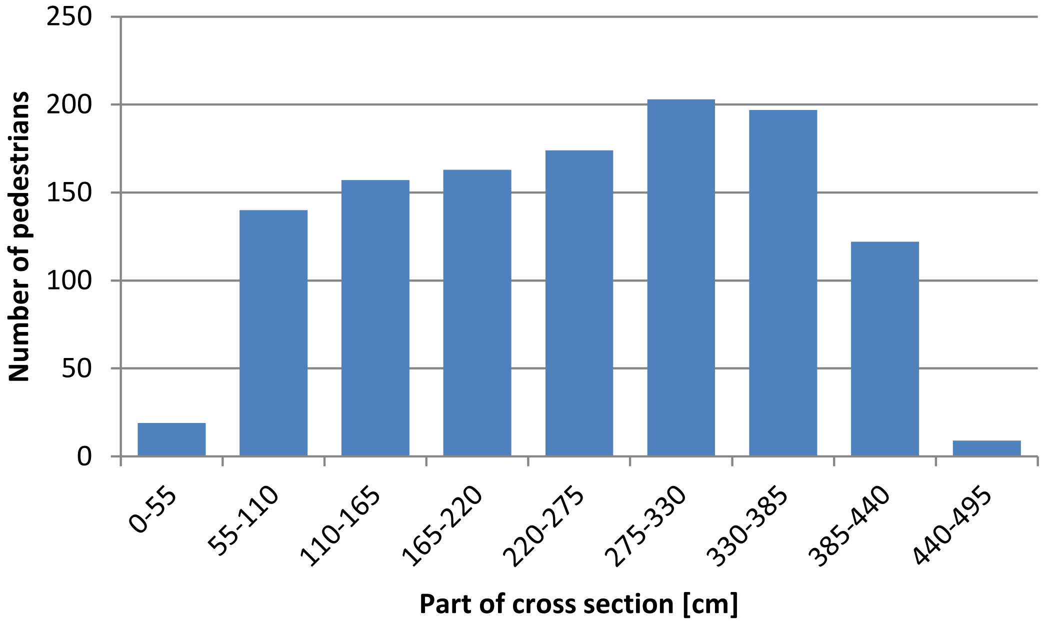

Density distribution in pedestrian flows

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Abstract

The density of pedestrians influences their average speed and the level-of-service of the infrastructures they use. Empirical research on pedestrian flows is often focused on these relationships. However, little can be found in literature about the spatial distribution of pedestrians along the cross section of a (one-dimensional) flow. Analogies between pedestrian flows and fluid mechanics have been documented, so the existence of some form of flow profile for pedestrians is conceivable. This research is aimed at finding out whether a density distribution exists and attempts to analyze the microphenomena within pedestrian flows that could cause such a distribution.

Pedestrian flows were captured on video using commercially available high-definition cameras. Filming took place at two locations where high volumes of pedestrians were to be expected within short time periods. The first situation was the entrance of a lecture hall at ETH Zurich. Students exiting particularly well-attended lectures were filmed passing through a short, 3m wide corridor. The second location was a major rapid transit station in Zurich, where passengers leaving the station were filmed during the morning rush hour. In this case, the cross section of the flow area was roughly 5m. In total, over 3000 pedestrians were measured.

The videos were then evaluated statistically by dividing the flow cross sections in 50cm wide "lanes" and counting the instances of pedestrians passing through the observed area in each lane. Thus, the spatial distribution of pedestrians across the cross section is constructed. It was found that varying pedestrian densities result in different distributions across a cross section. Specifically, pedestrians spread more evenly at higher densities. An attempt is made to describe this relationship mathematically.

Keywords

pedestrian flow, pedestrian level-of-service, pedestrian density, shy away distance of pedestrians

1 Introduction

Pedestrian traffic flows have been a research topic since the 1940s (e.g. Reimer, 1947). The subject is of interest to civil engineers and planners because of its implications for many types of infrastructures and the functionality of transport systems. Well functioning pedestrian flows enable efficient access to public transport, short changeovers between trains and buses, connectivity in urban areas and a higher quality walking experience.

