

Fundamental diagrams of pedestrian flow characteristics: A review

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Abstract

Introduction The dimensionality of pedestrian infrastructure facilities have a great influence on pedestrian movements and a considerable impact on natural environment of the facility. Understanding the pedestrian movements are crucial to estimate the capacity of the system accurately, especially in the transportation terminals such as railway stations, bus terminals, airports and so forth, where large crowd gathers and transfers. To have a safe and comfortable movement in normal situation and also a quick evacuation in emergency situation, pedestrian movement patterns should be analysed and modelled properly.

Purpose Once the behaviour of pedestrians is established in terms of speed and density with respect to the environment, even for the colossal systems, the pedestrian flow characteristics can be modelled by applying extremely efficient simulations. The main modelling element in the context of flow models is the fundamental relationship among speed, flow and density. The objective of this study is to review the fundamental diagrams of pedestrian flow characteristics developed for various flow types and geometric elements. This paper also discusses the design values of flow parameters and walking speeds of pedestrians at various facilities.

Methods In order to achieve the goal of this paper, we presented a systematic review of fundamental diagrams of pedestrian flow characteristics developed by using various approaches such as field, experimental and simulation.

Conclusions After a thorough review of literature, this paper identifies certain research gaps which provides an opportunity to enhance the understanding of fundamental diagrams of pedestrian flow characteristics.

Keywords Fundamental diagrams · Pedestrian flow characteristics · Walking speed · Pedestrian infrastructure

1 Introduction

Understanding the pedestrian movement is complex when compared to vehicular movement as pedestrians have freedom to move in two dimensions. Also the graphical representation of pedestrian trajectories in both longitudinal and lateral direction is complicated. May [1] emphasized that “The two major differences between pedestrian and vehicular flow are the numerical values of flow characteristics and the use of lanes or width to define stream files. The lanes for the vehicular facilities may be well-defined whereas for pedestrian facilities, the facility width may vary over time and flow condition”. While comparing the vehicular flow and pedestrian flow, Treiber and Kesting [2] illustrate that every pedestrian has a desired direction in addition to the desired walking speed. Hence the desired velocity of a pedestrian is a vectorial quantity. Moreover, presence of cultural differences make the design values of pedestrian facilities in different regions to vary greatly. So it may not be appropriate to adopt one region design values for the design of another region’s pedestrian facilities. Many researchers [3–18] have conducted considerable amount of studies on pedestrian dynamics and developed numerous models

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over the past decades. For developing these models, researchers adopted different approaches such as experimental, field and simulation.

Empirical data from the field observations are essential for calibration and validation of any model. Acquiring permissions for collecting such data in public transport stations and some restricted areas is difficult because of security and privacy issues. Apart from these, the camera arrangements, tracking of pedestrians, lighting conditions, uncontrollable conditions etc. would make the data collection process complicated. In order to overcome the above problems researchers conduct experiments by simulating the real situations under controlled conditions either in open or closed areas with pedestrians as subjects [4]. Moreover, obtaining the practical data in the emergency situations or experimenting the panic situations is troublesome and the data obtained from these two methods may not be accurate and reliable. Hence simulation modelling would be a better approach to test “what if scenarios” in the complex systems, especially evacuation of people in emergency situations. A field and an experimental study has been carried out on the same stair case [9]. In this study, even though exact quantification of error is not given between the values of experimental and field observations, it was found that, for a particular density the corresponding flow values are slightly higher in experiments compared to field studies. Qu [19] compared the field observed walking speeds and simulated walking speeds on stairs and found the range of relative error 0.41 to 20.53 with an average relative error of 7.26%.

The pedestrian flow characteristics in congested and uncongested conditions can be well explained by Fundamental Diagrams (FDs) which shows the relationship between speed-flow-density. These diagrams are the basis for design of any infrastructural facility and helps in predicting the capacity of the system. In spite of extensive research in this area, the results from various studies shows that there exist wide variations in FDs. Even though the shape of the FDs remains same, the values of flow parameters vary immensely. These large variations encourage the researchers to study about FDs of pedestrian flow characteristics and different factors effecting them. Daamen et al. [20] presented FDs of pedestrian flow characteristics developed by different researchers based on the empirical studies conducted at different types of infrastructure and flow compositions (Fig. 1). However, it may not be appropriate to present the FDs developed for different conditions in a single diagram as they vary for various flow situations and also for different infrastructural elements. Personal and environmental characteristics influence the pedestrian motion. Moreover, capacity of the system depends on self-organization phenomena that includes zipper effect, oscillations at narrow bottlenecks, lane formations in uni-directional and bi-directional flows and so forth. This paper reviews the FDs of pedestrian flow characteristics for different geometric elements such as corridors, bottlenecks, stairs

and escalators with different flow situations being unidirectional, bidirectional and crossing in various pedestrian facilities. In addition the design values of flow parameters, walking speeds of pedestrians at various pedestrian facilities were also presented.

Rest of the paper is presented in five sections. Section 2 presents an overall critique on FDs. Section 3 presents FDs of different flow types. Section 4 reviews the FDs of various pedestrian infrastructural elements. Section 5 discusses the walking speed of pedestrians at various facilities. Finally in Section 6 the paper concludes by giving future directions to researchers.

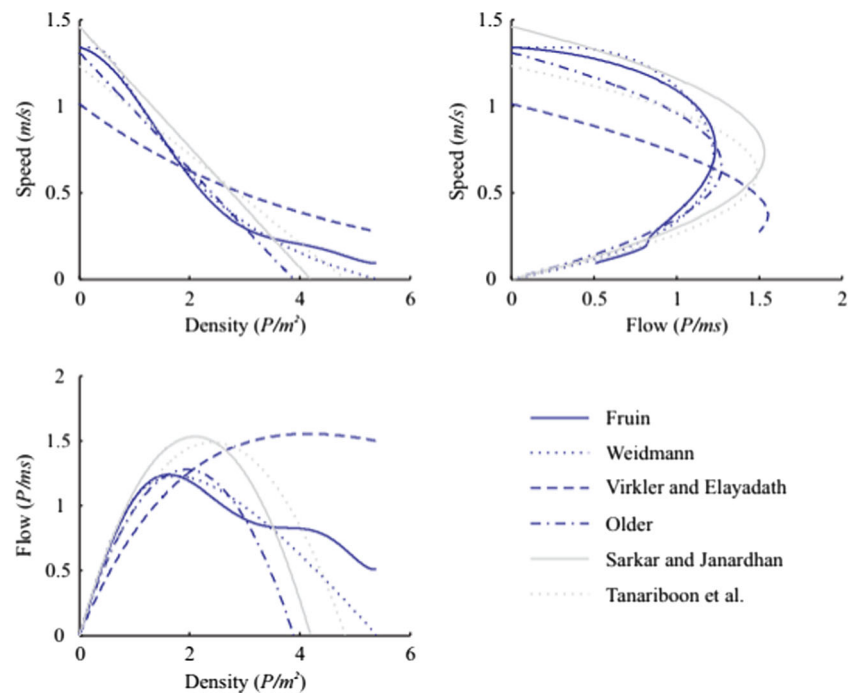
2 Fundamental diagrams of pedestrian flow characteristics

Macroscopic variables such as speed, flow and density have been used in assessing the performance of pedestrian facilities and these variables constitute the Fundamental Diagrams (FDs) of pedestrian flow. The fundamental diagram is the basic relation to characterise the pedestrian movements using the transport infrastructure. Firstly, the fundamental relationship helps in deriving the capacity and level of service values of the facility and thus allows for instant rating of emergency exits. Secondly, pedestrian flow models (macroscopic or microscopic) can be evaluated using empirical fundamental diagrams and it justifies the model capability in simulating pedestrian streams. Thirdly, pedestrian fundamental diagrams plays an important role in developing dynamic simulation models by providing equilibrium relationships between macroscopic variables. It can be concluded that, without proper understanding of the fundamental diagrams, it is difficult to design an efficient transport system.

