activities (baggage, use

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Table 1. Categorized average walking speed (ms^{-1}) of pedestrian at various locations

					Stairways (St)	
Authors/study location†	Gender	Particular	Side-walk	Passage-way	Ascending	Descending
USA[1]	Male	Age – <29	–	1.39	0.56	0.83
	Female		–		0.54	0.90
	Male	Age – 30–50	–	–	0.51	0.69
	Female		–	–	0.48	0.51
	Male	Age – >50	–	1.09	0.43	0.57
	Female		–		0.39	0.47
Bangkok[2]	Male	Adult*	1.27	–	–	–
	Female		1.17	–	–	–
	Male	Young*	1.27	–	–	–
	Female		1.2	–	–	–
	Male	Elderly – >60	0.85	–	–	–
	Female		0.8	–	–	–
Beijing[18]	Male	Youth – 18–35, St = 2.4 m	–	1.39	0.75	0.93
	Female	Middle age – 36–60 St = 1.2 m	–	1.22	0.66	0.83
	Male	Old age – >60	–	–	0.72	0.67
	Female		–	–	0.69	0.69
Delhi[19]	Combined	Children – <15	1.39	–	–	–
		Young – 16–25	1.3	–	–	–
		Middle age – 26–50	1.22	–	–	–
		Elderly – >50	1.1	–	–	–
	Male	–	1.3	–	–	–
	Female	–	1.17	–	–	–
Shanghai[20]	Male	Young 18–44	–	1.51	–	–
	Female		–	1.4	–	–
	Male	Middle age – 45–59	–	1.39	–	–
	Female		–	1.32	–	–
	Male	Elder >60	–	1.14	–	–
	Female		–	1.14	–	–
Dhaka (Bangladesh)[4#]	Combined	Young – 15–30	1.26	–	–	–
		Middle age – 30–50	1.16	–	–	–
		Elderly – >50	1.04	–	–	–
	Male	–	1.07	–	–	–
	Female	–	1.24	–	–	–
The Netherlands[3#]	Combined	Wide passageway	–	1.56	–	–
,		Narrow passageway		1.44		
		One direction flow		1.57		
		Opposite direction flow		1.55		

*Not specified; #Free flow speed; walking speed in ms^{-1}; – Not available. †Reference no. of earlier study.

of cell phone) on ascending and descending speed have not been observed earlier. Table 1 shows categorized average walking speed of pedestrian for different facilities at various locations in different countries.

From Table 1, the common inference is that the average walking speed of a young male pedestrian is higher than a female pedestrian in all cases. Also, descending speed is observed higher than the ascending speed. A discrepancy in average walking speed is observed in China. Yang[12] observed walking speed at stairways with two different widths keeping other variables constant and found higher walking speed at a width of 2.4 m in both directions. Also, walking speed of pedestrians at stairway is less than that at other pedestrian facilities. It also reveals that very few initiatives have been taken to estimate pedestrian free speed at sidewalk/passageways. However, free speed at stairway is not estimated particularly in India, where the pedestrian movement is not divided at the stairway. Hence, pedestrian flow becomes dynamic and complex, as pedestrians face heavy opposing flow during frequent arrival of a train, leading to dramatic changes in stairway directional split.

Many studies related to pedestrians for unidirectional flows, opposite flows and crossing flows have been carried out[3] and different types of pedestrian flows simulated at passageway, considering different widths. Higher speed at crossing ($1.64\ ms^{-1}$) than narrow bottleneck ($1.44\ ms^{-1}$) was also found. Also for opposite directional flow, the observed speed was about $1.53\ ms^{-1}$. In controlled experiments, generally, pedestrians follow

Table 2. Selection of stairway based on physical attributes and type of trains

Stairway no.	Trap length (m)	Trap area (sq. m)	Other geometrical attributes	Duration of videography	Type of station
Dst-1	3.8	8.58	Clear width: 2.67 m; tread: 0.29 m; riser: 0.13 m; inclination: 22.1°	Considering peaks and off peak during mid of June 2013	Suburban station
Dst-2	2.22	4.25	Clear width: 2.15 m; tread: 0.3 m; riser: 0.13 m; flight angle: 24.1°		
Vst-1	4.00	7.79	Clear width: 2.14 m; tread: 0.28 m; riser: 0.15 m; flight angle: 23.8°	In off peak, during mid of October 2012	Interstate station
Vst-2	3.82	8.58	Clear width: 2.45 m; tread: 0.3 m; riser: 0.15 m; flight angle: 23.6°		

St, Stairway; Dst, Dadar station; Vst, Vadodara station.

Figure 1. Pictorial view of pedestrian movement at stairways. ***a***, Dst-1; ***b***, Dst-2; ***c***, Vst-1; ***d***, Vst-2.

instructions – pedestrians are asked to walk on a dedicated path with normal or higher speeds. In this case, pedestrians behave in a well-organized manner, which does not replicate the real-world situation such as time pressure, overtake of slower pedestrians, closed interface, finding opportunity to increase walking speed, forcing pedestrians to move faster, etc. Hence, it has certain limitations and such pedestrian behaviour may not be consistent with field results and therefore, may vary significantly from a real-life behavioural situation.

