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Traffic operations in public walking spaces are to a large extent determined by differences in pedestrian traffic demand and infrastructure supply. Congestion occurs when pedestrian traffic demand exceeds the capacity. In turn, the latter is determined by a number of factors, such as the width of the bottleneck and the wall surface, as well as the interaction behavior of the pedestrians passing the bottleneck.

This article discusses experimental findings of microscopic pedestrian behavior in case of bottlenecks. Results for both a narrow bottleneck and a wide bottleneck are discussed and compared to the results of an experiment without a bottleneck. It is shown how pedestrians inside bottlenecks effectively form layers or trails, the distance between which is approximately 45 cm. This is less than the effective width of a single pedestrian, which is around 55 cm. The layers are thus overlapping, a phenomenon which is referred to as the "zipper" effect. The pedestrians within these layers follow each other at 1.3 seconds, irrespective of the considered experiment. For the narrow bottleneck case (width of one meter) two layers are formed; for the wide bottleneck case (width of two meters), four or five layers are formed, although the life span of these layers is rather small.

The zipper effect causes the capacity of the bottleneck to increase in a stepwise fashion with the width of the bottleneck, at least for bottlenecks of moderate width (less than 3 m). This has substantial implications for the design of walking facilities.

Key words: pedestrian traffic flow; bottleneck capacity estimation; level of service; pedestrian behavior
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1. Introduction

Insight into the behavior of pedestrians, and tools to predict this behavior, are essential in the planning and design of public pedestrian facilities such as airports, transfer stations, and shopping malls. Also, when designing timetables for public transit, pedestrian simulation models can be applied to analyze the impact of pedestrian flows between access and egress points (train platforms, bus stations, etc.), entries and exits, on the walking times, and pedestrian comfort levels. Managing pedestrian flows through these facilities, for instance by information provision, requires knowledge of the pedestrian flow characteristics as well as of the walking behavior that constitutes the flow. To perform (ex ante) model studies, simulation models predicting pedestrian flows in walking facilities can be used. A number of simulation tools have been developed for this purpose, for example, PEDROUTE (Halcrow 2002a) and PAXPORT (Halcrow 2002b), SimPed (Daamen and Hoogendoorn 2002), NOMAD (Hoogendoorn and Bovy 2002), and Legion (Still 2000). These models have been applied with success to assist in the evaluation or optimization of designs of new or existing walking facilities. Whether such pedestrian simulation models are used, or whether walking infrastructure design is carried out by other means, it is obvious that good insights into macroscopic features of the pedestrian flows, as well as insights into the microscopic behavior underlying these features, are very important.

This article describes new and important experimental findings of pedestrian flow theory, in particular, pertaining to behavior of pedestrians and characteristics of pedestrian flows in the case of bottlenecks. To this end, a brief state-of-the-art overview is presented first. In §3, the experimental design is discussed. Section 4 provides insight into the relations between pedestrian behavior and the macroscopic characteristics of the pedestrian flow. Section 5 provides an overview of the various phenomena that have been observed from the bottleneck experiments (spatial distribution of pedestrians, swaying, dynamic layer formation, and patterns inside the bottleneck). In §6, composite headway models—differentiating between free and constrained headways—are successfully estimated. Section 7 discusses the implication of the findings to bottleneck capacity analysis.

2. State-of-the-Art Overview

This section presents an overview of some of the empirical facts regarding pedestrian walking behavior and flow characteristics. The following aspects of walking will be distinguished: determinants of walking speeds, space requirements for unilateral interactions, and forms of interaction and cooperation. Finally, empirical relations between macroscopic flow variables are discussed, as well as issues of self-organization in pedestrian flows.

2.1. Determinants of Walking Speeds

Pedestrians observe their surroundings through a mostly subconscious process called *scanning* to sidestep small obstructions on the flooring (Goffman 1971). This scanning area is not a circle, but an ellipse, which is narrow to either side of the individual, and longest in front of him or her. The shape of the ellipse changes constantly according to the prevailing traffic conditions, which in turn affect the way in which a pedestrian can execute his or her walking task, as is reflected by the walking speed of a pedestrian as well as the space he or she requires. The latter is discussed in the following section.

Many factors thus affect the walking speeds of pedestrians, such as the *personal characteristics of pedestrians* (age, gender, size, health, etc.), *characteristics of the trip* (walking purpose, route familiarity, luggage, trip length), *properties of the infrastructure* (type, grade, attractiveness of environment, shelter), and, finally, *environmental characteristics* (ambient, and weather conditions). Besides the exogenous factors, the walking speed also depends on the pedestrian density; see, for example, Weidmann (1993).

2.2. Spatial Requirements in Unilateral Interactions

Two types of interactions can be distinguished:

(1) Unilateral interactions, where only one pedestrian is required (or able) to undertake action to avoid a collision;

(2) Bilateral interactions, in which case two pedestrians meet and subconsciously negotiate and decide upon the best maneuver (§2.3).

The former is most common in unidirectional flows, and pertains mostly to following behavior. This section discusses this following, or rather the spatial requirements such following entails. With respect to the pedestrian's space requirements, both adjustments in space needed in the direction of walking, and in a lateral sense, need to be distinguished. Regarding the latter, it is important to note that pedestrians will generally not be able to walk in a straight line, but will move their bodies from left to right each time a step is taken (Knoflacher 1987). This movement is referred to as swaying. As will be shown in the remainder of the article, frequency and amplitude of this oscillating movement depend on the walking speed. In turn, the required walkway width depends on the speed of a pedestrian as well.

The distance headways that pedestrians maintain with respect to their predecessors will increase with their walking speeds. This is in part caused by the additional space needed to take a step, but also includes a safety margin needed to avoid colliding into the leader pedestrian. Studies into the fundamental diagram show how density (and thus available space) and walking speeds relate, and how this relation is influenced by flow composition, walking infrastructure (level walkways, stairs, ramps, etc.), etc.; see Weidmann (1993).

2.3. Walking Behavior and Interaction

The previous section indicated that space requirements of pedestrians depend on the walking speed. For homogeneous unidirectional flows, maintaining sufficient space is largely a task of the individual pedestrian. For bidirectional and crossing flows, and when pedestrians want to pass a bottleneck, interaction and negotiation become important. In this respect, we recall Wolff (1973), arguing that a *high degree of cooperation between pedestrians* is an intrinsic part of pedestrian behavior, without which walking would be impossible.

