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EMPIRICAL RESULTS FOR PEDESTRIAN DYNAMICS AND THEIR IMPLICATIONS FOR MODELING

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Abstract. The current status of empirical results for pedestrian dynamics is reviewd. Suprisingly even for basic quantities like the flow-density relation there is currently no consensus since the results obtained in various empirical and experimental studies deviate substantially. We report results from recent large-scale experiments for pedestrian flow in simple scenarios like long corridors and bottlenecks which have been performed under controlled laboratory conditions that are easily reproducible. Finally the implications of the unsatisfactory empirical situation for the modeling of pedestrian dynamics is discussed.

1. **Introduction.** The understanding of pedestrian dynamics is not only interesting from a theoretical point of view, e.g. due to the variety of collective phenomena observed [29, 16, 38, 12, 28]. In addition, it offers important applications in safety analysis. Through simulations it has become possible to save not only money by avoiding costly errors in the design of facilities, planes or cruise ships, but probably also lifes.

All these applications require realistic and accurate models. However, in the end the quality of a model has to be decided by comparing its predictions with reality. This can only be achieved if reliable empirical data are available. Despite the long history of research (see e.g. [6] and the references in [26]) in pedestrian dynamics and its relevance for everyday life the situation is far from satisfactory. The situation is very different from that in vehicular traffic since measurements of pedestrian motion are much more difficult. In highway traffic precise measurements are possible (e.g. using single-vehicle data from inductive loops) without disturbing the traffic flow. Therefore consensus has been reached even about the quantitative aspects of basic

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quantities like the flow-density relation although there is still discussion about the interpretation of some of these results, see e.g. [11, 40].

Empirical data are not only relevant for the validation and calibration of mathematical or physical models. Basic quantities like the flow-density relation are also used as an input for certain models. In particular in the field of engineering macroscopic models [7, 26, 41] as well as microscopic models [39] use this relation to describe pedestrian flow for the design of pedestrian facilities or escape routes.

Validation and calibration can be performed on different levels, ranging from a macroscopic level by comparing qualitatively with the observed phenomena, to the microscopic level, e.g. trajectories of individual pedestrians. It is clear that the latter requires sophisticated experimental techniques in order to generate accurate trajectories from the motion of a dense crowd.

In the following we will critically review the current status of empirical and experimental results for pedestrian dynamics. We try to sensitise the reader for the subtleties of these studies because of the fundamental relevance of empirical results for the modeling. Since this is true for all types of modeling approaches we do not discuss specific models here and refer to other contributions in this special issue and other reviews and books [29, 38, 12, 28].

We focus on properties of the steady state in simple but relevant scenarios. It is shown that even in these cases currently no consensus even about the most basic properties exists. This is surprising and very different from the situation in related fields, e.g. highway traffic. Furthermore it has important implications for the modeling of pedestrian and crowd dynamics.

2. **Basic quantities and measurement methods.** Models of pedestrian dynamics are often applied in sensitive areas like safety analysis. This should make a proper validation and calibration of these models mandatory, especially if reliable quantitative results are required. Unfortunately up to now there is no accepted procedure how to evaluate these models. Many different criteria have been used but it appears that the choice was often biased in such a way to make the own model look better.

Another relevant aspect for this issue is the quality of available empirical results. The realism of any model has to be tested by comparison with empirical data. If data for the same quantity differ strongly between different observations or experiments it becomes quite difficult to perform a reliable validation of a model. Or – to put it the other way – it becomes easy to find appropriate data sets which support your favorite model. This uncertainty of empircial data is also reflected in legal regulations and recommendations in various handbooks which show considerable differences, sometimes even within one country.

In the following we will review the current status of empirical and experimental results for some of the most important characteristics of pedestrian flows. The fundamental diagram, i.e. the relation between flow and density (or equivalently between average velocity and density), is not only important for the dimensioning of pedestrian facilities, but also associated with qualitative self-organization phenomena, like the formation of lanes or the occurrence of jams. The behaviour at bottlenecks is of great relevance in evacuation scenarios because bottlenecks are typically the significant factors which determine evacuation times.

2.1. **Basic quantities.** The main characteristic quantities for the description of pedestrian streams are *flow* (or current) J, *velocity* v and *density* ρ. In empirical studies the relevant quantities are usually obtained from the entrance and exit times $t_i^{(\mathrm{en})}$ and $t_i^{(\mathrm{ex})}$ for a test section. This is achieved e.g. by using video recordings or time-lapse photography. It allows to determine the velocity

$$v_i = \frac{\ell}{t_i^{(\mathrm{ex})} - t_i^{(\mathrm{en})}} \tag{1}$$

of each pedestrian once the length ℓ of the measurement section is known.

