Empirical Results of Pedestrian and Evacuation Dynamics

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Article Outline

Glossary

Pedestrian
A pedestrian is a person travelling on foot. In this article, other characterisations are used, depending on the context, e.g. agent or particle.

Crowd
A large group of pedestrians who have gathered together. Depending on the perspective, more specific definitions exist.

Evacuation
Evacuation is the movement of persons from a dangerous place due to the threat or occurrence of a disastrous event. In normal situations this is called "egress" instead.

Flow rate
The flow rate J is a measure for the throughput and describes the performance of a pedestrian facility. It is defined as the number of persons passing a cross-section per unit time. The common unit of flow is "persons per second". Often the specific flow is used which is the flow rate per unit width.

Capacity
The maximal flow rate supported by a facility is called "capacity".

Hydrodynamic relation
The hydrodynamic relation $J = \rho v$ connects the flow rate J with the density ρ and the average velocity v in a one-dimensional particle stream. For motion in two dimensions it is given by $J = \rho v b$ where b is the width.

Fundamental diagram
In traffic engineering (and physics) the fundamental diagram describes the density-dependence of the flow: $J(\rho)$. Due to the hydrodynamic relation $J = \rho v b$ equivalent representations used frequently are $v(\rho)$ or $v(J)$. The

fundamental diagram is probably the most important quantitative characterization of traffic systems.

Trajectory
A trajectory of a pedestrian is its path in time. For controlled experiments this is most often derived from the motion of the top of the head including swaying and bobbing. The individual trajectory can be enriched with information changing over time (e.g. head or shoulder orientation) or static information (e.g. age or gender).

Lane formation
In bidirectional flows, lanes in which all pedestrians move in the same direction are often formed dynamically. The number of lanes is usually not constant in time and can be different for the different directions.

Bottleneck
A bottleneck is in general a part of a facility limiting pedestrian flows. This can be for example a door, a narrowing in a corridor, or stairs, i.e. locations of reduced capacity. At bottlenecks jamming occurs if the inflow is higher than the capacity.

Microscopic models
Microscopic models represent each pedestrian separately with individual properties like walking velocity or route choice behaviour and the interactions between them.

Macroscopic models
Macroscopic models do not distinguish individuals. The description is based on aggregate quantities, e.g. appropriate densities. Typical models belonging to this class are fluid-dynamic approaches.

Crowd disaster
Crowd disaster is an accident in which the specific behaviour of the crowd is a relevant factor, e.g. through competitive and non-adaptive behaviour. In the media, it is often called “panic” which is a scientifically not proven concept in crowd dynamics and should thus be avoided.

1 Definition of the Subject and its Importance

Today, there are many occasions where a large number of people gathers in a relatively limited space. Very large events related to sports, entertainment, culture and religion are held all over the world on a regular basis. Office buildings and apartment houses become much larger and more complex. This brings about serious safety issues for the participants and the organisers who have to prepare for any case of emergency or critical situation.

To reduce the risk of injuries or even fatalities in large crowds it is important to understand the basic mechanism that govern crowd motion or crowd behaviour in general. This requires reliable empirical data, both qualitative and quantitative, which can be analysed to uncover the basic underlying principles. This then allows the development of realistic models which in turn can be validated and tested against the empirical data.

Despite the obvious importance of empirical data, it is surprising that no consensus about the correct quantitative description exists even for the simplest scenarios . This is quite different from the situations in vehicular traffic where vast datasets obtained in an automated way from detectors on highways exist. However, this is not so easy to be transferred to pedestrian motion. The underlying physical principles of highway detectors (e.g. magnetic induction by moving metallic objects) can not be applied here. Furthermore the motion of vehicles is usually (quasi-)one-dimensional whereas pedestrian motion is a mixture of two-dimensional motions in different directions. This makes it difficult to use the analogue of floating-car data which is currently one of the standard techniques for obtaining data for vehicular traffic [86]. Methods based on GPS measurements do not have a sufficient accuracy of the order of 1 cm which would be required to determine trajectories of pedestrians. Therefore new techniques have to be developed.

2 Introduction

One of the main goals of pedestrian science is to enhance safety in public places. The awareness that the reasonable setting of emergency exits is one of the most important factors to ensure the safety of occupants in buildings can be traced more than 100 years. However, the disasters due to the fires in the Ringtheater in Vienna and the urban theatre in Nizza at 1881 with several hundred fatalities lead to a rethinking of the safety in buildings [45]. Firstly it was tried to improve the safety by using non-flammable building materials. But the disaster at the Troquois Theater in Chicago with more than 500 fatalities, where only the decoration burned, caused a rethinking. It was a starting point for studying the influences of emergency exits and thus the dynamics of pedestrian streams [45, 54].

In this context evacuation dynamics plays a special role. In general, evacuation is the egress from an area, a building or vessel to a relatively safe place due to a potential or actual threat. The dynamics can be quite complex because of the large number of people and their interactions, external factors like fire, complex building geometries, etc. Evacuation dynamics has to be described and understood on different levels: physical, physiological, psychological, and social. Its investigation is difficult and involves many research areas and disciplines.

Due to joint and interdisciplinary efforts, much progress in the understanding of pedestrian and evacuation dynamics has been made in recent years. The origin of the apparent complexity lies in the fact that one is concerned with a many-‘particle’ system with complex interactions that are not fully understood. Therefore empirical investigations are required for a better understanding of the underlying processes. One of the new methods is laboratory experiments under controlled conditions, which can be repeated all over the world and has become more and more important. Using up to the order of 1000 participants allows to study subtle effects like the influence of the cultural background on the important quantities in traffic science, the flow-density relation or fundamental diagram.

In this article we focus on empirical studies on pedestrian and evacuation dynamics but not modelling approaches which are reviewed in a companion article [34]. Empirical results are important for the design, validation and calibration of models. As we will show here, not for all situations there is currently a consensus on the relevant empirical data. The origin of the discrepancies among different observations is not always clear. The resulting ambiguity involves serious problems in testing modelling approaches quantitatively.

The article is organised as follows. In Sec. 3 we introduce the definitions of the main observable that characterise the properties of pedestrian streams as well as discussing the problems in their determination. Sec. 4 provides an overview of the main collective effects that have been found in systems of pedestrians. Probably the most important quantitative characterisation of traffic systems is the fundamental diagram, which is described in Sec. 5 for different geometries. In Sec. 6 observations from crowd disasters are discussed. These help to improve safety e.g. by optimising evacuation procedures. In Sec. 7 we describe how controlled laboratory experiments can contribute to a better understanding of pedestrian dynamics.

3 Definition of Observables

3.1 Introduction

Pedestrians are three-dimensional objects and a complete description of their highly developed and intricate motion sequence is rather difficult. To extract transport characteristics of a system with many pedestrians the motion is usually treated in two-dimensional space by considering the vertical projection of the body.

In the following sections we review the present knowledge of empirical results. These are relevant not only as basis for the development of models, but also for applications like safety studies and legal regulations.

We start with the phenomenological description of collective effects, some of which are known from daily experience and serve as benchmark tests for any kind of modelling approaches. Any model that is not able to reproduce these effects is missing some essential part of the dynamics. Next the foundations of a quantitative description are laid by introducing the fundamental observables of pedestrian dynamics. Difficulties arise from different definitions and inhomogeneities in space and time. Then pedestrian dynamics in several simple scenarios (corridor, stairs etc.) is discussed. Surprisingly even for these simple cases no consensus about the basic quantitative properties exists. Finally, more complex scenarios are discussed which are combinations of the simpler elements.

Before we review experimental studies, the commonly used observables are introduced.

3.2 Flow Rate

The flow rate J of a pedestrian stream gives the number of pedestrians crossing a fixed location of a facility per unit of time. Usually it is taken as a scalar quantity since only the flow normal to some cross-section is considered. There are various methods to measure the flow rate. The most natural approach is to determine the times t_i at which pedestrians passed a fixed measurement location. The time gaps $\Delta t_i = t_{i+1} - t_i$ between two consecutive pedestrians i and $i+1$ are directly related to the flow rate

$$J = \frac{1}{\langle \Delta t \rangle} \qquad \text{with} \qquad \langle \Delta t \rangle = \frac{1}{N} \sum_{i=1}^{N} (t_{i+1} - t_i) = \frac{t_{N+1} - t_1}{N} \,. \tag{1}$$

Such a definition allows to estimate the flow rate for a given number of observed pedestrians. Similarly, estimation of the flow for a given time interval can be obtained thanks to the cumulative flow function $N(t)$ numbering pedestrians as they pass the cross-section and describes the evolution of this number over time (formally, $N(t) = \sum_i \mathbb{1}_{t_i<t}$, with $\mathbb{1}_A = 1$ if A holds and $\mathbb{1}_A = 0$ otherwise). It is related as the Moskowitz function in the traffic theory [43]. The flow rate is then the derivative in time of the cumulative flow in the continuous limit $J_0 = N'(t)$. On a discrete time interval T the flow rate is (see Fig. 1)

$$J_T = \frac{\Delta N}{T}, \qquad \text{with} \qquad \Delta N = N(t) - N(t+T). \tag{2}$$

Another possibility to measure the flow rate of a pedestrian stream is borrowed from fluid dynamics. The flow rate through a facility of width b determined by the average density ρ and the average speed v of a pedestrian stream as

$$J = \rho \; v \; b = J_s b \,. \tag{3}$$

where the *specific flow*

$$J_s = \rho \; v \tag{4}$$

gives the flow per unit-width. This relation is also known as *hydrodynamic relation*. In strictly one-dimensional motion often a line density (dimension: 1/length) is used. Then the *flow* is directly given by $J = \rho v$.

There are several problems concerning the way how velocities, densities or time gaps are measured and the conformance of the two definitions of the flow rate. The flow according to eq. (1) is usually measured as a mean value over time at a certain location while the measurement of the density

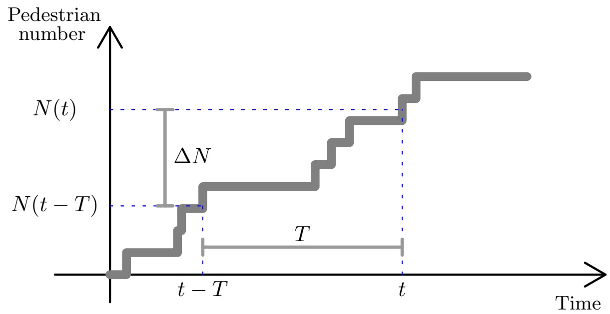

Fig. 1. Illustration for the measurements of the flow rate on a time interval T with the cumulative flow function $N(t)$.

in eq. (3) is connected with an instantaneous mean value over space. This can lead to a bias caused by the underestimation of fast moving pedestrians at the average over space compared to the mean value of the flow over time at a single measurement line, see the discussion for vehicular traffic e.g. in [71, 87, 105]. Furthermore most experimental studies measuring the flow rate according to equation (3) combine for technical reasons an *average* velocity of a single pedestrian over time with an *instantaneous* density. To ensure a correspondence of the mean values the average velocity of all pedestrians contributing to the density at a certain instant has to be considered. However this procedure is very time consuming and not realised in practice up to now. Moreover the fact that the dimension of the test section has usually the same order of magnitude as the extent of the pedestrians can influence the averages over space. These all are possible factors why different measurements can differ in a large way, see discussion in Sec. 5.

3.3 Density

Another way to quantify the pedestrian load of facilities has been proposed by Fruin [59]. The "pedestrian area module" is given by the reciprocal of the density. Thompson and Marchant [180] introduced the so-called "inter-person distance" d, which is measured between centre coordinates of the assessing and obstructing persons. According to the "pedestrian area module" Thompson and Marchant call $\sqrt{\frac{1}{\rho}}$ the "average inter-person distance" for a pedestrian stream of evenly spaced persons [180]. An alternative definition is introduced in [73] where the local density is obtained by averaging over a circular region of radius R,

$$\rho(\vec{r},t) = \sum_i f(\vec{r}_i(t) - \vec{r}), \tag{5}$$

where $\vec{r}_i(t)$ are the positions of the pedestrians i in the surrounding of $\vec{r}$ and $f(...)$ is a Gaussian, distance-dependent weight function. The kernel function f

depends on a bandwidth parameter to calibrate. In the Voronoi method [174], the kernels are uniform on the cells given by the Voronoi diagram (see Fig. 2). The Voronoi method is devoid of additional parameter.

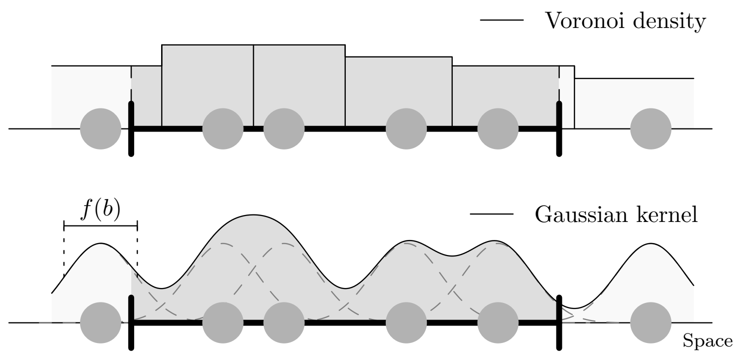

Fig. 2. Examples of Voronoi and Gaussian kernel estimations for the density of pedestrians in one dimension. The Gaussian kernel estimation depends on a bandwidth parameter b to calibrate.