An understanding of the fundamental relationship between flow - speed - density is important in the planning, design and operation of pedestrian facilities. The shape of the fundamental diagram is characterised by type of facility, gender, age, space requirements for the pedestrians and so on. In the early stage of pedestrian research, linear relationship between speed - density was assumed but with different linear relationships for different type of pedestrians. The linear speed-density relationship was used to develop a speed-space relationship and finally converted into speed-flow and flow-density relationship [1].

Considerable amount of research has been done for development and application of pedestrian fundamental diagrams. Several factors have been considered such as width of the facility, gradients and pedestrian characteristics. Critical investigations have taken place in areas such as bottlenecks, escalators and staircases. Influence of different flow types such as uni-directional, bi-directional, merging and crossing situations on fundamental diagrams is also studied.

Fig. 1 Fundamental diagrams of pedestrian flow characteristics from Literature (Daamen et al. [20])



Fundamental diagrams are critical in identifying congested and uncongested condition while monitoring pedestrian movement in small to large gatherings. Development of FDs are also relevant in emergency and evacuation planning.

Even though FDs are helpful in solving many problems, some issues are still persisting. They are as following.

1. Discrepancies in developing planning handbooks based on fundamental diagrams for different elements like staircases, escalators, emergency routes etc.
2. Differences between field, experimental and simulation data across different cultures and environments needs to be established and suitable adjustment factors between these studies should be proposed.
3. The flow density relationship for different geometric elements is important and further analysis like spatial and temporal development of the basic quantities (velocity, density and flow) on different elements like corridors, stairs and bottlenecks should be considered. Microscopic trajectory data offers the great opportunity to take a deeper look at influences of measurement method and selected measurement area. For example, till now these influences are not scrutinized and even the shape of the function has not been completely understood. A direct comparison of empirical data is possible only when the experiments under controlled conditions as well as field studies are conducted on the same facility. In general, field studies do not provide the favourable circumstances for the analysis on a microscopic scale, but they are helpful in gaining an overview about the basic quantities. Selection of location of the measurement area on a particular element (Example:

entry or exit point of the stairs) could influence the developed fundamental diagram [9].

4. Since the data compared is obtained under various experimental situations and different measurement methods, it is difficult to conclude whether and how the type of flow (uni- or bidirectional) influences the fundamental diagram. Till date there is no consensus on the origin of discrepancies between various types of pedestrian flows [21].
5. The extent to which various factors such as pedestrian and environmental characteristics influence the fundamental diagrams is unknown [3]. Further studies are needed in this direction.

3 Fundamental diagrams of various flow types

Different types of flow situations exist in pedestrian facilities such as uni-directional, bi directional and crossing. Unidirectional and bidirectional flow conditions can be commonly observed in corridors, stairs and bottlenecks of pedestrian facilities such as transport terminals, shopping malls etc. Crossing can be observed especially at junctions of transfer stations. The research studies shows that the FDs and the corresponding flow parameter values for all these flow situations are different. The studies conducted for different flow situations are as follows:

Daamen [3] conducted various experiments consisting of unidirectional, bidirectional and crossing flow situations at Delft University of Technology, Netherlands. The estimated

free flow speed from unidirectional flow experiment is found to be higher than the observations in literature. Also the average walking speeds in bidirectional flow situations are found lower than for unidirectional flows. From the single file experiment conducted by Lv et al. [4] found that the speed and distance headway are correlated nonlinearly. Zhang and Seyfried [22] observed a clear difference in FDs of uni and bidirectional pedestrian streams with the maximum flow value of 2 (ms)^{-1} and 1.5 (ms)^{-1} respectively. As there is a significant difference between uni and bidirectional flows, the design of pedestrian facilities should consider these characteristics. Figure 2 shows the FDs of unidirectional and bidirectional flow developed from various studies.

Cheung and Lam [23] examined the influence of bidirectional pedestrian flows on stairs and passageways and observed that with the increase in unbalanced pedestrian flow ratio, there is an increase in reduction of effective capacity of the facilities for a specific direction. In minor flow direction, the reduction in walking speeds was observed at capacity. A study conducted by Lam et al. [5] revealed that the free-flow speed was not influenced by the presence of counter flows. Further, it is noticed that effective capacity and at-capacity walking speeds are decreasing with the increase in the inequalities in the pedestrian flow ratios. Moreover presence of bidirectional flows influences minor flow direction significantly compared to major flow direction. Also the influence of bidirectional flow is more on shopping areas compared to commercial areas. Kretz et al. [24] found that as the group size increases, the passing times for each opposing flow fraction increases linearly. Zhang et al. [21] considered stable separated lanes (SSL - Stable Separated Lanes - pedestrians are addressed to choose the exits freely) and dynamical multi lanes (DML - Dynamic Multiple Lanes - pedestrians are addressed to choose specific exits) to categorize bidirectional flows. Also studied the influence of flow ratio on opposing pedestrian flows by introducing Balanced Flow Ratio (BFR) and Unbalanced Flow Ratio (UFR). The outcomes of the study

reveals that, for different degrees of ordering there is no significant difference in the FDs for densities less than 2.0 m^{-2} . Zhang and Seyfried [22] shows that head-on conflicts in the bidirectional streams has not affected the FD. Moreover the ordering of the stream is improved by self-organized lanes which provide relief to the conflicts.

There are limited studies available in investigating the crossing flows. However Zhang and Seyfried [25] found that FDs are not influenced by intersecting angles of 90° and 180° .

4 Fundamental diagrams for various infrastructural elements

The fundamental relationship between pedestrian flow characteristics for different geometric elements was not yet completely understood. Capturing the realistic behaviour of pedestrians in various pedestrian facilities with different geometric elements such as corridors, bottlenecks, stairs, escalators etc. is essential in order to estimate the flow parameters accurately. The important parameters such as width of the bottleneck, slope of the stairs plays a vital role in deciding the capacity of the respective element. Further, it is important to identify how the variations in these parameters influence the capacity. This section discusses the FDs of pedestrian characteristics for various elements such as corridors, bottlenecks, stairs and escalators. The FDs developed for pedestrian flow characteristics given by different planning guidelines and researchers are shown in Fig. 3. The line diagrams of these infrastructural elements are shown in Fig. 4.