Rahman *et al.*[4] carried out a survey at uninterrupted walking facilities with pedestrian traffic flows restricted by fence, wall, shops, or road with high traffic of vehicles. They observed that the overall mean free-flow speed of observed pedestrians was 1.15 ms^{-1} considering minimal traffic density at free flow. They also observed that the young pedestrian group of Bangladesh was faster than others. Speed variability among this group was also highest, as this group covered mainly teenagers and matured pedestrians. However, they have not discussed a threshold of flow and density level at which probing speed may be accorded as free speed. Also, there is a research gap in deciding the major influencing parameter, which may enable practitioners to describe the free flow condition.

The above discussion indicates that earlier studies related to pedestrian uni-directional, opposite direction, crossing, at various pedestrian facilities were based on some assumptions or controlled experiments, which may not replicate real field conditions. Study related to free speed at undivided stairway is rare. These gaps have motivated the present authors to study the walking speed at different levels of flow and density and estimate the free speed of pedestrians from the observed data on stairways at two different railway stations (functionally) namely, busy sub-urban interchange railway station, Dadar in Mumbai and Vadodara inter-city station. The stations were selected based on cultural diversity and difference in scale of activities. At sub-urban station, most passengers are daily travellers or commuters, whereas casual travellers are observed in case of inter-city stations.

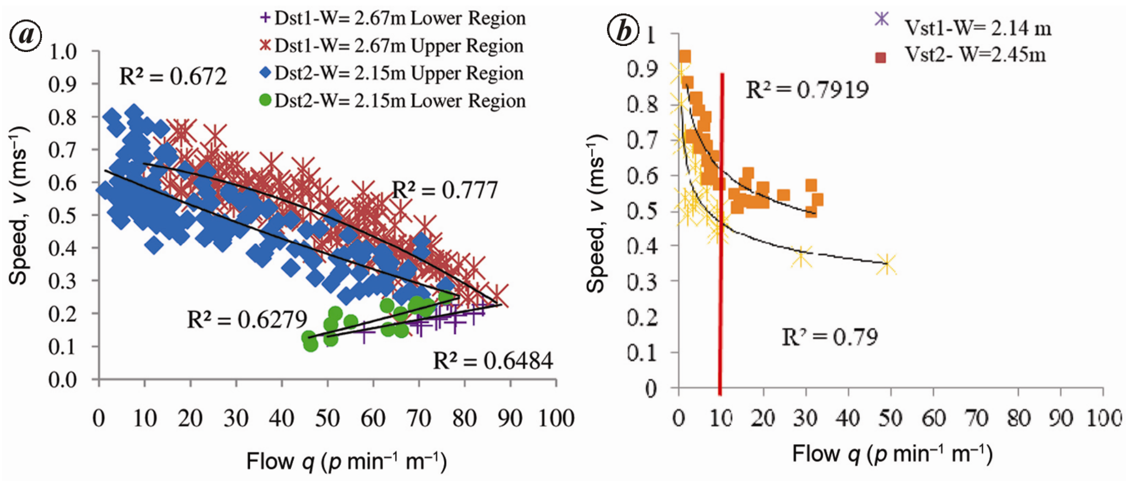

Figure 2. Flow-speed relationship: ***a***, suburban station; ***b***, interstate station.

The study was conducted for different stairways considering pedestrian flow characteristics at the macroscopic level. To understand the macroscopic phenomena, an experimental set-up was installed at selected stairways having varying geometry and dimensions, as presented in the next section. The methodology of data acquisition and extraction is also explained. This is followed by a macroscopic analysis of flow–speed–density characteristics to provide an idea of free flow condition, which is presented later. Our findings are reported in the concluding section.

Pedestrian flow data collection

Data was collected at identified stairways at different locations in station premises. A high digital camera (having frame rate of 29 frames per second) was mounted at the ceiling of the stairway, at a height of 3.0 m such that it covered the complete area of the stairway (approx. 3.5 m by 15 m). Further, pedestrian flow data was recorded for the prescribed survey duration of the railway authority. Pedestrian flow data like flow, speed and density was extracted with high precision manually by noting the entry and exit times of pedestrians in the laboratory through a repeated play of video files.

Pedestrians in the flow were categorized on the basis of age, gender, directional movement and performance of activity like carrying baggage and/or children. The age group was identified on the basis of visual perception. The age band was classified in three groups of children (age <15), younger/adult pedestrians (age between 15 and 60) and the elders (age >60). Pedestrian flow data was extracted from the video for every one-minute interval for the entire survey.

The bi-directional volume, Q (p min^{-1}) data was collected by observing each category of pedestrians passing the marked base trap section comprising of steps on the stairway as shown in Table 2. The average walking speed v (ms^{-1}) was calculated for randomly selected five samples in each pedestrian category by noting down the entry and exit time required to cross the marked trap length on the steps as shown in Figure 1. For measuring density, ρ (pm^{-2}) of pedestrians, video files were converted into 30 frames per minute[13] and the number of pedestrians occupying the marked trap area for each frame was counted. Based on these values, an average number of pedestrians occupying the trap area was calculated for every minute.

