

New insights into pedestrian flow through bottlenecks

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Abstract

Capacity estimation is an important tool for the design and dimensioning of pedestrian facilities. The literature contains different procedures and specifications which show considerable differences with respect to the estimated flow values. Moreover do new experimental data indicate a stepwise growing of the capacity with the width and thus challenge the validity of the specific flow concept. To resolve these differences we have studied experimentally the unidirectional pedestrian flow through bottlenecks under laboratory conditions. The time development of quantities like individual velocities, density and individual time gaps in bottlenecks of different width is presented. The data show a linear growth of the flow with the width. The comparison of the results with experimental data of other authors indicates that the basic assumption of the capacity estimation for bottlenecks has to be revised. In contradiction with most planning guidelines our main result is, that a jam occurs even if the incoming flow does not overstep the capacity defined by the maximum of the flow according to the fundamental diagram.

Keywords: Pedestrian dynamics, traffic flow, traffic and crowd dynamics, capacity of bottlenecks

1 Introduction

Today more than half of the mankind is living in cities, while 50 years ago this were only 30 percent [29]. The growth of cities worldwide is inexorable and a great challenge for the urban development and architecture. In this context knowledge about pedestrian dynamics is important and allows e.g. the design and optimization of facilities with respect to safety, level of service and economy. A basic practical application is the capacity estimation which allows the dimensioning or evaluation of facilities [3, 4, 6, 25, 30]. For this purpose one is interested in the number of pedestrians, ΔN , which is able to pass the facility in a certain time interval, Δt . The specifying quantity is the flow:

$$J = \frac{\Delta N}{\Delta t}. \quad (1)$$

The capacity is defined as the maximal value for the flow, $C = J_{max}$, and allows e.g. the estimation of the minimal time needed for emptying of a given facility or of the minimal width

of the facility which allows the emptying in a given time. In the case of a classical bottleneck, like a narrowing in a corridor, it is generally assumed that a jam will occur when the incoming flow exceeds the capacity of the bottleneck [7, 20, 25, 30]. At first glance this seems to be a reasonable assumption which can be justified by reference to the continuity equation. This equation trivially implies the increase of the density in a control volume if the incoming flow is larger than the outgoing flow. However, this establishes J_{max} only as an upper limit for the incoming flow which produces a jam and does not exclude its formation for smaller flow values already.

In the literature one can find different specifications to estimate the capacity of a pedestrian facility. The flow equation in combination with empirical measurements is commonly used, see for example [2, 4, 6, 19, 20, 23, 25, 26, 30]. With the width of the pedestrian facility, b , the flow equation can be written

$$J = \underbrace{\rho v}_{=J_s} b. \quad (2)$$

The specific flow, J_s , gives the flow per unit-width and can be calculated as the product of the average density, ρ , and the average speed, v , of a pedestrian stream. The velocity and thus the flow is a function of the density. The empirical relation between flow and density, $J = J(\rho)$, is called the fundamental diagram for which one can find different representations. With a given fundamental diagram in the representation $J(\rho)$ the capacity of a facility is defined as the maximum of this function. In general it is assumed that for a given facility (e.g. corridors, stairs, doors) Equation 2 is valid, which implies that the fundamental diagrams for different b merge into one universal diagram for the specific flow J_s . Consequently the capacity, C , is assumed to be a linear function of the width, b . This assumption is used for all kinds of facilities and pedestrian streams (uni- or bidirectional). In this article we concentrate on unidirectional pedestrian movement through bottlenecks under normal conditions. If in the following the term movement under normal conditions is used it is meant, that panic or in particular non adaptive behavior which can occur in critical situation or under circumstances including rewards [14] are excluded.

Figure 1 shows various fundamental diagrams used in handbooks and planing guidelines for the capacity estimations of openings, doors or bottlenecks. The fundamental diagrams differ with respect to both, the height of the maximum (i.e. the capacity) and the corresponding density value. According to the handbook of the Society of Fire Protection Engineers (SFPE) and the guideline of Weidmann (WM) the maximum is located at a density around $\rho = 1.8 \text{ m}^{-2}$, while the maximum considered from Predtechenskii and Milinskii¹ (PM) is located at densities larger than $\rho = 7 \text{ m}^{-2}$. The predicted capacities differ from $C = 1.2 \text{ (ms)}^{-1}$ to 1.6 (ms)^{-1} . But as mentioned above all this procedures assume a linear dependence between capacity and bottleneck-width.

Contrary to this, Hoogendoorn and Daamen [9, 10] claim that the capacity is growing in a step-wise manner. This statement is based on their observation that inside a bottleneck the formation of lanes occurs, resulting from the zipper effect during entering the bottleneck. The zipper effect is a self organization phenomenon leading to an optimization of the available

¹We note, that the data of PM are gained from Equation 7, 8 and 9 in chapter III in [25] and not from the tabular in the appendix of the book. For the scaling of the density we chose $A = 0.113 \text{ m}^2$ which gives the area of horizontal projection of a pedestrian in mid-season street dress and the fundamental diagram for movement under normal conditions.

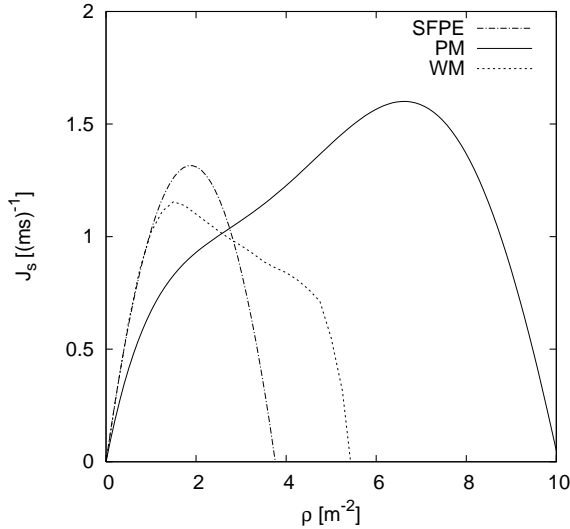


Figure 1: Fundamental diagrams for pedestrian movement through openings and doors according to the SFPE Handbook SFPE [20] and the guidelines of Predtechenskii and Milinskii PM [25] and Weidmann WM [30].

space and velocity inside the bottleneck. The data in [9,10] indicate that the distance between these lanes is independent of the bottleneck-width. This would imply that the capacity increases only when an additional lane can develop, i.e. that this would occur in a stepwise manner with increasing width [9]. Consequently, either the specific flow would decrease between the values where the steps occur or the flow equation in combination with the concept of a specific flow would not hold. One goal of this work is to examine this claim (and especially Section 4 is devoted to this question).