The flow J of a pedestrian stream is defined as number of pedestrians crossing a fixed location of the test section per unit of time. It can be measured in different ways. The most natural approach determines the times t_i at which pedestrians have passed a fixed measurement location. The flow is then calculate from the time gaps $\Delta t = t_{i+1} - t_i$ between two consecutive pedestrians i and $i+1$:

$$J = \frac{1}{\langle \Delta t \rangle} \qquad \text{with} \qquad \langle \Delta t \rangle = \frac{1}{N} \sum_{i=1}^{N} (t_{i+1} - t_i)\,. \tag{2}$$

The flow through a facility of width b is often normalized to the *specific flow* $J_s = J/b$ giving the flow per unit-width. By analogy with fluid dynamics sometimes the definition

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

is used, where ρ is the average density and v the average speed of the pedestrian stream. Restrictions of the comparabilty of the different definitions for the flow will be discussed in Sec. 2.2. Usually the flow is taken as a scalar quantity since only the flow normal to some cross-section is considered. In strictly one-dimensional motion (single-file motion) the line density with dimension 1/length is used so that the flow is given by $J = \rho v$.

For the density, several rather different definitions have been used in the literature. All of these methods have certain disadvantages and it is often not clear which choice is preferable in a certain situation. On the other hand, as has been shown e.g. in [34, 42], the choice of the density definition can have a considerable influence on the results.

The classical method associates a density

$$\rho = \frac{N}{A} \tag{4}$$

with a certain area A by counting the number of pedestrians N within the selected area A. This approach for the local density can be generalized by averaging over a circular region of radius R,

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

where $\vec{r}_j(t)$ are the positions of the pedestrians j in the surrounding of $\vec{r}$ and $f(...)$ is a Gaussian, distance-dependent weight function [8].

Another method takes the body size of the pedestrians into account [26]. The (dimensionless) density

$$\tilde{\rho} = \frac{\sum_j f_j}{A} \tag{6}$$

is defined by the ratio of the sum of the projection areas f_j of the bodies and the total area A of the pedestrian stream. The projection area f_j can vary strongly for different types of persons (e.g. it is much smaller for a child than an adult), so that the densities for different streams consisting of the same number of persons and the same stream area can be quite different.

As already mentioned all of these definitions suffer from certain disadvantages, e.g. there is some arbitrariness in the choice of the function f in (5) and the projection area f_j in (6) is difficult to determine in field studies. The classical density (4) which is often used has the disadvantage of large fluctuations. These fluctuations make the interpretation of results rather difficult and therefore a method with small fluctuations is desirable.

The concept of density is borrowed from fluid dynamics where the size of the particles is much smaller than the measurement area. In pedestrian dynamics these scales have the same order of magnitude and thus measurements based on the classical definition suffer from large fluctuations. In principle the fluctuations can be reduced by taking averages over time or position of the area, but at the cost of resolution. In [37] a method is introduced which reduces these fluctuations and allows measurements on a scale smaller than the size of a pedestrian. The method uses a decomposition of space by a Voronoi diagram, assigning to every person a *Voronoi cell* consisting of all points closer to that person than to any other. For a given distribution of persons $\{\vec{x}_1, \vec{x}_2, ..., \vec{x}_M\}$ the Voronoi diagram is computed giving the Voronoi cell A_i with size $|A_i|$ for each person i. With theses cells the density distribution is

$$p_i(\vec{x}) = \left\{ \begin{array}{rcl} \frac{1}{|A_i|} & : & \vec{x} \in A_i \\ 0 & : & \text{otherwise} \end{array} \right\} \qquad \text{and} \qquad p(\vec{x}) = \sum_i p_i(\vec{x}). \tag{7}$$

In a given measurement area A the Voronoi-density is than defined by

$$\rho_V = \frac{\int_A p(\vec{x})\, d\vec{x}}{|A|} \tag{8}$$

Fig. 1 illustrates the difference of the classical and the Voronoi method for a jamming situation in front of a bottleneck.

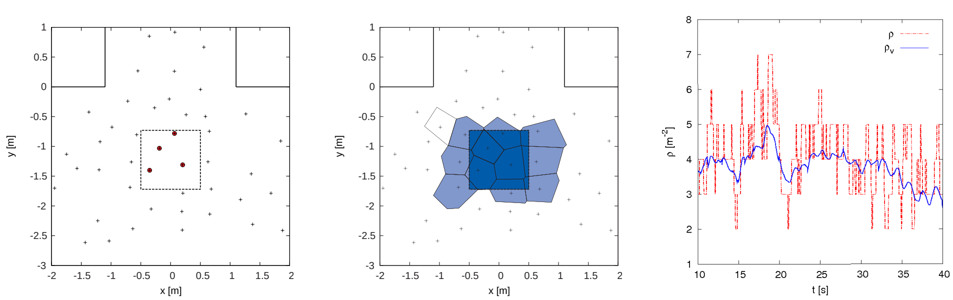


FIGURE 1. Left: Crosses and points give the position of pedestrians in a jamming situation in front of a bottleneck. The rectangle gives the measurement area. The points in the vicinity of the border of this area are responsible for large jumps in small time intervals when the classical density definition (4) is used. Middle: The light blue cells denote the Voronoi cells contributing to the density in the measurement area (dark blue). Right: Time sequence of the classical (red) and the Voronoi definition (blue) of the density.