In contrast to the density definitions above, Predtechenskii and Milinskii [140] consider the ratio of the sum of the projection area f_i of the bodies and the total area of the pedestrian stream A, defining the (dimensionless) density $\tilde{\rho}$ as

$$\tilde{\rho} = \frac{\sum_i f_i}{A}\,, \tag{6}$$

a quantity known as *occupancy* in the context of vehicular traffic. Since the projection area f_i depends strongly on the type of person (e.g. it is much smaller for a child than an adult), the densities for different pedestrian streams consisting of the same number of persons and the same stream area can be quite different.

Beside technical problems due to camera distortions and camera perspective there are several conceptual problems, like the association of averaged with instantaneous quantities, the necessity to choose an observation area in the same order of magnitude as the extent of a pedestrian together with the definition of the density of objects with non zero extent and much more. A detailed analysis how the way of measurement influences the relations is necessary but still lacking.

3.4 Mean Speed

As for flow rate and density, there exist various methods to measure the mean speed. Let us first consider a simple example. A pedestrian goes from a point

A to a point B with a given speed v_1 before to come back from B to A with a speed v_2. We denote L the distance between A and B. What is the mean speed of the pedestrian during the round trip? The time mean speed

$$V = \frac{1}{L+L}(v_1 L + v_2 L) = \frac{1}{2}(v_1 + v_2), \tag{7}$$

is the arithmetic mean of v_1 and v_2. Yet, the time spent on the way out is $t_1 = L/v_1$ while it is $t_2 = L/v_2$ on the return. Therefore the space mean speed is

$$V_H = \frac{1}{t_1+t_2}(v_1 t_1 + v_2 t_2) = \frac{2}{1/v_1 + 1/v_2}. \tag{8}$$

It is the harmonic mean of v_1 and v_2. The Jensen inequality shows that the harmonic mean is smaller than the arithmetic mean as soon as v_1 is different from v_2. For instance if $v_1 = 1$ and $v_2 = 2$, then $V = 3/2$ while $V_H = 4/3$. Note that only the space mean speed allows to recover the travelled time over the round trip $L/v_1 + L/v_2 = 2L/V_H$.

Time and space mean speeds do not estimate the same quantity. This statement, closely related to double loops detector measurement technique, has been early pointed out for traffic flow [188]. However, the difference can be substantial for pedestrian flows as well. It has been empirically estimated up to a factor four [92]. The time mean speed is generally measured thanks to crossing times of two consecutive points (as with a double loops detector). For instance, one can consider that the speeds v_i of pedestrians crossing a section is the length of the section L divided by the difference between the exit t^{out} and enter times t^{in} into the section (the travel time). Then the arithmetic mean

$$V = \frac{1}{n}\sum_i v_i = \frac{1}{n}\sum_i \frac{L}{t_i^{\text{out}} - t_i^{\text{in}}} \tag{9}$$

corresponds to the time mean speed. It does not allow to recover the mean travel time of the pedestrian into the room, neither the hydrodynamic relation borrowed from fluid dynamics $J = \rho V$. The harmonic mean

$$V_H = \frac{n}{\sum_i 1/v_i} = \frac{n}{\sum_i (t_i^{\text{out}} - t_i^{\text{in}})/L} = \frac{L}{\frac{1}{n}\sum_i t_i^{\text{out}} - t_i^{\text{in}}} \tag{10}$$

should be used instead to recover (asymptotically) the space mean speed [188]. Note that the harmonic mean speed corresponds to the section length divided by the (arithmetic) mean travel time.

The difference between time and space mean speeds can be nicely tackle thanks to trajectories. Let us denote d_i the travelled distance and t_i the travelled time of pedestrian trajectories in the space/time diagram. The speed of pedestrian i is therefore $v_i = d_i/t_i$. A natural way due to Edie [49] to estimate the mean speed of the trajectories consists in dividing the total travelled distance by the total travel time:

$$V_E = \frac{\sum_i d_i}{\sum_i t_i}. \tag{11}$$

Let us fix now the travelled distance to a fix value d (estimation of the mean speed on a horizontal band in the time/space diagram of the trajectories, see Fig. 3). Such a methodology is the one used above with entry and exit times. One gets the harmonic mean

$$V_E = \frac{\sum_i d}{\sum_i t_i} = \frac{n}{\sum_i 1/v_i}. \tag{12}$$

since in this case $t_i = d/v_i$. If we fix the travelled time to a fixed value t (estimation of the speeds thanks to two successive photographies of the system, this corresponds to estimation of the mean speed on a vertical band in the time/space diagram of the trajectories, see Fig. 3), then one gets

$$V_E = \frac{\sum_i d_i}{\sum_i t} = \frac{1}{n}\sum_i v_i, \tag{13}$$

since in this case $d_i = v_i t$. As expected, Edie's definition for the mean speed of trajectories corresponds in any case to the space mean speed.

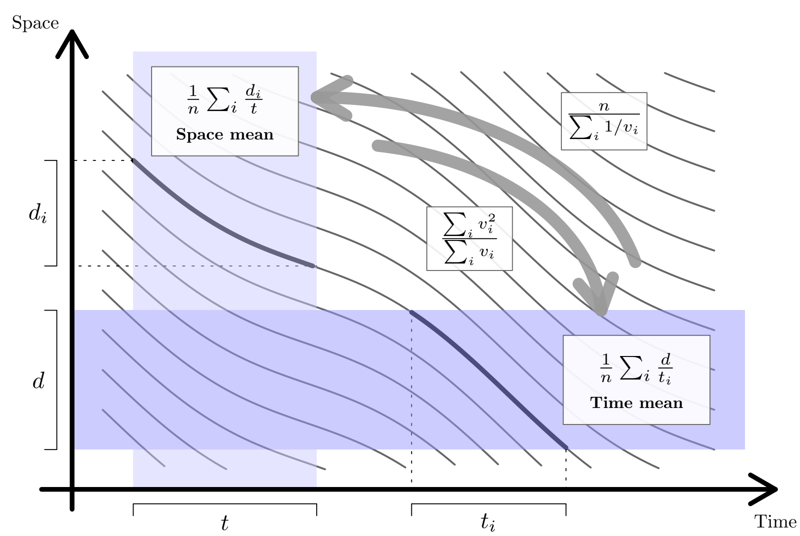

Fig. 3. Illustration for the measurements of the mean speed for trajectories with a fixed time interval (space mean speed, vertical band) and a fixed distance (time mean speed, horizontal band), and the harmonic and contraharmonic means allowing to recover asymptotically one definition from the other.

4 Collective Effects

One of the reasons why the investigation of pedestrian dynamics has attracted the interest of physicists is the large variety of collective effects and self-organisation phenomena that can be observed. These macroscopic effects reflect the individuals' microscopic interactions and thus give also important information for modelling approaches.

4.1 Jamming and Clogging

Jamming and clogging typically occur for high densities. Clogging is typically observed at locations where the inflow exceeds the capacity. This kind of jamming phenomenon does not depend strongly on the microscopic dynamics of the particles. Rather it is a consequence of an exclusion principle: space occupied by one particle is not available for others. Locations with reduced capacity are called *bottlenecks*. Typical examples of bottlenecks are exits (Fig. 4) or narrowings. For practical applications, especially evacuation simulations, a detailed understanding of the conditions under which clogging occurs is important. In [139] it is described how these obstruction occurs due to the formation of arches in front of the door under high pressure. This is very similar to the well-known phenomenon of arching occurring in the flow of granular materials through narrow openings [192].

Fig. 4. Clogging in front of a bottleneck.

Other types of jamming occur e.g. in the case of counterflow where two groups of pedestrians mutually block each other. This also typically happens at high densities and when it is not possible to turn around and move back, e.g. when the flow of people is large.

4.2 Density Waves, Stop-and-Go Waves

Density waves in pedestrian crowds can be generally characterised as quasi-periodic density variations in space and time. A typical example is the movement in a densely crowded corridor (e.g. in subway-stations close to the density that causes a complete halt of the motion) where phenomena similar to stop-and-go vehicular traffic can be observed, e.g. density fluctuations in longitudinal direction that move backwards (opposite to the movement direction of the crowd) through the corridor.

Stop-and-go waves have been observed in real crowds, e.g. on the Jamarat Bridge in Makkah (during the Hajj pilgrimage 2006) [73], as well as in controlled experiments [138, 164]. One surprising difference to stop-and-go traffic observed in vehicular traffic is the separation into standing and slowly moving pedestrians. In contrast, in highway traffic a separation into standing and fast moving cars is found (neglecting a narrow transition layer). This is usually explain by so-called slow-to-start behaviour of cars [8]. Therefore in pedestrian motion additional mechanisms are at work which have not yet been fully understood.

4.3 Lane Formation

In counterflow, i.e. two groups of people moving in opposite directions, dynamically varying lanes are formed where people move in just one direction [126, 130, 194]. In this way, strong interactions with oncoming pedestrians are reduced which is more comfortable and allows higher walking speeds.

The occurrence of lane formation does not require a preference of moving on one side. It also occurs in situations without left- or right-preference. However, cultural differences for the preferred side have been observed. Although this preference is not essential for the phenomenon itself, it has an influence on the kind of lanes formed and their order.

Several quantities for the quantitative characterisation of lane formation have been proposed. Yamori [194] has introduced a band index which is basically the ratio of pedestrians in lanes to their total number. In [25] a characterisation of lane formation through the (transversal) velocity profiles at fixed positions has been proposed. Lane formation has also been predicted to occur in colloidal mixtures driven by an external field [28, 48, 145]. Here an order parameter $\phi = \frac{1}{N}\left\langle \sum_{j=1}^{N} \phi_j \right\rangle$ has been introduced where $\phi_j = 1$ if the lateral distance to all other particles of the other type is larger than a typical density-dependent length scale and $\phi_j = 0$ otherwise.

The number of lanes can vary considerably with the total width of the flow (see Fig. 5). It is usually not constant and changes in time, even if there are relatively small changes in density. The number of lanes in opposite directions is not always identical. This can be interpreted as a sort of spontaneous symmetry breaking.

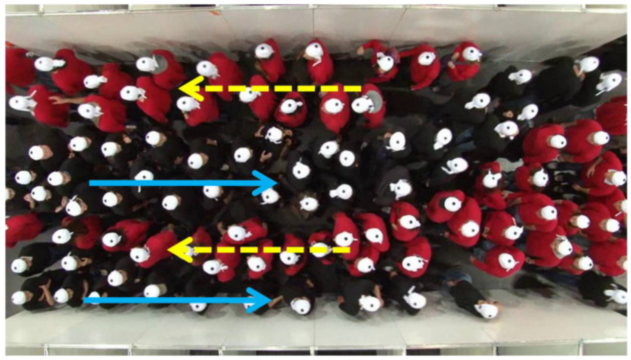

Fig. 5. Bidirectional flow with two comparative lanes in each flow direction.

Quantitative empirical studies of lane formation are rare [97, 194, 200]. At high densities theoretical models predict a jamming transition, i.e. the transition to a state where no movement is possible anymore (gridlock). However, there is no empirical evidence for such a transition, and experiments showed that the lower density limit for the transition is larger than 3.5 Persons/m^2 [200].

4.4 Oscillations

In counterflow at bottlenecks, e.g. doors, one can sometimes observe oscillatory changes of the direction of motion. Once a pedestrian is able to pass the bottleneck it becomes easier for others to follow in the same direction until somebody is able to pass (e.g. through a fluctuation) the bottleneck in the opposite direction.

4.5 Patterns at Intersections

At intersections various collective patterns of motion can be formed. A typical example are short-lived roundabouts which make the motion more efficient. Even if these are connected with small detours the formation of these patterns can be favourable since they allow for a "smoother" motion.

4.6 Emergency Situations, "Panic"

In emergency situations various collective phenomena have been reported that have sometimes misleadingly been attributed to *panic behaviour*. However, there is strong evidence that this is not the case. Although a precise accepted definition of *panic* is missing, usually certain aspects are associated with this concept [85]. Typically "panic" is assumed to occur in situations where people compete for scarce or dwindling resources (e.g. safe space or access to an exit) which leads to selfish, asocial or even completely irrational behaviour and contagion that affects large groups. A closer investigation of many crowd disasters has revealed that most of the above characteristics have played almost no role and most of the time have not been observed at all (see e.g. [83]). Often the reason for these accidents is much simpler, e.g. in several cases the capacity of the facilities was too small for the actual pedestrian traffic, e.g. Luschniki Stadium Moscow (October 20, 1982), Bergisel (December 4, 1999), pedestrian bridge Kobe (Akashi) (July 21, 2001) [184]. Therefore the term "panic" should be avoided, *crowd disaster* being a more appropriate characterisation. Also it should be kept in mind that in dangerous situations it is *not* irrational to fight for resources (or your own life), if everybody else does this [38, 115]. Only from the outside this behaviour is perceived as irrational since it might lead to a catastrophe [172]. The latter aspect is therefore better described as *non-adaptive behaviour*.

We will discuss these issues in more detail in Sec. 6.2.

5 Fundamental Diagram

5.1 Overview

The fundamental diagram describes the relation between density ρ and flow rate J. The name already indicates its importance and naturally it has been the subject of many investigations. Due to the hydrodynamic relation there are three equivalent forms: $J_s(\rho)$, $v(\rho)$ and $v(J_s)$, which are basic input in applications for the design and dimensioning of pedestrian facilities [59, 127, 139]. Furthermore it is a quantitative benchmark for models of pedestrian dynamics [40, 88, 114, 167].