$b [m]$	$C = J_{max} [s^{-1}]$						
	Estimation				Measurement		
	SFPE	PM	WM	HG	Kretz	Nagai	Müller
0.8	1.04	1.28	0.98		1.43	2.58	
0.9	1.17	1.44	1.10		1.58		2.26
1.0	1.30	1.60	1.23	0.78	1.85		
1.2	1.56	1.92	1.47	0.78	2.15	3.27	2.75
1.5	1.95	2.40	1.84	1.56			3.59
1.6	2.08	2.56	1.96	1.56		3.86	

Table 1: Comparison of estimated and measured capacities for bottlenecks. The results reveal the differences not only between measurements and estimations, but also among the estimation methods or specifications.

In Table 1 these uncertainties in the capacity estimations are compared with selected experimental data on pedestrian flow. The table includes the methods according the SFPE Handbook [20], the guideline of Predtechenskii and Milinskii (PM) [25], the guideline of Weidmann

(WM) [30], the specification of Hoogendoorn (HG) in [9] and the experimental measurements by Kretz [12], Nagai [18] and Müller [17]. Some authors introduce an effective width, taking into account that pedestrians keep a distance to walls. The clear width, measured from wall to wall, is reduced in dependence of handrails, wall structure or obstacles. For a better comparability we neglected the effective width concept used in [20,30] as well as in [9]. To consider the effective width would lead to smaller flows and larger differences to the experimental measurements. Table 1 reveals the differences among the results of estimation procedures, which can exceed a factor of two. Given that these estimations come without error margins there is, strictly speaking, no contradiction. However in the context of evacuation-time predictions a discrepancy of 100 percent is unacceptable. The experimental measurements of the capacity of bottlenecks show also non negligible variations. The variation between experimental data and estimation procedures can exceed a factor of four, see Table 1. For the differences among the experimental measurements there are multiple possible reasons. However one has to note that all measurements were performed under well controlled laboratory conditions and that in all experiments the test persons were asked to move normally. Hence the influence of panic or pushing can be excluded. Other possible reasons are e.g. the geometry of the bottleneck or the initial conditions in front of the bottleneck. A detailed discussion will be possible together with the experimental results presented in this paper and can be found in Section 4.

Another important question concerns the situation when a jam in front of a facility is present. Predtechenskii and Milinskii [25] assume that in this case the flow through the bottleneck is determined by the flow in front of the bottleneck. They suppose that the density inside the jam will be higher than the density associated with the capacity and thus it is possible that the reduced flow in front of the bottleneck will cause a flow through the bottleneck smaller than the bottleneck-capacity.

Recapitulating the above discussion there are several open questions. The central one is if the flow equation in combination with the concept of a specific flow is adequate for capacity estimations leading to a linear increase of the capacity with the width. The next question is why the experimental flow measurements exceed the estimated capacities up to a factor of four. The closing question is which flow will tune in if a jam occurs in front of the bottleneck and if it is conserved at the value of the capacity.

To answer this questions and to resolve the discrepancies among the estimation results an experiment is arranged where the density and the velocity and thus the flow inside the bottleneck is measured while a jam occurs in front of the bottleneck. Our experiment is performed under laboratory conditions with a homogeneous group of test persons and equal initial conditions for the density and position of the test persons in front of the bottleneck. Exclusively the width of the bottleneck and the number of the pedestrians are varied. For the analysis the trajectories inside the bottleneck are determined and used to resolve the time dependence of the flow, the density and the velocity.

2 Experimental setup

For the experimental setup the given priority is to measure the influence of the bottleneck width and to exclude as far as possible other effects which can influence the flow. Thus one main point was to ensure same conditions of all runs with different widths. Moreover one has to consider the limited resources and thus to study the dependence of the results on the number of test persons. Our experiment was arranged in the auditorium ‘Rotunde’ at

the Central Institute for Applied Mathematics (ZAM) of the Research Centre Jülich. The configuration is shown in Figure 2. The group of test persons was composed of students and ZAM staff. The boundary of the corridor in front of the bottleneck and the bottleneck was arranged from desks. The height of the bottleneck assured a constant width from the hips to the shoulders of the test persons. The length of the bottleneck amounted to $l_{bck} = 2.8\text{ m}$. The holding areas ensured an equal initial density of the pedestrian bulk in front of the bottleneck for each run. The distance from the center of the first holding area to the entrance of the bottleneck was three meter.