2.2. **Measurement method.** Most of the measurements combine a time-averaged velocity or flow with an *instantaneous* density. This can have large consequences for the fundamental diagram $J(\rho)$ or equivalently $v(\rho)$. To demonstrate the magnitude of the variations we consider a simple example, the single-file motion in a system with periodic boundary conditions. Similar scenarios have frequently been studied for vehicular traffic which allows us to adopt the discussion in [14, 11] to the case of pedestrian streams. We will consider two popular approaches to measure observables like flow, velocity and density which are illustrated in Fig. 2.

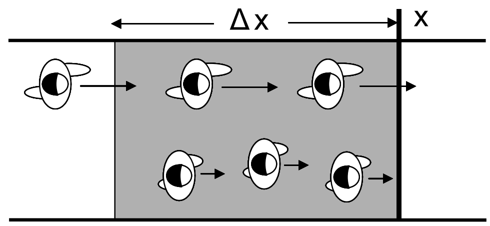


FIGURE 2. Illustration of different measurement methods to determine the fundamental diagram. Local measurements at cross-section with position x averaged over a time interval Δt have to be distinguished from measurements at a certain time averaged over space Δx.

Method A uses local measurements of the observable O at a certain location x, averaging then over a time interval Δt. We denote such averages by $\langle O\rangle_{\Delta t}$. Measurements at a certain location allow a direct determination of the flow J and the velocity v:

$$\langle J\rangle_{\Delta t} = \frac{N}{\Delta t} = \frac{1}{\langle \Delta t\rangle_{\Delta t}} \qquad \text{and} \qquad \langle v\rangle_{\Delta t} = \frac{1}{N}\sum_{i=1}^{N} v_i \,. \tag{9}$$

The flow is given as the number of persons N passing a specified cross-section at x per unit time. The average velocity $\langle v\rangle_{\Delta t}$ during the time interval Δt is determined as the average over the individual velocities v_i of the N pedestrians passing the location x during this time interval.

In *Method B* the average $\langle O\rangle_{\Delta x}$ of an observable O over space Δx at a specific time t is calculated. For an observation area of size $b\cdot\Delta x$ density ρ and velocity v can be determined directly:

$$\langle \rho\rangle_{\Delta x} = \frac{N'}{b\,\Delta x} \qquad \text{and} \qquad \langle v\rangle_{\Delta x} = \frac{1}{N'}\sum_{i=1}^{N'} v_i \,. \tag{10}$$

This method was often used in combination with time-lapse photography [23, 20].

Using the hydrodynamic equation $J = \rho\, v\, b$ the two methods can be related. The flow equation can be derived from the definition of the observables introduced above by using the distance $\Delta\tilde{x} = \langle v\rangle_{\Delta t}\,\Delta t$:

$$J = \frac{N}{\Delta t} = \frac{N}{b\Delta\tilde{x}}\,\frac{b\Delta\tilde{x}}{\Delta t} = \tilde{\rho}\; b\; \langle v\rangle_x \qquad \text{with} \qquad \tilde{\rho} = \frac{N}{b\Delta\tilde{x}}. \tag{11}$$

It should be emphasized that mean values $\langle O\rangle_x$ and $\langle O\rangle_t$ are usually different (see e.g. [5]). This is illustrated by Fig. 2 where the upper lane consists of faster pedestrians than the lower lane. Averaging over Δx does not consider the last pedestrian in the lane, in contrast to averaging over Δt at x_0 for appropriate Δt. Thus densities calculated by $\tilde{\rho} = \langle J \rangle_{\Delta t} / \langle v \rangle_{\Delta t}$ can differ from direct measurements via $\langle \rho \rangle_{\Delta x}$. This is exemplified in Fig. 3 which shows results from experiments performed with up to 70 persons. For more details of the setup we refer to [32]. The data analysis was performed with the program *PeTrack* which allows the automatic determination of trajectories from video recordings of the measurement area with high accuracy ($x_{\text{err}} \pm 0.02$ m) [1].

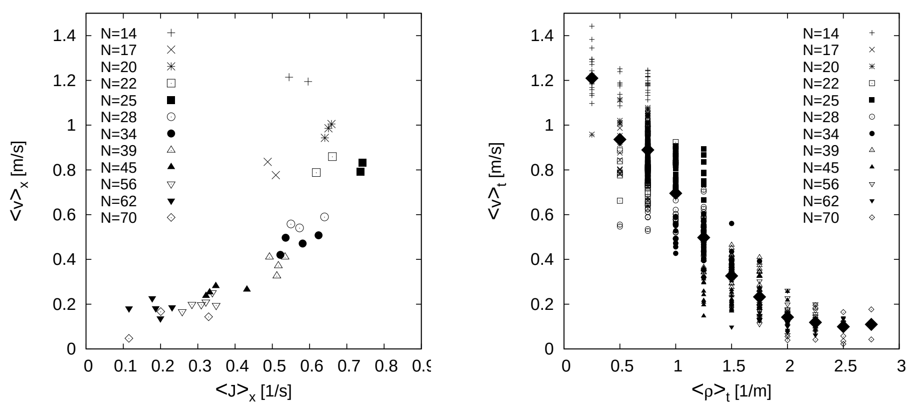


FIGURE 3. Density-dependence of the velocity measured at the same set of trajectories but with different methods. Left: Measurement at a certain cross-section averaging over time interval (Method A). Right: Measurement at a certain point in time averaging over space (Method B). Large diamonds give the overall mean value of the velocity for one density value.