Fig. 6 shows various fundamental diagrams used in planing guidelines and measurements of two selected empirical studies representing the overall range of the data. All diagrams agree in one characteristic: velocity decreases with increasing density. However, the comparison reveals that specifications and measurements disagree considerably. In particular the maximum of the function giving the capacity $J_{s,\max}$ ranges from 1.2 $(\mathrm{ms})^{-1}$ to 1.8 $(\mathrm{ms})^{-1}$, the density value where the maximum flow rate is reached ρ_c ranges from 1.75 m^{-2} to 7 m^{-2} and, most notably, the density ρ_0 where the velocity approaches zero due to overcrowding ranges from 3.8 m^{-2} to 10 m^{-2}. Several explanations for these deviations have been suggested, including cultural and population differences [29, 73, 117], differences between uni- and multidirectional flow [101, 126, 142], short-ranged fluctuations [142], influence of psychological factors given by the incentive of the movement [139], the type of traffic (commuters, shoppers) [130] and different types of facilities etc.

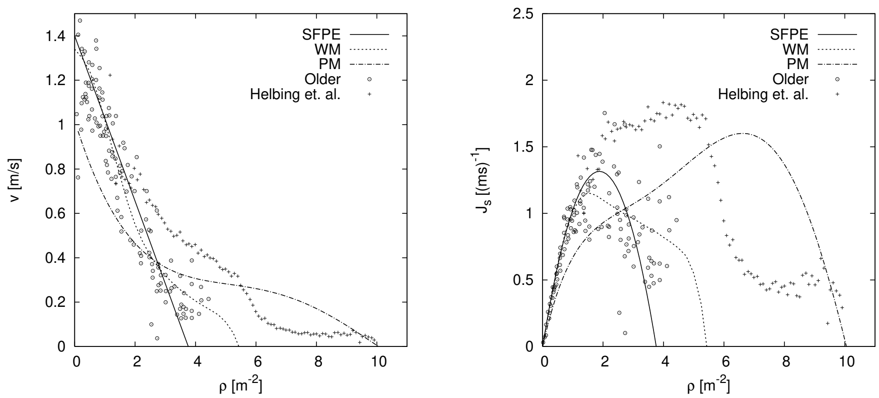

Fig. 6. Fundamental diagrams for pedestrian movement in planar facilities. The lines refer to specifications according to planing guidelines (SFPE Handbook [127]), Predtechenskii and Milinskii (PM) [139], Weidmann (WM) [190]). Data points give the range of experimental measurements (Older [131] and Helbing [73]).

5.2 Classical Experiments

In this section, we mainly refer to uni- and bidirectional pedestrian flow on planar facilities like sidewalks, corridors or halls. Several factors such as measurement methods, width of facility, gradients and pedestrian characteristics have been considered to study the difference of the fundamental diagrams.

For the movement of pedestrians along a line, The speed for walking pedestrians depends linearly on the step size [190] and the inverse of the density [166]. The internal friction, other lateral interference and the curvature effects of path have no influence on the fundamental diagram at the density domains considered [166, 201]. However, different relation is obtained across cultures [29, 110]. The speed of Indian is less dependent on density than the speed of German. Instead of changing continuously, the adaptation time takes three discrete values [82] in France. For the group composed of young students with nearly the same age, only two adaptation times are observed [27]. Especially, the density under ship trim or heeling conditions is not the main factor that affects pedestrian speed. Trim angles show larger impact on speed and the pedestrian is more likely to be influence by the front neighbour rather than other pedestrians in front [176].

Actually, pedestrians have freedom to move in two dimensions. Corridors are simple and common elements in almost all types of pedestrian facilities designed for uni- and bidirectional pedestrian flow. Different measurement methods mainly influence the range of the fluctuations of the fundamental diagram, which can be unified in one diagram for specific flow for the same type of facility but different widths [70, 126, 130, 131, 198] (see Fig. 7 left). However, Navin and Wheeler observed in narrow sidewalks more orderly movement

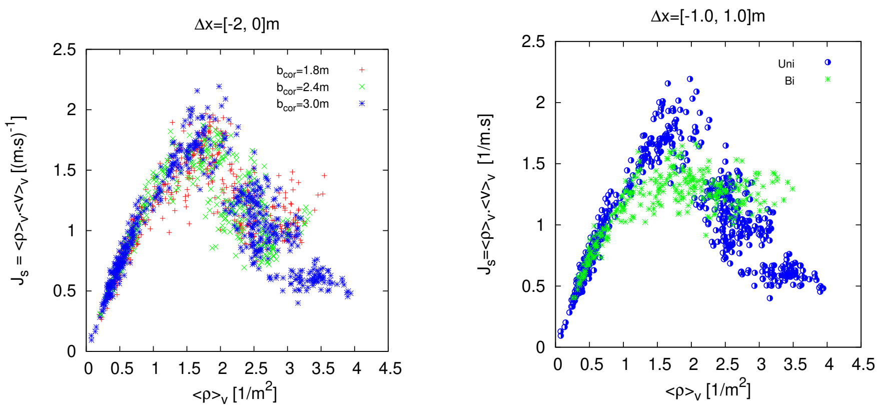

Fig. 7. Fundamental diagrams for pedestrian movement in a straight corridor. The left results are obtained from unidirectional movement in corridors with three different widths [198], while in right the fundamental diagrams of uni- and bidirectional flow are compared [200].

leading to slightly higher specific flows than for wider sidewalks [126]. Weidmann [190] neglected differences between uni- and multidirectional flow in accordance with Fruin, who states in his often cited book [59] that the fundamental diagrams of multidirectional and unidirectional flow differ only slightly. Nevertheless, clear differences in fundamental diagrams of uni- and bidirectional pedestrian streams are observed in (see Fig. 7 right) [101, 126, 200]. Refer to the influence of flow ratio of bidirectional stream, it seems not an independent factor influencing the fundamental diagram and no consensus is reached up to now [2, 53, 102, 183]. Surprisingly some studies found that the sum of flow and counterflow in corridors is larger than the unidirectional flow and for equally distributed loads it can be twice the unidirectional flow [97].

5.3 Bottleneck Flow

To describe the performance of bottlenecks two cases have to be distinguished. In the free flow case the flow through the bottleneck is equivalent to the incoming flow. If the incoming flow exceeds the capacity – the maximal possible flow rate – of the bottleneck a congestion occurs and the density in front of the bottleneck increases. This is named congested case. In the congested case the density in front of the bottleneck is higher than inside the bottleneck [41, 139, 165]. The measured maximal flow rate at bottlenecks can exceed the maximum of the empirical fundamental diagram. In case of a congestion pedestrians could cooperate or compete while entering the bottleneck. The competition is triggered by a reward [115] which could be the survival in case of a threat or an uncritical but limited resource like a seat in a carrier. One strategy to successfully enter a bottleneck in a competitive situation is pushing. But pushing could lead to blockages (clogs) limiting the flow through the bottleneck. While the phenomenon of blockages at bottlenecks appears also in systems of inanimate particles [202, 203] the influence of rewards to the degree of competition or to the strength of the pushing is connected with socio-psychological factors [171].

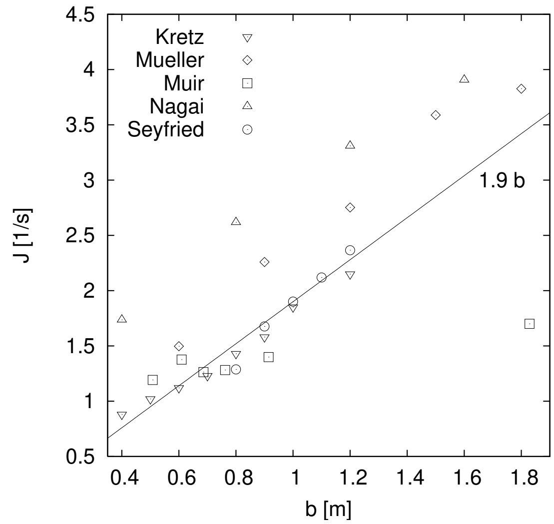

Fig. 8. Influence of the width of a bottleneck on the flow. Experimental data [121, 122, 125, 165] of different types of bottlenecks and initial conditions. All data are taken under laboratory conditions where the test persons are advised to move normally.

Here we focus on pedestrian movement in cooperative situations. One of the most important practical questions is how the capacity of the bottleneck increases with the width, which is already studied in the beginning of the 20th century [45, 54]. A stepwise increase of capacity with the width is up to now a assumption of several building codes and design recommendations [124, 135]. The empirical results in [77, 78] also implies a stepwise increase of capacity. However, the investigation was restricted to two values of the width. In contrast, the study [165] considered more values of the width of different laboratory experiments [99, 121, 122, 125, 165] (see Fig. 8) and found that the flow does not necessarily depend on the number of lanes. That the capacity is given by the maximum of the fundamental diagram and a linear function of the width is assumed in [59, 127, 139, 181, 190] . The exact geometry of the bottleneck is of only minor influence on the flow [165] while a high initial density in front of the bottleneck can increase the resulting flow values [125].

However, it is found later that shorter bottlenecks provide higher flow than longer ones [108, 153, 163]. The width of of the passage [146] and the the existence of the obstacle [72, 195] in front of bottleneck also influences the flow through bottleneck. The total flow rate at bottlenecks with bidirectional movement is higher than it is for unidirectional flows [72]. Lanes in bottlenecks are solely a boundary effect and in case of wide bottlenecks only two lanes at the boundaries are observable [108]. Besides, population with 5% disabled pedestrians leads to a lower flow and that with mainly children leads to the highest flow [42].

Empirical studies of competitive situation where people push while entering the bottleneck are [64, 72, 121, 122, 195]. In [122] soldiers entered a short bottleneck with the advice 'every man from himself'. Temporal blockages are reported but with an increase of the width their frequency decreases. Muir et al. [121] studied emergency evacuation in aircrafts. The motivation was varied by a reward and the dependence of the evacuation time on the width of a bottleneck, here the galley unit, was studied. A comparison of the relation between evacuation time and the width of the bottleneck with and without rewards showed a crossover. While for narrow bottlenecks the evacuation time for high motivation was lower than for normal motivation the opposite is the case for wider bottlenecks. The high motivation improves the performance and minimise the evacuation time. These two studies are in conformance showing that as long as no blockages occur a higher motivation could increase the flow through a bottleneck. Blockages are only observable at narrow bottlenecks which may limit the performance. Experimental results on how a column in front of a narrow bottleneck could improve the flow under high competition can be found in [72, 195].

To describe the intermittent flow in case of blockages quantitatively, knowledge about the probability of the occurrence of blockages is necessary. A deeper analysis of the statistical properties of this phenomenon was studied in [64]. Cumulative distribution functions of the time gaps were analysed for two door width and three degrees of competition. They showed that the distribution of the time lapses between the passage of two consecutive pedestrians display heavy-tailed distributions.

5.4 Stairs

Stairs are significant elements in most evacuation scenarios like in multi-storey or high-rise buildings and are a major determinant for the evacuation time. Due to their physical dimension which is often smaller than other parts of a building or due to a reduced walking speed, stairs generally have to be considered as bottlenecks for the flow of evacuees. There are studies on various details, mostly the free speed, of motion on stairs in dependence of the incline [59–61, 66], conditions (comfortable, normal, dangerous) [140], age and sex [59], tread width [58], the length of a stair [96], and in consideration of various disablement [17].

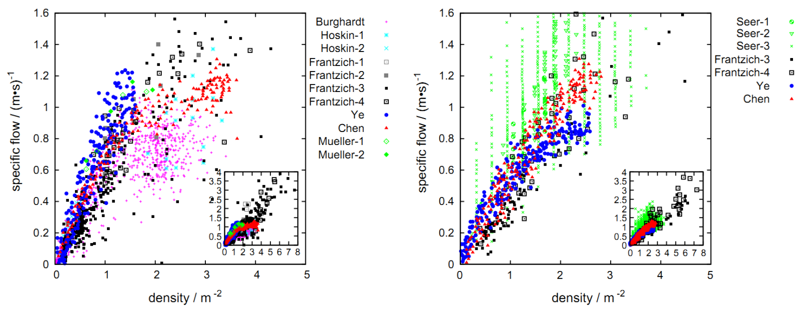

Fig. 9. Fundamental diagram for pedestrian movement on stairs (left: downwards, right: upwards) [24].

Compared to the movement on flat terrain, there are more degrees of freedom (e.g., upward and downward movement, the influence of riser height and tread length, exhaustion effects for upward motion etc.) which influence the fundamental diagram of movement on stairs. In four well-known planning handbooks for pedestrian facilities and evacuation routes [59,127,139,190], different fundamental diagrams for stairs are presented. Weidmann, Predtechenskii and Milinskii, and Fruin distinguish between up- and downwards motion and do not consider the angle of stairs while Nelson and Mowrer focus on different angles and not on direction. Burghardt et al. [24] collected fundamental diagram for up- and downward movement on stairs from literatures [23, 31, 57, 58, 66, 70, 79, 98, 100, 161, 177, 179, 196] (see Fig. 9). These empirical data are obtained from different conditions (e.g., different location and slope of the stairs, different measurement methods etc.). However, a linear increase of the specific flow is observable with minor differences of the incline at low densities for both up- and downward motions. The flow rate decreases with increasing slope of stairs [24, 66]. In the experiment of [24], the density range where the specific flow reaches the maximum is larger for downwards than for upwards motion. For downwards motion the specific flow at the external staircase fades into a plateau for densities higher than 2.0 m^{-2}. For the stairs located in the lower tier of the grandstand the specific flow increases with higher densities while in the upper tier a decrease of flow appears.