4.1 Corridors

Corridors are simple and common elements in almost all types of pedestrian facilities designed to provide unidirectional and bidirectional flows. A study conducted by Hankin and Wright [27] at London subway reveals that the maximum flow and

Fig. 2 Fundamental diagrams of uni and bidirectional pedestrian flow from various studies (a) Density–speed and (b) density–specific flow (Zhang and Seyfried [22])

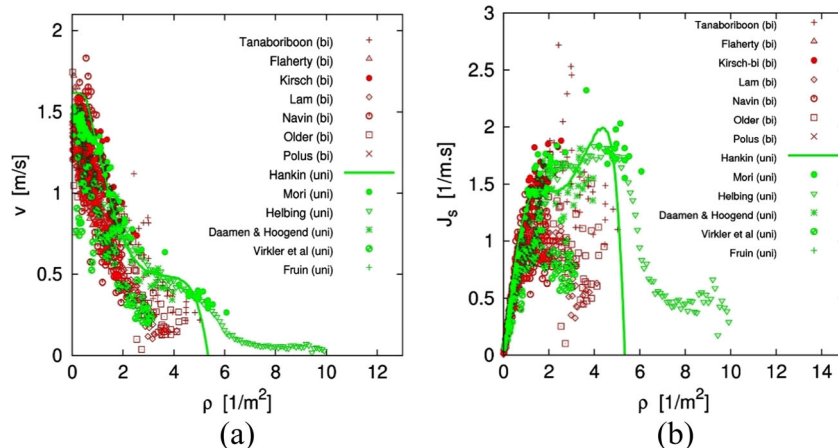
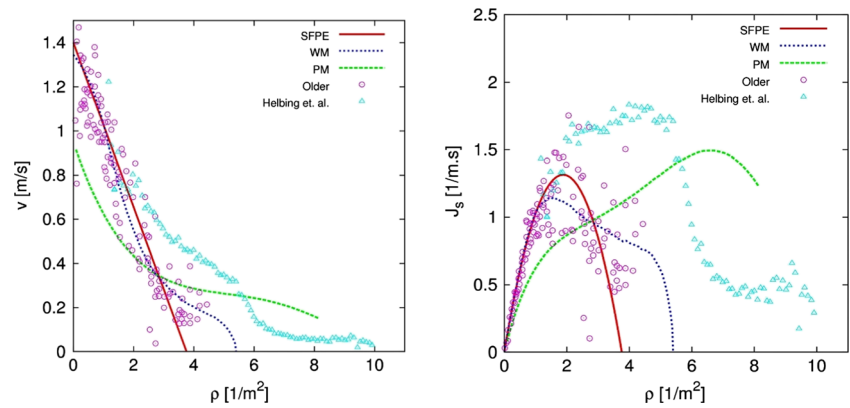


Fig. 3 Fundamental diagrams for pedestrian movement in planar facilities [Lines represent specifications given by planning handbooks (SFPE: Handbook, PM: Predtechenskii and Milinskii, WM: Weidmann). Points represent observations of experiments] (Seyfried et al. [26])



width of corridor are proportional to each other for a corridor width of at least above a minimum of 4 ft. Chattaraj et al. [6] found that FD is not influenced by corridor width. Zhang et al. [28] found that for densities less than 3 m^{-2} , the specific flow approach works well for different widths of corridors. While comparing the FDs of same type of corridor with various widths it was found that the results were matching with Hankin’s findings. Moreover, the outcomes of this study concur with the assumption that specific flow does not depend on the facility width. Zhang and Seyfried [22] found that straight corridors have highest flow when compared to bottlenecks which can be considered as an important point in the design

of emergency exits. The experimental results of Zhang et al. [29] shows that FDs developed for various widths of the corridor agrees well and supports the assumption that flow – density relations for the same type of facility can be combined into single diagram for specific flow. Moreover FDs developed by various measurement methods show equal tendency however with different accuracy.

4.2 Bottlenecks

Bottlenecks are the crucial elements of pedestrian infrastructure where the capacity reduces drastically. Their capacities

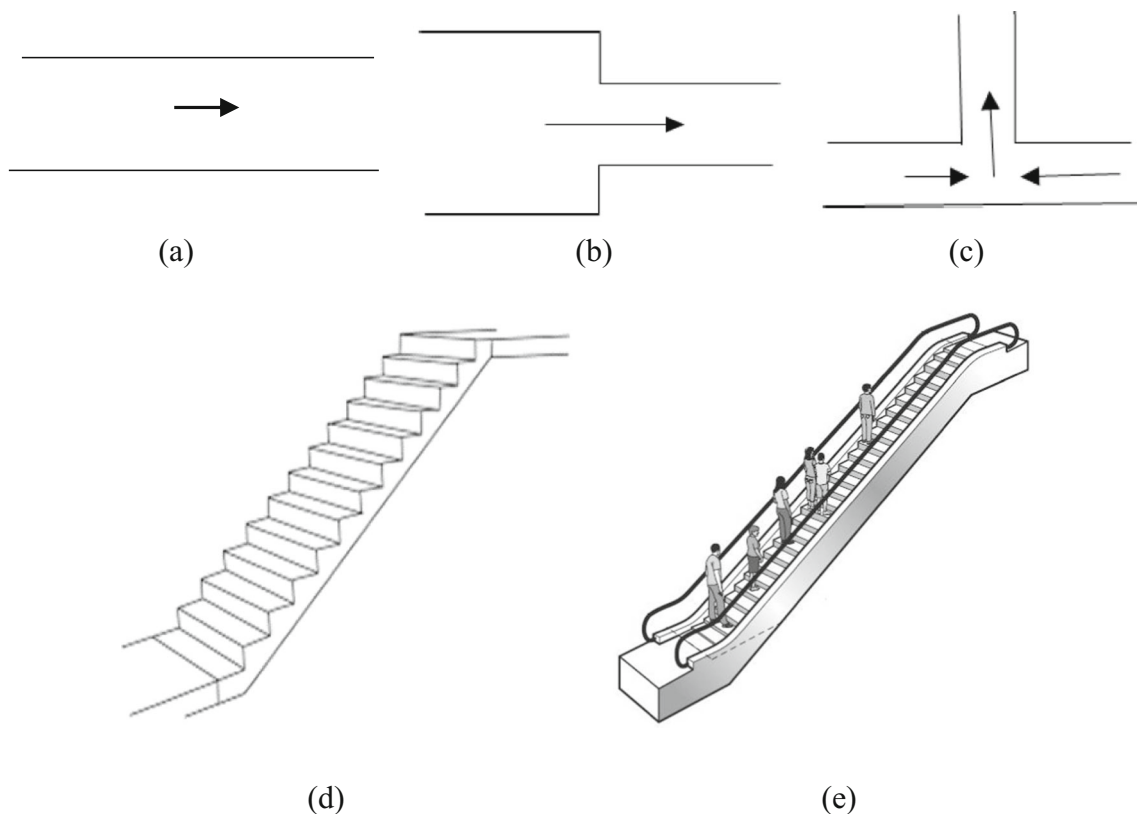
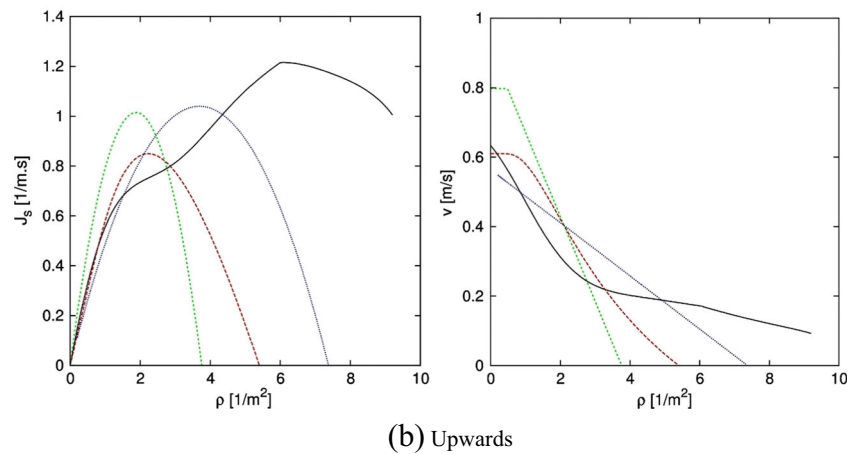
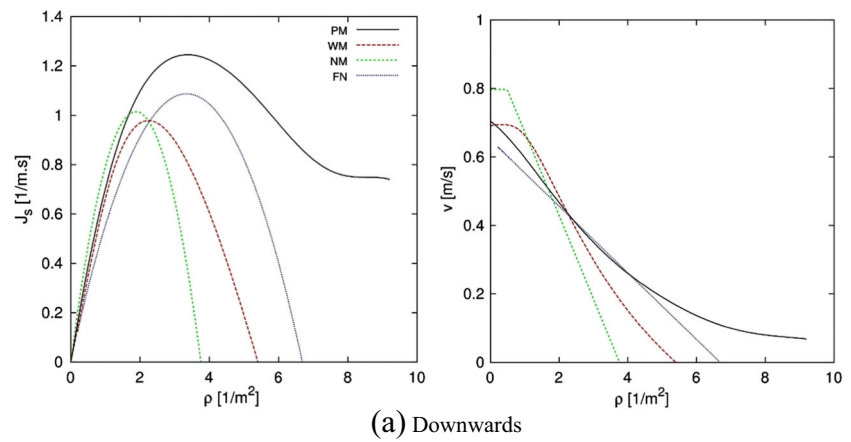