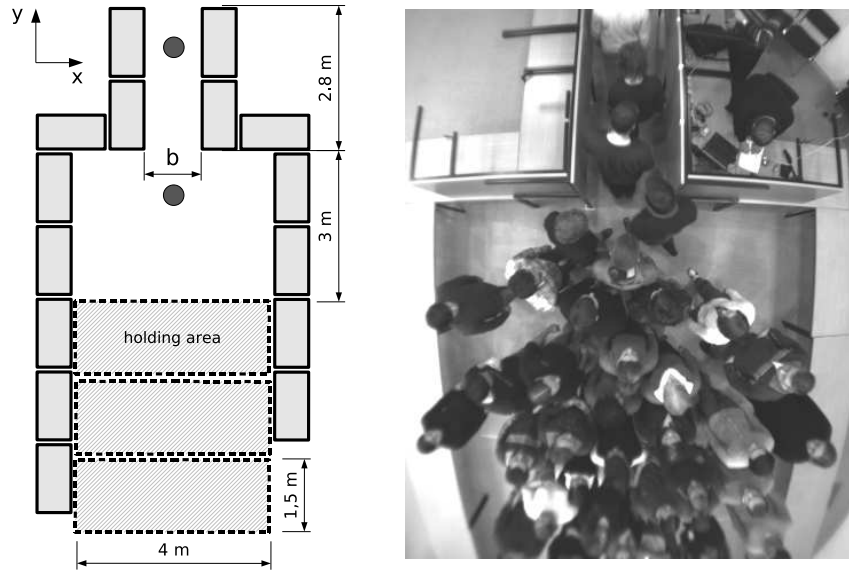


Figure 2: Experimental setup. In the left drawing the position of the video cameras are marked with circles. The holding and measurement areas are hatched. The photo shows the situation for $b=0.8\text{ m}$ in front of the entrance in the bottleneck.

A stepwise increase of the flow due to lane formation is expected more pronounced for small numbers of lanes. Bottleneck widths smaller than $b = 0.8\text{ m}$ are not relevant in practice. For $b > 1.2\text{ m}$ it was estimated that even with $N = 60$ a steady state will hardly be reached. Thus the width of the bottleneck was increased from the minimal value of $b = 0.8\text{ m}$ in steps of 0.1 m to a maximal value of $b = 1.2\text{ m}$. For every width we performed three runs with $N = 20, 40$ and 60 pedestrians in front of the bottleneck. All together 18 runs were performed to analyze the effect of the bottleneck-width, b , and the influence of the number of pedestrians, N . At the beginning of each run N test persons were placed in the holding areas with a density of $\rho_{ini} = 3.3\text{ m}^{-2}$. The test persons were advised to move through the bottleneck without haste but purposeful. It was emphasized not to push and to walk with normal velocity. The test persons started to move after an acoustic signal. The whole cycle of each run was filmed by two cameras, one situated above the center of the bottleneck and the other above the entrance of the bottleneck (indicated by the circles in Figure 2).

3 Data analysis

3.1 Specific flow

In a first step we have calculated the flow on the basis of the crossing time of the first and the last pedestrian, according Equation 1.

b [m]	J_s [(ms) ⁻¹]		
	$\Delta N = 60$	$\Delta N = 40$	$\Delta N = 20$
0.8	1.61	1.77	1.86
0.9	1.86	1.91	2.06
1.0	1.90	2.08	2.19
1.1	1.93	1.93	1.78
1.2	1.97	1.81	2.31

Table 2: The specific flow, J_s , is calculated by $\Delta N/(\Delta t b)$. The time interval Δt between the passage of the first person and last person is measured at the center of the bottleneck at $y = 0.4$ m.

In Table 2 we collect these values divided by the width, b , to examine if they approach a constant value for the specific flow, J_s . For $N = 60$ the data show a small but systematic increase of specific flow with width indicating an influence of the zipper effect and of the boundaries of the bottleneck, where the optimization through the zipper effect can not act. Nevertheless this variation is small compared to the variation in Table 1 and for $N < 60$ partly washed out by fluctuations. Furthermore for small N the time is not sufficient to reach a stationary state. To control the influence of fluctuations, non stationary states and how the zipper effect acts, the trajectories and the time development of density $\rho(t)$, velocity $v(t)$ and flow $J(t)$ are analyzed.

3.2 Trajectories and probability distributions

For the determination of the trajectories a manual procedure based on the standard video recordings of a camera above the bottleneck is used. The camera recording is done in digital CCIR 601 format on Mini-DV tape: PAL size of 720×576 rectangular pixel with aspect ratio of 1.0666 : 1 and a frame rate of 25 frames per second. These recordings are analyzed with the software tool *Adobe After Effects* [1]. To determine the trajectory the center of the head is marked and followed in time manually. To facilitate the positioning of the marker on the center of the head by hands and by visual judgment a circle around the marker is drawn, see Figure 3. For this procedure every second frame (80 ms) is used.

The trajectory of each pedestrian is exported to the format *Adobe Motion Exchange* and re-processed. The re-processing is used to minimize the errors by checking the plausibility of the data and correcting distortions based on pixel sizes and camera perspective. The plausibility check looks for backward movement, speed limits, and positions of singular trajectory points in between the boundaries. To ensure equally scaled measurements in pixel row and column the correction of the distortion has to scale the pixels to quadratic ones. Furthermore the unit meter per pixel is measured at several reference points to scale pixel sizes to real metric values. Then the picture is rectified because of a slightly non-perpendicular camera view. No

radial distortion is required. The last step rotates and moves the coordinate system to the left bottom corner of the bottleneck with the negative y axis in direction of movement.



Figure 3: A snapshot from the camera above the bottleneck. The trajectory are determined by marking the center of the head of each person manually.

For the further data analysis the individual trajectories $(x_{i,j}, y_{i,j}, t_{i,j})$ were used. The index i marks the pedestrian, while j marks the sequence of the points in time. To study the microscopic properties and the time dependence of the flow the individual time gap, Δt_i , is introduced

$$J = \frac{\Delta N}{\Delta t} = \frac{1}{\langle \Delta t_i \rangle} \quad \text{with} \quad \langle \Delta t_i \rangle = \frac{1}{N-1} \sum_{i=1}^{N-1} t_{i+1} - t_i. \quad (3)$$

Where $\langle \Delta t_i \rangle$ is the mean value of the time gaps between the crossings of two following pedestrians.