Method B uses a fixed length $\ell = 4$ m of the observation area which leads to discrete density values with spacing $\Delta\rho = \ell^{-1}$ (where $\ell = 4$ m)). One can clearly see large fluctuations around the mean value $\langle v \rangle_t$ of the velocity for each density which is represented by a large diamond in Fig. 3(right). The most common form $J(\rho)$ of the fundamental diagram can be obtained from the direct measurements of Method A and B by using the flow equation (11).

Fig. 4 compares fundamental diagrams derived from the same set of trajectories but with different measurement methods. Strong deviations can be observed especially for high densities where jam waves are present. Here the trajectories show inhomogeneities in time and space which do not correspond [25]. Then the average over different degrees of freedom, time Δt for Method A and space Δx for Method B, leads to different distributions of individual velocities. Thus one reason for the deviations is the inequivalence of time- and space-averages of the velocity (see also [14, 5]). However, the straightforward use of the flow equation neglects these differences. It has been suggested [14] that the harmonic average for the calculation of the mean velocity for Method A leads to much better results. We have found that this in not true in general. One has to take into account the fluctuations and calculate the mean velocity by the harmonic average. However, for congested states with intermittent stopping of the motion, fluctuations of the density measured with Method A are extremly large and can span over the whole density range observed. The reason is that the density in Method A is determined

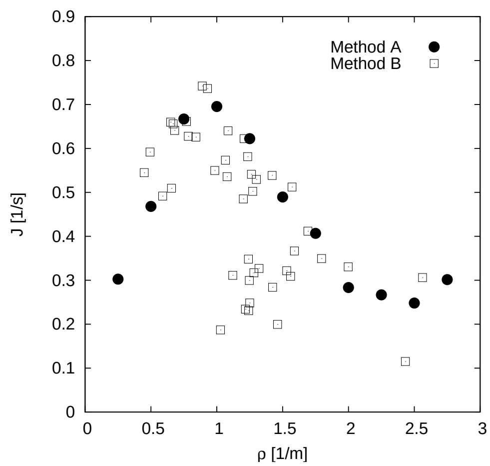


FIGURE 4. Fundamental diagram determined by different measurement methods. *Method A*: Direct measurement of the flow and velocity at a cross-section. The density is calculated via $\rho = \langle J \rangle_{\Delta t} / \langle v \rangle_{\Delta t}$. *Method B*: Measurement of the density and velocity at a certain time point averaged over space. The flow is given by $J = \rho \langle v \rangle_{\Delta x}$.

indirectly by calculating $\tilde{\rho} = \langle J \rangle_{\Delta t} / \langle v \rangle_{\Delta t}$. In the high density range the flow as well as the velocity have small values causing high fluctuations for the calculated density.

3. **Empirical results.** In the following we will review the current status of empirical results for two simple scenarios: the motion along long corridors with periodic boundary conditions and the behaviour at bottlenecks. For both cases the most interesting quantity is the flow in dependence of the relevant parameters (density, width,...). We also report our recent large-scale laboratory experiments which have been performed under controlled and reproducible conditions. This allows to study the dependence of the results on certain external parameters, like the cultural influence.

3.1. **Fundamental diagram.** The fundamental diagram, i.e. the relation between density and flow (or between average velocity and flow) is the most important quantity for the characterization of pedestrian streams. In applications it is often a basic input for most engineering methods developed for the design and dimensioning of pedestrian facilities [26, 7, 21]. Most results have been obtained for planar facilities like sidewalks, corridors or halls whereas stairs or ramps are less well studied although the shape of the diagrams can differ from the planar case.

Generically the fundamental diagram consists of a free-flow branch at low density, where the flow increases with increasing density, and a congested branch at higher densities. Here the flow decreases with increasing density due to the formation of jams. Natural quantities for the characterization of fundamental diagrams are

- the capacity $J_{\mathrm{s,max}}$, i.e. maximum of the fundamental diagram,
- the density ρ_c where the maximum flow is reached,
- the density ρ_0 where the velocity approaches zero due to overcrowding.

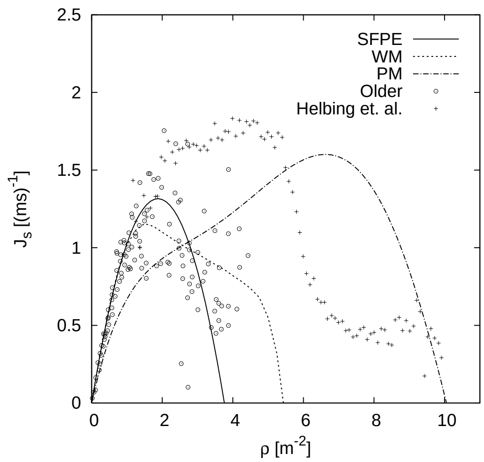


FIGURE 5. Fundamental diagrams for pedestrian movement in planar facilities. Lines refer to specifications in planning guidelines (PM: Predtechenskii and Milinskii [26]; SFPE: Nelson and Mowrer [21] and WM: Weidmann [41]). Data points are obtained from experimental measurements [23, 8].