5.5 Other Geometries

Besides the above mentioned elements, fundamental diagram of pedestrian flow through other structures like T-junction, crossing (see Fig. 10) are also studies recently. In T-junctions, bottleneck flow, merging flow or split flow are all possible to take place in different situations. Around corners, it is still not known how the effective width of the corridor reduces and changes with increasing inflow. The existing empirical data shows that the fundamental diagrams of streams in front and behind the turning at the corner agree well and are in accordance with that from T-junction flow behind the merging [197]. The fundamental diagram obtained in the main stream is different from that in branches [199]. At crossing pedestrians from different direction have different preferred velocities with different orientations. Thus, the usual way for measuring local velocity or flow rate is not applicable and adapted definitions has been proposed [26, 107]. Surprisingly, the fundamental diagrams for bidirectional flow and four-directional crossing flow show no apparent difference in the density ranges covered in the experiments. However, it indicates that different measurement methods, motivations of test persons and experimental setup may lead to large differences.

Fig. 10. Crossing with four entrances and equal flow from and to all branches.

6 Evacuations and Crowd Disasters

We have focused in the previous sections on the main variables and empirical results for pedestrian motion in rather simple scenarios. As we have seen there are many open questions where no consensus has been reached, sometimes even about the qualitative aspects. This becomes even more relevant for full-scale descriptions of evacuations from large buildings, e.g., train stations, malls, theatre or stadium and or again for crowd disasters.

6.1 Evacuation

Evacuation is the movement of persons leaving a place due to a danger, threat or occurrence of a disastrous event. In normal situations a evacuation is called "egress" instead. In a normal situation, visitors of a building might have complex itineraries which are usually represented by origin-destination matrices.

In the case of an evacuation, however, the aims and routes are known and usually the same, i.e. the exits and the egress routes. This is the reason why an evacuation process is rather strictly limited in space and time, i.e. its beginning and end are well-defined (sound of the alarm, initial position of all persons, safe areas, final position of all persons, and the time, the last person reaches the safe area). Five different phases can be distinguished [69, 118, 141] during an evacuation: (1) detection time, (2) awareness time, (3) decision time, (4) reaction time, and (5) movement time. In IMO's regulations [118, 119], the first four are grouped together into *response time*. Usually, this time is are called *pre-movement time*.

Knowledge about bottleneck capacities (i.e. flows through doors and on stairs) is very important when assessing the layout of a building with respect to evacuation. The purpose of empirical data in the context of evacuation processes (and modelling in general) is threefold [62, 80]: (1) identify parameters (factors that influence the evacuation process, e.g. bottleneck widths and capacities), (2) quantify (calibrate) those parameters, e.g. flow through a bottleneck in persons per meter and second, and (3) validate simulation results, e.g. compare real evacuation times to simulation or calculation results. However, real data of evacuation are relatively scare. Furthermore, real cases of evacuation have generally very specific contexts. Experimental evacuations present also important difficulties. Due to practical, financial, and ethical constraints, an evacuation trial cannot be realistic by its very nature. Therefore, an evacuation exercise does not generally convey the increased stress of a real evacuation.

6.2 Guidelines and Legal Requirements for Evacuation Processes

The evacuation of a building can either be an isolated process (due to fire restricted to this building, a bomb threat, etc.) or it can be part of the evacuation of a complete area. In the following we focus on the single building evacuation. For the evacuation of complete areas, e.g. because of flooding or hurricanes, cf. [144] and references therein.

In many countries there is no strict criterion for the maximum evacuation time of buildings. The requirements in legal building regulations, standards or guidelines are usually based on specifications of maximal escape path length as well as on maximal number of occupants permitted in combination with minimum exit widths. These specifications can vary from country to country significantly, see [55]. These variations base on different assumptions with respect to capacity as well as the dependence of the capacity on the width, see 3.2.

Safety during an building evacuation is furthermore assured by the quality of the escape routes or building services. This includes for example measures to ensure smoke and fire free escape routes for a certain time or the the planing of doors that can be opened in the direction of the evacuation movement.

Building services to enhance the evacuation include automatic fire detection systems, alarming systems or sprinkler systems.

For passenger ships, a distinction between High Speed Craft (HSC), Ro-Ro passenger ferries, and other passenger vessels (cruise ships) is made. High Speed Craft do not have cabins and the seating arrangement is similar to aircraft. Therefore, there is a separate guideline for HSC [119]. For an overview over IMO's requirements and the historical development up to 2001 cf. [46]. In addition to the five components for the overall evacuation time listed in Sec. 6.1, there are three more specific for ships: (6) preparation time (for the life-saving appliances, i.e. lifeboats, life-rafts, davits, chutes), (7) embarkation time, and (8) launching time. Therefore, the evacuation procedure on ships is more complex than for buildings.

For High Speed Craft, the time limit is 17 minutes for evacuation [37], for Ro-Ro passenger ships it is 60 minutes [118], and for all other passenger ships (e.g. cruise ships) it is 60 minutes if the number of main vertical zones is less or equal than five and 80 minutes otherwise [118].

For aircraft, the approach can be compared to that of HSC. Firstly, an evacuation test is mandatory and there is a time limit of 90 seconds that has to be complied to in the test [52].

A number of real evacuations has been investigated and reports are publicly available. Among the most recent ones are: Beverly Hills Club [20], MGM Grand Hotel, [20], retail store [7], department store [1], World Trade Center [67] and `www.wtc.nist.gov`, high-rise buildings [134, 160], theatre [189] for buildings, High Speed Craft "Sleipner" [129] for HSC, an overview up to 1998 [132], exit width variation [121], double deck aircraft [84], another overview from 2002 [120] for aircraft, and for trains [62, 155].

6.3 Crowd Disasters

A non-exhaustive list of examples for crowd disasters include the Victoria Hall Disaster (1883) [139], the crowning ceremony of Tsar Nicholas II (1896) [154], the Iroquois theater in Chicago (1903), or more recently a governmental Christmas celebration in Aracaju (2001), the distribution of free Saris in Uttar Pradesh (2004), the opening of an IKEA store in Jeddah (2004), crowd movements in football stadium (Luzhniki Stadion in 1982, Hillsborough Stadion in 1989, Johannesburg Stadion in 2001, Abidjan Stadion in 2009), the pilgrimage to Mecca (1990, 2006, 2015), or again during festivals (e.g., Spring festival in Peking in 2004, Love Parade in Duisburg in 2010, Watter Festival in Phnom Penh in 2010, Patna's Gandhi Maidan Festival in 2014).

Although empirical data on crowd disasters exist, e.g. in the form of reports from survivors or even video footage, it is almost impossible to derive quantitative results from them. Qualitatively, most of crowd disasters are connected with overfilled areas (rooms or other structural installations) and to small exits or other to small parts of a pedestrian facility. Crowd disasters occur in situation with and without external threats putting into question the role of irrational behaviour due to fear. First jamming occurs which could develop to strong pushing and showing. Rewards could increase the possibility that a simple jam evolve to a pushing crowd [115, 121, 171]. Their could be very high rewards like the reward to survive (e.g. in case of a fire) but also seemingly small rewards (e.g. reaching a certain attraction) could initiating the pushing of individuals in a crowd.

The concept of "panic" and its relevance for crowd disasters is not scientifically proven and discussed rather controversially. Panic is usually used to describe irrational, selfish and unsocial behaviour. In the context of evacuations empirical evidence shows that this type of behaviour is rare [6,36,85,172]. On the other hand, there are indications that fear might be "contagious" [44]. Furthermore related concepts like "herding" and "stampede" seem to indicate a certain similarity of the behaviour of human crowds with animal behaviour [83, 150]. The origin of this view on panic behaviour in crowds could be traced back to LeBon and the riots of the Paris commune [103]. LeBon developed a theory to explain these riots basing on the idea of a certain collectivity. Nowadays social psychologist rate the concept of LeBon and the theory of collective behaviour initiating a panic as an oversimplification with a weak (or better no) scientific background [111, 159].

This terminology is quite often used in the public media. It seems to be natural that herding for instance exists in certain situations, e.g. limited visibility due to failing lights or strong smoke when exits are hard to find. However, notion of herding or stampede are difficult to quantify and measure in human crowds.

Causes for congestions should be discriminated from causes for death. Some police reports note asphyxiation as one cause of death. However, it is not clear how and why the victims suffocated. In cases of heavy pushing eyewitness reported (e.g. from the Love Parade in Duisburg) that people were lying on the ground not being able to stand up again, even with the help of other people. Several persons suffocated since the pressure due to the pushing was too high. Why people fell to the ground (being pushed or stumble) is still unclear. Fatalities occurred also at stampedes where people were overrun.

7 Controlled Experiments

To understand and thereupon to model pedestrian dynamics reliable empirical data is needed. The dynamics of a person, a group or crowd has a large variety of influencing aspects. Personal factors are the plan or goal in mind, the local knowledge of the place, experience of the current situation, constitution, motivation, stress level or cultural affiliation and much more. Some of these factors in turn are influenced by the age, gender, weight, body size or disabilities (from visual aid to wheelchair). Interpersonal aspects are for example the size and density of the crowd, flow directions, atmosphere, dynamic, togetherness and grouping (family or friends). The personal as well as the interpersonal factors are influenced by the surrounding like the facility design (e.g. complexity of a building, signage), lighting conditions or available routes.

Thus motion and behaviour are influenced by a variety of factors and furthermore crowds can be rather inhomogeneous so that for the investigation of single parameters other influencing aspects should be kept as constant as possible. This can be facilitate by controlled experiments, although the motivation of the participants can decrease over a long term study or an adaptation to the procedure of the experiment can happen. But only with laboratory experiments one is able to selectively analyze parameters under well defined constant conditions without undesired influences, vary these parameters of interest as needed and adjust them to irregularly or seldom situations in field studies like a specific quantity of disabled people [35] or very high densities [168]. For self-initiated experiments the location and the structure of the test persons (e.g. culture, fitness, age, gender, size) can be determined. Moreover, optimal conditions in artificial environments ensure the extraction of high precise data with low error [13] and enables the measurement of quantities like psychological aspects [171] not possible to survey in observations.

For field studies collecting data is cheaper whereby the precision is lower and extracting meaningful information is much harder. The situation at field studies is more realistic and some parameters influencing pedestrian dynamics are difficult to set up artificially (e.g. as mentioned in Sec. 6.2 the stress of a real evacuation in comparison to an evacuation exercise).

To give the possibility to reproduce findings and to allow further analysis of data extracted from elaborate experiments sharing this data can push forward the field of pedestrian dynamics. An open access data archive can be found at [56]. This is a good starting point for experimental studies on pedestrian dynamics.

7.1 Measurement Techniques

The level of detail of the extracted information from observations and experiments presented in the literature varies. For getting an impression of the overall movement of a crowd, determining abnormal behaviour or separating the crowd in areas of different activity the optical flow can help [3,95,133]. Also the calculation of the velocity in a certain area is possible without detecting single pedestrians. An estimation of the density is feasible as well [116, 147]. A high level of detail detects and tracks the skeleton of a person. First studies analysing precise motion sequences already started with the chronophotography in the 19th century [123]. Today the Microsoft Kinect for gaming or motion capturing systems in film productions for steering virtual characters are able to do the skeletal detection and tracking automatically in real-time [65].

For the analysis of peoples' motion the highest possible level would be the best, but for crowds with high density at present no system is able to track the full locomotor system of each subject. This is one reason why up to now most of the models simulating pedestrian dynamics do not consider the motion of all parts of a body, although taking, for example, the gait into account may enhance the quality of the simulation results [33, 162, 186]. Therefore most experimental data provided for analysis and model pedestrian dynamics are trajectories of every single pedestrian, sometimes enriched with additional global (e.g. distribution of age and gender) or individual (e.g. body size, head or shoulder orientation) information.

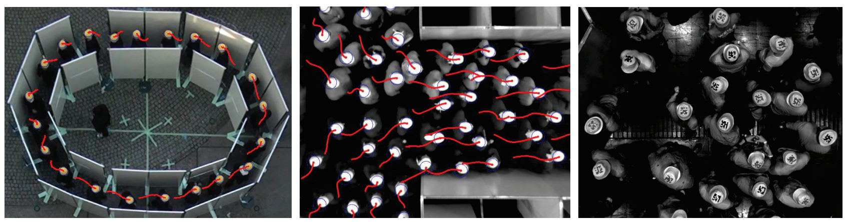

Fig. 11. Laboratory experiments using colored caps, structured marker with a black dot or code marker. For the left and middle picture the determined position is encircled in blue, and the red path is the way of every person in the last second.

By coding each participant individually as shown in the right of Fig. 11 it is possible to identify every person and fuse everyone's trajectory with static information like human factors, age or gender gathered by handed out questionnaires [12, 21, 113, 175]. In addition a unique code of a person during a series of experiments allows the identification of individuals across different runs. But also without individualized trajectories a questionnaire study is able to reveal how people perceive and evaluate a situations.

To track more than only the head or shoulder of a person in a crowd the use of inertial sensors started. Inertial measurement units consist of an accelerometer, gyroscope and magnetometer measuring the acceleration, angular rate and magnetic field of a moving object. With those readings it is possible to keep track of relative changes of the position of body parts [12, 158] so that e.g. the invisible stepping in a crowd can be analysed.