In Figure 4 we have collected for the runs with $N = 60$ the trajectories, the probability distribution to find a pedestrian at the position x averaged over y and the probability distribution of the individual time gaps, Δt_i , at center of the bottleneck at $y = 0.4 \text{ m}$. For the determination of the time gaps at $y = 0.4 \text{ m}$ we interpolate linearly between adjacent trajectory points with the current velocity. The double peak structure in the probability distribution for $b \geq 0.9 \text{ m}$ of the positions display the formation of lanes. The separation of the lanes is continuously growing with the width of the bottleneck. As a consequence of the zipper effect one expects also a double peak distribution for the time gaps Δt . However this is not so articulated as in the separation of lanes in the position. One can only observe a broadening of the time gap distribution with increasing b and a drift to smaller values. The changes in these figures as a function of the width are all continuous except for the transition from one to two lanes and there are no indications of a stepwise increase or decrease in any observable.

3.3 Time dependence of ρ , v_i , and Δt_i

For the first pedestrian passing the bottleneck in a run the velocity and density will be different from the velocity and the density of the following pedestrians. One expects that the density will increase while the velocity will decrease in time. A systematic drift to a stationary state, where only fluctuation around a constant value will occur, is expected. For the analysis of

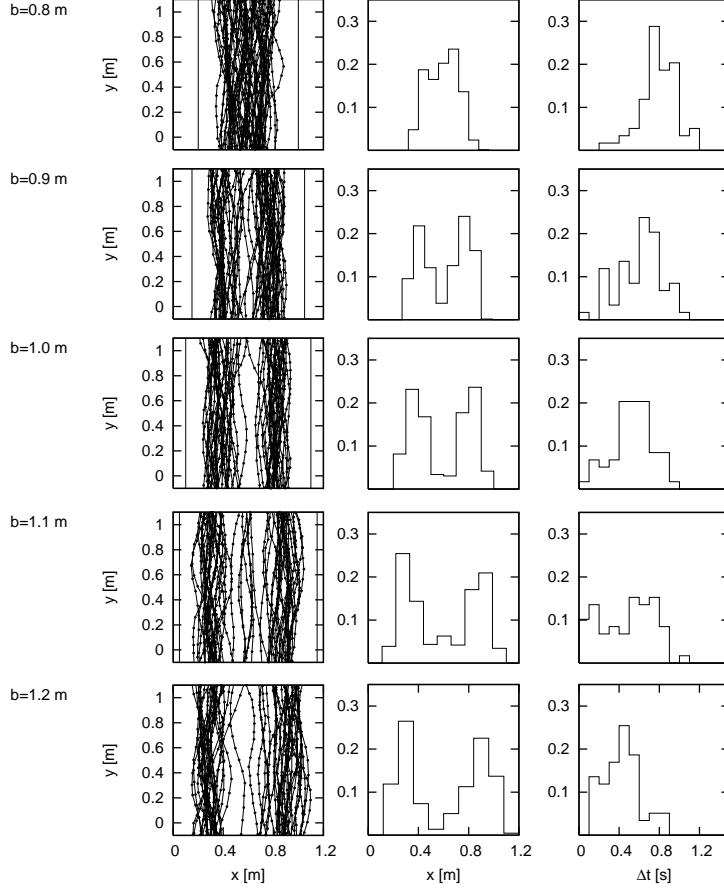


Figure 4: For the runs with $N = 60$ and from top to bottom with increasing b : The trajectories (left), the probability to find a pedestrian at position x (middle) and probability distribution of the time gaps Δt_i at $y = 0.4 \text{ m}$ (right). For $b \geq 0.9 \text{ m}$ the formation of lanes is observable. However the distance between the lanes increases continuously with b leading to a continuous decrease of time gaps between two following pedestrians, see Figure 5. Thus no indications of a stepwise change of the flow can be found.

the time dependence of the individual velocities, v_i , and density, ρ , we calculate the following quantities

$$v_i(t_{i,j}) = \frac{y_{i,j+2} - y_{i,j-2}}{t_{i,j+2} - t_{i,j-2}}. \quad (4)$$

The time, $t_{i,j}$, corresponds to the first trajectory point $(x_{i,j}, y_{i,j}, t_{i,j})$ behind $y = 0.4 \text{ m}$, the center of the bottleneck. For the density $\rho(t)$ we use the momentary number $n(t)$ of persons inside the measurement section reaching from $y = [0.9 \text{ m}, -0.1 \text{ m}]$ at the instant t , see Figure 3. With the unit length of the observation area the density is

$$\rho(t) = \frac{n(t)}{b}. \quad (5)$$

Figure 6 shows the time-development of the individual velocities and the density for the run

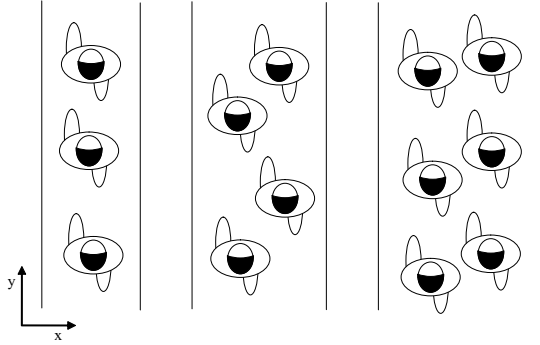


Figure 5: A sketch of the zipper effect with continuously increasing lane distances in x : The distance in y , the walking direction, decreases with increasing distance in x . This leads to a monotonous increase of the flow with increasing width.

with $N = 60$ and $b = 1.1 m$. Plots for other runs can be found in [27]. The concept of a momentary density in this small observation area is problematic because of the small (1-4) number of persons involved and leads to large fluctuations in the density. But one can clearly identify the decrease of the velocity and the increase of the density.

For the individual time gaps, see Eq. 3, a time dependence or a trend to a stationary state is hard to identify, see Figure 7, because the velocity decrease and the density increase compensate largely. A potential time dependence is covered by large and regular jumps from small to high time gaps caused by the zipper effect.