Fig. 4 Line diagrams of Geometric elements (a) Corridor (b) Bottleneck (c) T – Junction (d) Stair case (e) Escalator

Fig. 5 Fundamental diagrams of stairs given by different planning guidelines [PM: Predtechenskii and Milinskii (1978) [32], NM: Nelson and Mowrer (2002) [33], FN: Fruin (1971) [34], WM: Weidmann (1993) [35]] (Burghardt et al. [9])



should be examined with at most care especially to deal the evacuation of pedestrians in emergency situations. Several experimental and simulation studies have been performed to analyse the pedestrian flow characteristics in bottleneck with unidirectional and bidirectional flows. Hoogendoorn and Daamen [7] found that, with the increase in bottleneck width the capacity increases in a stepwise manner because of zipper effect. Whereas, Seyfried et al. [8], Tian et al. [30] shows that flow is linearly increasing with bottleneck width. To analyse

the pedestrian microscopic movement characteristics, Tian et al. [31] conducted a series of experiments in a bottleneck through which the lane formation phenomena was observed. One, two and three lanes were observed when the bottleneck width is kept as 0.5–0.7 m, 0.8–1.1 m, 1.2–1.4 m respectively. Zhang and Seyfried [22] found that long bottlenecks have lower flow values compared to short bottlenecks which shows that emergency exits should be planned and designed keeping in view of shape and geometry of the facility.

Fig. 6 Measurements of the fundamental diagram for stairs obtained from various field and experimental studies. Full range of observation points has been shown in the small diagram enclosed (Burghardt et al. [9])

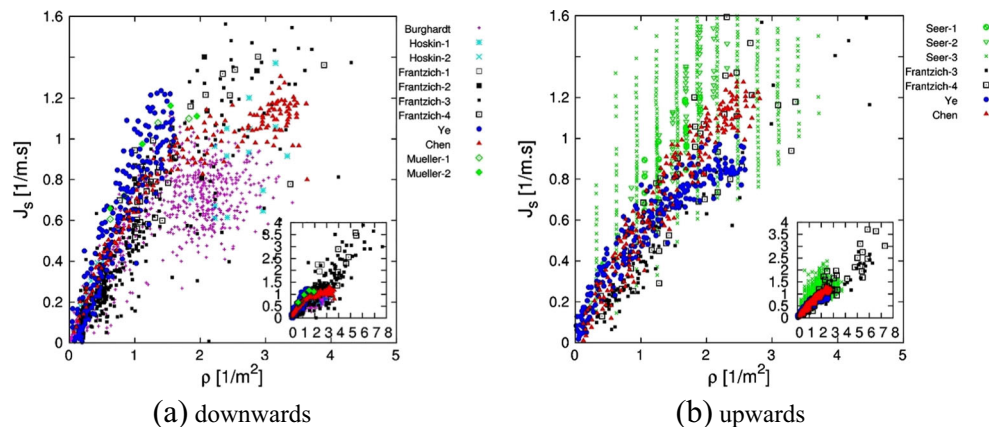


Table 1 Review of Fundamental diagrams of pedestrian flow characteristics

Author	Purpose	Element	Type of Flow	Country	Design values	Remarks
Field Studies Lam et al. [5]	Speed-flow Relationship	Indoor walkways	B	Hong Kong, SAR, China	Description Effective capacity (ped/m/min) 1.0 At-capacity walking speed (m/min) 0.1	Proposed a generalized walking time function with bi-directional Pedestrian flow ratio (GBPR) commercial area 75.0 66.7 51.01
Lee [11]	FD	Stairways, Escalators	U	Netherlands	Description V_f (m/s) 0.77 q_{max} (ms) ⁻¹ 0.86 Description Maximum flow rate (Ped/min) 48.25 Median flow rate (Ped/min) 47.6	Escalators d a 0.88 0.82 0.93 0.67 Stairs - 111.11
Seer et al. [38]	FD	Meanders, stairs	U	Austria	Description Maximum flow rate (Ped/min) 48.25 Median flow rate (Ped/min) 47.6 Median headway (sec) 1.26 Different capacity values for different directional split ratios with different age group of pedestrians	Pedestrians personal characteristics, infrastructure type and directions of movement influences free speeds Maximum and effective capacities for meanders and stairs were estimated from the developed FD's.
Alhajyaseen et al. [39]	Speed-flow relationship	Crosswalk	B	Japan	Description Median headway (sec) 1.26 Different capacity values for different directional split ratios with different age group of pedestrians	Reduction in capacity is maximum at approximately equal directional split. Capacity may reduce up to 30% because of presence of elderly pedestrians. Flow decreases with increase in stair gradient. Flow values for a given density in experiments are slightly higher than field observations Pedestrians walk faster during the afternoon or day time compared to evening. Presence of the pedestrians with luggage has significant effect on reduction in the average walking speed of pedestrian.
Burghardt et al. [9]	Effect of stair gradient on FD	Stairs	U	Germany	Description $q_{smax} = 1.1$ (ms) ⁻¹ $K_{max} = 3.4$ m ⁻²	Pedestrian flow characteristics are different for indoor and outdoor facilities
Shah et al. [40]	FD	Stairs	-	India	Description V_{avg} (during afternoon) - 29.70 m/min V_{avg} (during evening) - 23.73 m/min Different design values on different staircases	FDs shows that co-flow speed are higher for descending pedestrians than for ascending ones. Speeds in counter-flows appear to be higher than in corresponding co-flows Pedestrians walked downstairs faster than upstairs. Sub-group behaviour and lane formation were observed
Kawsar et al. [41]	FD	walkways and stairs inside a hall room	U	Malaysia	Description Level walkways Stairs (a) Stairs (d)	Flow rate (ped.(ms) ⁻¹) min 1.41 max 0.27 0.51 0.73 0.54 0.08 0.88
Corbetta et al. [42]	FD	Corridor between stairs	B	Netherlands	Description -	FDs shows that co-flow speed are higher for descending pedestrians than for ascending ones. Speeds in counter-flows appear to be higher than in corresponding co-flows Pedestrians walked downstairs faster than upstairs. Sub-group behaviour and lane formation were observed
Qu et al. [19]	FD	Stairs	U	China	Description -	FDs shows that co-flow speed are higher for descending pedestrians than for ascending ones. Speeds in counter-flows appear to be higher than in corresponding co-flows Pedestrians walked downstairs faster than upstairs. Sub-group behaviour and lane formation were observed
Experimental Studies Daamen and Hoogendoorn [43]	FD	Narrow bottleneck	U	Netherlands	Description $V_{fmin} = 0.86$ m/s $V_{fmax} = 2.18$ m/s $V_{avg} = 1.58$ m/s Capacity = 1.5 (ms) ⁻¹	Usage of bottleneck is different during near-capacity and capacity flow conditions compared to free flow situations
Seyfried et al. [44]	FD for single-file motion of pedestrians	Corridor	U	Germany	Description Different flow parameter values for different bottleneck widths	Observed linear relation between Speed and the inverse of density
Seyfried et al. [8]	Capacity estimation from FD	Bottleneck	U	Germany	Description Bottleneck	Observed linear growth of flow with width
Seer et al. [38]	FD	Meanders and stairs	U	Austria	Description Group Median Flow rate (Ped/min) Headway (sec) Flow rate (Ped/min)	Maximum and effective capacities for meanders and stairs were estimated from the developed FD's.
					1.08 - 1.12 - 89.82 113.65	