The use of eye tracker allow for example the investigation of the perception of signs, capturing objects which get the most attention or studying the collision avoidance behaviour [90].

The captured dynamic sensor data focus up to now on the physical momentum inside the crowd. For a better exploration of the social and psychological character of the crowd and to combine aspects of behavioural biology [10] and social psychology [171] with the natural scientist perspective additional data like electrodermal activities or pulse is helpful.

As mentioned above currently the common extracted data to study pedestrian dynamics in crowded situations are paths of each person. For the extraction of these trajectories different techniques have been developed. To perform field studies methods have to be chosen without intervention and preparation of the observed people. These methods often also have to get along with the restriction having to work in real-time (e.g. for privacy protection) and using already installed surveillance cameras with a slanted viewing angle (large observation space, but high occlusion level). To detect individual persons in crowds monocular cameras [128], stereo cameras [15, 185], multi camera systems [89,137], near-infrared cameras [68], thermographic cameras [149], RGB-D sensors [39, 81] or time-of-flight cameras [9] have been used.

Also other systems exist, but according to Teixeira [178] the best modality across the board for detection and tracking of people is vision (i.e. cameras and other imagers) and computer vision is far ahead from other instrumented modalities especially with respect to spatial-resolution and precision metrics. Nevertheless Dollar stated in [47] that also under favorable conditions with pedestrians at least 80 pixels tall, 20–30 % of all pedestrians are missed with at most one false alarm every ten images. Also Nguyen writes in 2015 [128] that effective detectors can only be constructed for applications where a full upright body is visible or a upper body with less deformation. All camera systems have in common that the detection error increases with increasing density.

Prior information helps to enhance the detection rate. For laboratory experiments one is able to mark the participants, thus most of the researchers collecting data from these experiments use utilities to ease the detection. Fig. 11 shows three laboratory experiments with different marker types (colored cap, structured marker and code marker). The detected position of every pedestrian is encircled in blue while red paths show the position of the last second. For the code marker the picture shows only one view of a camera grid to enable the automatic read-out of the code. Most studies use colored caps [30, 42, 76, 106, 109, 110, 148, 169, 170, 181, 182, 193]. Others utilize structured marker, e.g. for indicating the head [14, 51] or the shoulder direction [104] or code additional information [21, 112, 113, 175] for a more precise trajectory [11, 22].

7.2 Data Extraction

To extract a real metric position from a raster graphics image an intrinsic and extrinsic calibration have to be performed. The intrinsic calibration determines camera parameters like focal length and principal point and nonlinear parameters describing the lens distortion. This camera resectioning uses a model that never fits perfectly the real distortion of a lens system, but rectifies the image so that one pixel covers ideally an equal volume in real space. The extrinsic calibration calculates the position and the heading of the camera in real world. Thereby a real position can be calculated for a specified distance to the camera [19].

For the detection of a person most researcher use caps to mark a subject. Colored caps are most common. The centre of a head sized segment with pixel colors in a specified color space volume depicts the position of that person.

To detect in every frame the same point on the head caps with labels can be used for more precise trajectories. These structured marker often codes additional information like the height, the line of sight or an individual code. These features can be extracted e.g. by isolines of the same brightness with appropriate shape [14].

The tracking of detected positions between successive frames can be done by methods like the Lucas Kanade feature tracker [16], Kalman filter [143], mean-shift tracker [4] or Camshift tracker [18].

For extracting the path of each person in crowds the viewing angle should be as perpendicular as possible to have minimal occlusion for small focal lengths. From the people only the head or at most the shoulders are visible and thus can be detected. The trajectories of people tracked in that way describe the path of the head including the swaying and not the center of mass. This data can be used for analyzing the stepping locomotion. For other derived quantities these data have to be filtered. To determine e.g. the velocity in the main moving direction the swaying inside the trajectory has to be smoothed [174] best done by considering the stepping locomotion [82] or the locomotion of the whole body.

To minimize the errors resulting from the perspective view one should use small angle of view and thus high mounted cameras to capture the whole experimental area. The small angle of view also decreases the risk of occlusion and lens systems for large focal lengths generally have a smaller optical distortion error, which are easier to reproduce by a camera model used for undistortion. The accuracy of a detected position is more accurate to the center of an image.

The measurement errors made during the detection of people's position have different reasons [11]. Missing (false negative) or surplus (false positive) detections are a big issue for field studies, but are negligible for well designed laboratory experiments. The camera calibration uses a model that never fits perfectly the real distortion of a lens system so that one has to take this into account especially to the border of images resulting from wide angle lenses.

As mentioned most researchers use colored caps. Depending on the angle at which these caps are seen by the perspective view of the camera the resulting geometric center of the color segments belong to different positions on the head of the persons. For a perpendicular view of the camera people moving towards the image center are seen from the front and people moving from the image center to the border are seen from the back as show on the top of Fig. 12. This leads to a systematic shift of the position to the image center and thus e.g. to an underestimation of the velocity of a person. This error e_c is sketched in the bottom right of Fig. 12 for an idealized colored cap as hemisphere, a viewing angle α and a distance to the camera z_0 with an assumed head radius of r. For typical distances z_0 the error can be estimated by $e_c \approx \alpha \cdot 0.0012\,\mathrm{m}/^\circ$. For structured marker this error is not existing.

The perspective view of a camera and its perspective distortion leads to an error of the position, if the distance between the detected head and the

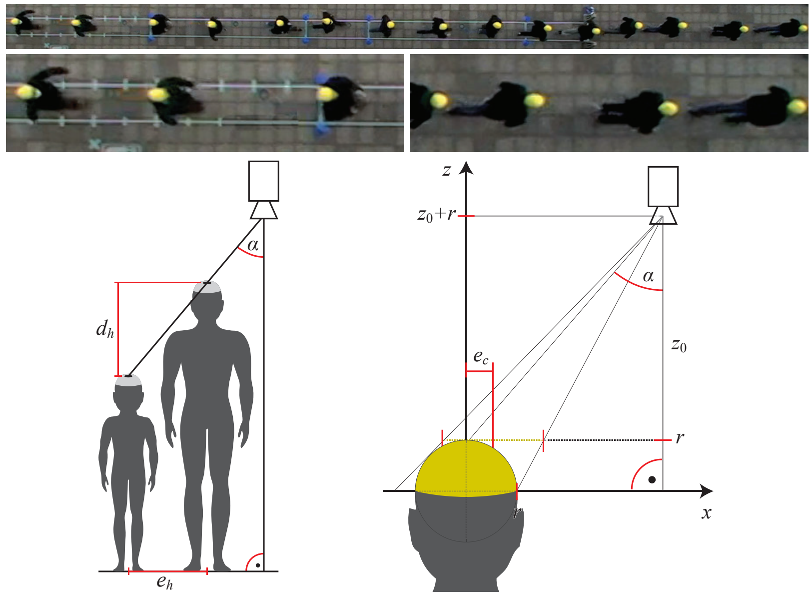

Fig. 12. Top: people with colored caps walking below a camera. The cap on the left is seen from the front and on the right from the back (magnification of the outer part in the second row). Bottom left: the same pixel in a perspective camera image corresponds to different positions on the ground plane due to differing heights of the persons. Bottom right: the geometric center of the segment of an idealized colored cap as hemisphere in a perspective image is shifted by e_c to the center of the head.

camera or the height of the person for plane experiments respectively is not known. A pixel in the image may correspond to different heights at different positions on the ground plane as illustrated on the bottom left of Fig. 12. An average height (considering the bobbing) can be chosen, but produces an error e_h of the position on the ground plane of $e_h = |d_h \tan \alpha|$ for a viewing angle α and a height difference d_h. The error variance of the position increases from the image center to the border of the image. To decrease this error one can use marker coding the height [14] or use techniques like stereo cameras or RGB-D sensors to measure the distance between the camera and the head. These 3D sensors also enables to capture the bobbing of the body movement [15].

Sometimes the area to be observed is to large for one camera, especially if the ceiling height is low so that trajectories of overlapping camera views have to be merged [14]. For this purpose the cameras have to be calibrated to the same space and time. For un-synchronized cameras a temporal intra-frame shift can decrease the error while fusing the views.

For trajectory extraction on uneven terrains like stairs, knowing peoples' height is no longer sufficient to get a correct position in space. Beside the assumption that all heads are located on a plane in 3D space [30] 3D systems

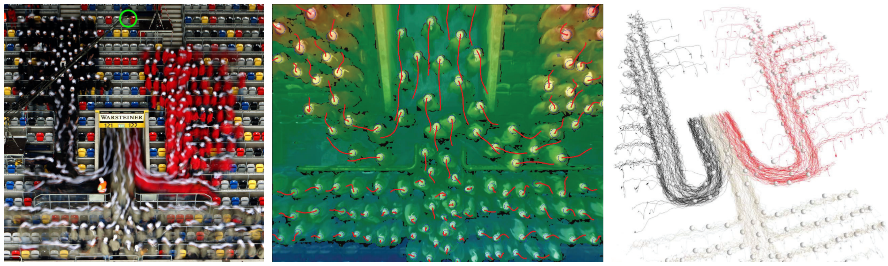

Fig. 13. Left: Experiment with 300 pedestrians leaving a grandstand in a stadium through one port. The green circle points to the position of a stereo camera. Center: Plane view of the stereo recording in front of the port color coded to the distance to the camera. The red paths show the head movement in the last second. Right: All trajectories color coded to the shirt color on the left. White spheres indicate the peoples' position to a fixed time.

like stereo cameras or RGB-D sensors can be used to indicate the 3D position of an image coordinate [15]. Fig. 13 shows an experiment at a grandstand in a stadium. One stereo camera mounted on a dolly above the port is circled green. The resulting image of one view with an overlaying disparity map and the trajectories of the last second is shown in the middle. The disparity map is color coded from red to blue according to the distance of 5 m to 11 m to the camera. The right part of Fig. 13 shows all extracted trajectories in 3D space color coded to the shirt color on the left. White spheres indicate the peoples' position to a fixed time.

8 Conclusions

The increasing importance of safety in public spaces has inspired new approaches to the investigation of pedestrian dynamics. It has been realised that more and better empirical data are needed for a more detailed understanding of the underlying principles. This is also essential for improving modelling approaches and their calibration, e.g. for applications in safety analysis and planning.

Motion and behaviour of people and crowds are influenced by a variety of factors (personal and environmental). Due to the difficulties in extracting quantitative data from observations (and potential legal issues) in recent years laboratory experiments with pedestrians have become the standard tool to collect data for pedestrian streams. They have the advantage of being reproducible and thus allow to study subtle factors like the influence of the cultural background. Besides, controlled experiments allow the investigation of single parameters under well defined constant conditions.

Currently the most common data gathered at laboratory experiments for studying pedestrian dynamics in crowded situations are paths of each person. For the detection and tracking of these paths the best modality is vision. Marker allow a robust and precise detection, but lens distortion, perspective view and peoples' height have to take into account. 3D devices allow the extraction of 3D trajectories. Coding people enables the identification of individuals. inertial sensors give the possibility to capture the full body motion of pedestrians in crowds and other devices show the viewing direction or measure the pulse. In short, for further use of the valuable data the experiments have to be well defined, documented and publicly available.

9 Future Directions

The discussion has shown that the problem of crowd dynamics and evacuation processes is far from being well understood. A basic problem that still remains is the empirical basis. Despite the progress in recent years it is difficult to perform controlled experiments on a sufficiently large scale as in most human systems. These experiments are necessary since data from actual emergency situations is usually not available, at least in sufficient quality. Further progress in the automated and accurate tracking of the motion of individual pedestrians in large crowds without the requirement of equipping the observed people would allow to obtain much more reliable data in natura.

Reliable empirical data are also essential for improving theoretical approaches and the validation and calibration of models. Realistic models in combination with detection techniques can be used to improve safety at large-scale events. An example are evacuation assistants which, in case of emergency, make a prediction for the dynamics of the evacuation process. This allows to identify critical situations (e.g. high density areas) early on and introduce countermeasures to avoid them. An example for such a system is described in [74, 75, 151].

Another issue for future research concerns the influence of socio-psychological factors. Although there seems to be a consensus that such factors are relevant and need to be considered in modelling and applications, it is difficult to separate them from the aspects that are related solely to physics, even in laboratory experiments. To make progress in this direction interdisciplinary research efforts are necessary.