To find stationary values for the velocity and density by means of regression analysis the tool *MINUIT* [11] for function minimization is used with the following model function borrowed from relaxation processes:

$$f(t) = f_{stat} + A \exp -\frac{t}{\tau} \quad \text{for} \quad f(t) = v(t) \quad \text{and} \quad f(t) = \rho(t) \quad (6)$$

The relaxation time τ characterizes the time in which a stationary state will be reached. The amplitude A gives the difference between the stationary state and the initial velocity or density. The velocity or density at the stationary state is labeled f_{stat} . For the fit we use the data of all three runs for one width with different N , see Figure 8. The resulting stationary values and relaxation times are collected in Table 3. Note, that the model function for the regression only describes the overall decrease in time and does not account for the density-fluctuations due to the small observation area or the fluctuations of the velocity in a stable state. Consequently we do not quote an error margin in Table 3.

The results of the regression analysis are collected in Table 3. For $b \geq 1.0 m$ even with $N = 60$ the stationary state is not reached, see e.g. Figure 6. The results for A and τ indicate that the relaxation into the stationary state is almost independent of the width. However, for a final judgment more data or a larger number of test persons would be necessary. Nevertheless, the results are accurate enough to check at which position of the fundamental diagram the stationary state will be located. Again, the increase of the stationary values for the density ρ_{stat} can be explained by means of the zipper effect in combination with boundary effects. Given that the space at the boundaries can not be used as efficient as in the center of the bottleneck the density will increase for bigger width. While the stationary values of the

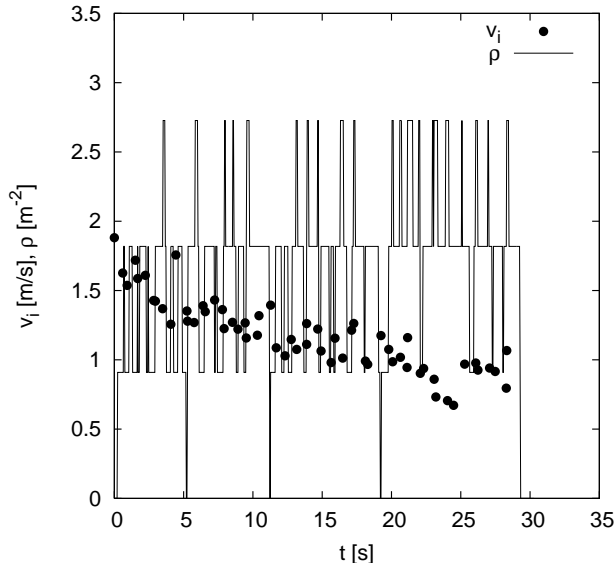


Figure 6: Development of individual velocity, Eq. 4, and density, Eq. 5, in time for the run with $N = 60$ and $b = 1.1$ m. While the velocity decreases the density increases.

b [m]	$f(t) = v(t)$			$f(t) = \rho(t)$		
	v_{stat} [m/s]	A_v [m/s]	τ_v [s]	ρ_{stat} [m ⁻²]	A_ρ [m ⁻²]	τ_ρ [s]
0.8	1.18	0.354	3.55	1.42	-1.82	0.24
0.9	1.22	0.604	3.00	1.50	-1.20	0.95
1.0	1.17	0.485	3.83	1.59	-1.87	0.31
1.1	0.94	0.745	7.33	1.73	-1.30	2.10
1.2	0.99	0.836	5.63	1.70	-1.28	1.45

Table 3: Results for the fit to $v_i(t)$ and $\rho(t)$.

densities increase the velocities shows a less pronounced decrease with b according to the fundamental diagram. Again, for a final judgment an improved data basis is needed.

4 Combined analysis with data from other experiments

In this section we compare and combine our results with the data of previous measurements. We will show that the apparent discrepancies between the different flow measurements at bottlenecks can be traced back to different initial conditions. This allows a conclusive judgment on the question if the dependence of the flow and the bottleneck-width is linear. In addition does these results have a bearing on the question at which flow value a jam occurs.

4.1 Comparison with the data of other experiments

In Figure 9 we have collected experimental data for flows through bottlenecks. All measurements were performed under laboratory conditions. The amount of test persons ranged from

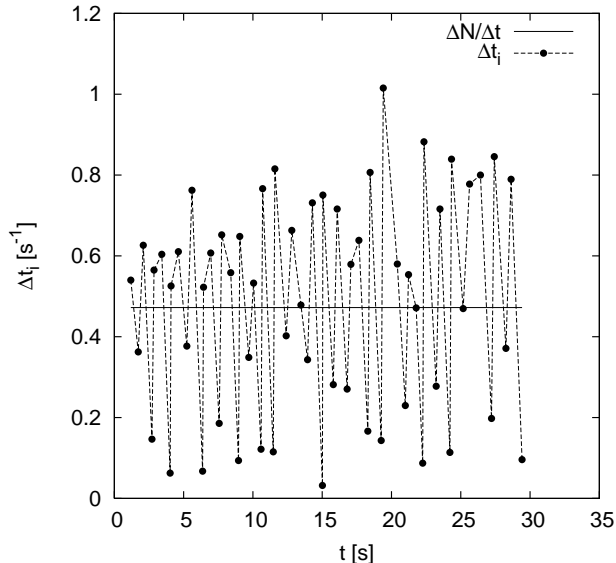


Figure 7: Development of the individual time gaps for the run with $b = 1.1 \text{ m}$ and $N = 60$ in time. The zipper effect is responsible for the systematic alternations from small to large time gaps.

$N = 30$ to 180 persons. The influence of panic or pushing can be excluded as the collection is limited to measurements where the test persons were asked to move normally. However, the experimental arrangements under which this data were taken differ in many detailed respects which provide possible explanations for the discrepancies. The outlines of the different experimental arrangements are sketched in Figure 10. Significant differences concern:

- the geometry of the bottleneck, i.e. its length and position with respect to the incoming flow.
- the initial conditions, i.e. initial density values and the initial distance between the test persons and the bottleneck.