The density of pedestrians influences their average speed and the level-of-service of the infrastructures they use (Oeding, 1963, Fruin, 1970). Empirical research of pedestrian flows is often focused on these areas (e.g., Hankin and Wright, 1958, Virkler and Elayadath, 1994). The relation between density and flow or velocity was termed fundamental diagram by Mumayiz (1985). It was conceived as an analogy to traffic flow theory of motorized transport, with one of the most cited versions being Weidmann's (Weidmann, 1993).

The models for pedestrian flows are typically macroscopic and do not provide a spatial context for density. The simplest model, a unidirectional flow of pedestrians in a plane or corridor of constant width, simply relates the density in a cross section with the flow through the cross section. Empirical research on the spatial distribution of pedestrians is scarce. Still, some examples can be found (e.g., Habicht and Braaksma, 1984, Hughes, 2002)

Based on analogies between pedestrian flows and fluid mechanics (Henderson, 1974), the existence of a cross-sectional flow profile for pedestrians is conceivable. If such a phenomenon exists, a microscopic approach to the density-speed dependence might lead to a better understanding of density distributions within pedestrian flows. This research was aimed at improving this understanding and analyzing the micro-phenomena that occur within flows and could cause the aforementioned distributions.

2 Theory

Parallels between high-density pedestrian flows and the movement of fluids can be observed intuitively. Henderson (1974) was the first to use gas-kinetic and fluid-dynamic models to describe pedestrian crowds. Helbing pointed out the problem with the assumptions that are made for applying the theory for ordinary fluids to pedestrian flows. (Helbing, 1992).

For this research we explore the fluid dynamic theory of laminar (or disrupted) and turbulent flows (Batchelor, 2000) and its possible application to pedestrian flows. The flow profile of laminar pipe flows can be expressed as

$$\frac{v\,(y)}{v_{max}} = 1 - \frac{y^2}{r^2} \tag{1}$$

where v is the flow velocity, v_{max} the velocity in the center of the pipe, and r the pipe radius (Bollrich, 2007). For turbulent flows, the law of the wall states that the average velocity of a turbulent flow at a certain point is proportional to the logarithm of the distance from that point the boundary of the fluid region. The flow profile for turbulent flows can be approximated by

$$\frac{v\,(y)}{v_{max}} = 1 + \frac{0.884 \cdot \sqrt{\lambda}}{1 + 1.326 \cdot \sqrt{\lambda}} \cdot ln\left(1 - \frac{y}{r}\right) \tag{2}$$

where λ is the Darcy friction factor.

As shown in Eq. (1), fluids have a certain velocity v_{max} in the center of the flow and $v = 0$ at the "wall". Analogously, pedestrians keep a distance to the wall (known as the shy away distance, see e.g. Daamen, 2004) when walking in a corridor. In other words, the density *at* the wall is zero. However, every pedestrian flow has a certain density and velocity in its cross section, as described by the fundamental diagram (see Section 1). This analogy will be further explored in two experiments designed to determine the density distribution over the cross section of a pedestrian flow.

3 Experiment

Pedestrian movement was filmed at two locations where high-density pedestrian flows occur. Filming was done with high-definition video cameras. The first experiment took place in a corridor near the entrance of a lecture hall at ETH Zurich. Between lectures most students enter or leave the room through one particular entrance, resulting in a highly concentrated stream of people. The measurement location is a section of hallway of about six meters length with a constant cross section. The area was filmed from above and to the side. Figure 1 shows the filming location and camera position.

At the chosen location pedestrian flows that occur immediately before a lecture starts or after it

Figure 1: Location of the first experiment. Hallway at the exit of a lecture hall at ETH Zurich. The camera is visible in the top left of the image.

ends are unidirectional. Typically, 100 - 300 students leave the room within 2 to 4 minutes. In the opposite direction, densities are slightly lower on average. The characteristics of the flow are quite specific because of the type of pedestrians involved: young, mostly male, and often walking in groups. Parts of the video had to be cut because students occasionally waited for others in the measurement area, thus blocking part of the cross section.