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10 Bibliography

Books and Reviews

1. V.M. Predtechenskii and A.I. Milinskii: *Planing for foot traffic flow in buildings*, Amerint Publishing, New Delhi (1978)
2. P.J. DiNenno (Ed.): *SFPE Handbook of Fire Protection Engineering*, National Fire Protection Association (2002)
3. M. Schreckenberg and S.D. Sharma (Eds.): *Pedestrian and Evacuation Dynamics*, Springer (2002)
4. V.L. Knoop and W. Daamen (Eds.): *Traffic and Granular Flow '15*, Springer (2016) (see also previous issues of this conference series)
5. W. Song, J. Ma, and L. Fu (Eds.): *Pedestrian and Evacuation Dynamics 2016*, available from `http://collective-dynamics.eu/index.php/cod/article/view/A11` (see also previous issues of this conference series)
6. H. Timmermans (Ed.): *Pedestrian behavior - Models, Data Collection and Applications*, Emerald (2009)
7. K. Still: *Introduction to Crowd Science*, CRC Press (2013)
8. J.S. Tubbs and B.J. Meacham: *Egress Design Solution - A Guide to Evacuation and Crowd Management Planning*, Wiley and Sons (2007)
9. A. Schadschneider, D. Chowdhury, K. Nishinari: *Stochastic Transport in Complex Systems: From Molecules to Vehicles*, Elsevier (2010)
10. *Collective Dynamics* - A multidisciplinary journal for pedestrian dynamics, vehicular traffic and other systems of self-driven particles, `http://collective-dynamics.eu`
11. T.B. Moeslund, A. Hilton, V. Krüger, and L. Sigal (Eds.): *Visual Analysis of Humans - Looking at People*, Springer (2011)
12. S. Ali, K. Nishino, D. Manocha, and M. Shah (Eds.): *Modeling, Simulation and Visual Analysis of Crowds: A Multidisciplinary Perspective*, Springer New York (2013)
13. Online database of experiments studying the dynamics of pedestrians: `http://ped.fz-juelich.de/database`

Primary Literature

1. Abe, K. *The Science of Human Panic.* Brain Publ. Co., Tokyo, 1986. (in Japanese).
2. Alhajyaseen, W. K., Nakamura, H., and Asano, M. Effects of bi-directional pedestrian flow characteristics upon the capacity of signalized crosswalks. *Procedia - Social and Behavioral Sciences 16* (2011), 526 – 535.

3. Ali, S., and Shah, M. A lagrangian particle dynamics approach for crowd flow segmentation and stability analysis. In *Conference on Computer Vision and Pattern Recognition* (2007), pp. 1–6.
4. Allen, J. G., Xu, R. Y. D., and Jin, J. S. Object tracking using camshift algorithm and multiple quantized feature spaces. In *Proceedings of the Pan-Sydney area workshop on Visual information processing* (Darlinghurst, Australia, Australia, 2004), VIP '05, Australian Computer Society, Inc., pp. 3–7.
5. Appert-Rolland, C., Chevoir, F., Gondret, P., Lassarre, S., Lebacque, J.-P., and Schreckenberg, M., Eds. *Traffic and Granular Flow '07* (Berlin Heidelberg, 2009), Springer.
6. ASA. In disasters, panic is rare; altruism dominates. Tech. rep., ASA, Aug 2002.
7. Ashe, B., and Shields, T. J. Analysis and modelling of the unannounced evacuation of a large retail store. *Fire and Materials 23* (1999), 333–336.
8. Barlovic, R., Santen, L., Schadschneider, A., and Schreckenberg, M. Metastable states in cellular automata for traffic flow. *Eur. Phys. J. B 5* (1998), 793.
9. Benedek, C. 3d people surveillance on range data sequences of a rotating lidar. *Pattern Recognition Letters, Special Issue on Depth Image Analysis* (2014).
10. Bode, N. W. F., Holl, S., Mehner, W., and Seyfried, A. Disentangling the impact of social groups on response times and movement dynamics in evacuation. *PLOS ONE 10* (2015), 0121227.
11. Boltes, M., Holl, S., Tordeux, A., Seyfried, A., Schadschneider, A., and Lang, U. Influences of extraction techniques on the quality of measured quantities of pedestrian characteristics. In *Pedestrian and Evacuation Dynamics 2016* [173], pp. 500–547.
12. Boltes, M., Schumann, J., and Salden, D. Gathering of data under laboratory conditions for the deep analysis of pedestrian dynamics in crowds. In *2017 14th IEEE International Conference on Advanced Video and Signal Based Surveillance (AVSS)* (2017).
13. Boltes, M., and Seyfried, A. Collecting Pedestrian Trajectories. *Neurocomputing, Special Issue on Behaviours in Video 100* (2013), 127–133.
14. Boltes, M., Seyfried, A., Steffen, B., and Schadschneider, A. Automatic extraction of pedestrian trajectories from video recordings. In *Pedestrian and Evacuation Dynamics 2008* (Berlin Heidelberg, 2010), W. W. F. Klingsch, C. Rogsch, A. Schadschneider, and M. Schreckenberg, Eds., Springer, pp. 43–54.
15. Boltes, M., Seyfried, A., Steffen, B., and Schadschneider, A. Using stereo recordings to extract pedestrian trajectories automatically in space. In Peacock et al. [136], pp. 751–754.
16. Bouguet, J.-Y. Pyramidal Implementation of the Lucas Kanade Feature Tracker . *OpenCV Documents* (1999).
17. Boyce, K. E., Shields, T. J., and Silcock, G. W. H. Toward the Characterization of Building Occupancies for Fire Safety Engineering: Capabilities of Disabled People Moving Horizontally and on an Incline. *Fire Technology 35* (1999), 51–67.
18. Bradski, G. R. Computer vision face tracking for use in a perceptual user interface. *Intel Technology Journal 2* (1998), 1–15.

19. Brown, D. C. Close-range camera calibration. *Photogrammetric Engineering 37* (1971), 855–866.
20. Bryan, J. L. Behavioral response to fire and smoke. In *SFPE Handbook of Fire Protection Engineering*, P. J. DiNenno, Ed., second edition ed. National Fire Protection Association, Quincy MA, 1995, ch. 3, p. 263.
21. Bukáček, M., Hrabák, P., and Krbálek, M. Experimental study of phase transition in pedestrian flow. *Transportation Research Procedia 2* (2014), 105–113.
22. Bukáček, M., Hrabák, P., and Krbálek, M. Experimental analysis of two-dimensional pedestrian flow in front of the bottleneck – experimental analysis of 2d pedestrian flow. In Chraibi et al. [32], pp. 93–101.
23. Burghardt, S., Seyfried, A., and Klingsch, W. Improving egress design through measurement and correct interpretation of the fundamental diagram for stairs. In *Developments in Road Transportation* (NIT Rourkela, Odisha, India., 2010), M. Panda and U. Chattaraj, Eds., Macmillan Publishers India Ltd, pp. 181–187.
24. Burghardt, S., Seyfried, A., and Klingsch, W. Performance of stairs - fundamental diagram and topographical measurements. *Transportation Research Part C: Emerging Technologies 37* (2013), 268.
25. Burstedde, C., Klauck, K., Schadschneider, A., and Zittartz, J. Simulation of pedestrian dynamics using a two-dimensional cellular automaton. *Physica A 295* (2001), 507–525.
26. Cao, S., Seyfried, A., Zhang, J., Holl, S., and Song, W. Fundamental diagrams for multidirectional pedestrian flows. *Journal of Statistical Mechanics: Theory and Experiment* (2017), 033404.
27. Cao, S., Zhang, J., Salden, D., Ma, J., Shi, C., and Zhang, R. Pedestrian dynamics in single-file movement of crowd with different age compositions. *Physical Review E 94* (2016), 012312.
28. Chakrabarti, J., Dzubiella, J., and Löwen, H. Reentrance effect in the lane formation of driven colloids. *Phys. Rev. E 70* (2004), 012401.
29. Chattaraj, U., Seyfried, A., and Chakroborty, P. Comparison of pedestrian fundamental diagram across cultures. *Advances in Complex Systems 12*, 3 (2009), 393–405.
30. Chen, J., Lo, S. M., and Ma, J. Pedestrian ascent and descent fundamental diagram on stairway. *Journal of Statistical Mechanics: Theory and Experiment 2017*, 8 (2017), 083403.
31. Chen, X., Ye, J., and Jian, N. Relationships and characteristics of pedestrian traffic flow in confined passageways. *Transportation Research Record: Journal of the Transportation Research Board 2198* (2010), 32–40.
32. Chraibi, M., Boltes, M., Schadschneider, A., and Seyfried, A., Eds. *Traffic and Granular Flow '13* (Heidelberg, 2015), Springer.
33. Chraibi, M., Seyfried, A., and Schadschneider, A. Generalized centrifugal force model for pedestrian dynamics. *Physical Review E 82* (2010), 046111.
34. Chraibi, M., Tordeux, A., Schadschneider, A., and Seyfried, A. *Modelling of pedestrian dynamics.* Springer, 2018.
35. Christensen, K., Sharifi, M. S., Stuart, D., Chen, A., Kim, Y. S., and Chen, Y. Overview of a large-scale controlled experiment on pedestrian walking behavior involving individual with disabilities. In *The 93rd Annual Meeting of the Transportation Research Board* (2014).

36. Clarke, L. Panic: Myth or reality? *contexts 1* (2002), 21–26.
37. Code, H. International Code of Safety for High-Speed Craft, 2000 (2000 HSC Code). Tech. rep., International Maritime Organization (IMO), 2000. Resolution MSC.97(73).
38. Coleman, J. S. *Foundation of Social Theory.* Belknap, Cambridge, Massachusetts, 1990. Chapter 9.
39. Corbetta, A., Bruno, L., Muntean, A., and Toschi, F. High statistics measurements of pedestrian dynamics. *Transportation Research Procedia 2* (2014), 96–104.
40. Daamen, W., Bovy, P. H. L., and Hoogendoorn, S. P. Modelling pedestrians in transfer stations. In Schreckenberg and Sharma [156], pp. 59–73.
41. Daamen, W., and Hoogendoorn, S. P. Flow-density relations for pedestrian traffic. In Schadschneider et al. [152].
42. Daamen, W., and Hoogendoorn, S. P. Capacity of doors during evacuation conditions. *Procedia Engineering 3*, 0 (2010), 53 – 66. 1st Conference on Evacuation Modeling and Management.
43. Daganzo, C. F. On the variational theory of traffic flow: well-posedness, duality and applications. *Networks and Heterogeneous Media 1* (2006), 601.
44. de Gelder, B., Snyder, J., Greve, D., Gerard, G., and Hadjikhani, N. Fear fosters flight: A mechanism for fear contagion when perceiving emotion expressed by a whole body. *Proc. Natl. Acad. Sci. 101*, 47 (2004), 16701–16706.
45. Dieckmann, D. *Die Feuersicherheit in Theatern.* Jung (München), 1911. (in German).
46. Dogliani, M. An overview of present and under-development IMO's requirements concerning evacuation from ships. In Schreckenberg and Sharma [156], pp. 339–354.
47. Dollár, P., Wojek, C., Schiele, B., and Perona, P. Pedestrian detection: An evaluation of the state of the art. *Pattern Analysis and Machine Intelligence, IEEE Transactions on 34*, 4 (2012), 743–761.
48. Dzubiella, J., Hoffmann, G. P., and Löwen, H. Lane formation in colloidal mixtures driven by an external field. *Phys. Rev. E 65* (2002), 021402.
49. Edie, L. Discussion of traffic stream measurements and definitions. In *Proc. 2nd Int. Symp. Theory of traffic flow* (1963), J. Almond, Ed., pp. 139–154.
50. El Yacoubi, S., Chopard, B., and Bandini, S., Eds. *Cellular Automata - 7th International Conference on Cellular Automata for Research and Industry, ACRI 2006* (Perpignan, France, 2006), Springer.
51. Ezaki, T., Ohtsuka, K., Chraibi, M., Boltes, M., Yanagisawa, D., Seyfried, A., Schadschneider, A., and Nishinari, K. Inflow process of pedestrians to a confined space. *Collective Dynamics 1* (2016), 1–18.
52. FAA, F. A. A. Emergency evacuation - cfr sec. 25.803. Regulation CFR Sec. 25.803, Federal Aviation Administration, 1990.
53. Feliciani, C., and Nishinari, K. Empirical analysis of the lane formation process in bidirectional pedestrian flow. *Physical Review E 94* (2016), 032304.
54. Fischer, H. *Über die Leistungsfähigkeit von Türen, Gängen und Treppen bei ruhigem, dichtem Verkehr.* Dissertation, Technische Hochschule Dresden, 1933. in German.
55. Forell, B., Seidenspinner, R., and Hosser, D. Quantitative comparison of international design standards of escape routes in assembly buildings. In Klingsch et al. [91], pp. 791–801.

56. Forschungszentrum Jülich, Jülich Supercomputing Centre. Data archive of experiments on pedestrian dynamics. `http://ped.fz-juelich.de/database` (30.01.2017).
57. Frantzich, H. A model for performance-based design of escape routes. Tech. Rep. 1011, Department of Fire Safety Engineering, Lund Institute of Technology, 1994.
58. Frantzich, H. Study of movement on stairs during evacuation using video analysing techniques. Tech. rep., Department of Fire Safety Engineering, Lund Institute of Technology, 1996.
59. Fruin, J. J. *Pedestrian Planning and Design.* Elevator World, New York, 1971.
60. Fujiyama, T., and Tyler, N. An explicit study on walking speeds of pedestrians on stairs. In *10th International Conference on Mobility and Transport for Elderly and Disabled People* (2004).
61. Fujiyama, T., and Tyler, N. Pedestrian Speeds on Stairs: An Initial Step for a Simulation Model. In *Proceedings of 36th Universities' Transport Studies Group Conference* (2004).
62. Galea, E. R. Simulating evacuation and circulation in planes, trains, buildings and ships using the EXODUS software. In Schreckenberg and Sharma [156], pp. 203–226.
63. Galea, E. R., Ed. *Pedestrian and Evacuation Dynamics 2003* (London, 2003), CMS Press.
64. Garcimartín, A., Parisi, D. R., Pastor, J. M., Martín-Gómez, C., and Zuriguel, I. Flow of pedestrians through narrow doors with different competitiveness. *Journal of Statistical Mechanics: Theory and Experiment* (2016), 043402.
65. Gmiterko, A., and Liptak, T. Motion capture of human for interaction with service robot. *American Journal of Mechanical Engineering 1* (2013), 212–216.
66. Graat, E., Midden, C., and Bockholts, P. Complex evacuation; effects of motivation level and slope of stairs on emergency egress time in a sports stadium. *Safety Science 31* (1999), 127–141.
67. Grosshandler, W., Sunder, S., and Snell, J. Building and fire safety investigation of the world trade center disaster. In Galea [63], pp. 279–281.
68. Hadi, H. S., Rosbi, M., and Sheikh, U. U. A review of infrared spectrum in human detection for surveillance systems. *International Journal Of Interactive Digital Media 1*, 3 (2013), 13–20.
69. Hamacher, H. W., and Tjandra, S. A. Mathematical modelling of evacuation problems – a state of the art. In Schreckenberg and Sharma [156], pp. 227–266.
70. Hankin, B. D., and Wright, R. A. Passenger flow in subways. *Operational Research Quarterly 9*, 2 (1958), 81–88.
71. Helbing, D. Traffic and related self-driven many-particle systems. *Rev. Mod. Phys. 73* (2001), 1067.
72. Helbing, D., Buzna, L., Johansson, A., and Werner, T. Self-organized pedestrian crowd dynamics: Experiments, simulations, and design solutions. *Transportation Science 39* (2005), 1–24.
73. Helbing, D., Johansson, A., and Al-Abideen, H. Z. Dynamics of crowd disasters: An empirical study. *Physical Review E 75* (2007), 046109.