The flow measurements of [16] show a leveling off at $b > 0.6 \text{ m}$. But the range of the flat profile from $b = 0.6 \text{ m}$ to $b = 1.8 \text{ m}$ indicates that obviously the passage width is not the limiting factor for the flow in this setup. The data of [18] and [17] are shifted to higher flows in comparison with the data of [12], [16] and our data. The height of the flows in the experiments of Müller and Nagai can be explained by their use of much higher initial densities which amount to $\rho_{ini} \approx 5 \text{ m}^{-2}$. That the initial density has this impact is confirmed by the study of Nagai et al., see Figure 6 in [18]. There it is shown that for $b = 1.2 \text{ m}$ the flow grows from $J = 1.04 \text{ s}^{-1}$ to 3.31 s^{-1} when the initial density is increased from $\rho_{ini} = 0.4 \text{ m}^{-2}$ to 5 m^{-2} .

Next we will discuss the influence of the geometry and the position of the bottleneck. As can be seen in Figure 9 there is a fair agreement between our data and the results obtained by Kretz. This indicates the minor importance of the bottleneck-length, given that in our

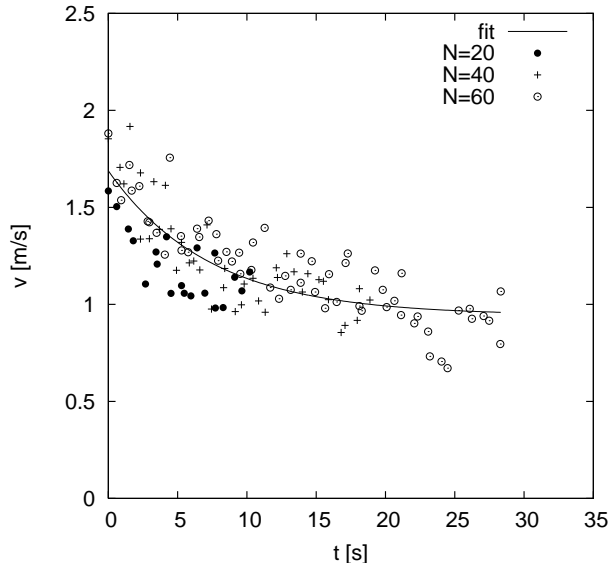


Figure 8: Development of individual velocities in time for the run with $b = 1.0 \text{ m}$. The velocity decreases to a stationary value. For the runs with different N the relaxation process is comparable.

experiment it amounts to $l_{bck} = 2.8 \text{ m}$ while Kretz has chosen a bottleneck of $l_{bck} = 0.4 \text{ m}$ length only.

While in our and Kretz’s experiment the bottleneck was centered, Nagai used a bottleneck located on the left side of the corridor. The comparison of the measurements for $b = 1.2 \text{ m}$ of Nagai for the initial densities of $\rho = 1.66 \text{ m}^{-2}$ (not displayed in Figure 9) with the data of Kretz and our results show that the flow of $J \approx 2.0 \text{ s}^{-1}$ is in good agreement with our measurements. The same applies to the flow measured by Muir which is particularly noteworthy since Muir has measured these values for the movement of a bottleneck in an airplane, where even the corridor is very small and the bottleneck is build by the galley units before the main embarkation point [16].

Finally we have to discuss the differences between the flow values of Mueller and Nagai. As noted above this can not be explained by the initial densities since both used similar (high) values. However, Müller measured at a simple opening in a thin wall of shelves while Nagai used a bottleneck with $l_{bck} = 0.4 \text{ m}$. This fact could be used to explain higher flow values for Müller, given the common and reasonable assumption that the flow is correlated to the liberty of action which is higher for less deep bottlenecks. However, just the opposite is being observed, i.e. Müller’s result lie below Nagai’s data. A possible explanation is provided by the different distances from the bottleneck to the first pedestrians at time $t = 0$. While Nagai positioned the test persons directly in front of the bottleneck Müller arranged a distance of 2.5 m between the exit and the first pedestrians. Thus it is expected that the density will decrease during the movement from the initial position to the bottleneck resulting in a smaller density directly in front of the bottleneck.

From all this we conclude that details of the bottleneck geometry and position play a minor role only while the initial density in front of the bottleneck has a major impact.

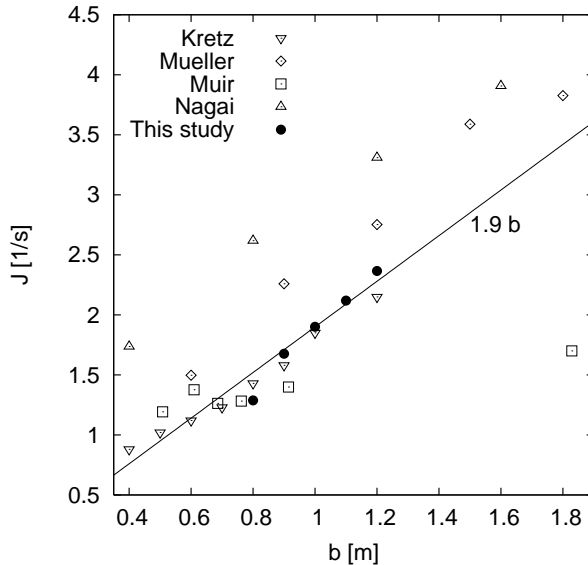


Figure 9: Influence of the width of a bottleneck on the flow. Experimental data from other authors at different types of bottlenecks and initial conditions in comparison with the results of the above described experiment.

4.2 Linear dependence of flow and bottleneck-width

As mentioned in the introduction one goal of this work is to examine if the flow or the capacity is a linear function of the width, b , of a bottleneck or if it grows in a stepwise manner, as suggested by [9]. Such a stepwise growth would question the validity of the specific flow concept used in most guidelines, see Section 1.