Goffman's notion of scanning the infrastructure is also applicable to describe the interaction with other pedestrians. Goffman describes that a pedestrian reacts only to those pedestrians that are in a small circle around him or her. Pedestrians who are one or two persons away are neglected. Two subconscious actions occurring during an encounter can be distinguished, namely, the *emission of critical sign* and an *establishing moment*. Only after both moments have passed are actual changes in the courses of the pedestrians put into effect. Goffman (1971) notes that sometimes the signals become confused, resulting in two opposing pedestrians coming into some sort of "reciprocal dance," something occurring more frequently to tourists in foreign countries. The latter can be explained by the differences in critical signs that exist between the different countries. Wolff (1973) is the first to describe the so-called *step-and-slide movement*. Experimental studies of Sobel and Lillith (1975) report a relatively high number of *brushes* in situations where actions to avoid collisions were one-sided. It appears that pedestrians are reluctant to unilaterally withdraw from an interaction until the last moment. On top of this, brushing sends signals to the offender to cooperate. Dabbs and Stokes (1975) have studied the extent to which pedestrians *grant space to other pedestrians*. Their research indicated that groups are generally given wider berth than individuals; pedestrians grant more space to approaching male than to female pedestrians. On the contrary, Sobel and Lillith (1975) observed that women are often granted more room than men. Willis, Gier, and Smith (1979) suggested that power may not be as important as gallantry in deciding who moves where during collision avoidance maneuvers. They found that persons or groups moved for larger groups; younger groups tended to move for older groups. They indicated that, besides power and gallantry, maneuverability may also play a decisive role.

In sum, it can be concluded that cooperation and negotiation play an important role in bidirectional flows, but also when trying to pass a bottleneck, although the latter has not been reported explicitly in literature.

2.4. Relation Between Speed, Flow, and Density

Given the fact that, on average, pedestrians will behave the same under similar average conditions, there will exist some statistical relation between speed, flow, and density—the fundamental diagram. Many researchers have reported their empirical findings on this particular aspect, including the flow-density relation for various types of infrastructure, flow composition, etc. Examples can be found in Al-Gadhi, Mahmassani, and Herman (2001); Virkler and Elayadath (1994); and Weidmann (1993).

2.5. Collective Behavior and Self-Organization

It is well known that in pedestrian crowds, flows of pedestrians walking in opposing directions tend to separate. This common phenomenon will be referred to as *dynamic lane formation* or *streaming* (Older 1968). The formation of lanes is the main reason for the relatively small loss of capacity in the case of bidirectional pedestrian flows (in the range of 4% to 14.5%; see Weidman 1993 and Lam et al. 2002). Several models have been proposed that reproduce lane formation; see Blue and Adler (2001), Helbing (1997), Helbing and Molnar (1997), and Hoogendoorn and Bovy (2002).

Similar results have been established for crossing flows (Toshiyuki 1993; Daamen and Hoogendoorn 2003), albeit in the form of strips or moving clusters composed of pedestrians walking in the same direction. Helbing (1997) and Hoogendoorn and Bovy (2002) discuss formation of strips in crossing flows using microscopic pedestrian flow models.

3. Experimental Design

Experimental research entails interfering with natural processes to obtain more insight into the causal relations between the independent process variables (stimuli) and the observed phenomena (response). By performing experiments we can determine the causes and relations that determine the behavior of pedestrians. Apart from the methodological advantages, experiments allow observations of conditions that are not available, or are very difficult to observe, in normal conditions. The process variables are both the input and output variables that are deemed relevant. It is important that in an early phase of the research a clear distinction is made between primary and secondary factors. In this case, the important primary factors have been determined from expert knowledge and literature surveys; for details, see Daamen and Hoogendoorn (2003). In the end, pedestrian trajectories are determined from the video imagery (Hoogendoorn and Daamen 2003). These trajectories are the most elementary and most valuable unit of analysis in traffic flow research and provide all information required for analysis of both the microscopic and macroscopic characteristics.

3.1. Overview of Experiments

In total, 10 different walking experiments were performed. In each of these experiments, approximately 60–90 individuals were involved. The participants were divided into eight groups, which were given separate walking tasks for each experiment (walk slowly, walk fast, etc.). The groups themselves were heterogeneous, and consisted of men and women of different ages. The group participants were indicated by the color of their caps (red or green). The red caps convey the ordinarily behaving pedestrians, while the green caps were pedestrians that had to follow specific instructions (walk aggressively, walk slowly, etc.). The groups were not used to indicate the walking direction, as this could be determined from the video images straightaway. For a detailed description of the experimental setup, see Daamen and Hoogendoorn (2003).

3.2. Measurement Setup

The walking experiments were conducted in a large hallway. The ambient conditions were favorable. A digital camera was mounted at the ceiling of the hallway, at a height of 10 m, observing an area of approximately 14 m by 12 m. A wide lens was used, enabling the camera to view the entire walking area. The digital camera has a resolution of 720×576 pixels. The distortions in the pedestrian trajectories caused by the slight pincushion effect and camera rotation were corrected for. After these corrections, the trajectories were established (Hoogendoorn, Daamen, and Bovy 2003).

3.3. Description of Experiments

In this article, three unidirectional flow experiments (no bottleneck, a wide bottleneck of 2 m, and narrow bottleneck of 1 m) are analyzed in detail. For these situations, the walking area had a length of 10 m and a width of 4 m. It is stressed that the experiments pertain to normal circumstances: Participants in the experiments were asked to walk as they would under regular circumstances. Walking behavior in safety-critical (panic, emergencies) situations, or even considering pedestrians being in a hurry to catch their train, may be very different.

The *no-bottleneck experiment* involves pedestrians gradually entering the walking area. This gradual increase in traffic demand was achieved by dividing the participants into heterogeneous groups (consisting of men and women of different ages). Having entered, the participants walked to the end of the area, after which they walked around it, and re-entered the area directly. At the end of the experiment, the participants were removed group by group from the walking area.

The *narrow bottleneck experiment* is characterized by the presence of a bottleneck having a length of 5 m and a width of 1 m. The width is such that pedestrians inside the bottleneck are not able to pass each other. As the pedestrian demand increased, it exceeded the capacity of the bottleneck. From that time onward, congestion appeared just upstream of the bottleneck, moving upstream toward the entry of the area. When the pedestrians were removed from the walking area, congestion resolved in due time.

The *wide bottleneck situation* is similar to the narrow bottleneck; in this case, the bottleneck has a width of 2 m. Neither in the wide bottleneck experiment, nor in the no-bottleneck experiment, did congestion occur. The total duration of the experiments lasted between 15 to 25 minutes.

3.4. Approach to Data Extraction

Hoogendoorn, Daamen, and Bovy (2003) discuss an approach to extract individual pedestrian data from digital video footage. In the first phase of the pedestrian-tracking process, different image-processing operations, such as radiometric correction and correction for lens distortion, are applied. Next, the pedestrians are detected by identifying the colored caps that the pedestrians wore during the experiment. This detection occurs in a special zone where lighting conditions are optimal. Next, pedestrian tracking is achieved by application of a newly developed tracking technique. This is achieved by minimizing the so-called merit function. After tracking has been achieved, a Kalman filter is applied to reduce the errors made during tracking. It turns out that the pedestrian trajectories can be determined with high accuracy.

4. Causal Relations Between Behavior and Flow Characteristics

To assess and improve ways in which walking facilities are used on a macroscopic scale, knowledge regarding the microscopic processes and walking behavior is required. Figure 1 shows hypothesized causal relations between microscopic and macroscopic characteristics of pedestrian flows. The figure shows a simplified view to walking behavior by breaking it up into following, lateral distance keeping, and walking at a certain speed. These microscopic characteristics in turn determine the width of the so-called *dynamic layers* (described in the next section) and the headways adopted within these layers. From these headways, the dynamic layer saturation flows can be determined. Note that the way in which the layers are used, together with the width of the bottleneck, will determine the capacity of the latter.