Measurement of free speed

Free-flow speed estimation approach is very well explained in vehicular traffic flow. However, little attention has been paid for estimation of free speed for pedestrian facilities. Some of the approaches for vehicular traffic are presented as follows:

(a) Extrapolation of the speed-flow relation at flow nearer to zero[14]. However, it might be an underestimated value due to interrupted extrapolation of the vehicular speed, for estimation of free-flow speed.
(b) Estimation of free speed at low volume[15]. But, Daamen and Hoogendoorn[3] pointed out that traffic composition of the flow in this model varies at different periods of time, i.e. peak and off-peak, and hence, traffic behaviour and free speed distribution may also vary at different periods of time.
(c) Assuming that the vehicles move in free-speed, when the time between two consecutive vehicles (time headway) is more than 8 sec, and the volume of a vehicle is less than 1300 veh/h/lane.
(d) Through simulation of vehicular data at low flow rate.
(e) Free speed distribution[1,16].

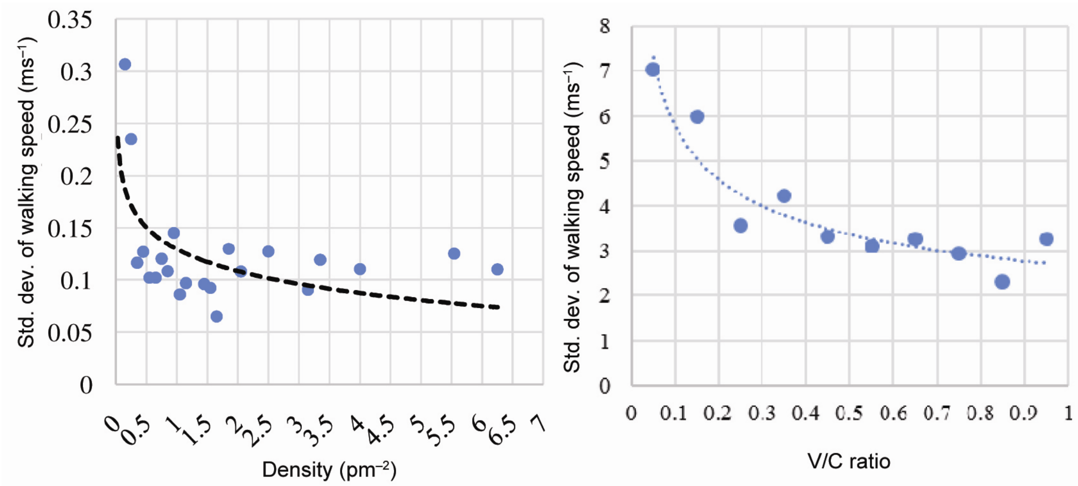

Figure 3. Variation in speed with increase in density and V/C ratio.

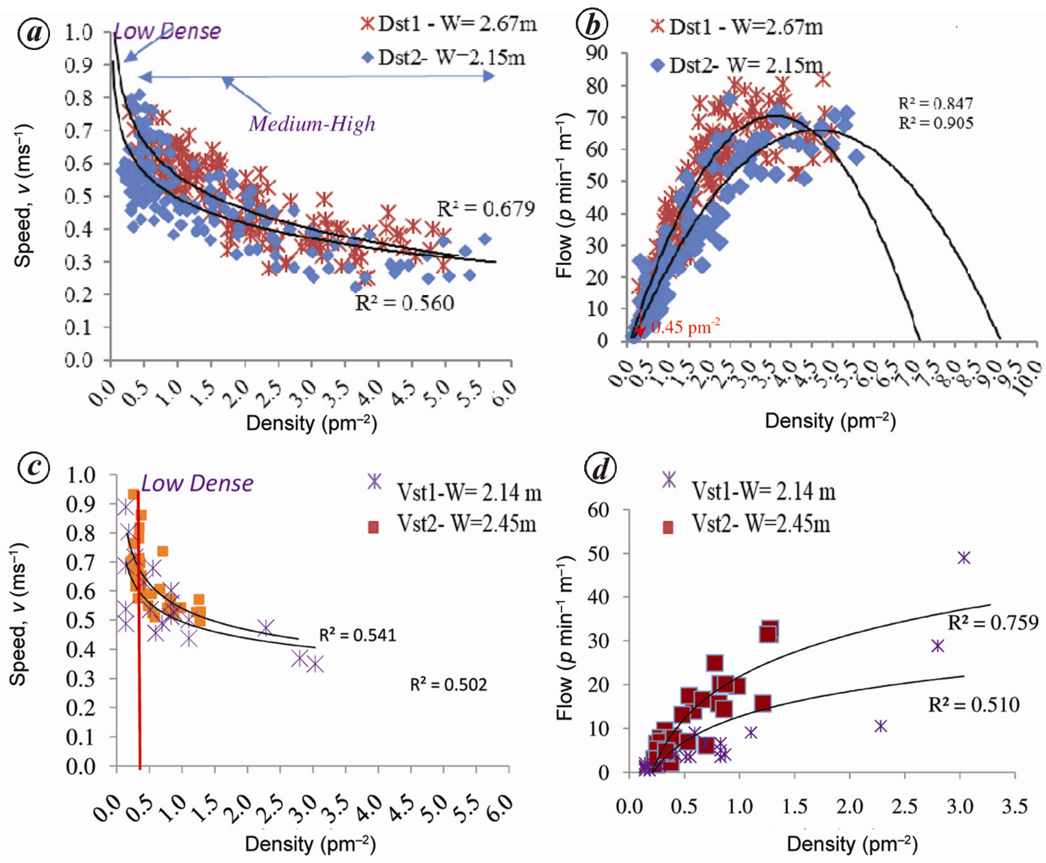

Figure 4. Fundamental relationships (***a*** and ***b***) for suburban and (***c*** and ***d***) for interstate station.