The second experiment was carried out at the exit of Hardbrücke station, a rapid transit stop in a business area in the city of Zurich. The location is immediately outside a pedestrian tunnel and represents the main exit of the station. Filming took place during the morning rush hour, when dense throngs of commuters alight the trains and leave the station. The measurement area is part of a 5 - 6 meters wide ramp leading up to street level from the tunnel exit. The ramp is lightly tapered and the camera is positioned above the tunnel, filming in the direction of people leaving the station. The second location is shown in Fig. 2.

Here, the observed pedestrians are typically commuters at the start of their work day. Since there is a high concentration of businesses in the vicinity of the station the flow is largely unidirectional, with the vast majority of pedestrians leaving the station. Filming times were between 6:55am and 8:30am. Several parts of the recordings had to be cut for similar reasons as in the first experiment. In total, 58 usable minutes of pedestrian flow were recorded.

The recordings were evaluated by stopping the videos in short intervals and counting pedestrians within a defined measurement area. The measurement area is chosen in such a way that two

Figure 2: Location of the second experiment. Station exit at Zurich Hardbrücke. The image represents the point of view of the measurement camera.

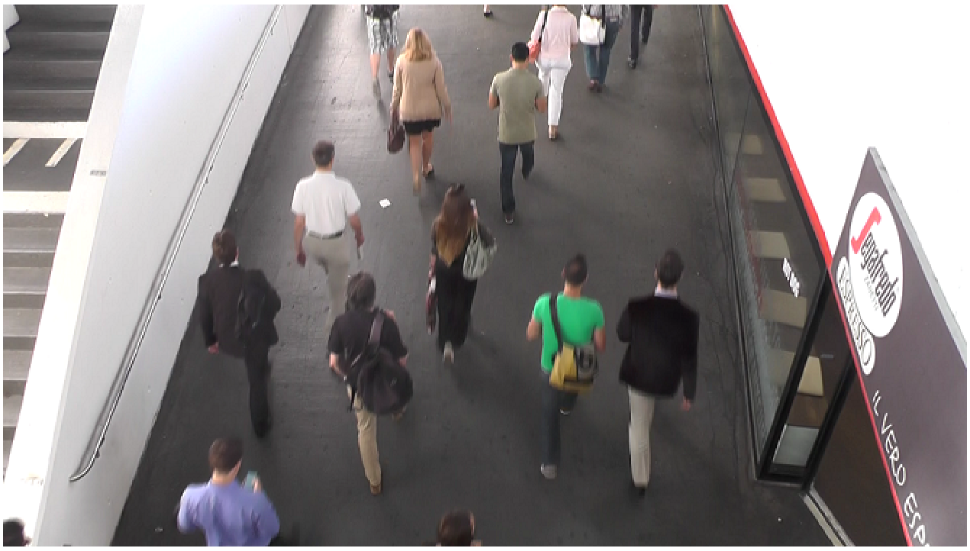
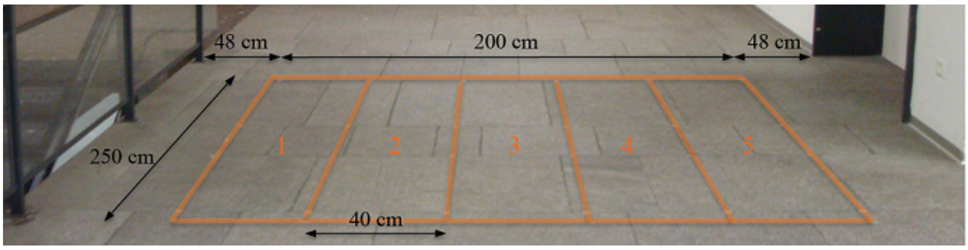


Figure 3: Analysis principle of the experiments. The number of pedestrians in each "lane" as well as the total number of pedestrians in the area is counted in short intervals.