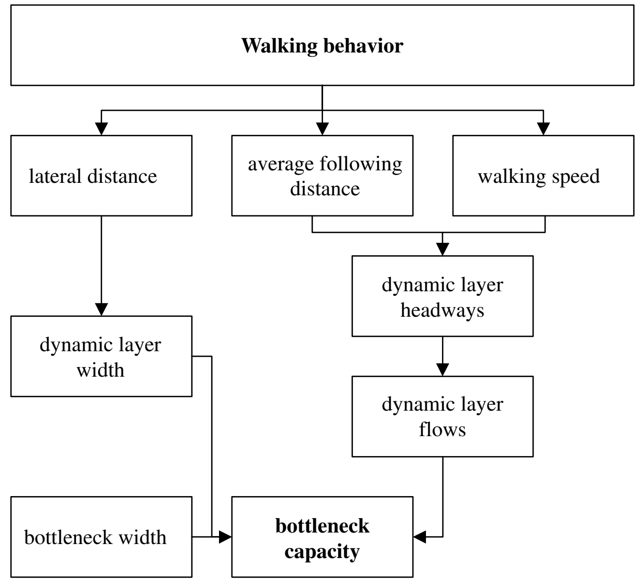

Figure 1 Causal Diagram of Factors Affecting Flow Levels and Flow Distributions

Figure 1 illustrates the assumption of the self-organization of unidirectional layers under capacity conditions. Recall that the issue of *dynamic lane formation* has been studied for bidirectional as well as crossing pedestrian flows (see §2.5). The *dynamically formed layers* are fundamentally different from the lanes formed in bidirectional or crossing flows (in fact, the lanes that are formed in a bidirectional flow may often consist of one or more layers): The speeds of two adjacent layers are generally equal (approximately 1 m/s). This is caused by the fact that the layers are overlapping, that is, pedestrians in one layer use up some space in the other layer (with their shoulders), also due to the swaying. This *overlapping of layers* will be referred to as the *zipper effect*.

5. Flow Characteristics at Bottlenecks

This section focuses on the microscopic characteristics of a pedestrian flow at a bottleneck. The section discusses swaying, the way the available space upstream of the bottleneck is used, spatial distribution of speeds, dynamic layer formation, and, finally, the layer patterns that emerge in the bottleneck.

5.1. Spatial Distribution Characteristics and Speeds

Before discussing the microscopic characteristics of the pedestrian flow, this section briefly considers other important issues pertaining to the way pedestrians use the available space upstream of the bottleneck, as well as the average speeds.

Figure 2 shows densities and speeds for three periods during the simulation. In the first period, low densities and relatively high speeds (free speeds) are observed. The figure clearly shows how only a small portion of the walking area is used. In the second period [120 s, 240 s], the densities are still relatively low, but the speeds start to decrease. Obviously, pedestrians are not able to walk at their free speed. The walking area is still not fully used. Note that at the edges of the used area, speeds are considerably higher than in the middle due to pedestrians that walk around the low-speed region near the center. In the period [360 s, 480 s], congestion is present upstream of the bottleneck, and a larger portion of the walking area upstream of the bottleneck is used. Density rises to 2.5 P/m^2; the average speed in the bottleneck is around 1 m/s. The average speed upstream of the bottleneck has decreased to about 0.3 m/s. Please note that although pedestrians received no additional instructions on the way the walking area should be used, the figures show that the used walkway width increases with the distance to the bottleneck. The shape of the used area resembles one-half of an ellipse, the center of which lies on the entry of the walking area ($x = 10$ m). This is quite contrary to what most microscopic pedestrian-simulation models predict, showing that pedestrians position themselves in one-half of a circle, the center of which lies inside the bottleneck.

5.2. Swaying and Lateral Space Requirements

As mentioned in the introduction, pedestrians require space in both the longitudinal direction and in the lateral direction. The latter encompasses the shoulder width of the pedestrian, the shy-away distance from obstructions and other pedestrians directly beside him or her, but also the distance taken up by swaying (see §2.2). Swaying pertains to the oscillations in the trajectories (see Figure 4) due to the inability of pedestrians to walk in a straight line because of the body movements occurring each time a step is taken. It is emphasized that these oscillations are not artifacts of the trajectory extraction method.

From the pedestrian trajectories (Figure 4 and Figure 5), swaying can be identified easily. From these trajectories, characteristics of swaying can be studied. Figure 3(a) shows the relation between the step frequency and the average walking speed for the narrow bottleneck experiment. The relation can be adequately described by a quadratic function of the speed v, showing that the change in step frequency is relatively high for low speeds and low for high speeds. The figure shows that the step frequency and walking speed are positively correlated, and also that the results from the experiments are in line with the findings from the literature (i.e., step frequency of 2 Hz).

Figure 3(b) shows the relation between the swaying amplitude and the walking speed, which turns out to be *negatively correlated*: Amplitude of the swaying motion will reduce when the walking speed increases. By fitting a linear relation between the speed and amplitude, it can be concluded that the decrease in the swaying amplitude equals 1.7 cm per m/s.

5.3. Dynamic Layer Formation

From the narrow bottleneck experiment, it was observed that once congestion occurs, i.e., when the bottleneck becomes oversaturated, two layers inside the bottleneck were formed. The pedestrian trajectories in the xy plane clearly show this. Figure 4 depicts example trajectory projections collected at different time periods. The figure shows how the spatial behavior changes when congestion sets in: Upstream of the bottleneck ($x > 5$ m), pedestrians will use more of the available space in front of the bottleneck. Some will join the tail of the queue near the middle ($y = 2$ m), while others will walk around it. Inside the bottleneck ($x < 5$ m), layers are formed as soon as the bottleneck becomes oversaturated.

Figure 5 shows the results for the wide bottleneck. Some dynamic layer formation can still be observed inside the bottleneck (four or five layers are formed). Note that in this case, traffic demands were not large enough to cause the bottleneck to become oversaturated. As a result, densities and flows inside the wide bottleneck are below the critical flow, and there are a relatively large number of passing opportunities. As a result, the lifespan of the dynamic layers is rather short.

From the observations above we may conclude that when a bottleneck is operating under capacity conditions, i.e., when nearly all pedestrians are constrained in their movement and are following their predecessor, dynamic layers are formed. For the narrow bottleneck case, the experiment suggests that these layers are fixed in terms of their lateral location (i.e., they are located at $y = 2.0 \pm 0.22$ m)[1]; the lateral centers of the layers have a distance of approximately 0.45 m. The latter also holds for the wide bottleneck experiment, although the layers last for shorter periods of time.