All methods have some limitations and cannot be adopted directly for pedestrian flow as pedestrian behaviour is rather different when compared to vehicular flow in terms of the degree of freedom[3]. As such, pedestrians have a higher degree of freedom in walking, manoeuvre with frequent lateral movement as well as opposite flow, which restricts pedestrian movement, particularly under physically-constrained condition. In such a case, it is difficult to estimate the free speed of pedestrians using methods generally adopted for vehicular flow. Daamen and Hoogendoorn[3] adopted a probabilistic approach with modified Kaplan-Meier approach[16] considering distance to another pedestrian to estimate free speed distributions. However, at the transit station, time pressure plays an important role in the walking speed of pedestrians irrespective of distance. For example, pedestrians who

Table 3. Descriptive statistics of walking speed (ms^{-1}) for different density (pm^{-2}) levels for suburban and interstate station

Density	*N*	Mean	Std. dev.	Std. error	Density	*N*	Mean	Std. dev.	Std. error	Density	*N*	Mean	Std. dev.	Std. error
Suburban station														
<0.15	10	0.58	0.181	0.040	1.05–1.15	108	0.54	0.102	0.022	2.05–2.15	76	0.46	0.103	0.012
0.15–0.25	16	0.62	0.253	0.055	1.15–1.25	95	0.52	0.097	0.024	2.15–2.25	68	0.49	0.091	0.015
0.25–0.35	38	0.61	0.246	0.048	1.25–1.35	98	0.53	0.105	0.015	2.25–2.35	64	0.46	0.102	0.018
0.35–0.45	45	0.60	0.280	0.055	1.35–1.45	106	0.54	0.095	0.011	2.35–2.45	73	0.45	0.085	0.009
0.45–0.55	152	0.56	0.208	0.034	1.45–1.55	89	0.54	0.125	0.025	2.45–2.55	39	0.45	0.046	0.010
0.55–0.65	148	0.56	0.192	0.030	1.55–1.65	65	0.53	0.118	0.018	2.55–3.00	28	0.42	0.054	0.017
0.65–0.75	116	0.55	0.123	0.011	1.65–1.75	52	0.52	0.108	0.009	3.00–3.50	22	0.38	0.027	0.010
0.75–0.85	98	0.52	0.102	0.027	1.75–1.85	61	0.53	0.092	0.010	3.50–4.00	15	0.36	0.042	0.012
0.85–0.95	102	0.52	0.112	0.025	1.85–1.95	73	0.53	0.116	0.021	4.00–4.50	13	0.30	0.019	0.007
0.95–1.05	112	0.53	0.098	0.020	1.95–2.05	48	0.48	0.090	0.008	>4.5	34	0.31	0.032	0.009
Intercity station														
<0.15	–	–	–	–	0.65–0.75	35	0.58	0.125	0.021	1.25–1.35	18	0.51	0.098	0.011
0.15–0.25	18	0.58	0.432	0.045	0.75–0.85	27	0.50	0.112	0.027	1.35–1.45	16	0.46	0.102	0.014
0.25–0.35	12	0.56	0.345	0.052	0.85–0.95	38	0.51	0.110	0.022	2.05–2.15	09	0.45	0.083	0.011
0.35–0.45	25	0.52	0.298	0.052	0.95–1.05	19	0.50	0.108	0.021	2.15–2.25	12	0.49	0.101	0.015
0.45–0.55	29	0.55	0.212	0.044	1.05–1.15	28	0.51	0.082	0.019	2.55–3.00	15	0.35	0.044	0.016
0.55–0.65	12	0.50	0.182	0.040	1.15–1.25	45	0.49	0.085	0.014	3.00–3.50	11	0.31	0.037	0.009

–, Data was not available.

reached the station/platform before the scheduled time of train can walk with slower speed than desired. It is contrary in the case of delayed or departed pedestrians, where pedestrians hastily walk towards the stairway to catch the next mode. This enforces them to walk faster and come out quickly from the crowded situation, which may occur within few minutes after pedestrians have departed from train and moved towards the common stairway. In addition, pedestrian characteristics are important attributes, which may restrict walking speed by lateral placement when overtaking slow moving pedestrians. In this case, the corresponding density and flow play an important role in restricting the individual speed to some extent. Hence, the level of density and flow may be the appropriate measure for estimation of free speed. The present study adopted the density based speed estimation to determine free flow speed.