Fig. 5 shows fundamental diagrams which are frequently used in planning guidelines together with those from two selected empirical studies. Surprisingly the curves differ considerably in the three characteristics specified above:

$$1.2\ (\mathrm{ms})^{-1} < \quad J_{\mathrm{s,max}} \quad < 1.8\ (\mathrm{ms})^{-1} \tag{12}$$
$$1.75\ \mathrm{m}^{-2} < \quad \rho_c \quad < 7\ \mathrm{m}^{-2} \tag{13}$$
$$3.8\ \mathrm{m}^{-2} < \quad \rho_0 \quad < 10\ \mathrm{m}^{-2} \tag{14}$$

Unfortunately it is difficult to determine the origin of these discrepancies. We will discuss this in more detail in Sec. 3.3.

3.2. **Bottlenecks.** An important scenario of direct relevance for most applications is the flow of pedestrians through bottlenecks. *Bottlenecks* are areas where the capacity is locally reduced which leads to variety of phenomena, e.g. the formation of lanes at the entrance to the bottleneck [9, 13, 33], or clogging and blockages at narrow bottlenecks [26, 6, 18, 17]. Bottleneck capacities provide important information for the design and dimensioning of pedestrian facilities. Therefore it is important to understand the influence of the width and the length of a bottleneck on its capacity, especially how it increases with increasing width. Surprisingly also here no consensus has been reached even about the most basic aspects of this dependence. Two different scenarios have been suggested, either a stepwise increase or a continuous increase. The stepwise increase of the capacity could be expected due to the formation of lanes inside the bottleneck. If these lanes are independent, i.e. pedestrians in different lanes do not influence each other, the capacity will only increase when an additional lane can be formed.

However, a recent study [33] has provided strong evidence that the situation is more subtle. For $b < 1.2$ m it has been observed that the lane distance increases continuously with increasing width due to kind of "zipper effect" (Fig. 7). Moreover this continuous increase leads to a very weak dependence of the density and velocity

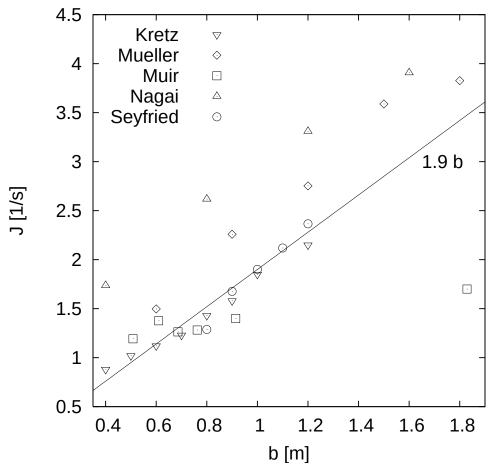


FIGURE 6. Influence of the bottleneck width on the flow. Experimental data [13, 33, 18, 17, 19] for different bottleneck types and initial conditions. All data are taken under laboratory conditions where the test persons are advised to move normally.

inside the bottleneck on its width. This finding is also consistent with a re-analysis of most older experiments.

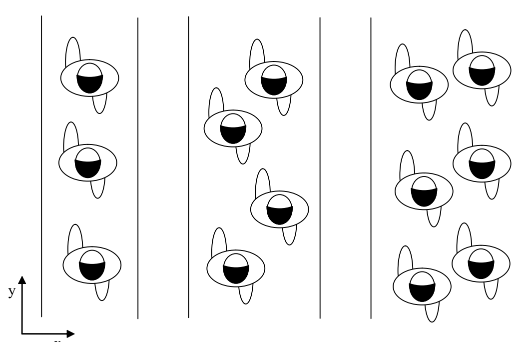


FIGURE 7. Zipper effect with continuously increasing lane distances: The distance in the walking direction decreases with increasing lateral distance. Density and velocities are the same in all cases, but the flow increases continuously with the width of the section.

Another suprising finding is that the flow through a bottleneck can be much larger than flows in a corridor [18, 19]. This leads to the interesting question how the bottleneck flow is connected to the fundamental diagram. General results from nonequilibrium physics [24] predict that the flows through a bottleneck can never be larger than those of a system with periodic boundary conditions. This is clearly violated by the empirical data of [18, 19]. So far it is not fully understood what the origin of this discrepancies is. Several reasons are possible, ranging from finite-size effects to psychological factors.

3.3. **Possible origins of the discrepancies.** It is surprising that so many discrepancies for even the most fundamental quantities of pedestrian dynamics exist, especially considering their importance for applications in safety analysis etc. Several explanations for these deviations have been suggested, e.g.

- cultural and population differences [8],
- differences between uni- and multidirectional flow [20, 27],
- short-ranged fluctuations [27],
- influence of psychological factors given by the incentive of the movement [26],
- type of traffic (commuters, shoppers) [22].

Currently no consensus about the relevance of these factors has been reached. For example it is not even clear whether there is a difference between fundamental diagrams obtained from uni-directional and multi-directional flows. In some studies these differences are either neglected [41] or argued to be small [7]. Other investigations, however, found large discrepancies for these two types of flow, e.g. a reduction of the flow in dependence of directional imbalances [20] .