Table 1 (continued)

Author	Purpose	Element	Type of Flow	Country	Design values	Remarks
Seyfried et al. [26]	Influence of measurement method on FD	Corridor	U	Germany	—	Application of different measurement methods leads to large deviations in the results
Chattaraj et al. [45]	Effect of culture, length of corridor on FD	Corridor	U	India and Germany	$V_f(\text{India}) = 1.27 (\pm 0.16) \text{ m/s}$ $V_f(\text{Germany}) = 1.24 (\pm 0.15) \text{ m/s}$	Indian subjects speeds are higher than those of German subjects, Corridor length has no impact on the distance headway-speed relation
Zhang et al. [21]	Influence of ordering in bidirectional flows on FD	Corridor	B	Germany	$V_{\text{avg}} = 1.55 \pm 0.18 \text{ m/s}$ $q_{\text{max}} = 1.5 (\text{ms})^{-1} \text{ (U)}$ $q_{\text{max}} = 2.0 (\text{ms})^{-1} \text{ (U)}$ $q_{\text{max}} = 1.5 (\text{ms})^{-1} \text{ (B)}$	Up to densities of 2 m^{-2} there is no significant difference observed in the FDs for various degrees of ordering (DML, SSL, BFR and UFR)
Zhang et al. [28]	Influence of measurement method on FD comparison of FD for T-Junction and corridor	T-Junction and Corridor	U	Germany	—	Different methods produces agreeable results with some differences. FDs of various elements cannot be compared
Zhang et al. [29]	FD	Corridor	U	Germany	—	FDs developed by various methods show equal tendency however with different accuracy. FDs for the same type of facility can be combined into single diagram for specific flow.
Tian et al. [30]	FD	Corridor acting as bottleneck	U	China	—	Observed a linear relationship between Flow rate and bottleneck width. Pedestrians behaviour in the corridor has a significant effect on time headways and their distribution when they form lanes
Yang et al. [46]	Speed-flow-density relationship	Stairs	U	China	Different values of parameters for different stairs and also for different situations	Flow rate and density exhibited different tendency for stairs with different dimensions. In emergency situation, the effect of velocity on density was more significant compared to normal situation
Ly et al. [4]	Pedestrian movement behaviour	Different environments	U	China	$V_{\text{max}} = 1.56 \text{ m/s}$	Incorporating local direction-changing mechanism, self-slowing and visual hindrance information, a 2-D continuous model has been proposed
Burghardt et al. [9]	Effect of stair gradient on FD	Stairs	U	Germany	$q_{\text{max}} = 1.1 (\text{ms})^{-1} \text{ (U)}$ $K_{\text{max}} = 2.6 \text{ m}^{-2}$	Flow decreases with increase in stair gradient. Flow values for a given density in experiments are slightly higher than field observations
Zhang and Seyfried [22]	FD	Corridor	U&B	Germany	$q_{\text{max}} = 2.0 (\text{ms})^{-1} \text{ (U)}$ $q_{\text{max}} = 1.5 (\text{ms})^{-1} \text{ (B)}$	Observed a clear difference between the FD's of unidirectional and bidirectional flows
Bandini et al. [47]	FD	Corridor	U&B	Italy	—	High density conditions are simulated by extending the floor-field CA
Zhang and Seyfried [25]	Influence of intersection of pedestrian flows on FD	Corridor and other scenarios	B&C	Germany	Different flow parameters for different flow situation scenarios	Intersecting angles of 90° and 180° has no influence on the FD's of various flow types.
Flötteröd and Lämmel [13]	FD	Straight corridor and round corridor	B	Germany	—	Proposed a one-on-one mapping between FD parameters of uni and bidirectional flows
Simulation Studies Seyfried et al. [14]	Effect of remote action and required space on FD	Corridor	U	Germany	Intended speed values are normally distributed with $\mu = 1.24 \text{ m/s}$ $\sigma = 0.05 \text{ m/s}$	Modified the Social force model. The replication of classical FD is achievable by increasing the required space and prevailing velocity of a person
Bruno [15]	Speed-Density Relation	Footbridge	—	Italy	$V_{\text{avg}} = 1.34 \text{ m/s}$	Proposed a model that considers the influence of travel purpose, geographic area and effect of lateral vibrations of platform on Speed-Density relation

Table 1 (continued)

Author	Purpose	Element	Type of Flow	Country	Design values	Remarks
Hao et al. [16]	FD	Unknown	U	China	—	A lattice gas model with parallel update rules is used to study unidirectional pedestrian flow
Chattaraj et al. [6]	Single file pedestrian movement	Corridor	U	India & Germany	—	Dissimilarities exist in FD due to cultural differences
Lv et al. [4]	Pedestrian movement behaviour	Different environments	U	China	For Evacuation simulation, $V_{max} = 0.75$ m/s For Bottleneck simulation, q_s obtained is $2.25(\text{ms})^{-1}$	Simulation of passage and bottleneck were carried out using 2-D continuous model
Bandini et al. [47]	FD	Corridor	U&B	Italy	Pedestrian Speed = 1.2 m/s	High density conditions are simulated by extending the floor-field CA
Qu et al. [19]	FD	Stairs	U	China	Different simulation results for different staircases	Estimated the evacuation time and capacity of stairs using simulations
Flötteröd and Lämmel [13]	FD	Straight corridor and round corridor	B	Germany	—	Proposed a one-on-one mapping between FD parameters of uni and bidirectional flows
Fu et al. [48]	Lock-step effect and Random slowdown process influence on FD	Unknown	U	China	Pedestrian desired Speed = 1.6 m/s	Influence of lock-step was analysed by Estimating-Correction Cellular Automaton (ECCA) model

4.3 T - Junction

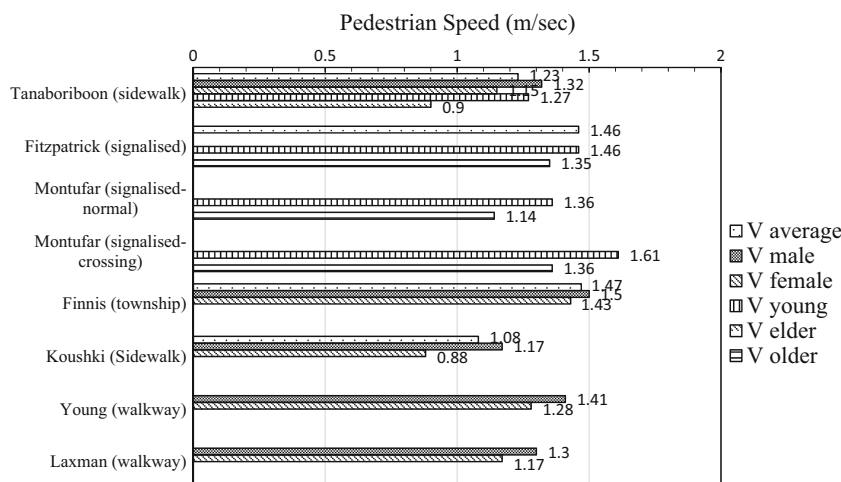
While limited research is available on pedestrian characteristics in other geometric elements, Zhang et al. [28] compared the FDs for a T-Junction and straight corridor and expressed that FDs of various facilities cannot be compared because of the inequality existed between inflow and outflow which leads to a transition between low densities and high densities in the pedestrian flow.