To estimate free speed, fundamental characteristics of pedestrian flow such as flow, speed and density are studied. These characteristics are observed and studied at macroscopic and microscopic levels. Macroscopic characteristics are measured based on groups of pedestrians rather than an individual. Generally, macroscopic analysis is considered fit for large-scale systems analysis at an aggregate level, in which behaviour of groups as a whole is important to explain the pedestrian flow characteristics and the result obtained is useful for further estimation of free speed of pedestrian flow. To understand the speed behaviour, different macroscopic characteristics of pedestrian flow were analysed and fundamental relationships developed. The walking speed is a function of flow and density. Relationships developed between pedestrian flow and speed characteristics both for suburban and intercity transit station stairways are shown in Figure 2.

Figure 2 shows that as flow of pedestrians increases, walking speed decreases gradually for both stairways. It may be noted that, up to lower flow level of 10 p min^{-1} m^{-1}, there is relatively large variation in walking speed (0.4 to 0.8 ms^{-1} for suburban stairway and 0.45 to 0.95 ms^{-1} for intercity stairway), specifically at intercity station, as depicted in Figure 2 *b*, plot with a high rate of change of slope of the best-fit line. This implies that up to flow rate of 10 p min^{-1} m^{-1}, the flow does not affect the individual walking speed but governed by the individual pedestrian's characteristics such as age, luggage carrying condition and direction of movement, ascending or descending.

In order to study further on variation in speed with an increase in density, the standard deviation in walking speeds for every 0.1 pm^{-2} density and change in every 0.1 V/C ratio is plotted (Figure 3). It is observed that when density reaches 0.45 pm^{-2}, the standard deviation curves tend to become flatter with a lower value, indicating less speed variation at higher pedestrian density. As the corresponding average available space is found to be higher (2.23 m^2 p^{-1}), it seems that pedestrians have enough space to manoeuvre and move with minimal hindrance by pedestrian(s) in surrounding. However, beyond density of 0.45 pm^{-2}, pedestrian speed trend decreases with gradual increase in density (Figure 4 *a*) and the corresponding flow rate (Figure 4 *b*).

Figure 4 shows that the different density regions (<0.45 pm^{-2} such as low density region (LDR); >0.45 pm^{-2}

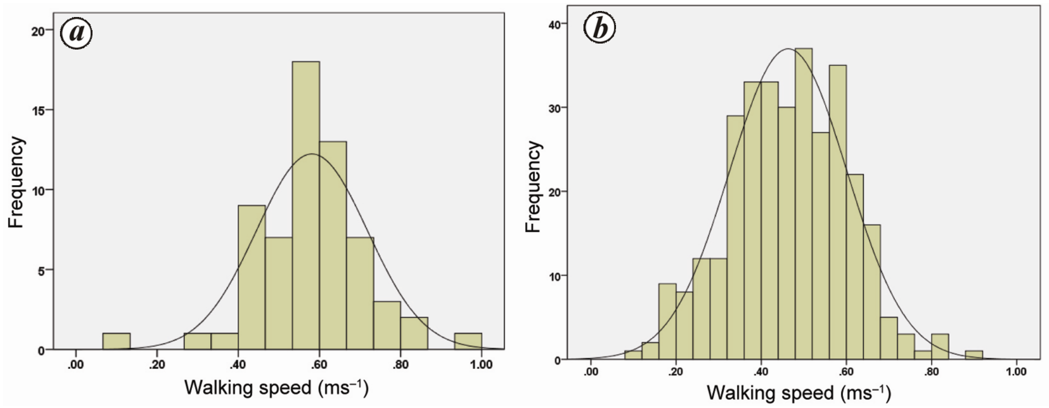

Figure 5. Frequency distribution of walking speed at different density regions for suburban station. ***a***, Density <0.45 pm^{-2}; ***b***, Density >0.45 pm^{-2}.

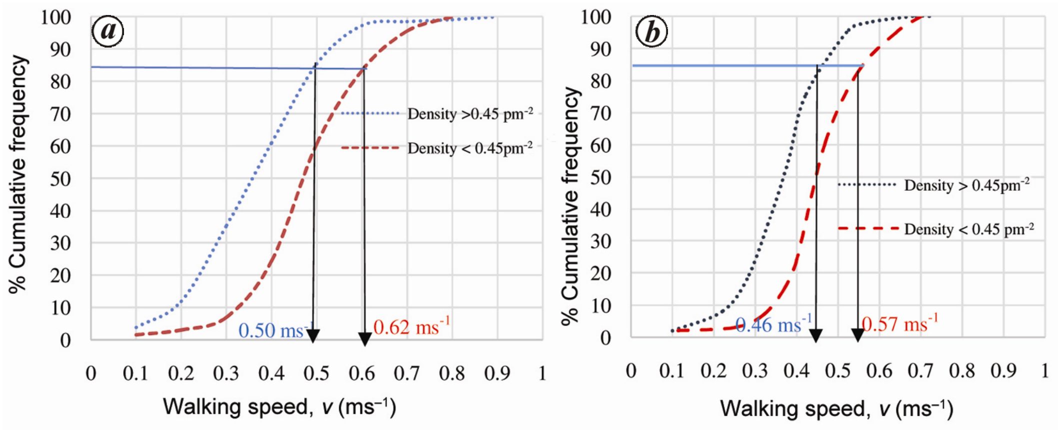

Figure 6. Cumulative percentage distribution of walking speed: ***a***, Suburban; ***b***, Interstate station.

and medium to high density region (MDR and HDR)) have variation in pedestrian walking speeds. In the case of intercity station stairway (Figure 4 *c* and *d*), data has been observed in low to medium density region. At the density level, beyond 3 pm^{-2}, pedestrian flow increases for both stairways. Pedestrian walking speed at different regions, viz. LDR, and MDR to HDR, had also been analysed (Table 3).