74. Holl, S., Schadschneider, A., and Seyfried, A. Hermes: An evacuation assistant for large arenas. In Weidmann et al. [191], p. 345.
75. Holl, S., and Seyfried, A. Hermes - an evacuation assistent for mass events. *inSiDe 7* (2009), 60.
76. Hoogendoorn, S., Daamen, W., and Bovy, P. Extracting microscopic pedestrian characteristics from video data. In *TRB2003 Annual Meeting* (2003).
77. Hoogendoorn, S. P., and Daamen, W. Pedestrian behavior at bottlenecks. *Transportation Science 39 2* (2005), 0147–0159.
78. Hoogendoorn, S. P., Daamen, W., and Bovy, P. H. L. Microscopic pedestrian traffic data collection and analysis by walking experiments: Behaviour at bottlenecks. In Galea [63], pp. 89–100.
79. Hoskin, K. J., and Spearpoint, M. Crowd characteristics and egress at stadia. In *Human Behaviour in Fire* (London, 2004), T. J. Shields, Ed., Intersience, pp. 367–376.
80. ISO-TR-13387-8-1999. Fire safety engineering – part 8: Life safety - occupant behaviour, location and condition. Tech. rep., International Organization for Standardization, 1999. www.iso.org.
81. Jafari, O. H., Mitzel, D., and Leibe, B. Real-time rgb-d based people detection and tracking for mobile robots and head-worn cameras. In *IEEE International Conference on Robotics and Automation (ICRA)* (2014).
82. Jelić, A., Appert-Rolland, C., Lemercier, S., and Pettré, J. Properties of pedestrians walking in line: Fundamental diagrams. *Physical Review E E 85*, 85 (2012), 9.
83. Johnson, N. R. Panic at "The Who Concert Stampede": An Empirical Assessment. *Social Problems 34* (1987), 362–373.
84. Jungermann, H., and Göhlert, C. Emergency evacuation from double-deck aircraft. In *Foresight and Precaution. Proceedings of ESREL 2000, SARS and SRA Europe Annual conference* (Rotterdam, 2000), M. Cottam, D. Harvey, R. Pape, and J. Tait, Eds., A.A. Balkema, pp. 989–992.
85. Keating, J. P. The myth of panic. *Fire Journal* (May 1982), 57–62.
86. Kerner, B. *Breakdown in Traffic Networks - Fundamentals of Transportation Science*. Springer, Berlin Heidelberg, 2017.
87. Kerner, B. S. *The Physics of Traffic*. Springer, 2004.
88. Kirchner, A., Klüpfel, H., Nishinari, K., Schadschneider, A., and Schreckenberg, M. Discretization effects and the influence of walking speed in cellular automata models for pedestrian dynamics. *J. Stat. Mech. 10* (2004), P10011.
89. Kiss, Á., and Szirányi, T. Localizing people in multi-view environment using height map reconstruction in real-time. *Pattern Recognition Letters 34*, 16 (2013), 2135–2143.
90. Kitazawa, K., and Fujiyama, T. Pedestrian vision and collision avoidance behavior: investigation of the information process space of pedestrians using an eye tracker. In Klingsch et al. [91], pp. 95–108.
91. Klingsch, W., Rogsch, C., Schadschneider, A., and Schreckenberg, M., Eds. *Pedestrian and Evacuation Dynamics 2008* (Berlin Heidelberg, 2010), Springer.
92. Knoop, V., Hoogendoorn, S., and van Zuylen, H. Empirical differences between time mean speed and space mean speed. In *Traffic and Granular Flow*

'07, C. Appert-Rolland, F. Chevoir, P. Gondret, S. Lassarre, J.-P. Lebacque, and M. Schreckenberg, Eds. Springer-Verlag Berlin Heidelberg, 2009.

93. Knoop, V. L., and Daamen, W., Eds. *Traffic and Granular Flow '15* (Berlin, Heidelberg, 2016), Springer.
94. Kozlov, V., Buslaev, A., Bugaev, A., Yashina, M., Schadschneider, A., and Schreckenberg, M., Eds. *Traffic and Granular Flow '11* (Heidelberg, 2013), Springer.
95. Krausz, B., and Bauckhage, C. Loveparade 2010: Automatic video analysis of a crowd disaster. *Computer Vision and Image Understanding 116*, 3 (2012), 307 – 319. Special issue on Semantic Understanding of Human Behaviors in Image Sequences.
96. Kretz, T. *Pedestrian traffic - Simulation and experiments*. PhD thesis, Universität Duisburg-Essen, Fachbereich Physik, Theoretische Physik, 2007.
97. Kretz, T., Grünebohm, A., Kaufman, M., Mazur, F., and Schreckenberg, M. Experimental study of pedestrian counterflow in a corridor. *J. Stat. Mech.* (2006), P10001.
98. Kretz, T., Grünebohm, A., Kessel, A., Klüpfel, H., Meyer-König, T., and Schreckenberg, M. Upstairs walking speed distributions on a long stairway. *Safety Science 46*, 1 (jan 2008), 72–78.
99. Kretz, T., Grünebohm, A., and Schreckenberg, M. Experimental study of pedestrian flow through a bottleneck. *J. Stat. Mech.* (2006), P10014.
100. Lam, W. H. K., and Cheung, C. Y. Pedestrian speed/flow relationships for walking facilities in hong kong. *Journal of Transportation Engineering 126* (2000), 343–349.
101. Lam, W. H. K., Lee, J. Y. S., Chan, K. S., and Goh, P. K. A generalised function for modeling bi-directional flow effects on indoor walkways in Hong Kong. *Transportation Research Part A: Policy and Practice 37* (2003), 789–810.
102. Lam, W. H. K., Lee, J. Y. S., and Cheung, C. Y. A study of the bi-directional pedestrian flow characteristics at Hong Kong signalized crosswalk facilities. *Transportation 29* (2002), 169–192.
103. Le Bon, G. *The Crowd: A Study of the Popular Mind (Psychologie des Foules)*. Sparkling Books, 1895.
104. Lemercier, S., Moreau, M., Moussaïd, M., Theraulaz, G., Donikian, S., and Pettré, J. Reconstructing motion capture data for human crowd study. *Lecture Notes in Computer Science 7060* (2011), 365–376.
105. Leutzbach, W. *Introduction to the Theory of Traffic Flow*. Springer, 1988.
106. Lian, L., Mai, X., Song, W., and Kit, Y. K. An experimental study on four-directional intersecting pedestrian flows. *J. Stat. Mech* (2015), P08024.
107. Lian, L., Mai, X., Song, W., Richard, K. Y. K., Wei, X., and Ma, J. An experimental study on four-directional intersecting pedestrian flows. *Journal of Statistical Mechanics: Theory and Experiment 2015*, 8 (2015), P08024.
108. Liddle, J., Seyfried, A., Klingsch, W., Rupprecht, T., Schadschneider, A., and Winkens, A. An experimental study of pedestrian congestions: Influence of bottleneck width and length. In *Traffic and Granular Flow 2009* (2009).
109. Liu, X., Song, W., Fu, L., and Fang, Z. Experimental study of pedestrian inflow in a room with a separate entrance and exit. *Physica A: Statistical Mechanics and its Applications 442* (2016), 224–238.

110. Liu, X., Song, W., and Zhang, J. Extraction and quantitative analysis of microscopic evacuation characteristics based on digital image processing. *Physica A: Statistical Mechanics and its Applications 388*, 13 (2009), 2717–2726.
111. McPhail, C., and Tucker, C. Collective behaviour. In *Handbook of Symbolic Interactionism*, L. Reynolds and H.-K. NJ., Eds. Walnut Creek, Altamira, 2003, pp. 721–741.
112. Mehner, W., Boltes, M., Mathias, M., and Leibe, B. *Robust Marker-Based Tracking for Measuring Crowd Dynamics.* Springer International Publishing, Cham, 2015, pp. 445–455.
113. Mehner, W., Boltes, M., and Seyfried, A. Methodology for generating individualized trajectories from experiments. In Knoop and Daamen [93], pp. 3–10.
114. Meyer-König, T., Klüpfel, H., and Schreckenberg, M. Assessment and analysis of evacuation processes on passenger ships by microscopic simulation. In Schreckenberg and Sharma [156], pp. 297–302.
115. Mintz, A. Non-adaptive group behaviour. *The Journal of abnormal and social psychology 46* (1951), 150–159.
116. Morerio, P., Marcenaro, L., and Regazzoni, C. S. People count estimation in small crowds. In *Advanced video and signal-based surveillance (AVSS), 2012 IEEE Ninth International Conference on* (2012), pp. 476–480.
117. Morrall, J. F., Ratnayake, L. L., and Seneviratne, P. N. Comparison of central business district pedestrian characteristics in Canada and Sri Lanka. *Transportation Research Record 1294* (1991), 57.
118. MSC-Circ.1033. Interim guidelines for evacuation analyses for new and existing passenger ships. Tech. rep., International Maritime Organization, Marine Safety Committee, London, June, 6th 2002. MSC/Circ. 1033.
119. MSC-Circ.1166. Guidelines for a simplified evacuation analysis for high-speed passenger craft. Tech. rep., International Maritime Organisation, 2005.
120. Muir, H. C. Airplane of the 21st century: Challenges in safety and survivability. In *Airplane Survivability Issues in the 21st Century* (2002).
121. Muir, H. C., Bottomley, D. M., and Marrison, C. Effects of Motivation and Cabin Configuration on Emergency Aircraft Evacuation Behavior and Rates of Egress. *The International Journal of Aviation Psychology 6*, 1 (1996), 57–77.
122. Müller, K. *Zur Gestaltung und Bemessung von Fluchtwegen für die Evakuierung von Personen aus Bauwerken auf der Grundlage von Modellversuchen.* Dissertation, Technische Hochschule Magdeburg, 1981.
123. Muybridge, E. *Animal locomotion, Plate 519.* Da Capo Press New York, 1887.
124. MVStättV - Erläuterungen: Musterverordnung über den Bau und Betrieb von Versammlungsstätten, Erläuterungen, Juni 2005. www.is-argebau.de.
125. Nagai, R., Fukamachi, M., and Nagatani, T. Evacuation of crawlers and walkers from corridor through an exit. *Physica A 367* (2006), 449–460.
126. Navin, F. D., and Wheeler, R. J. Pedestrian flow characteristics. *Traffic Engineering 39* (1969), 30–36.
127. Nelson, H. E., and Mowrer, F. W. Emergency Movement. In *SFPE Handbook of Fire Protection Engineering*, P. J. DiNenno, Ed. National Fire Protection Association, Quincy MA, 2002, ch. 14, pp. 367–380.