4.4 Stairs and escalators

Stairs are considered as one of the most important part of the egress routes (Fig. 4d). Understanding the evacuation dynamics of pedestrians on stairs is crucial especially to analyse the emergency situations. Different planning guidelines, empirical and experimental studies proposed FD's and flow parameter values for stairs in ascending and descending directions. To know the variation in flow parameters of different guidelines, values obtained from different experimental studies the reader is advised to refer Burghardt et al. [9]. A comparison of FD's of stairs given by different planning guidelines, measurements of FD obtained from various field and experimental studies was published in Burghardt et al. [9] and is presented in Figs. 5 and 6 respectively.

Cheung and Lam [23] observed higher values of capacities and walking speeds on stairways and passageway at Hong Kong Metro stations compared to London underground stations. Further, it is found that the effect of bidirectional pedestrian flows on staircase are more significant compared to passageway. Cheung and Lam [10] investigated the relationship between speed and flow on stairs and escalators (ascending, descending) and found that pedestrians behaviour differ when they use the facilities in both directions. It is noticed that the pedestrians are more susceptible to relative delay on both the facilities in descending direction compared to ascending direction. Further, it is observed that 85% of pedestrians are desirous to use an escalator in descending direction when the relative delay is 7.8 s while in ascending direction it can be up to 17.4 s. This is interpreted by the fact that the effort in walking in descending direction of a staircase is perceived to be less than walking in ascending direction. Graat et al. [36] found that the capacity and speed are higher on stairs with normal slope (30°) than the stairs with steeper slope (38°) which clearly shows that stair gradient effects the velocity and capacity. Lee [11] conducted a study on escalators and staircase in public transport facilities and observed that direction of movement, infrastructure type and pedestrian personal characteristics influences free speeds. Further, it is noticed that men walk faster than women. At Hong Kong MTR stations Lee and Lam [37] investigated the walking speed variations on a unidirectional walkway and a

Fig. 7 Pedestrian walking speeds from various studies



bidirectional stairway and observed that, when the pedestrian flow is reaching the capacity of the facility, the variation in the walking speed is found to be minimal. In addition, it was also observed that the walking times are normally distributed. To predict the pedestrian walking speeds on staircase a linear regression model is developed by Fujiyama and Tyler [12] by considering stair gradient, leg extensor power of pedestrian and weight of the participant. This model shows that the walking speeds are different on various gradients of stairs, while the designers generally neglect these differences. In addition the model is presenting a specific profile in predicting the walking speeds of people. Burghardt et al. [9] conducted an experimental study and a field study on the same staircase and observed a maximum density of 2.9 m^{-2} and 3.4 m^{-2} respectively. Further, it was observed that the flow values for a given density in experiments are slightly higher than the field values.

A comprehensive review of FDs of pedestrian flow characteristics is presented in Table 1. The studies described in Table 1 mostly discuss FDs and factors effecting it for exclusive pedestrian facilities.

Pedestrian walking speed is of special interest to transportation engineers and planners because it greatly influences the level of service and capacity of the system. For instance, if the percentage of women and older pedestrians increases the speeds decreases thereby capacity of the system also reduces because of their smaller step length and less step frequency etc. Hence, to understand the capacity of a facility and also to know the evacuation characteristics, it is important to understand the walking speeds in various environments. From various sources it is observed that individual pedestrian characteristics and external conditions are influencing the pedestrian speeds. Some of the factors mentioned are age, culture, gender, shy away distance, temperature, travel purpose, type of infrastructure, walking direction [3].

5 Walking speeds at various facilities

Pedestrian walking speed is an important parameter in the design of walking infrastructure as it decides the capacity of a facility. Pedestrian speeds are greatly influenced by pedestrian environment and the characteristics of the surrounding crowd. For example, pedestrians in shopping and commercial areas walk slowly when compared to walking in the public transport places [3]. Pedestrian walking behaviour may differ with respect to geographic location due to the presence of cultural differences. Hence it is necessary to consider this particular aspect of pedestrian dynamics for the design of facility specific to a country or region. For instance Indians maintain higher speeds and less headways when compared to Germans [45]. From the previous studies, [49–53] it is evident that younger pedestrians maintain higher speeds when compared to old pedestrians. Also men walk at higher speeds while compared to women [17, 49–55]. Tanaboriboon et al. [49] reported the mean walking speed in Singapore as 74 m/min which is relatively slower than the walking speeds in American counterparts. Further, the maximum flow rate obtained is 89 pedestrians/m/min which is higher than the values obtained in western countries. This is interpreted by the reason that the Singaporeans require less space for the movement because of their smaller physique. Koushki [54] in Riyadh, found the average walking speed of pedestrians as 65 m/min which is less when compared to the walking speeds of United States, England and Singapore. Young [55] reveals that the moving walkway in the corridor affects the walking speeds of pedestrians those who use it. The standing persons on the moving walkways becomes obstacles to the following pedestrians who are using the system next to them results in congestion on the system thus reduces the average walking speeds and leads to increased travel times. Montufar et al. [51] shows that walking speeds in summer are greater than in winter for both younger and older pedestrians. Further, they found that

the normal walking speed is less than the crossing walking speed for different age groups in different seasons. In contrast, Avineri et al. [53] shows that irrespective of different age groups, pedestrian walking speeds are higher on sidewalks or footpaths while compared to the signalized and unsignalized intersections. While analysing the group behaviour of pedestrians Moussaid et al. [18] observed a continuous decrease in walking speeds with the increase in group size. Based on fundamental relationships HCM [56] presents that walking speeds differ for different classes of pedestrians such as shoppers, students and commuters. Laxman et al. [17] conducted a study in India under mixed traffic conditions and found that the pedestrian free speed is 84 m/min which is higher than in Singapore and China and a little lower than Germany. Further, the means speeds are reduced by 10% when they are carrying baggage. Among the explanatory variables such as longitudinal gradient, effective footway width, age, individuals or group, gender and time of the day Silva et al. [57] found that the longitudinal gradient of the footway is the most significant variable in explaining the walking speed. Figure 7 shows the comparison of pedestrian walk speeds from various studies. It is quite evident that barring a couple of studies, most speeds are in the range of 1.0–1.5 m/s. Further, the differences amongst various age groups and gender are also shown. Travel purpose is found to influence the walking speeds of pedestrians. According to Daamen [3] higher walking speeds were observed for pedestrians travelling for business followed by commuters, shoppers and then pedestrians walking in leisure. Especially, higher free speeds are observed in transfer stations compared to shopping areas. The possible reason may be because the pedestrians are in hurry to catch a train or bus thus increasing their walking speeds whereas the shopping is a leisure trip and with maintaining lower speeds.

V_f – Free speed, V_{favg} – Mean free speed, V_{max} = Maximum Speed, V_{avg} – Mean Speed, q_{max} – Maximum flow, q_s – Specific flow, q_{smax} – Maximum specific flow, K – Density, K_{max} – Maximum density, d – descending, a – ascending, U – Unidirectional flow, B – Bidirectional flow, C – Crossing.

6 Conclusions and future directions

The paper presented a comprehensive review of FDs of pedestrian flow characteristics. Based on the review, this paper draws the following conclusions and identifies the research gaps and hence the scope for further studies. Exploring these gaps will enhance the understanding of FDs of pedestrian flow characteristics. This would also help improve the modelling based on the suggestions made.