Descriptive statistics for the walking speed in Table 3, revealed that as density increases, average walking speed and variation (standard deviation and error) in walking speed decrease in general. However, large variation in walking speed was observed at a low-density value of 0.45 pm^{-2} (LDR), which indicates that pedestrians could achieve desirable walking speed with minimal influence from the surrounding. Nevertheless, it was observed that as density increases beyond 0.45 pm^{-2} (MDR), average walking speed decreased, which indicates that beyond that density, pedestrians were influenced by other pedestrians, resulting in reduction in walking speed and standard deviation. Before quantifying the effect of density on free flow walking speed, a statistical check was also conducted through univariate multifactor analysis of variance (ANOVA) to test whether the effect of different density levels on pedestrian speeds, was statistically significant or not. Analysis showed significant difference between different density regions, i.e. density <0.45, >0.45, 2.0 and 4.5 pm^{-2}.

To estimate free speed, walking speed below 0.45 pm^{-2} and corresponding flow rate of 10 p min^{-1} m^{-1} was considered. However, at this density, it seemed that pedestrians were under minimal influence by other pedestrians. To minimize the effect, the cumulative distribution function of speed gives a better perspective of free flow speed. Beholding above issues, data was first checked for normality at 5% level of significance for different density levels (density <0.45 pm^{-2} and >0.45 pm^{-2}). Test results indicated that walking speed for different density levels followed the normal distribution, with *P*-value greater than 0.05 (Figure 5). It also showed that the variability in walking speed was higher at a lower density of 0.45 pm^{-2}. Further, the cumulative distribution function of walking speed was drawn to get the different percentile speeds of interest. Also, to understand pedestrian characteristics at the intercity station, pedestrian free speed was analysed considering different density regions. In vehicular

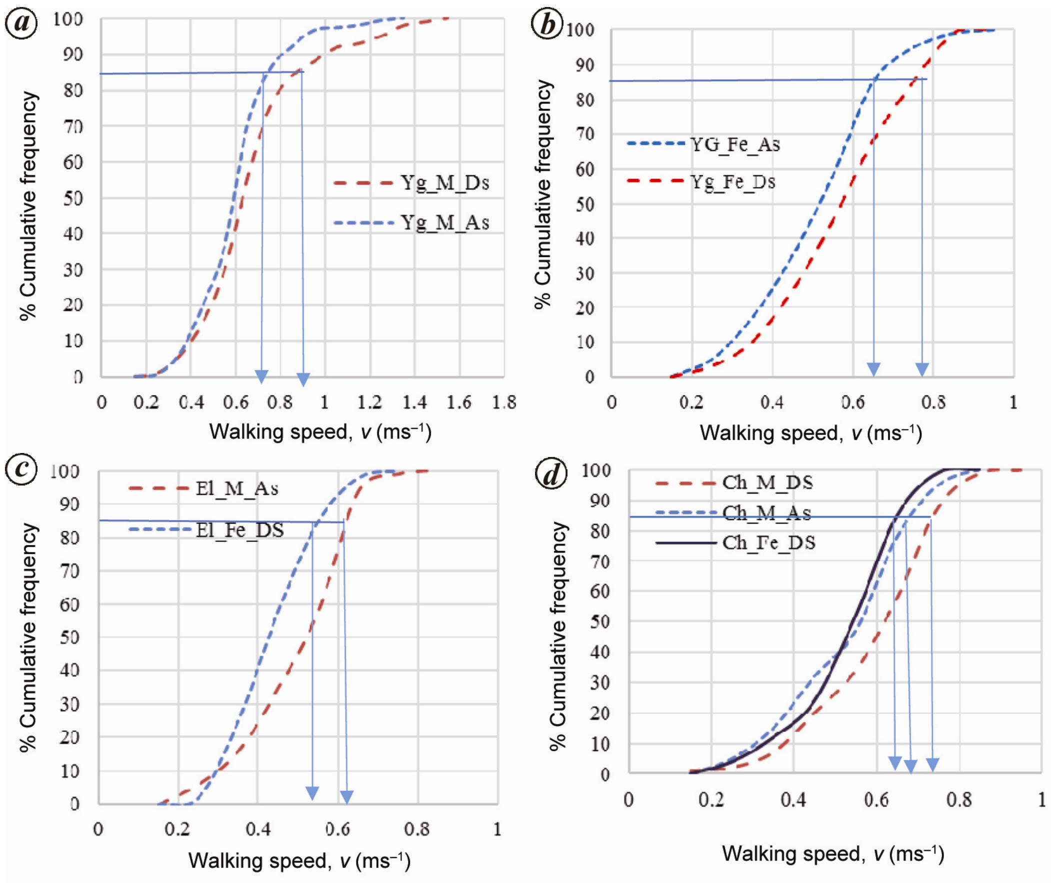

Figure 7. Cumulative percentage distribution of walking speed for different age and gender groups for suburban station. ***a***, Young male; ***b***, Young female; ***c***, Elder (male and female); ***d***, Children (male and female). Yg, Young; El, Elder; Ch, Children; M, Male; Fe, Female; As, Ascending, Ds, Descending.