The lateral distances between the dynamically formed layers also illustrate what we refer to as the "zipper effect" expressing the fact that the lateral space required by a pedestrian is less than the lateral distances between the layers. The required lateral

[1] In general, lateral distances to the obstacles depend on the wall surface, which was in this case soft and clean.

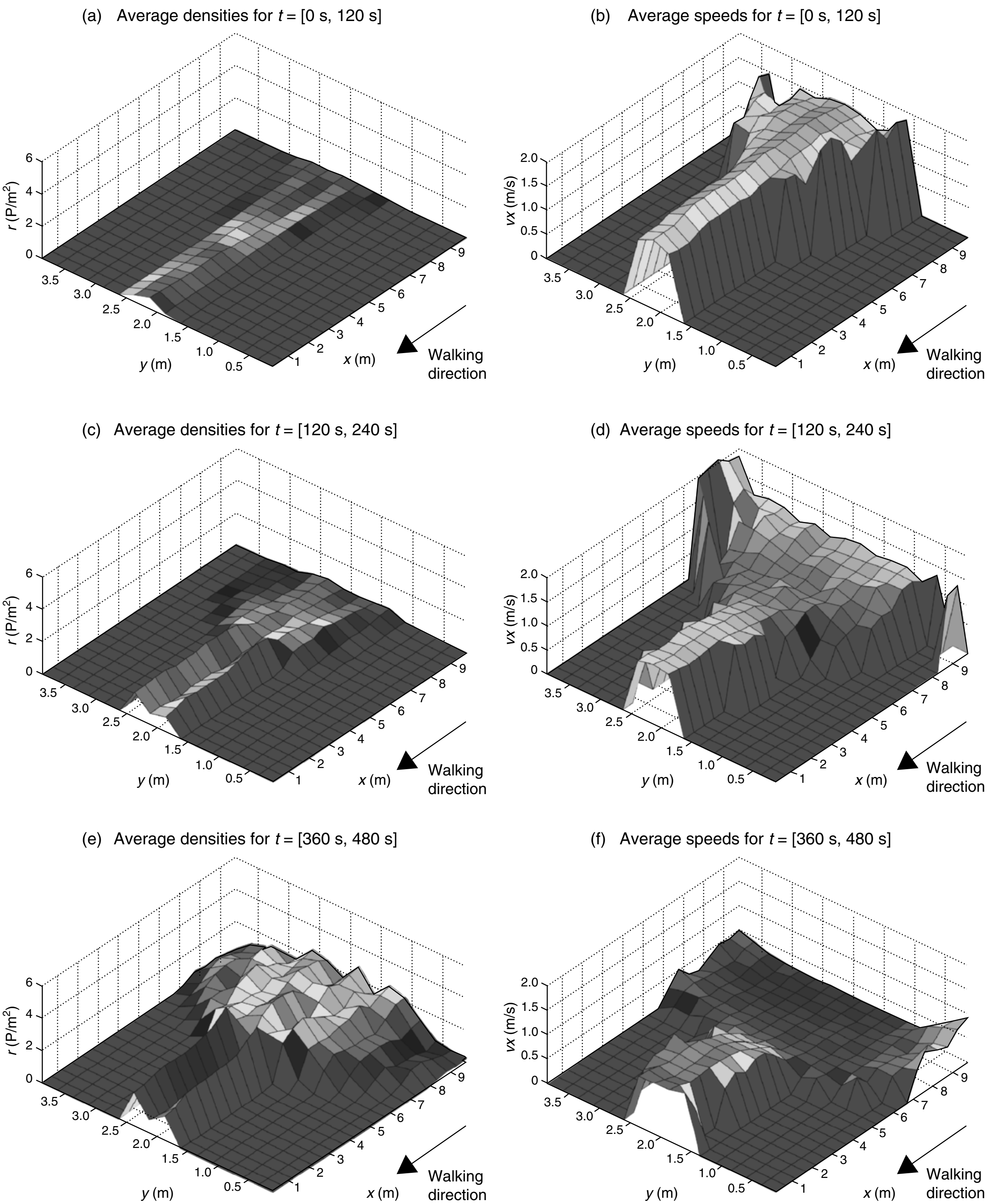

Figure 2 **Surface Plots Showing Pedestrian Densities (Figures 2a, c, e) and Speeds (Figures 2b, d, f) Determined for Rectangles of 0.5 m Length and 0.25 m Width**

Note. Figures show free-flow periods (Figures 2a and b), periods with minor congestion (Figures 2c and d), and major congestion (Figures 2e and f). The figure pertains to the narrow bottleneck experiment.

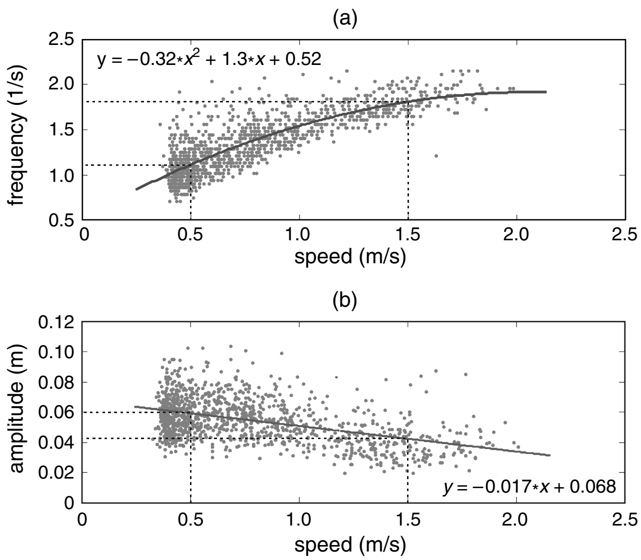

Figure 3 **Step Frequency and Swaying Amplitude as a Function of Walking Speed Determined for the Narrow Bottleneck Experiment**

space is the shoulder width (approximately 46 cm; see Weidmann 1993) and additional lateral distance required due to the swaying motion described in the previous section. At capacity ($v \approx 1$ m/s), the swaying amplitude is approximately 5 cm, implying that the additional lateral distance equals 10 cm. This implies that the total width taken up by a pedestrian is such that pedestrians inside the narrow bottleneck in which two layers are formed cannot pass.

In sum, it is concluded that, under saturated conditions, pedestrians in fact walk in a staggered fashion, i.e., that the layers that are formed are overlapping, albeit not, per se, physically overlapping. The speeds of the layers are thus by necessity equal (around 1 m/s). Furthermore, it can be shown that the positions of a pedestrian p and the pedestrian q' in the adjacent layer directly in front (for definitions, see Figure 7) are statistically independent, or, rather, p mostly reacts to the pedestrian q directly in front: It turns out that the lead (and also the lag gap) is nearly uniformly distributed.

It is again stressed that the layer formation and the zipper effect are fundamentally different from lane formation in bidirectional pedestrian flows. A unidirectional lane of a bidirectional flow will in general consist of one or more layers.