- Even though a considerable amount of literature on development of FDs based on theoretical and experimental concepts is available, literature based on empirical findings are limited. From the previous studies it is observed that mostly the research is focused on experiments. As the emotional status of the participants is relaxed during the experiments, they cannot at times reflect the actual behaviour of pedestrians which exists in real life situations. Hence there is a great need to focus on development of FDs by conducting field studies for various pedestrian infrastructure elements with different flow situations.
- Because of the favourable controlled conditions, researchers [3, 4, 6–9, 22, 24–26, 28–31, 43–46] are interested in conducting experimental studies. The results obtained in experiments can be comparable only if the field studies are conducted on the same element [9]. Otherwise the accuracy of the experimental results cannot be justified. Moreover, differences between field, experimental and simulation data across different cultures and environments needs to be established and suitable adjustment factors between these studies should be proposed.
- Zhang et al. [29] shows that the FDs of same element with different widths can be combined into a single diagram whereas for different elements it cannot be combined. For instance, the FDs of T-junctions and corridors cannot be combined as the inflow and outflow are different [28]. This shows that FDs are different for different elements as well as different flow conditions. So further deep examination is needed in this area.
- Cultural differences do influence the pedestrian flow characteristics as well as capacities of the pedestrian infrastructural facilities [10, 12, 36, 45, 58]. In order to understand the cultural differences, it is suggested to conduct the research in various regions and compare the design values of flow parameters across various cultures. In addition, it is observed that individual pedestrian characteristics and external conditions are influencing the pedestrian speeds. Some of the factors are age, culture, gender, shy away distance, temperature, travel purpose, type of infrastructure, walking direction. Moreover, the extent to which these factors influence the fundamental diagrams is unknown. [3] Future studies need to focus in this direction.
- Fundamental relationships of pedestrian flow characteristics for various classes of pedestrians are different [3, 56]. This infers that pedestrians walking speed differs with respect to the facility and trip purpose. Hence the application of walking speeds of one facility for the design of other facility may not lead to fruitful results. As walking speeds decides capacity of the facility, it needs to be examined with respect to the context.
- Even for a simple element like a corridor, the application of various measurement methods leads to a large variation in the observations of FD [26]. This reveals that measurement method does influence the results and hence it should be examined further.

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References

- May AD (1990) Traffic Flow Fundamentals. Prentice-Hall, Inc., New Jersey
- Treiber M, Kesting A (2013) Traffic Flow Dynamics. Springer, Heidelberg
- Daamen W (2004) Modelling Passenger Flows in Public Transport Facilities. PhD Thesis, Delft University of Technology
- Lv W, Song WG, Ma J, Fang ZM (2013) A Two-Dimensional Optimal Velocity Model for Unidirectional Pedestrian Flow Based on Pedestrian's Visual Hindrance Field. IEEE Trans Intell Transp Syst 14(4):1753–1763. <https://doi.org/10.1109/TITS.2013.2266340>
- Lam WHK, Chan KS, Goh PK (2003) A Generalised Function for Modeling Bi-Directional Flow Effects on Indoor Walkways in Hong Kong. Transp Res A Policy Pract 37(9):789–810. [https://doi.org/10.1016/S0965-8564\(03\)00058-2](https://doi.org/10.1016/S0965-8564(03)00058-2)
- Chattaraj U, Seyfried A, Chakroborty P, Biswal MK (2013) Modelling Single File Pedestrian Motion Across Cultures. Procedia Soc Behav Sci 104:698–707. <https://doi.org/10.1016/j.sbspro.2013.11.164>
- Hoogendoorn SP, Daamen W (2005) Pedestrian Behavior at Bottlenecks. Transp Sci 39(2):147–159. <https://doi.org/10.1287/trsc.1040.0102>
- Seyfried A, Rupperecht T, Passon O, Steffen B, Klingsch W, Boltes M (2007) New Insights into Pedestrian Flow through Bottlenecks. Transp Sci 43:395–406 43 (3): 16. <https://doi.org/10.1287/trsc.1090.0263>
- Burghardt S, Seyfried A, and Klingsch W (2013) Performance of stairs—fundamental diagram and topographical measurements. Trans Res Part C: Emerg Technol 37:268–278. <https://doi.org/10.1016/j.trc.2013.05.002>
- Cheung CY, Lam WHK (1998) Pedestrian Route Choices between Escalator and Stairway in MTR Stations. J Transp Eng 124(3):277–285. [https://doi.org/10.1061/\(ASCE\)0733-947X\(1998\)124:3\(277\)](https://doi.org/10.1061/(ASCE)0733-947X(1998)124:3(277))
- Lee YC (2005) Pedestrian walking and choice behavior on stairways and escalators in public transport facilities. Master of Science Thesis, Delft University of Technology 1: 1050–1100
- Fujiyama T and Tyler N (2010) Predicting the walking speed of pedestrians on stairs. Trans Plann Technol 33(2):177–202. <https://doi.org/10.1080/03081061003643770>
- Flötteröd G, Lämmel G (2015) Bidirectional Pedestrian Fundamental Diagram. Transp Res B Methodol 71:194–212. <https://doi.org/10.1016/j.trb.2014.11.001>
- Seyfried A, Steffen B, Lippert T (2006) Basics of Modelling the Pedestrian Flow. Phys A Stat Mech Appl 368(1):232–238. <https://doi.org/10.1016/j.physa.2005.11.052>
- Bruno L (2008) The pedestrian speed-density relation: modelling and application. Proceedings Footbridge 2008, Porto
- Hao Q-Y, Jiang R, Hu M-B, Jia B, Wu Q-S (2011) Pedestrian Flow Dynamics in a Lattice Gas Model Coupled with an Evolutionary Game. Phys Rev E 84(3):1–8. <https://doi.org/10.1103/PhysRevE.84.036107>
- Laxman KK, Rastogi R, Chandra S (2010) Pedestrian flow characteristics in mixed traffic conditions. J Urban Plan Dev 136(1)
- Moussaid M, Perozo N, Garnier S, Helbing D, Theraulaz G (2010) The Walking Behaviour of Pedestrian Social Groups and Its Impact on Crowd Dynamics. PLoS One 5(4):e10047 5 (4): 1–7. <https://doi.org/10.1371/journal.pone.0010047>
- Qu Y, Gao Z, Xiao Y, Li X (2014) Modeling the Pedestrian ' S Movement and Simulating Evacuation Dynamics on Stairs. Saf Sci 70:189–201 70: 189–201
- Daamen W, Hoogendoorn SP, Bovy PHL (2005) First-Order Pedestrian Traffic Flow Theory. Transp Res Rec J Transp Res Board 1934:43–52
- Zhang J, Klingsch W, Schadschneider A, Seyfried A (2011a) Ordering in bidirectional pedestrian flows and its influence on the fundamental diagram. J Stat Mech: Theory Exp 2012.02(2012): P02002 1:9. <https://doi.org/10.1088/1742-5468/2012/02/P02002>
- Zhang J, Seyfried A (2013) Empirical Characteristics of Different Types of Pedestrian Streams. Unpublished Manuscript, University of Wuppertal and Forschungszentrum Jülich
- Cheung CY and Lam WHK (1997) A study of the bi-directional pedestrian flow characteristics in the Hong Kong mass transit railway stations. J Trans Eng 2(5):1607–1619
- Kretz T, Grünebohm A, Kaufman M, Mazur F, Schreckenberg M (2006) Experimental study of pedestrian counterflow in a corridor. J Stat Mech: Theory Exp no. P10001. <https://doi.org/10.1088/1742-5468/2006/10/P10001>
- Zhang J, Seyfried A (2014) Comparison of Intersecting Pedestrian Flows Based on Experiments. Phys A Stat Mech Appl 405:316–325. <https://doi.org/10.1016/j.physa.2014.03.004>
- Seyfried A, Boltes M, Klingsch W, Portz A, Rupperecht T, Schadschneider A, Steffen B, Winkens A (2008) Enhanced empirical data for the fundamental diagram and the flow through bottlenecks. In: Pedestrian and evacuation dynamics 2008. Springer, p 145
- Hankin BD, Wright RA (1958) Passenger Flow in Subways. Oper Res Q 9:81–88 9 (2): 2318–22. <https://doi.org/10.1093/brain/awt057>
- Zhang J, Klingsch W, Schadschneider A, Seyfried A (2011) Transitions in Pedestrian Fundamental Diagrams of Straight Corridors and T-Junctions. J Stat Mech: Theory Exp 2011.06(2011):P06004
- Zhang J, Klingsch W, Seyfried A (2012) High precision analysis of unidirectional pedestrian flow within the Hermes project." Unpublished Manuscript, University of Wuppertal and Forschungszentrum Jülich, 1–8
- Tian W, Song W, Ma J, Fang Z, Seyfried A, Liddle J (2012) Experimental Study of Pedestrian Behaviors in a Corridor Based on Digital Image Processing. Fire Saf J 45(2012):8 47: 8–15. <https://doi.org/10.1016/j.firesaf.2011.09.005>
- Tian W, Song W, Lü W, Fang Z (2011) Experiment and Analysis on Microscopic Characteristics of Pedestrian Movement in Building Bottleneck. SCIENCE CHINA Technol Sci 54(7):1730–1736. <https://doi.org/10.1007/s11431-011-4425-x>
- Predechenskii VM, Milinskii AI (1978) Planning for foot traffic flow in buildings. Amerind Publishing, New Delhi, Translation of: Proektirovanie Zhdanii s Uchetom Organizatsii Dvizheniya Lyudskikh Potokov. Stroizdat Publishers, Moscow
- Nelson HE, Mowrer FW (2002) Emergency movement. In: SFPE Handbook of fire protection engineering, 3rd edn, pp 367–380 (Chapter 14). National Fire Protection Association, Quincy, MA
- Fruin JJ, (1971) Pedestrian planning and design. Elevator World, New York
- Weidmann, U., 1993. Transporttechnik der Fussgänger. Institut für Verkehrsplanung, Transporttechnik, Strassen- und Eisenbahnbau, ETH Zürich. Tech. Rep. Schriftenreihe des IVT Nr. 90.