traffic, 85th percentile speed is the operating speed for the given road section. Hence, on similar lines, for pedestrian facilities also it can be assumed that at 85th percentile speed as operating speed, pedestrian are not influenced by surrounding pedestrians. Figure 6 depicts the cumulative percentage frequency of the different density regions.

Figure 6 shows that at higher density levels (>0.45 pm^{-2}), pedestrians could not achieve their desired speed. It also clearly indicates that even at 85th percentile, pedestrian walking speed was significantly lower (0.5 ms^{-1} for suburban and 0.46 ms^{-1} for intercity station) for high density level, than 85th percentile pedestrian walking speed at density levels lower than 0.45 pm^{-2} (0.62 ms^{-1} for suburban and 0.57 ms^{-1} for intercity station). Furthermore, the effect of pedestrian demographic characteristics such as age, gender and direction of the movement on free speeds was studied. This may be useful to determine free-speed values based on different pedestrian characteristics at density (<0.45 pm^{-2}). Figure 7 shows the distribution function of walking speed considering age, gender and direction of the movement for suburban station.

Among the groups, speed variability was higher in the group classified based on gender and age. It is intuitive that as a pedestrian becomes older, her/his walking capacity tends to decline. From the figure, it can also be seen that pedestrians required greater effort to climb the stairway, resulting in reduction in walking speed. Pedestrian characteristics, and hence walking speeds on stairway at suburban railway station, are significantly different than walking speeds on stairway at the intercity station because of the functional activity difference. In the present study, male pedestrians constituted a majority of pedestrian flow on both stairways with 86% (St_1) and 91% (St_2) with younger/adult pedestrian (age 15–60 years) being the dominant groups with total 96% share, whereas children and elders constituted negligibly small proportion (2%) of pedestrian flow for ascending and descending movements (average of both the stairways in each direction). At intercity station, younger pedestrians were 78%, followed by 17% elders and 5% children; with approximately 76% of male pedestrians across all age groups. Vadodara station, being an intercity transit station, has influence on pedestrian walking speeds, because of proportion of pedestrians with luggage/baggage. In the case of the station considered in this study, 22% of pedestrians were observed with luggage such as trolley bag, large bag-pack or carrying children. Literature reveals

Table 4. Descriptive statistics of free speed at stairway

Combinations				N	Free speed (ms^{-1})	Std. deviation (ms^{-1})	CV
Gender		Male		75	0.70	0.547	1.233
		Female		75	0.63	0.065	0.154
Age			Children	29	0.68	0.121	0.239
			Young	75	0.75	0.023	0.128
			Elder	32	0.56	0.049	0.166
Considering: Gender – age							
Male			Children	23	0.72	0.118	0.204
			Young	73	0.79	0.087	0.143
			Elder	36	0.58	0.089	0.172
Female			Children	8	0.60	0.130	0.232
			Young	76	0.67	0.086	0.152
			Elder	15	0.52	0.090	0.210
Considering: Direction – luggage – gender – age							
Ascending	Without luggage	Male	Children	8	0.68	0.083	0.151
			Young	69	0.75	0.121	0.204
			Elder	12	0.62	0.133	0.270
		Female	Children	Inadequate sample			
			Young	44	0.63	0.117	0.221
			Elder	Inadequate sample			
Descending	Without luggage	Male	Children	17	0.73	0.196	0.303
			Young	69	0.85	0.085	0.135
			Elder	Inadequate sample			
		Female	Children	7	0.64	0.202	0.309
			Young	75	0.74	0.084	0.146
			Elder	9	0.56	0.0574	0.124
Considering: direction – gender							
Ascending		Male		68	0.69	0.064	0.110
		Female		45	0.63	0.105	0.198
Descending		Male		78	0.81	0.082	0.123
		Female		75	0.66	0.093	0.151
Considering: direction							
Direction		Ascending		67	0.67	0.092	0.166
		Descending		76	0.74	0.057	0.098

that the walking speed of pedestrians also depends on the proportion of persons with luggage. Obviously, pedestrian with luggage walk at a slower speed[17]. In this study, the number of pedestrians without luggage or small luggage was very high (93.72%) when compared to those with luggage in suburban station. In the case of intercity station, it was found to be an insignificant proportion and therefore walking speed of pedestrians at different density levels was found to be lower when compared to suburban station. To further study on this aspect, comparative walking free speed analysis considering pedestrian with-and-without luggage condition for both suburban and intercity railway stations was performed. For this purpose, pedestrian free-flow speeds from LDR were analysed for both stations (Table 4). A detailed comparison of free speed at two different stations (suburban and intercity) is presented in Table 6.