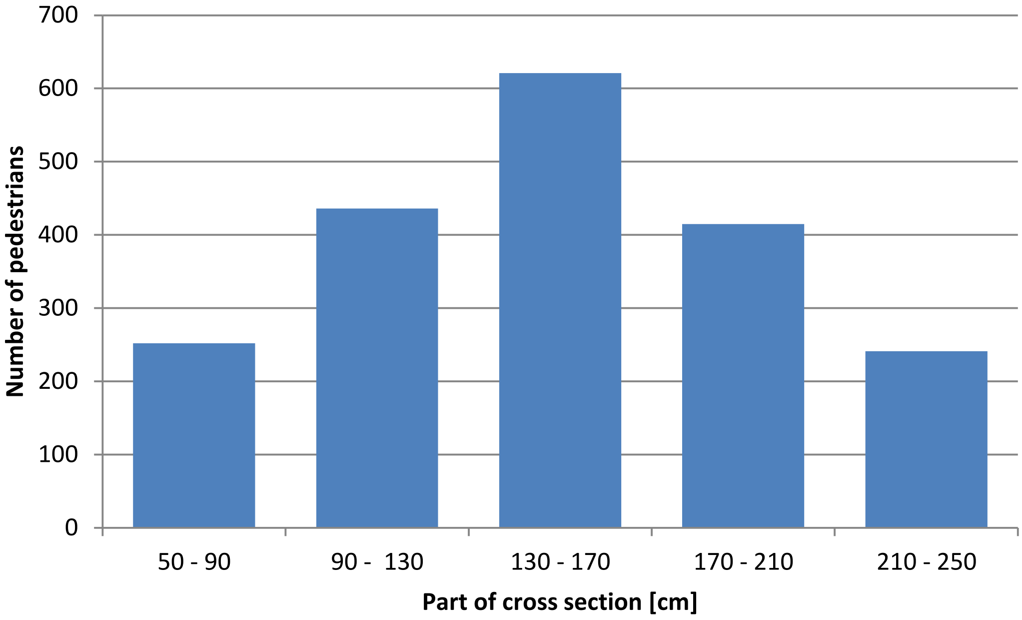


people walking behind each other do not influence each other's chosen path, yet the area remains small enough that the total density in the area influences the walking speed (as predicted by pedestrian traffic flow theory; see Section 1).

Figure 3 shows the measurement area of the first experiment. The area is divided into five strips, each 50 cm wide and 250 cm long. The number of pedestrians in each "lane" as well as the total number of pedestrians in the area is counted in short intervals. Since the total area contains varying numbers of pedestrians for individual counts, one observed distribution across the cross section is valid for a certain overall pedestrian density. This will be represented in the results of the experiments (see Section 4).

The second experiment is evaluated the same way. Here, the area consists of seven lanes of 55 cm width and 252 cm length and the measurement interval is set to two seconds. In total, over 3000 pedestrians were measured during the two experiments.

Figure 4: Total number of pedestrians counted outside the lecture hall at ETH Zurich. The chart shows the absolute numbers of pedestrians in each cross section segment.