5.4. Patterns Emerging in Bottleneck

The photographs shown in Figure 6 depict the different patterns that emerge (narrow bottleneck experiment). The arrows in the figure all have the same length and are used to show that the distance headways between pedestrians in a layer are approximately constant (except for Pattern 4). Pattern 1

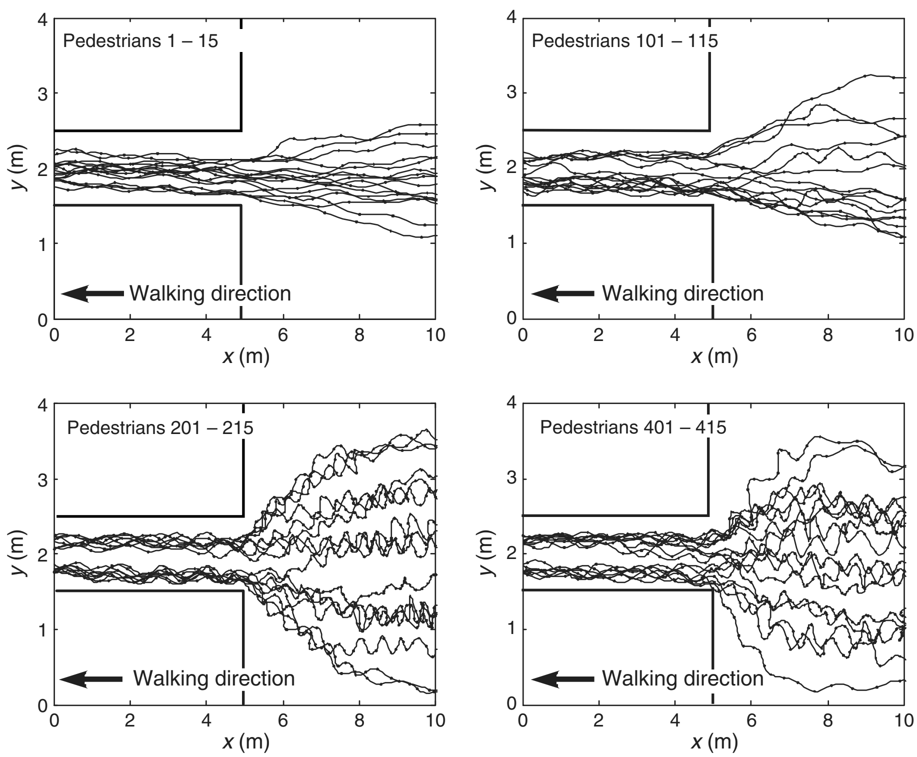

Figure 4 **Pedestrian Trajectories for Narrow Bottleneck Experiment**

Note. Ranges in upper left corner indicate pedestrian indices according to arrival time at entry.

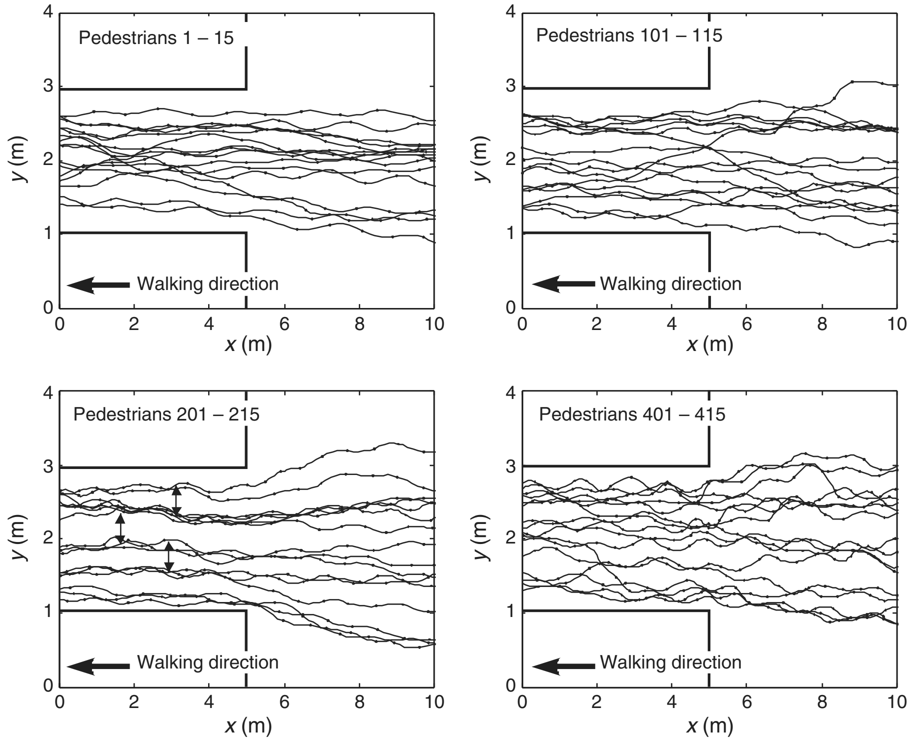

Figure 5 **Pedestrian Trajectories for Wide Bottleneck Experiment**
Note. Ranges in upper-left corner indicate pedestrian indices according to arrival time at entry.

shows the case in which the distance between pedestrians in different layers is also approximately constant, i.e., the lead gap and the lag gap are almost equal (see Figure 7 for definitions of lag and lead gaps). Patterns 2 and 3 are similar, and reflect cases in which the lead gap for the pedestrians in one layer is relatively small, while the lag gap is relatively large (or vice versa). Pattern 4 is a special pattern, the properties of which can be described using analogies with defects in solids. This particular defect is referred to as a *vacancy*[2] in solid-state physics. In a pedestrian flow, this defect is caused by inefficient merging behavior at the bottleneck entry, e.g., due to overly polite or aggressive behavior. The latter may be more proficient in case of panic situations, causing more defects in the pattern and a less efficient usage of the bottleneck. Despite the fact that quite a number of defects were observed, it is noted that Patterns 1 to 3 are more common.

6. Headway Distribution Modeling and Estimation

To gain more insight into the pedestrian-following behavior, this following behavior is analyzed by estimating a composite headway distribution model, distinguishing between constrained (or following) pedestrians and unconstrained (or freely moving) pedestrians. To apply these models, the first step is to determine which leader q is actually followed by pedestrian p. Let t_p denote the time pedestrian p passes the cross-section x; let $y_p(t_p)$ denote the lateral position of p at the instant t_p. The leader of p is the pedestrian with the largest index $q < p$ for which

$$|y_q(t_q) - y_p(t_p)| \leq a \tag{1}$$

for some value $a > 0$. The headway h_p of pedestrian p is then defined by

$$T_p = t_p - t_q. \tag{2}$$

Figure 7 depicts the definition of the time headways. It also shows the headway S_p of p with respect to the first pedestrian q' in the adjacent layer (the so-called *lead gap*) and the headway W_p of p with respect to the next pedestrian q'' in the adjacent layer (the so-called *lag gap*).

6.1. Composite Headway Model of Buckley Applied to Pedestrian Flows

To study the following behavior of pedestrians, we consider the semi-Poisson model due to Buckley (1968), distinguishing between constrained headways and free headways. *Free headways* are headways of pedestrians experiencing no hindrance from

[2] A vacancy is defined by a lattice position that is vacant because an atom is missing.