From Table 4, it is revealed that the free speed (0.702 ms^{-1}) of male pedestrian was higher than female (0.634 ms^{-1}) and the values were tested at a 0.05 significance level as shown in Table 5. Similar analysis was carried out for the other remaining stairways at intercity station and a summary of free speed of pedestrian for those stairways is provided in Table 6.

From Table 6, it is seen that the average walking speed of young pedestrians was found to be significantly higher than the elders and children in descending direction. In the present study, young pedestrians walk with 10% and 8% higher speed than children, and 20% and 27% higher than elders at suburban and interstate station respectively. Male pedestrians walk with higher speed (25% in descending and 12% in ascending) than females at the suburban station (28% in descending and 20% in ascending direction) at the interstate station.

In general, it can be concluded that as age increases, speed decreases significantly for both male and female. Hence, it can be inferred that, in the case of male and female, younger pedestrians walk at a higher speed than children and elders. Also, in descending direction pedestrians of all age groups, male and female, walk at higher

Table 5. Statistical analysis for pedestrian characteristics

Variable selected					Test performed	Sum of square (between the group)	F statistics	Std. error difference/SE (for ANOVA)	Sig. at 5%
Considered: direction – luggage – age – between gender									
Ascending	Without luggage	Children	Male	Female	t-test	–	5.067 (0.000)	–	–
		Young	Male	Female				0.0231	0.047
		Elder	Male	Female				–	–
Descending	Without luggage	Children	Male	Female	t-test	–	5.531 (0.000)	0.0474	0.984
		Young	Male	Female				0.0175	0.039
		Elder	Male	Female				–	–
Considered: direction – between gender									
Ascending		Male	Female		t-test	–	–	0.0207	0.001
Descending		Male	Female		t-test	–	–	0.0138	0.034
Considered: direction – gender – between luggage condition									
Direction	Ascending	Descending			t-test	–	–	0.0126	0.012

Table 6. Summary of free speed at two transit stations

		Free speed (ms^{-1})	
Direction of movement	Gender	Suburban	Intercity
Descending	Male	0.81	0.65
	Female	0.66	0.50
Ascending	Male	0.69	0.57
	Female	0.63	0.48
Descending	Children	0.68	0.62
	Young	0.79	0.68
	Elder	0.56	0.49
Ascending	Children	0.67	0.54
	Young	0.69	0.60
	Elder	0.62	0.47

speed. It can also be concluded that free speed of pedestrian varies with functional characteristics of the station.

Conclusions

The present study analysed the free speed of pedestrian flow on stairways. Stairway is a basic entity for the pedestrian to interchange their movement at different levels in various pedestrian zones. It is widely adopted worldwide, as it is cost effective. In developing countries like India, stairways remain a vital element, particularly in rail transit stations, where it is difficult to replace the stairway with other alternatives. At rail transit station, pedestrian flow varies with respect to the schedule of the train. Moreover, pedestrian movement becomes more complex within undivided stairway, particularly at peak period resulting in a reduction in walking speed. In such case, it is difficult to observe the free speed of the pedestrian under different circumstances. A similar condition also prevails in other developing countries. Hence, the present study was carried out to estimate the free speed of pedestrian flow at two different rail transit stations varying in functional characteristics. To estimate free speed, laboratory-based analysis was carried out in which unidirectional flows, and bi-directional flows for different pedestrian characteristics were considered. From statistical analysis, it was found that for a density less than 0.45 pm^{-2}, pedestrians have minimal influence from surrounding pedestrians at corresponding space of 2.23 $m^2 p^{-1}$. Hence, to nullify the effect, speed distribution function was adopted to estimate the free speed of pedestrian flow. In order to perceive free speed for pedestrian traffic, 85th percentile speed is suggested to estimate the free speed. Distributions were compared for all speeds (including LDR and MDR to HDR). The results show that at MDR, the pedestrians cannot achieve their desired speed. Whereas in LDR, the pedestrian can achieve higher walking speed. It is also clearly indicated that even at the 85th percentile, pedestrian walking speed is lower (0.5 ms^{-1} for suburban and 0.46 ms^{-2} for interstate station) for higher density level than that of density lower than 0.45 pm^{-2} (0.62 ms^{-1} for suburban and 0.57 ms^{-2} for interstate station). Further, analysis of free speed of different pedestrian characteristics shows that the walking speed of young pedestrian was significantly higher than elders and children in descending direction as compared to ascending direction. Result also shows that the descending speed of male and female pedestrian was 15% higher than the ascending at suburban station. From the comparison, it is revealed that the free speed of pedestrian varies with the functional characteristics of rail transit station.

The study methodology and the results obtained are useful for developing and calibrating simulation models as well as establishing fundamental pedestrian flow relationship where it is difficult to obtain the free speed of pedestrian flows in a similar situation. It can be also be validated through controlled experiments, which give a better idea of pedestrian flow characteristics under different situations. Findings of this study are likely to help in better understanding of the field situation and contribute towards formulating an effective policy and practice for planning and design of pedestrian stairway facilities at railway stations in prevailing conditions.

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