However, the previous section has argued for the coherence of our data set and previous measurements. All of these results are compatible with a linear and continuous increase of the flow with the width of the bottleneck. Only around $b = 0.7$ m it seems that the data of [12] show a small edge. The edge is located exactly at the width where the zipper effect can begin to act, i.e. provides no evidence for a stepwise behavior in general.

Moreover does the alleged stepwise increase of the flow follows from the assumption that inside a bottleneck the formation of lanes with constant distance occurs. In [9] this assumption is based on flow measurements at two different bottlenecks at $b = 1$ m and $b = 2$ m. It is doubtful whether this results can be extrapolated to intermediate values of the width. In fact our data show no evidence for the appearance of lanes with constant distance (see Section 3.2, in particular Figure 4).

4.3 The criteria for jam occurrence

The above results can be used to address a crucial question in pedestrian dynamics, namely the criteria for the occurrence of a jam. As mentioned already in the introduction it is commonly assumed that this happens when the incoming flow (through a surface in front of the bottleneck) exceeds the capacity of the bottleneck. Here the capacity of the bottleneck is defined as the maximum of the specific flow, $J_s(\rho)$, times its width.

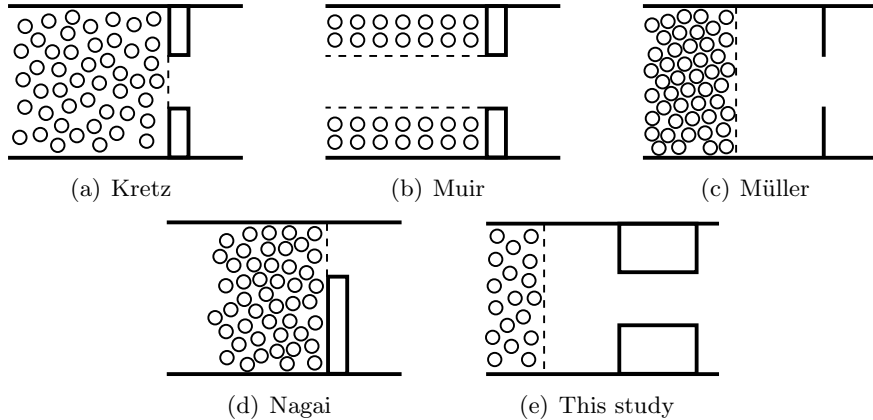


Figure 10: Outlines of the experimental arrangements under which the data shown in Figure 9 were taken.

A preliminary analysis of the situation one meter in front of the bottleneck entrance shows density fluctuations inside the jam between $\rho = 4$ to 6 m^{-2} independent from the width of the bottleneck. Our results from Section 3 can be used to examine which density and flow inside the bottleneck is present for a situation where a jam occurs in front of the bottleneck. For this purpose the fitted values for ρ_{stat} and v_{stat} are used (see Table 3).

Figure 11 indicates that the values for the stationary density derived from our experiment are exactly located at the position where the fundamental diagram according to the SFPE-Handbook and the guideline of Weidmann show the maximum of the flow (while the absolute value of the flow exceeds the predicted values), i.e. $\rho \approx 1.8 \text{ m}^{-2}$. This seems to support the common jam-occurrence criteria. However, two observations cast doubt on this conclusion. Already when discussing the data of Müller and Nagai we have mentioned that higher initial densities result in higher flow values, i.e. that the maximal flow can not be near $\rho = 1.8 \text{ m}^{-2}$. In addition do the fundamental diagrams of Mori [15], Hanking [5] and PM [25] display a completely different shape. According to Mori and Hanking and in agreement with the specification of PM the flow will increase from $\rho \approx 1.8 \text{ m}^{-2}$ or stay constant with increasing density. Moreover does the level of the flow measured in our experiment conforms much better with their specification.

In the literature one finds a multitude of different explanations for the deviations between fundamental diagrams, including cultural and population differences [8], differences between uni- and multidirectional flow [13, 19, 26], influence of psychological factors given by the incentive of the movement [25] and, partially related to the latter, the type of traffic like commuters or shoppers [21]. Moreover, in a laboratory experiment, the population is special, and the incentive will most likely be different from that in a field measurements. We assume that for densities higher than $\rho = 1.8 \text{ m}^{-2}$ cultural and population differences influence the required space and change the scaling of the density but not the shape of the diagram. The change in the scaling of the fundamental diagram due to the incentive of the movement and body size is accordance with Predtechenskii and Milinskii [25]. As a starting point of a further discussion we refer to influences due to multidirectional flow [13, 19, 26] and look in the origin of the fundamental diagrams shown in Figure 11. It seems that the most detailed one is given by Weidmann which used 25 data sets for generating his fundamental diagram. But if one performs an examination of the data which went into Weidmann's combination it turns out that

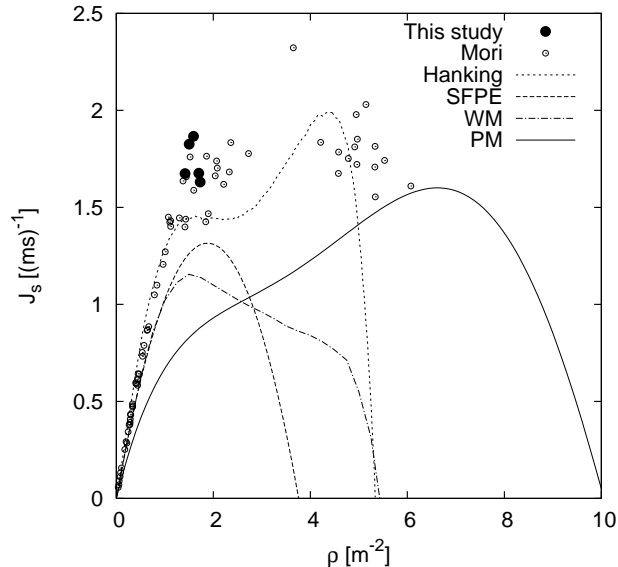


Figure 11: Experimental data of the flow and the associated density in the bottleneck in comparison with experimental data for the fundamental diagram of unidirectional pedestrian streams and the specifications for the fundamental diagram according to the SFPE Handbook and the guidelines of Weidmann and Predtechenskii and Milinskii.