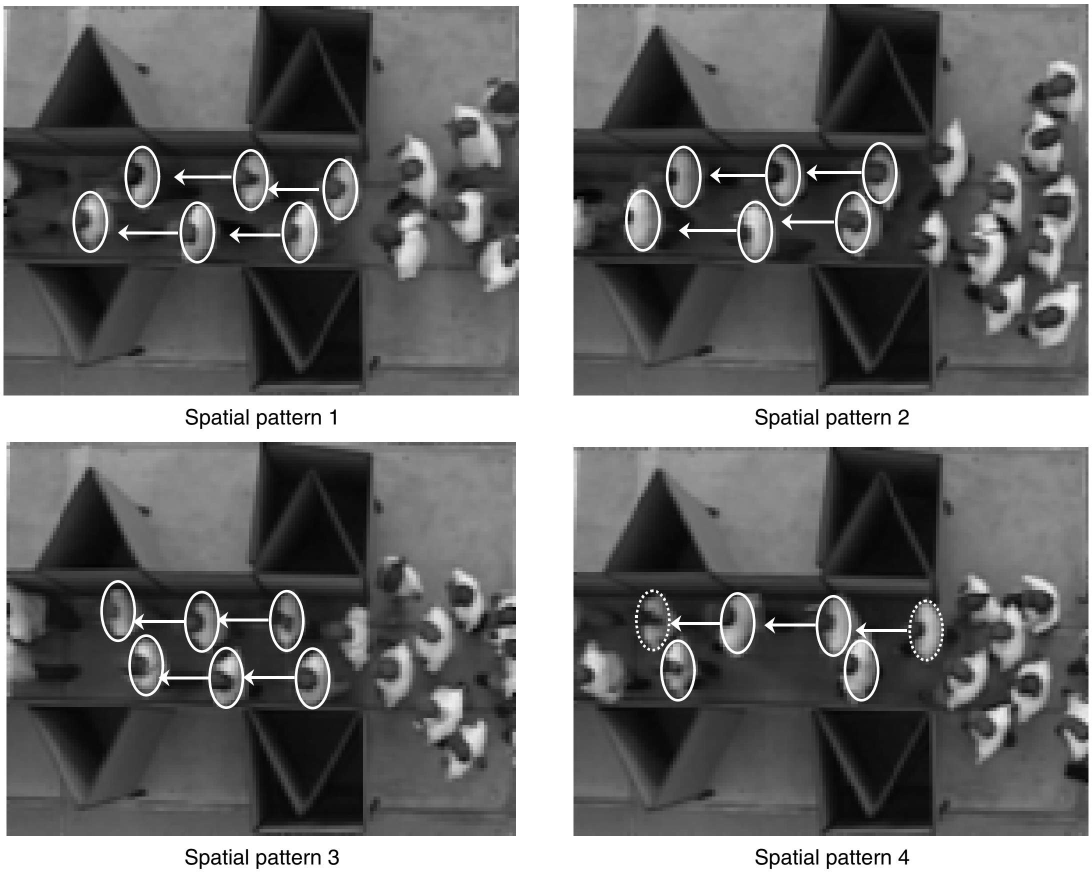

Figure 6 Emergent Zipping Patterns Inside the Bottleneck (Pedestrians Walk from Right to Left)

pedestrians ahead, and who are thus able to walk at their free speed. The distribution of the free headway is usually determined by drawing the analogy with a Poisson-point process. Consequently, the free headway is assumed to be exponentially distributed.

Constrained headways are headways of pedestrians following pedestrians in front that, because no direct overtaking opportunity exists, force constrained walking. The headway will fluctuate around a desired minimum headway (the so-called empty zone). We argue that different pedestrians will adopt different empty-zone sizes. Causes for these interpersonal variations are, among other things, subjectiveness in what is perceived as comfortable, differences in walking purpose, but also differences in kinematics (i.e., step size and frequency). Additionally, no pedestrian is able to maintain the same empty zone all the time, and thus the headway of a constrained pedestrian will fluctuate around a desired minimum headway (intrapersonal variations).

Let $g(t)$ and $h(t)$, respectively, denote the probability density functions of the empty zone and the free headway, and let ϕ denote the fraction of constrained pedestrians. The composite headway model

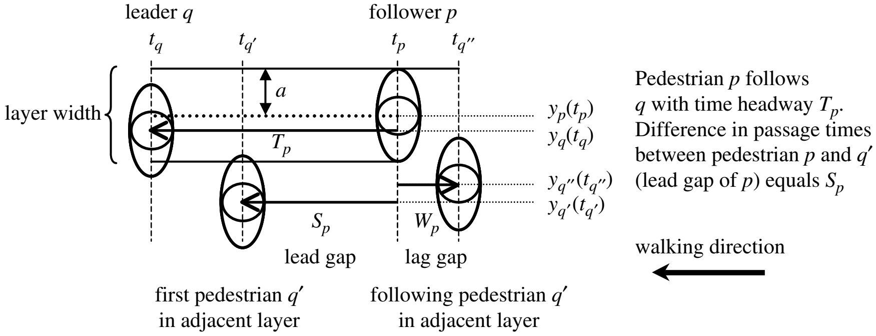

Figure 7 Definitions of Time Headways

of Buckley infers that the probability density function $f(t)$ of the composite headway T equals

$$f(t) = \phi g(t) + (1-\phi)h(t). \tag{3}$$

Furthermore, Buckley (1968) shows that the free headway density function satisfies

$$h(t) = \frac{1}{A}\lambda \exp(-\lambda t)\int_0^t g(\tau)\,d\tau \quad \text{where} \quad A = \int_0^\infty \lambda \exp(-\lambda\tau) g(\tau)\,d\tau. \tag{4}$$

A is the so-called normalization constant; λ denotes the free headway arrival rate.

In the remainder, we will briefly recall the approach used to estimate the parameters of the model, i.e., the free headway arrival rate λ, the fraction of constrained pedestrians ϕ, and the probability density $g(t)$ of the empty zone. Besides given information on the way pedestrians follow each other, information regarding the empty zone also provides opportunities to determine the capacities of a dynamic layer—i.e., by assuming that in saturated conditions, all pedestrians are following ($\phi = 1$) and noticing that the capacity c (in Ped/m/s) equals the inverse of the mean empty zone

$$c = \frac{1}{2aE(T)_{\phi=1}}, \tag{5}$$

where $2a$ denotes the average layer width. The capacity per lane c_l (in P/s/lane) equals

$$c_l = \frac{1}{E(T)_{\phi=1}}. \tag{6}$$

6.2. Parameter-Free Empty-Zone Distribution

This section summarizes the distribution-free estimation approach developed by Wasielewski (1979). The most important assumption is the existence of some maximum empty-zone value T^*, such that $g(t) = 0$, for all $t > T^*$ (i.e., all headway observations $T_p > T^*$ stem from freely walking pedestrians). Given this assumption, we can consider a subset $\{T_p \mid T_p > T^*\}$ of the headway observations. Wasielewski (1979) shows that the maximum-likelihood estimate for λ then equals