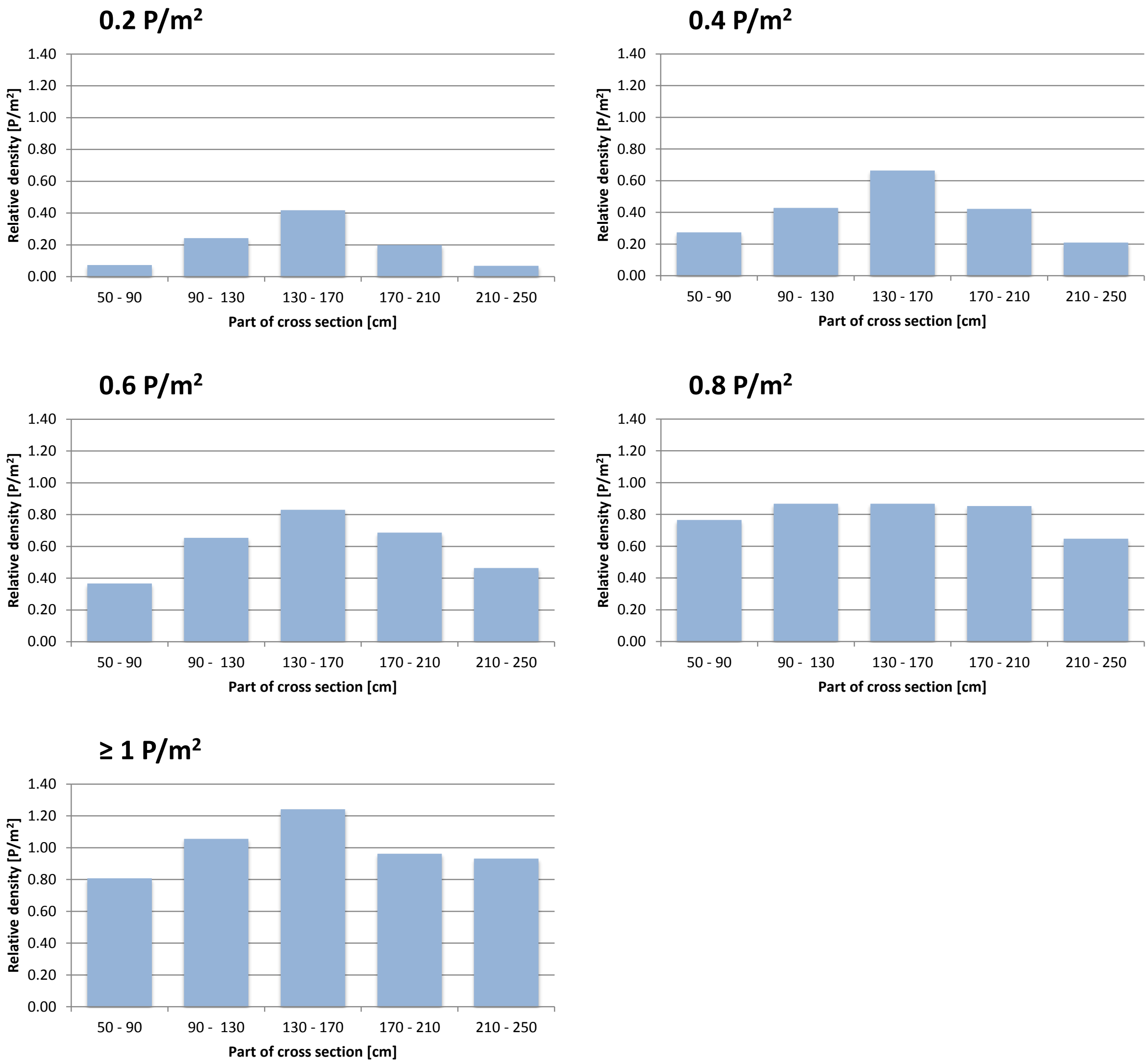
4 Results

For the analysis of the videos as described in Section 3 we used a one second analysis interval for the experiment at ETH Zurich and a two second interval at Hardbrücke, where the measurement area was larger and slightly lower speeds were observed because of the light incline. These values assure that pedestrians clear the area before the next measurement and no pedestrian is counted twice. The area difference is significant with 5 m^2 for the first experiment and over 12 m^2 for the second.

Results from the experiment outside the lecture hall are shown in Figs. 4 and 5. The density profiles in Fig. 5 could be described as "mesoscopic" densities within the separate walking lanes of the measurement area, as opposed to the macroscopic pedestrian density in the entire area.