A recent study [3, 31] has indeed provided strong evidence for the influence of culture on the fundamental diagram. In this empirical study the fundamental diagram has been obtained under almost identical conditions from experiments with German, Indian, Chinese and Japanese pedestrians. However, the differences found are not sufficient to explain the large discrepancies between earlier investigations.

4. **Laboratory experiments.** In the following we present the main results of large-scale experiments that have been performed under controlled conditions. This allows the reproduction of the experiments by varying certain parameters to study their influence on the flow properties of pedestrian streams.

4.1. **Fundamental diagram.** As mentioned before, the fundamental diagram is important not only for the calibration of a model, but also an input parameter e.g. for hydrodynamic approaches. We have performed several experiments with up to 250 participants under laboratory conditions. For details, we refer to [32, 36, 3, 31]. These studies have provided evidence for the influence of culture and motivation on the fundamental diagram as well as the importance of measurement techniques. A microscopic measurement based on the Voronoi density is used in [25, 34] to analyze the single-file movement (i.e. motion in one line without overtaking) at high densities. The resulting velocity-density relation shows a coexistence of moving and stopping states. The corresponding velocity distribution exhibits a typical double peak structure **(Fig. 8)** and indicates the complex structure of the fundamental diagram at high densities.

4.2. **Influence of bottleneck width and length.** The influence of bottleneck width and length was studied by well controlled experiments under laboratory conditions. Fig. 9 shows a still and a sketch of the setup. The experiments were performed in 2006 in the wardroom of the "Bergische Kaserne Düsseldorf" with a test group that was comprised of soldiers. The experimental setup allows to analyze the influence of the bottleneck width and length. In one experiment the width b was varied (from 0.9 m to 2.5 m) at fixed corridor length. In the other experiment the corridor length l was changed (0.06 m,2.0 m,4.0 m) while the width was fixed at $b = 1.2$ m. For more details of the experimental setup and data capturing we refer to [32, 1, 15]

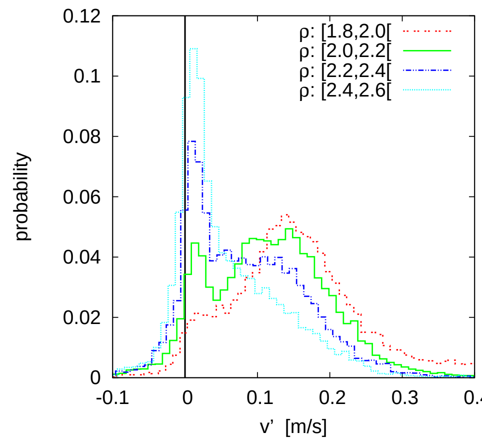
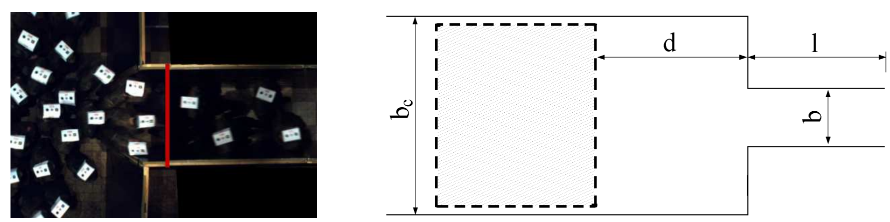


FIGURE 8. The velocity distribution depends on the density. At intermediate densities a characteristic double peak structure is observed. At high densities there is only one peak close to 0 and a low density a peak near the free walking speed.



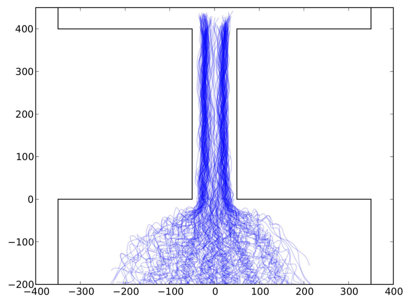
(a) Still taken from experiment. (b) Experimental setup.

FIGURE 9. Experimental setup used in our bottleneck experiments.

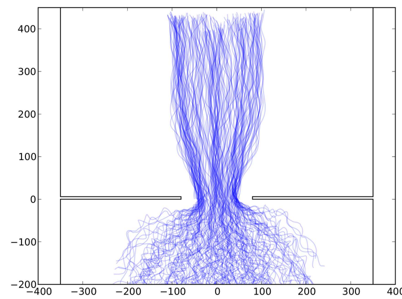
The data analysis based on individual trajectories of all pedestrian taking part in the experiment. Fig. 10 shows the accumulated trajectories for some of the runs. Due to the accurate trajectories the process of lane formation can be studied in detail. For increasing width distinct lanes remain at the boundaries of the bottleneck only. For $l = 4.0$ m two lanes are observable. For $l = 0.06$ m a third lane in the middle forms, indicating that in comparison to long bottleneck the use of the available space changes.

In the following we present results for the density in front of the bottleneck and the flow through the bottleneck in dependence of width and length. Results for the flow are compared with experimental studies form other authors.