$$\hat{\lambda} = \frac{1}{m}\sum_{p'=1}^{m}(T_p - T^*), \tag{7}$$

where m denotes the number of headway observations larger than T^*. We can then show that

$$\hat{A} = \frac{m}{n}\exp(\hat{\lambda}T^*), \tag{8}$$

where n is the total number of headways in the sample. Let $\hat{f}_n(t)$ denote an estimate for the composite headway distribution based on the sample $\{T_p\}$ (e.g., a histogram, or a Kernel estimate). An estimate $\hat{g} = (\hat{f}_n - \hat{h}_1)/\hat{\phi}$ for the empty-zone distribution can then be determined by solving the following integral equation for $\hat{h}_1 = (1-\hat{\phi})\hat{h}$:

$$\hat{h}_1(t) = \frac{\hat{A}\hat{\lambda}}{\hat{\phi}}\exp(-\hat{\lambda})\int_0^t (\hat{f}(\tau) - \hat{h}_1(\tau))\,d\tau, \tag{9}$$

subject to

$$\hat{\phi} = \int_0^\infty (\hat{f}(\tau) - \hat{h}_1(\tau))\,d\tau, \tag{10}$$

which can be solved iteratively (Wasielewski 1979).

6.3. Empty-Zone Distribution Functions

Let us now apply the approach outlined in the previous sections to the headways collected at different cross-sections inside the bottleneck. Let us assume $a = 22$ cm (half of the lateral distance between the dynamic layers) and consider periods in which the flow is stationary. Furthermore, we choose $T^* = 2.5$ s. We have used a histogram with a bin-size of 0.5 s as an estimate $\hat{f}(t)$ of the gross probability density function $f(t)$.

Figures 8(a)–8(d) depict estimation results for the wide bottleneck experiment for different cross-sections x inside the bottleneck. The figure shows the shape of the empty-zone distribution of the constrained pedestrians, which appears to be independent on the cross-section x where the headways are determined.

Figures 9(a)–9(d) show similar results for the narrow bottleneck (a, c) and the no-bottleneck experiment (b, d). Figure 9(a) and Figure 9(c) clearly show that the contribution of the empty zone to the total headway is large in the case of the narrow bottleneck, implying that nearly all pedestrians are effectively following. Figure 9(b) and Figure 9(d) show that in the case of the no-bottleneck experiment, the contribution of following pedestrians to the composite headway is substantially less than in the case of the narrow and the wide bottlenecks (small fraction of followers). The empty-zone distribution estimate $\hat{g}$ is nearly the same for both cases.

Table 1 shows an overview of the estimation results for the considered experiments (for $x = 2.5$ m, i.e., a specific cross-section inside the bottleneck). The mean empty zone is largely independent of the width of the bottleneck and the gross bottleneck flow rate for the different experiments, as is the estimated probability density function $\hat{g}$. Table 1 also shows that in the narrow bottleneck case the fraction of constrained pedestrians is nearly 1 (96% to be precise). For the wide bottleneck experiment, the fraction of constrained pedestrians is smaller (approximately 62%), due to the fact that this bottleneck is not oversaturated. Nevertheless, the empty zone, *and thus the bottleneck capacity*, can be estimated accurately from the available