Results from the second experiment at Hardbrücke station are shown in Figs. 6 and 7. Here, densities were on average lower, while the measurement area was larger. At Hardbrücke a number of pedestrians was recorded choosing a trajectory very close to the walls of the corridor, using the edge strips that were left out of the first experiment. This behavior was observed even at low densities. So as not to lose this data, the edge areas are included in the analysis as can be seen in Fig. 7. Consequently, the measurement are is divided into nine strips instead of seven as originally planned.

Figure 5: Densities measured outside the lecture hall at ETH Zurich. Shown are relative pedestrian densities of cross section segments, for different macroscopic flow densities.

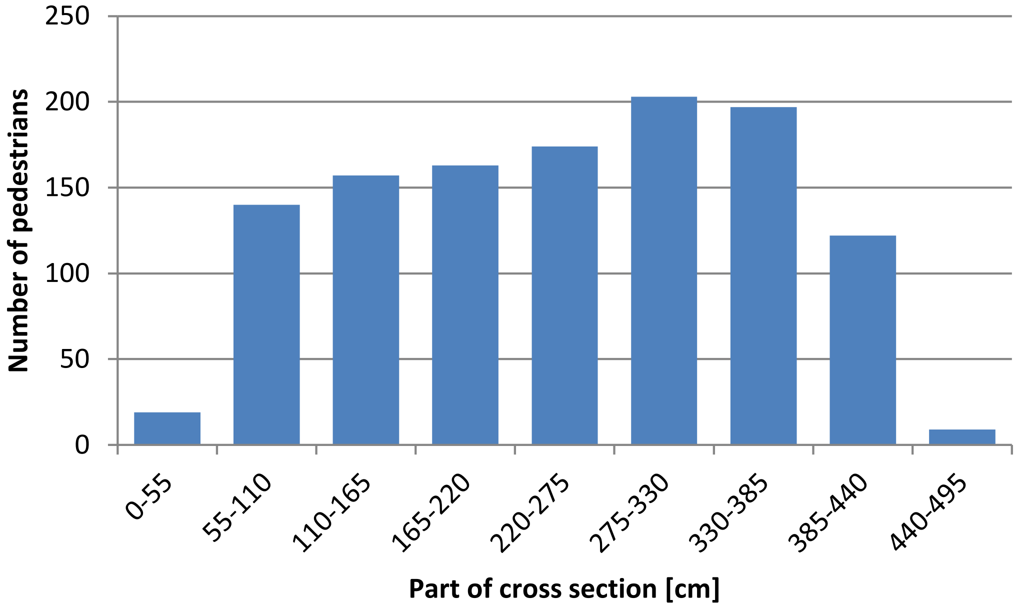


5 Discussion

Based on the results of the first experiment, the density distribution across the measured cross section appears to flatten as the overall density in the area increases (see Fig. 7). This trend might be explained by an analogy to the fluid-dynamic model (see Section 2). However, the second experiment at Hardbrücke station does not confirm the findings of the first experiment.

The differences might be explained by the social behavior of pedestrians or so-called self-organizing phenomena (Helbing *et al.,* 2001). As observed during filming, the students in the first experiment often passed the measurement area in small groups, resulting in two or three students occupying adjacent lanes. In contrast, the commuters in the second experiment tend

Figure 6: Total number of pedestrians counted at the location Hardbrücke. The chart shows the absolute numbers of pedestrians in each cross section segment.