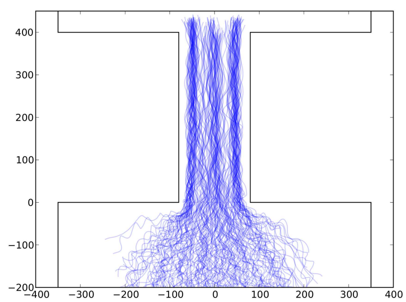
The time evolution of the classical density in front of the bottleneck is shown in Fig. 11. The position of the measurement area of size $A = 1$ m^{-2} is chosen directly in front of the entrance to the bottleneck. In all time evolutions the highest densities occur at the beginning of the experiment and reduce during the course of the runs. The highest densities develop in front of the narrowest bottlenecks (between 0 and 20 seconds) and reach $\rho_{max} = 9$ m^{-2}. For increasing width not only the time when the last person leaves the measurement area decrease but also



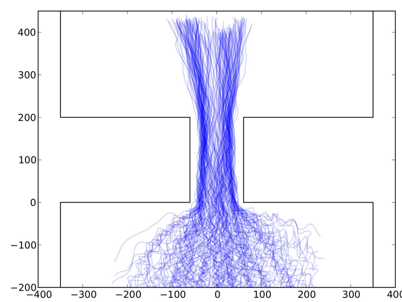
(a) $b = 1.2$ m, $l = 4.0$ m.



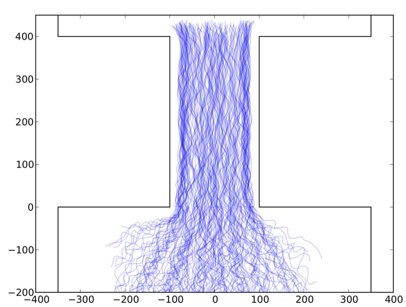
(d) $b = 1.2$ m, $l = 0.06$ m.



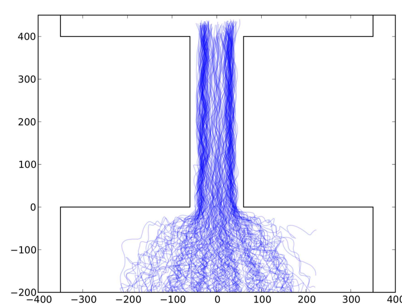
(b) $b = 1.2$ m, $l = 4.0$ m.



(e) $b = 1.2$ m, $l = 2.0$ m.



(c) $b = 2.0$ m, $l = 4.0$ m.

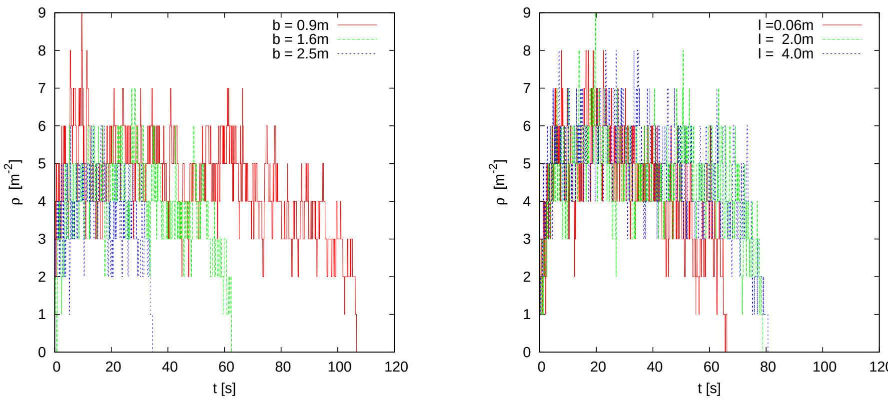


(f) $b = 1.2$ m, $l = 4.0$ m.

FIGURE 10. All pedestrian paths.

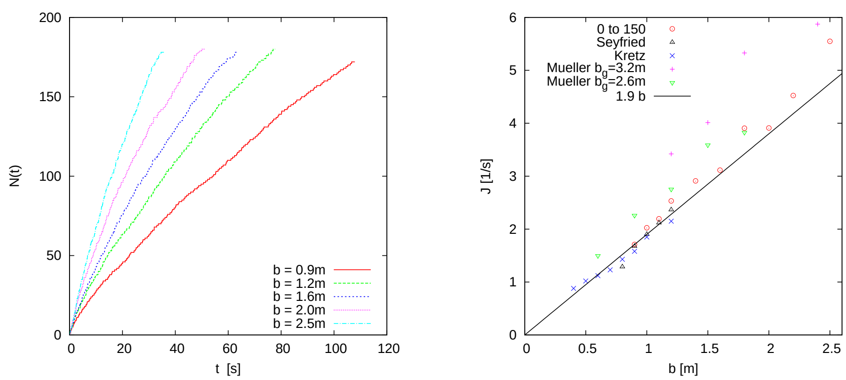
the high of the density lessens. For experiments with different bottleneck lengths l no significant difference in the densities can be observed (Fig. 11).