128. Nguyen, D. T., Li, W., and Ogunbona, P. O. Human detection from images and videos: A survey. *Pattern Recognition 51* (2016), 148–175.
129. NMJP. The High-Speed Craft MS Sleipner Disaster 26 November 1999. Official Norwegian Reports 2000:31, Norwegian Ministry of Justice and Police, Oslo, 2000.
130. Oeding, D. Verkehrsbelastung und Dimensionierung von Gehwegen und anderen Anlagen des Fußgängerverkehrs. Forschungsbericht 22, Technische Hochschule Braunschweig, 1963.
131. Older, S. J. Movement of pedestrians on footways in shopping streets. *Traffic Engineering and Control 10* (1968), 160–163.
132. Owen, M., Galea, E. R., Lawrence, P. J., and Filippidis, L. AASK – aircraft accident statistics and knowledge: a database of human experience in evacuation, derived from aviation accident reports. *Aero. J. 102* (1998), 353–363.
133. Pathan, S. S., and Richter, K. Pedestrian behavior analysis with image-based method in crowds. In Chraibi et al. [32], pp. 187–194.
134. Pauls, J. L. Evacuation drill held in the b. c. hydro building 26 june 1969. Building Research Note 80, NRCC, September 1971.
135. Pauls, J. L., Fruin, J. J., and Zupan, J. M. Minimum stair width for evacuytion, overtaking movement and counterflow - technical bases and suggestions for the past, present and future. In Waldau et al. [187], pp. 57–69.
136. Peacock, R. D., Kuligowski, E. D., and Averill, J. D., Eds. *Pedestrian and Evacuation Dynamics* (2011), Springer Berlin Heidelberg.
137. Pellicanò, N., Aldea, E., and Hegarat-Mascle, S. L. Geometry-based multiple camera head detection in dense crowds. In *Proceedings of 28th British Machine Vision Conference (BMVC) - 5th Activity Monitoring by Multiple Distributed Sensing Workshop* (2017).
138. Portz, A., and Seyfried, A. Analyzing stop-and-go waves by experiment and modeling. *Pedestrian and Evacuation Dynamics 2010* (2011), 577–586.
139. Predtechenskii, V. M., and Milinskii, A. I. *Planing for foot traffic flow in buildings*. Amerind Publishing, New Dehli, 1978. Translation of: Proekttirovanie Zhdanii s Uchetom Organizatsii Dvizheniya Lyuddskikh Potokov, Stroiizdat Publishers, Moscow, 1969.
140. Predtetschenski, W., and Milinski, A. *Personenströme in Gebäuden – Berechnungsmethoden für die Modellierung*. Müller, Köln-Braunsfeld, 1971.
141. Purser, D. A., and Bensilium, M. Quantification of behaviour for engineering design standards and escape time calculations. *Safety Science 38*, 2 (2001), 158–182.
142. Pushkarev, B., and Zupan, J. M. Capacity of walkways. *Transportation Research Record 538* (1975), 1–15.
143. Rameshbabu, K., Swarnadurga, J., Archana, G., and Menaka, K. Target tracking system using kalman filter. *International Journal of Advanced Engineering Research and Studies 2* (2012), 90–94.
144. Revi, A. Pre and post-cyclone & storm surge evacuation & emergency response in india. In Waldau et al. [187].
145. Rex, M., and Löwen, H. Lane formation in oppositely charged colloids driven by an electric field: Chaining and two-dimensional crystallization. *Physical Review E 75* (2007), 051402.

146. Rupprecht, T., Klingsch, W., and Seyfried, A. Influence of geometry parameters on pedestrian flow through bottleneck. In Peacock et al. [136], pp. 71–80.
147. Ryan, D., Denman, S., Sridharan, S., and Fookes, C. An evaluation of crowd counting methods, features and regression models. *Computer Vision and Image Understanding 130* (2014), 1–17.
148. Saadat, S., and Teknomo, K. Automation of pedestrian tracking in a crowded situation. In Peacock et al. [136], pp. 231–239.
149. Saito, H., Hagihara, T., Hatanaka, K., and Sawai, T. Development of pedestrian detection system using far-infrared ray camera. *Sei Technical Review 66* (2008), 112–117.
150. Saloma, C. Herding in real escape panic. In Waldau et al. [187].
151. Schadschneider, A., Eilhardt, C., Nowak, S., Wagoum, A. K., and Seyfried, A. Hermes - an evacuation assistant for large sports arenas based on microscopic simulations of pedestrian dynamics. In Kozlov et al. [94], p. 287.
152. Schadschneider, A., Pöschel, T., Kühne, R., Schreckenberg, M., and Wolf, D., Eds. *Traffic and Granular Flow '05* (Berlin, 2006), Springer.
153. Schadschneider, A., and Seyfried, A. Empirical results for pedestrian dynamics and their implications for modeling. *Networks and Heterogeneous Media 6* (2011), 545–560.
154. Schelajew, J., Schelajewa, E., and Semjonow, N. *Nikolaus II. Der letzte russische Zar.* Bechtermünz, Augsburg, 2000.
155. Schneider, U., Kath, K., Oswald, M., and Kirchberger, H. Evakuierung und Verhalten von Personen im Brandfall unter spezieller Berücksichtigung von schienengebundenen Fahrzeugen. Tech. Rep. 12, TU Wien, 2006.
156. Schreckenberg, M., and Sharma, S. D., Eds. *Pedestrian and Evacuation Dynamics* (Berlin Heidelberg, 2002), Springer.
157. Schreckenberg, M., and Wolf, D. E., Eds. *Traffic and Granular Flow '97* (Singapore, 1998), Springer.
158. Schumann, J., and Boltes, M. Tracking of wheelchair users in dense crowds. In *2017 International Conference on Indoor Positioning and Indoor Navigation (IPIN)* (2017).
159. Schweingruber, D., and Wohlstein, R. T. The madding crowd goes to school: Myths about crowds in introductory sociology textbooks. *Teaching Sociology 33*, 2 (2005), 136–153.
160. Seeger, P. G., and John, R. Untersuchung der Räumungsabläufe in Gebäuden als Grundlage für die Ausbildung von Rettungswegen, Teil III: Reale Räumungsversuche. Tech. Rep. T395, Forschungsstelle für Brandschutztechik an der Universität Karlsruhe (TH), 1978.
161. Seer, S., Bauer, D., Brändle, N., and Ray, M. Estimating pedestrian movement characteristics for crowd control at public transport facilities. In *11th International IEEE Conference on Intelligent Transport Systems* (2008).
162. Seitz, M. J., and Köster, G. Natural discretization of pedestrian movement in continuous space. *Phys. Rev. E 86* (2012), 046108.
163. Seyfried, A., Boltes, M., Kähler, J., Klingsch, W., Portz, A., Rupprecht, T., Schadschneider, A., Steffen, B., and Winkens, A. Enhanced empirical data for the fundamental diagram and the flow through bottlenecks. In Klingsch et al. [91], pp. 145–156.

164. Seyfried, A., Portz, A., and Schadschneider, A. Phase coexistence in congested states of pedestrian dynamics. *Lect. Notes Comp. Sci. 6350* (2010), 496.
165. Seyfried, A., Rupprecht, T., Passon, O., Steffen, B., Klingsch, W., and Boltes, M. Capacity estimation for emergency exits and bootlenecks. In *Interflam 2007 - Conference Proceedings* (2007).
166. Seyfried, A., Steffen, B., Klingsch, W., and Boltes, M. The fundamental diagram of pedestrian movement revisited. *J. Stat. Mech.* (2005), P10002.
167. Seyfried, A., Steffen, B., and Lippert, T. Basics of modelling the pedestrian flow. *Physica A 368* (2006), 232–238.
168. Shi, X., Ye, Z., Shiwakoti, N., and Li, Z. A review of experimental studies on complex pedestrian movement behaviors. In *CICTP 2015* (2015), pp. 1081–1096.
169. Shiwakoti, N., Gong, Y., Shi, X., and Ye, Z. Examining influence of merging architectural features on pedestrian crowd movement. *Safety Science 75* (2015), 15–22.
170. Shiwakoti, N., Shi, X., Zhirui, Y., and Wang, W. Empirical study on pedestrian crowd behaviour in right angled junction. In *37th Australasian Transport Research Forum (ATRF)* (2015).
171. Sieben, A., Schumann, J., and Seyfried, A. Collective phenomena in crowds - where pedestrian dynamics need social psychology. *PLOS ONE 12* (2017), 1–19.
172. Sime, J. D. The Concept of Panic. In *Fires and Human Behaviour*, D. Canter, Ed., vol. 1. John Wiley & Sons Ltd., London, 1990, ch. 5, pp. 63–81.
173. Song, W., Ma, J., and Fu, L. Proceedings of pedestrian and evacuation dynamics 2016. *Collective Dynamics 1*, 0 (2017), 618.
174. Steffen, B., and Seyfried, A. Methods for measuring pedestrian density, flow, speed and direction with minimal scatter. *Physica A 389* (2010), 1902–1910.
175. Stuart, D., Christensen, K., Chen, A., Kim, Y. S., and Chen, Y. Utilizing augmented reality technology for crowd pedestrian analysis involving individuals with disabilities. In *ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (2013).
176. Sun, J., Lu, S., Lo, S., Ma, J., and Xie, Q. Moving characteristics of single file passengers considering the effect of ship trim and heeling. *Physica A: Statistical Mechanics and its Applications 490* (2018), 476.
177. Tanaboriboon, Y., Hwa, S. S., and Chor, C. H. Pedestrian characteristics study in singapore. *Journal of Transportation Engineering 112* (1986), 229–235.
178. Teixeira, T., Dublon, G., and Savvides, A. A survey of human-sensing: Methods for detecting presence, count, location, track, and identity. *ACM Computing Surveys 5*, 1 (2010).
179. Templer, J. A. *The Staircase: Studies of Hazards, Falls, and Safer Design.* The MIT Press, 1992.
180. Thompson, P. A., and Marchant, E. W. Simulex; developing new computer modelling techniques for evaluation. In *Fire Safety Science – Proceedings of the Fourth International Symposium* (Interscience Communica-

tions Ltd, West Yard House, Guildford Grove, London, 1994), T. Kashiwagi, Ed., The International Association for Fire Safety Science, pp. 613–624. ISBN:1-88627-900-4.

181. Tian, W., Song, W., Ma, J., Fang, Z., Seyfried, A., and Liddle, J. Experimental study of pedestrian behaviors in a corridor based on digital image processing. *Fire Safety Journal 47* (2012), 8 – 15.
182. Tomoeda, A., Yanagisawa, D., and Nishinari, K. Escape velocity of the leader in a queue of pedestrians. In *Traffic and Granular Flow 2013* (2015), Springer, pp. 213–218.
183. Transportation Research Board. Highway capacity manual. Tech. rep., Transportation Research Board, Washington DC, 2000.
184. Tsuji, Y. Numerical simulation of pedestrian flow at high densities. In Galea [63], p. 27.
185. van Oosterhout, T., Englebienne, G., and Kröse, B. Rare: people detection in crowded passages by range image reconstruction. *Machine Vision and Applications 26* (2015), 561–573.
186. von Sivers, I., and Köster, G. Dynamic stride length adaptation according to utility and personal space. *Transportation Research Part B: Methodological 74* (2015), 104 – 117.
187. Waldau, N., Gattermann, P., Knoflacher, H., and Schreckenberg, M., Eds. *Pedestrian and Evacuation Dynamics 2005* (Berlin, 2006), Springer.
188. Wardrop, J. Some theoretical aspects of road traffic research. *Proceedings of the Institution of Civil Engineers 1* (1952), 325–362.
189. Weckman, L. S., and Mannikkö, S. Evacuation of a theatre: Exercise vs calculations. *Fire and Materials 23* (1999), 357–361.
190. Weidmann, U. Transporttechnik der Fussgänger. Tech. Rep. Schriftenreihe des IVT Nr. 90, Institut für Verkehrsplanung,Transporttechnik, Strassen- und Eisenbahnbau, ETH Zürich, 1993.
191. Weidmann, U., Kirsch, U., and Schreckenberg, M., Eds. *Pedestrian and Evacuation Dynamics 2012* (Zürich, 2014), Springer Berlin Heidelberg.
192. Wolf, D., and Grassberger, P., Eds. *Friction, Arching, Contact Dynamics* (Singapore, 1996), World Scientific.
193. Wong, S. C., Leung, W. L., Chan, S. H., Lam, W. H. K., Yung, N. H. C., Liu, C. Y., and Zhang, P. Bidirectional Pedestrian Stream Model with Oblique Intersecting Angle. *Journal of Transportation Engineering 136*, 3 (2010), 234–242.
194. Yamori, K. Going with the flow: Micro-macro dynamics in the macrobehavioral patterns of pedestrian crowds. *Psychological Review 105* (1998), 530–557.
195. Yanagisawa, D., Kimura, A., Tomoeda, A., Nishi, R., Suma, Y., Ohtsuka, K., and Nishinari, K. Introduction of frictional and turning function for pedestrian outflow with an obstacle. *Physical Review E 80* (2009), 036110.
196. Ye, J., Chen, X., Yang, C., and Wu, J. Walking behavior and pedestrian flow characteristics for different types of walking facilities. *Transportation Research Record: Journal of the Transportation Research Board 2048* (2008), 43–51.
197. Zhang, J., Klingsch, W., Rupprecht, T., Schadschneider, A., and Seyfried, A. Empirical study of turning and merging of pedestrian streams in T-junction. In *Fourth International Symposium on Agent-Based Modeling and Simulation (ABModSim-4)* (2012).

198. Zhang, J., Klingsch, W., Schadschneider, A., and Seyfried, A. Transitions in pedestrian fundamental diagrams of straight corridors and T-junctions. *Journal of Statistical Mechanics: Theory and Experiment* (june 2011), 06004.
199. Zhang, J., Klingsch, W., Schadschneider, A., and Seyfried, A. Experimental study of pedestrian flow through a T-junction. In Kozlov et al. [94].
200. Zhang, J., Klingsch, W., Schadschneider, A., and Seyfried, A. Ordering in bidirectional pedestrian flows and its influence on the fundamental diagram. *Journal of Statistical Mechanics: Theory and Experiment* (2012), P02002.
201. Ziemer, V., Seyfried, A., and Schadschneider, A. Congestion dynamics in pedestrian single-file motion. In *Traffic and Granular Flow 2015* (2016).
202. Zuriguel, I. Invited review: Clogging of granular materials in bottlenecks. *Papers In Physics 6* (2014), 060014.
203. Zuriguel, I., Parisi, D. R., Hidalgo, R. C., Lozano, C., Janda, A., Gago, P. A., Peralta, J. P., Ferrer, L. M., Pugnaloni, L. A., Clément, E., Maza, D., Pagonabarraga, I., and Garcimartín, A. Clogging transition of many-particle systems flowing through bottlenecks. *Scientific Reports 4* (2014), 7324.