most measurements with densities larger than $\rho = 1.8 \text{ m}^{-2}$ are performed with bidirectional streams, see [19, 21–24]. But also data gained by measurements on strictly unidirectional streams has been considered [4, 5]. The data of Hanking and Wright gained by measurements in London subway (UK) are in good agreement with the data of Mori and Tsukaguchi who measured in the central business district of Osaka (Japan). Their fundamental diagrams agree very well and differ notable from the fundamental diagram of the SFPE and Weidmann for densities larger $\rho = 1.8 \text{ m}^{-2}$. In accordance with Predtechenskii and Milinskii we assume that the maximum of the fundamental diagram for unidirectional movement is at much higher densities. Thus we conclude from our measurements of densities and velocities that the flow through the bottleneck under normal conditions will not reach the capacity defined through the maximum of the fundamental diagram and that a jam occurs well before the maximum is reached.

There are three possible reasons for jamming below the capacity limit. One is clearly flow fluctuations. Local density maxima higher than capacity-density cause obstructions that can be resolved only if the incoming flow is less than the outflow, which in this case is below capacity. A second reason is in the local organization of the pedestrians. At high densities, the full flow requires a fairly regular positioning of persons. This may be achieved by pre-arranging them - as in the experiments in [17, 18] - or possibly by funneling the flow into the bottleneck. Neither the random arrival at a narrow passage out of the almost free motion in a wide room nor the - also random - starting into the passage from waiting in a jam can achieve this. Therefore the actual bottleneck is the entrance into the passage, while in the passage itself the flow corresponds to the lower density associated with the observed flux (compare PM [25]). The third reason is motivational, people usually prefer larger distances

to the person in front than necessary unless there is the danger of somebody else filling the gap - or some other incentive for moving up close. These topics will be the subject of future research.

5 Summary

We have studied experimentally the flow of unidirectional pedestrian streams through bottlenecks under normal conditions. For the data analysis we used the trajectories to determine the time development of the individual velocities, local densities and time gaps for different widths of the bottleneck. The analysis shows that for a small variation of the width quantities like the time gap distribution or the lane distance change continuously if the zipper effect is acting. The results for velocities and densities are compared to common methods for the capacity estimation and to experimental data from other studies.

Except for the edge at $b \approx 0.7 \text{ m}$ due to zipper effect starting to act all collected data for flow measurements are compatible with a linear and continuous increase with the bottleneck-width. The linear dependency between the flow and the width holds for different kinds of bottlenecks and initial conditions. Hence the basic flow equation in combination with the use of the specific flow concept is justified for facilities with $b > 0.7 \text{ m}$. Moreover does the comparison with flow measurements through bottlenecks of different types and lengths show that the exact geometry of the bottleneck is of only minor influence on the flow.

The rise of the flow through the bottleneck with an increase of the initial density in front of the bottleneck from $\rho = 1.8 \text{ m}^{-2}$ to 5 m^{-2} indicates at least for this density region a rising of the slope of the fundamental diagram for unidirectional streams. This is in disagreement with most fundamental diagrams as documented in handbooks and guidelines but in agreement with empirical fundamental diagrams restricted to unidirectional movement and with the shape of the fundamental diagram according to Predtechenskii and Milinskii. Thus the capacity defined by the maximum of the fundamental diagram is expected for densities substantial higher than $\rho = 1.8 \text{ m}^{-2}$. With respect to the absolute flow values one needs to bear in mind that our results were obtained with young probands and under laboratory conditions.

Our measurements of densities and velocities inside the bottleneck show that the stationary flow will tune around densities of $\rho \approx 1.8 \text{ m}^{-2}$ when a jam occurs in front of the bottleneck. For higher densities higher flow values are expected in reference to the maxima of fundamental diagrams restricted to unidirectional streams. Supplementary an increase of the flow for $5.0 \text{ m}^{-2} > \rho > 1.8 \text{ m}^{-2}$ is observed in the experiments of [18]. Thus jamming occurs for flow values lower than maximal possible flow values. This contradicts the common assumption that a jam appears only when the capacity is exceeded. While the continuity equation trivially implies that the capacity is the upper limit for a jam producing flow, do our results indicate that this happens for smaller flow values already. Possible reasons are stochastic flow fluctuation, flow interferences due to the necessity of local organization or psychological founded changes of the incentive during the access into the bottleneck.

All experimental measurements of flow values through bottlenecks discussed in this paper are gained by laboratory experiments. Concerning differences between field measurements and laboratory experiments one has to note, that absolute values and figures obtained in a laboratory experiment cannot simply be used for design recommendations. The qualitative conclusions however - the bottleneck capacity grows about linear with width and jamming

may occur below maximum capacity - are not affected by changes in scaling of the flow measurements or of the fundamental diagram.

Tragic disasters like at the Löwenbräu-Keller in Munich, Germany (1973), Bergisel in Austria (1999) or Akashi Japan (2001) [28] have shown that already without the influence of panic insufficient dimensions of facilities can cause high densities in bottlenecks. At high densities small interferences in the crowd can not be balanced and may cause fatalities due to people stamped to the ground by high pressure. For a better evaluation of pedestrian facilities with respect to safety it is necessary to explore under which circumstances such an increase of the density inside the bottleneck occurs.

As a first step our results can be used to improve the capacity estimations in planing guidelines and handbooks to prevent such situations.

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