In Figs. 12(a) and 13(a), N the total number of pedestrians passing the measurement line are shown. To allow a comparison with the run $l = 0.06$ m the measurement line was chosen directly at the entrance to the bottleneck ($y = 0$ m). The slope of $N(t)$ gives the flow. It reduces in time which is in accordance with the observation that the densities in front of the bottleneck decrease with time, see Fig. 11. Thus the flow depends on the number of pedestrians considered. In this



(a) Dependence on b with $l = 4.0$ m. (b) Dependence on l with $b = 1.2$ m.

FIGURE 11. Time evolution of the density in front of bottleneck.



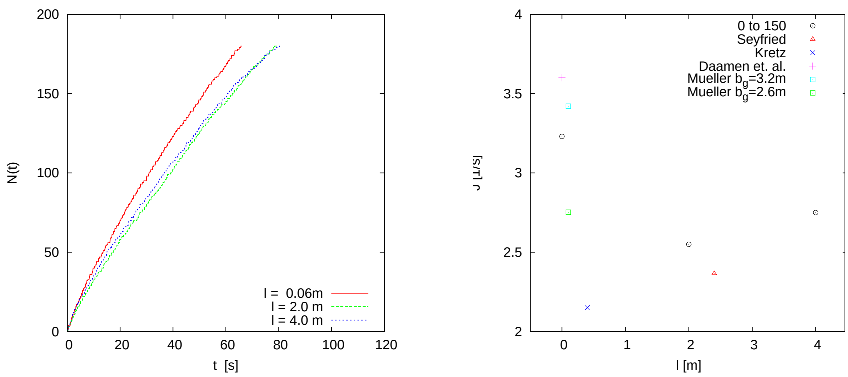
(a) $N(t)$. (b) $J(b)$

FIGURE 12. (a) Total number N of pedestrians passing the measurement line and (b) variation of the flow J with bottleneck width b.

analysis we calculate the flow using the first 150 people. Previous experiments have not observed this time dependence, as the participation in the experiments was not high enough (for example in [4] only 100 pedestrians took part). As expected the flow exhibits a strong dependence on the width of the bottleneck b, see Fig. 12. The bottleneck length l exerts virtually no influence on the flow, except for the case of an extremely short constriction (Fig. 12) where three lanes can be formed.

In Figs. 12(b) and 13(b), the flow from our experiment is compared with previous measurements. The black line in Fig. 12(b) represents a constant specific flow of $1.9\ (\mathrm{ms})^{-1}$. The difference between the flow at $l = 0.06$ m and $l = 2.0, 4.0$ m is $\Delta J \simeq 0.5\ \mathrm{s}^{-1}$.

The data points of Müller's experiments [18] lie significantly above the black line. The Müller experimental setup features a large initial density of around $6\ \mathrm{m}^{-2}$ and an extremely short corridor. The discrepancy between the Müller data and the empirical $J = 1.9b$ line is roughly $\Delta J \simeq 0.5\ \mathrm{s}^{-1}$. This difference can be accounted



(a) $N(t)$. (b) $J(l)$

FIGURE 13. (a) Total number N of pedestrians passing the measurement line and (b) variation of the flow J with bottleneck length l.

to the short corridor length, but may also be due to the higher initial density in the Müller experiment.

5. **Implications for modeling.** Empirical results are important for the validation and calibration of models [35, 10]. Therefore it would be desirable to have a collection of well-established empirical 'laws' or stylized facts as in highway traffic [11, 40] or economic systems [2]. These stylized facts could then be used as reference for validation. So far no set of facts exist which would be commonly accepted. As we have seen this is mostly a consequence of the unsatisfactory situation regarding empirical results. Therefore maybe the most important goal of pedestrian dynamics research should be to find a common basis of empirical results which could be used for testing modeling approaches.

For validation, one can distinguish between "qualitative" versus "quantitative" and "macroscopic" versus "microscopic" procedures [30]. Since we have seen that the measurement method can have a considerable influence on the results, quantitative validation should be based on a realistic implementation of the measurement methods used in the experiments. It should also be taken into account that experimental data of pedestrian flow are often connected with inhomogeneities in space and time, finite size effects and non-equilibrium conditions.

An ideal validation procedure should guarantee that the model works not only in the scenarios tested, but also in very general settings. However it is far from obvious how this can be achieved. One possibility is to formulate a number of test scenarios which allow to judge the quality of a model. Different types of tests on different levels are necessary, e.g.

- the reproduction of collective phenomena on a macroscopic level, e.g. jamming, lane formation, oscillations at bottlenecks,
- quantitative results related to collective phenomena, e.g. the density in jams,
- quantitative results for fundamental diagram, bottlenecks flows,...
- microscopic tests, e.g. on the level of trajectories.

A validation of models with fundamental diagrams for (quasi-) one-dimensional motion only is certainly not sufficient. Pedestrian dynamics is complex due to its two-dimensional nature. However, it is not unplausible that the behaviour in one-dimensional scenarios might reflect important aspects of the relevant interactions. Nevertheless this should be verified later e.g. by measuring fundamental diagrams for genuine two-dimensional motions.

So far the program sketched above has not been realized. It only makes sense if sufficient reliable empirical data are available. Here a lot of work remains to be done.

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