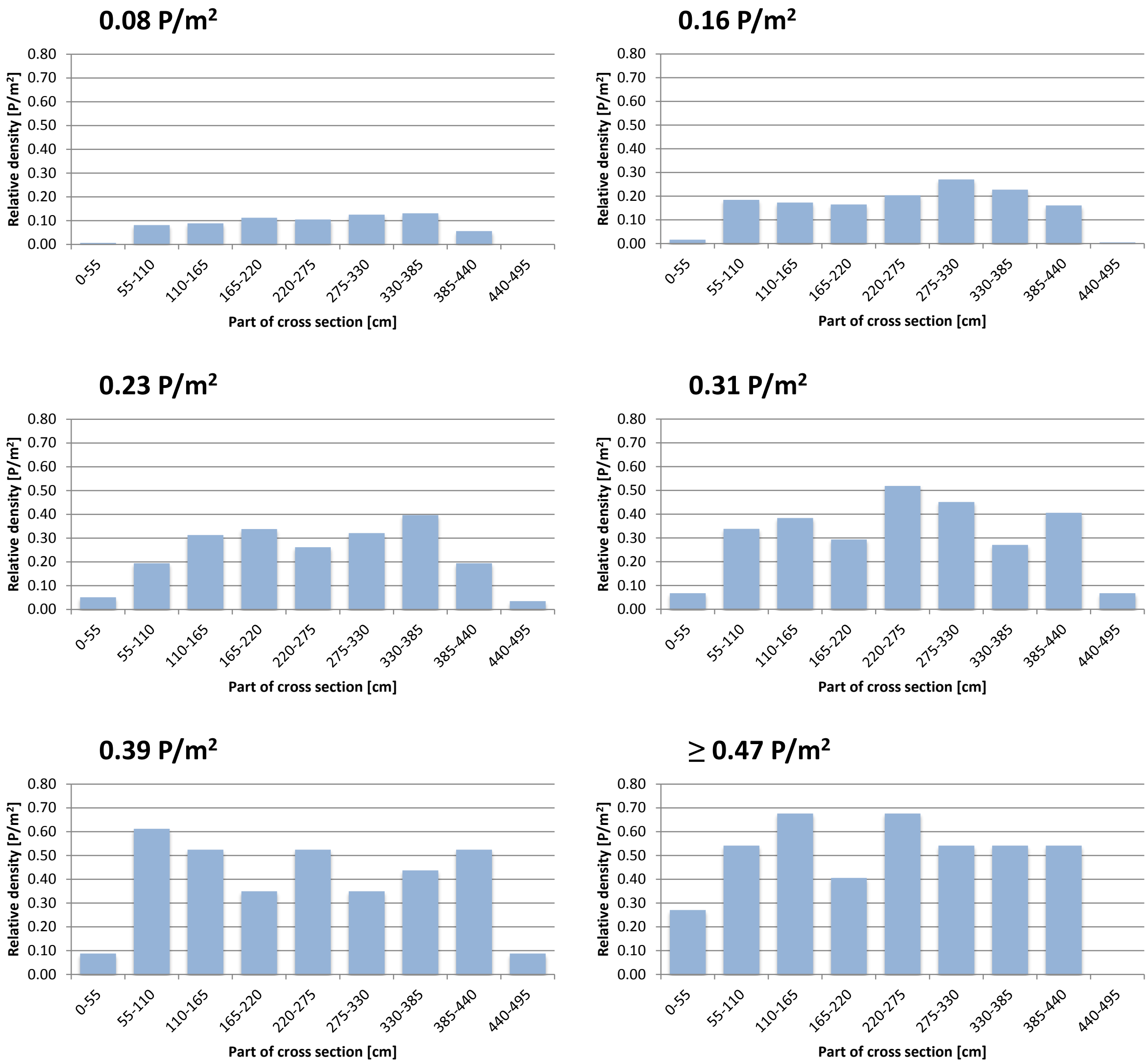


to maximize their mutual distances within the boundaries of the cross section. For example, when two pedestrians cross the measurement area at the same time they typically keep one or two lanes between them. This effect is increased by the more heterogeneous characteristics of commuters compared to a uniform group of pedestrians like students. They are expected to exhibit larger speed differences resulting in overtaking, during which a distance has to be observed in order no to impede others.

Another noticeable difference between the experiments is the much wider cross section at the second location. During the first experiment, a single pedestrian was likely to choose a path through the central lane, whereas in the second experiment a path through the lanes adjacent to the middle one might still be considered central. In addition, the flows in the second experiment were not purely unidirectional as was the case at the first location. A small proportion of counter flow was observed regularly. This is illustrated by the fact that the total distribution of pedestrians is skewed to the right side of the cross section (Fig. 6). As a result, people might be less prone to choosing a path in the central area of the cross section.