36. Graat E, Midden C, Bockholts P (1999) Complex evacuation; effects of motivation level and slope of stairs on emergency egress time in a sports stadium. *Saf Sci* 31(2):127–141
37. Lee J, Lam W (2006) Variation of Walking Speeds on a Unidirectional Walkway and on a Bidirectional Stairway. *Transp Res Rec* 1982(1):122–131. <https://doi.org/10.3141/1982-17>
38. Seer S, Bauer D, Brandle N and Ray M (2008) Estimating pedestrian movement characteristics for crowd control at public transport facilities. In *Intelligent Transportation Systems, 2008. ITSC 2008. 11th International IEEE Conference on* (pp. 742–747). IEEE. <https://doi.org/10.1109/ITSC.2008.4732689>
39. Alhajyaseen WKM, Nakamura H, Asano M (2011) Effects of Bi-Directional Pedestrian Flow Characteristics upon the Capacity of Signalized Crosswalks. *Procedia Soc Behav Sci* 16:526–535. <https://doi.org/10.1016/j.sbspro.2011.04.473>
40. Shah J, Joshi GJ, Parida P (2013) Behavioral Characteristics of Pedestrian Flow on Stairway at Railway Station. *Procedia Soc Behav Sci* 104:688–697. <https://doi.org/10.1016/j.sbspro.2013.11.163>
41. Kawsar LA, Ghani NA, Kamil AA, Mustafa A (2014) Empirical Relationships among Pedestrian Flow Characteristics in an Indoor Facility. *Res J Appl Sci Eng Technol* 8(8):952–963
42. Corbetta A, Bruno L, Muntean A, Toschi F (2014) High Statistics Measurements of Pedestrian Dynamics. *Transp Res Procedia* 2:96–104. <https://doi.org/10.1016/j.trpro.2014.09.013>
43. Daamen W, Hoogendoorn S (2003) Experimental Research of Pedestrian Walking Behavior. *Transp Res Rec* 1828(1):20–30. <https://doi.org/10.3141/1828-03>
44. Seyfried A, Steffen B, Klingsch W, Boltes M (2005) The fundamental diagram of pedestrian movement revisited. *J Stat Mech: Theory Exp* 10002. <https://doi.org/10.1088/1742-5468/2005/10/P10002>
45. Chattaraj U, Seyfried A, Chakroborty P (2009) Comparison of Pedestrian Fundamental Diagram Across Cultures. *Adv Complex Syst @World Scientific Publishing Company* 12(3):393–405. <https://doi.org/10.1142/S0219525909002209>
46. Yang L, Rao P, Zhu K, Liu S, Zhan X (2012) Observation Study of Pedestrian Flow on Staircases with Different Dimensions under Normal and Emergency Conditions. *Saf Sci* 50(5):1173–1179. <https://doi.org/10.1016/j.ssci.2011.12.026>
47. Bandini S, Mondini M, Vizzari G (2014) Modelling Negative Interactions among Pedestrians in High Density Situations. *Transp Res C Emerg Technol* 40:251–270. <https://doi.org/10.1016/j.trc.2013.12.007>
48. Fu Z, Zhou X, Chen Y, Gong J, Peng F, Yan Z, Zhang T, Yang L (2015) The Influence of Random Slowdown Process and Lock-Step Effect on the Fundamental Diagram of the Nonlinear Pedestrian Dynamics : An Estimating-Correction Cellular Automaton. *Commun Nonlinear Sci* 20(3):832–845 20: 832–45
49. Tanaboriboon Y, Siang S, Division T (1986) Pedestrian Characteristics Study in Singapore. *J Transp Eng* 114:6 112 (3): 229–35
50. Fitzpatrick K, Brewer M, Turner S (2006) Another look at pedestrian walking speed. *Trans Res Rec J Trans Res Board* 1982(2006):21–29
51. Montufar J, Arango J, Perter M, Nakagawa S (2007) The normal walking speed of pedestrians and how fast they walk when crossing the street. *Annual Meeting of the Transportation Research Board, Washington, D.C. 250* (July 2006): 1–16
52. Finnis KK, Walton D (2007) Field observations of factors influencing walking speeds. In *2nd International conference on sustainability engineering and science*
53. Avineri E, Shinar D, Susilo YO (2012) Pedestrians' Behaviour in Cross Walks: The Effects of Fear of Falling and Age. *Accid Anal Prev* 44(1):30–34. <https://doi.org/10.1016/j.aap.2010.11.028>
54. Koushki PA (1988) Walking characteristics in central riydah, Saudi Arabia. *J Trans Eng* 114(6):735–744
55. Young SB (1999) Evaluation of Pedestrian Walking Speeds in Airport Terminals. *Transp Res Rec* 1674(99):20–26
56. *Highway Capacity Manual* (2010) TRB Washington
57. Bastos AMC, da Cunha JRR and da Silva JPC (2014) Estimation of pedestrian walking speeds on footways. *Proc Inst Civil Eng* 167(1): 32. <https://doi.org/10.1680/muen.12.00048>
58. Daamen W, Hoogendoorn SP (2006) Free speed distributions for pedestrian traffic. In: *Proceedings of the 85th Annual Meeting of Transportation Research Board, Washington, DC, USA*, pp. 22–26