The flatter distribution curves in the second experiment (see Figs. 5 and 7) provide a more adequate representation of the pedestrian fundamental diagram, which considers the flow cross section macroscopically and does not predict a specific distribution of density. Further research of commuter flows is needed to confirm this assumption.

Figure 7: Densities measured at the location Hardbrücke. Shown are relative pedestrian densities of cross section segments, for different macroscopic flow densities.



In future measurements, the velocity of pedestrians would preferably be measured simultaneously to their density to further explore the microscopic implications of the fundamental diagram. The tracking of pedestrians using 3D cameras which has recently become available as a commercial product could be beneficial for such research.

During the measurements at Hardbrücke station it was observed that the outer lanes are indeed used by pedestrians, but mostly at higher densities. It can therefore be concluded that the practice of subtracting a fixed minimum wall distance when calculating the capacity or level-of-service of a pedestrian area is a simplification of reality (e.g. Daamen, 2004). For the design of pedestrian facilities, an increased minimum wall distance might be needed at lower densities. To be able to apply this knowledge in facility design, further research is needed.

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6 References

Batchelor, G. K. (2000) *An Introduction to Fluid Dynamics*, Cambridge University Press, ISBN 9780521663960.

Bollrich, G. (2007) *Technische Hydromechanik: Grundlagen*, Huss-Medien, ISBN 9783345009129.

Daamen, W. (2004) Modelling passenger flows in public transport facilities, Trail Thesis Series, Netherlands TRAIL Research School, Delft.

Fruin, J. J. (1970) Designing for Pedestrians: A Level-Of-Service Concept, Dissertation, Polytechnic Institute of Brooklyn, New York.

Habicht, T. A. and J. P. Braaksma (1984) Effective Width of Pedestrian Corridors, *Journal of Transportation Engineering*, **110** (1) 80–93, ISSN 0733-947X.

Hankin, B. and R. Wright (1958) Passenger Flow in Subways, *Operational Research Quarterly*, **9** (2) 81–88, ISSN 1473-2858. ArticleType: research-article / Full publication date: Jun., 1958 / Copyright © 1958 Operational Research Society.

Helbing, D. (1992) A Fluid Dynamic Model for the Movement of Pedestrians, *Complex Systems*, **6**, 391–415.

Helbing, D., P. Molnár, I. J. Farkas and K. Bolay (2001) Self-Organizing Pedestrian Movement, *Environment and Planning B: Planning and Design*, **28** (3) 361–383.

Henderson, L. F. (1974) On the fluid mechanics of human crowd motion, *Transportation Research*, **8** (6) 509–515, ISSN 0041-1647.

Hughes, R. L. (2002) A continuum theory for the flow of pedestrians, *Transportation Research Part B: Methodological*, **36** (6) 507–535, ISSN 0191-2615.

Mumayiz, S. A. (1985) A methodology for planning and operations management of airport passenger terminals: a capacity/level of service approach, Thesis, © S.A. Mumayiz.

Oeding, D. (1963) Verkehrsbelastung und Dimensionierung von Gehwegen und anderen Anlagen des Fussgängerverkehrs, Dissertation, Technische Hochschule Carolo-Wilhelmina zu Braunschweig, Braunschweig. Heft 22.

Reimer (1947) Die Bewegung der Menschenmassen in Verkehrsräumen, *Glasers Annalen*, **71** (7) 121–131.

Virkler, M. R. and S. Elayadath (1994) Pedestrian Speed-Flow-Density Relationships, *Transportation Research Record*, (1438) 51–58, ISSN 0361-1981.

Weidmann, U. (1993) *Transporttechnik der Fussgänger - Transporttechnische Eigenschaften des Fussgängerverkehrs (Literaturauswertung)*, zweite ergänzte auflage edn., no. 90 in Schriftenreihe des IVT, Institut für Verkehrsplanung, Transporttechnik, Strassen- und Eisenbahnbau, ETH Zürich, Zürich.