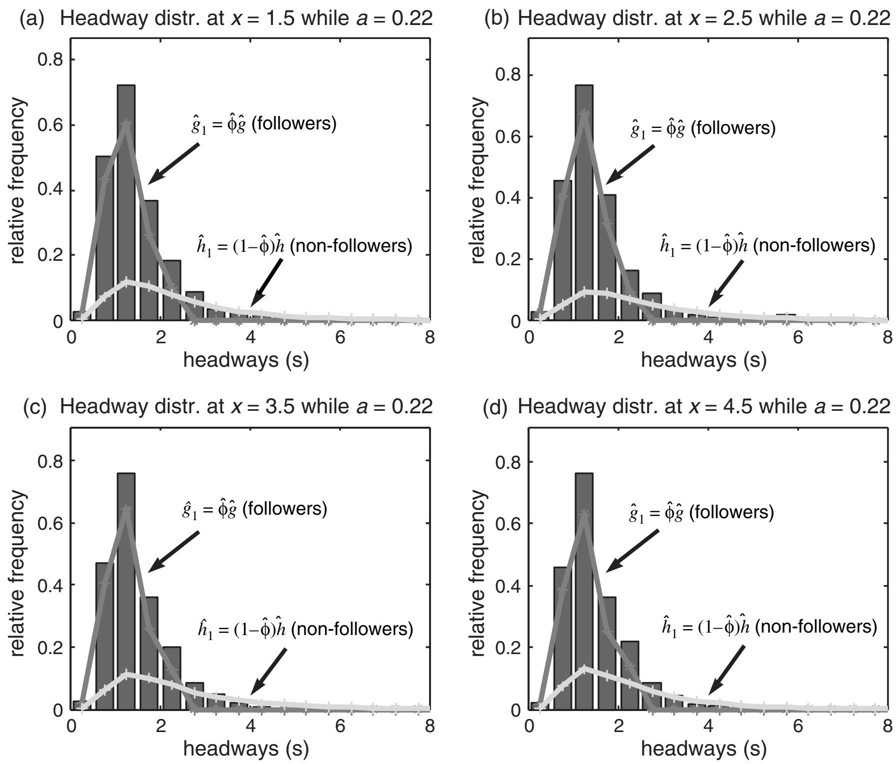

Figure 8 **Results of Headway Estimation for the Wide Bottleneck Experiment**

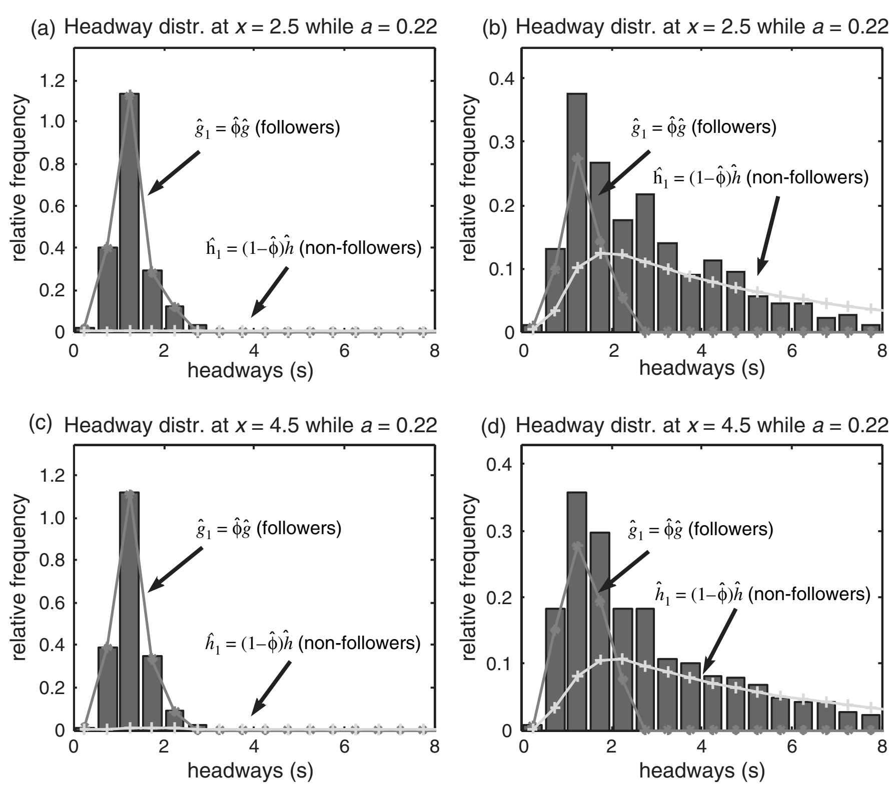

Figure 9 **Results of Headway Estimation for Narrow Bottleneck ((a) and (c)) and No-Bottleneck ((b) and (d)) Experiments for Locations** $x = 2.5$ **((a) and (b)) and** $x = 4.5$ **((c) and (d))**

Table 1 Composite Headway Model Estimation Results for Different Experiments

	Narrow bottleneck	Wide bottleneck	No bottleneck
$\hat{\lambda}$ (1/s)	0.356[‡]	0.685	0.202
$\hat{\phi}(\cdot)$	0.956	0.623	0.276
Mean empty zone (s)	1.282	1.288	1.364
Capacity (Ped/m/lane)	0.780	0.776	0.733
Capacity[§] (Ped/m/s)	1.774	1.765	1.666

[‡]The estimate for the free arrival rate in the case of the narrow bottleneck is not reliable, due to the large fraction of constrained pedestrians (only 4% of the pedestrians are walking freely).

[§]The capacity estimate determined using the composite headway model is in line with the capacity estimates determined from the bottleneck saturation flows.

data using the composite headway model of Buckley (1968). Note that the capacity estimate determined by using the composite headway model is in line with the capacity estimates determined from the bottleneck saturation flows.

For the no-bottleneck experiment, the fraction of constrained pedestrians is even less, only 28%. As shown by Equation (5), the estimate of the mean empty zone allows estimation of the maximum pedestrian flow based on the maximum flow at a cross-section of the dynamically formed layers.

In sum, the results indicate that composite headway distribution models can be successfully used for unidirectional pedestrian flows, given that we adopt the headway definition presented in this section. The concept of the empty zone (constrained headway) makes sense, as does the notion of constrained walking; both can thus be applied to pedestrian flow modeling and analysis.

7. Interpretation of Results and Implications for Bottleneck Capacity

From the results presented in the previous section, it can be concluded that, inside the bottleneck, layers are formed dynamically. These layers consist of pedestrians following each other (in case of oversaturated conditions). The distance between the layers (approximately 45 cm) is less than the width of its constituent pedestrians (zipper effect). It can thus be concluded that although a pedestrian may be blocked effectively by a pedestrian in an adjacent layer that is partly overlapping, he or she will follow the pedestrian directly in front. A possible explanation of this phenomenon is that a pedestrian needs sufficient space to take a step, but needs relative little lateral space to do so. Pedestrians in adjacent layers will, hence, not interfere, but the pedestrian directly ahead will.

Amongst the conclusions that can be drawn from the observations and estimation results is the fact that for *unidirectional flows, the bottleneck capacity will not be a linear function of the bottleneck width*, but will increase in a stepwise manner. This implies that general design guidelines (Weidmann 1993), namely that the capacity of the bottleneck can be determined by its effective width multiplied by the unit width capacity, does not hold.

We argue that the correct way to determine the capacity of a bottleneck (in case of a unidirectional flow) is to first determine the effective width of the bottleneck, and subsequently determine the number of layers that can be accommodated by this effective width. The minimum *effective width* of a bottleneck must encompass at least one layer, and must hence be larger than the expected maximum shoulder width of a pedestrian (say, 50 cm), assuming that wider pedestrians will take up some of the unused bottleneck width W_{unused}. For example, this means that in case the bottleneck surface is made of concrete ($W_{\text{unused}} \approx 25$ cm), the gross width of a bottleneck that can accommodate one layer equals 50 cm + 50 cm = 100 cm. To be able to serve more than one layer, we need an additional 40 cm effective bottleneck width for each additional layer.

Following this line of reasoning, a bottleneck with an effective width of 80 cm can accommodate only one layer. The capacity of this bottleneck would be 0.78 P/s. A bottleneck with an effective width of 90 cm can accommodate two layers, and thus has a double capacity of 1.56 P/s. Note that in the case of the narrow bottleneck experiment discussed here, two layers are formed. The required effective width is thus $2 \times 25 + 40 = 90$ cm. The soft surface of the obstructions making up the bottleneck was such that pedestrians apparently needed only a few centimeters distance between themselves and the obstruction. Note that the headway distribution-based estimate of 1.56 P/s is very near the Product Limit Method estimate of 1.61 P/s for the capacity of the narrow bottleneck, showing the validity of the proposed approach.

Derived from the above, the following expression can be used to determine the capacity of a (unidirectional) bottleneck

$$c = c_l \cdot \left\lfloor \frac{W_{\text{eff}} - (w_{\max} - d_{\text{layer}})}{d_{\text{layer}}} \right\rfloor = c_l \cdot \left\lfloor \frac{W_{\text{eff}}}{d_{\text{lane}}} - \frac{w_{\max}}{d_{\text{layer}}} + 1 \right\rfloor, \tag{11}$$

where $\lfloor x \rfloor$ denotes the smallest integer near x, e.g., $\lfloor 2.7 \rfloor = 2$; $w_{\max}$ denotes the maximum shoulder width of a pedestrians (approximately 50 cm), and w_{layer} denotes the lateral distance between two layers (approximately 45 cm). Relation (11) applies to relatively narrow bottlenecks (say, up to 3 m); for wider bottlenecks, the linear relation between bottleneck width and capacity may be equally appropriate, because the formed layers will be less stable.

8. Conclusions

In this contribution, we have discussed the results of a large set of experiments conducted to gain more insights into walking behavior. This paper focuses on pedestrian flow operations in bottlenecks of varying width, in particular to the microscopic behavior inside the bottleneck.

It turns out that under saturated conditions, layers are formed dynamically. The lateral distances between the layers are less than the average shoulder width of the pedestrians, implying that the layers are in fact merged together and move at the same speed.

Using a dedicated definition of pedestrian headways, composite headway distribution models have been estimated from the experimental data. The composite headway model distinguished between constrained and unconstrained walking, and allows for the estimation of both. In the paper the approach is applied successfully, yielding estimates for the distribution of the constrained headways. It is shown that the constrained headway distribution is largely independent of bottleneck geometry and traffic demand levels.

The model shows that under saturated conditions, nearly all pedestrians are following the pedestrian directly ahead (i.e., in the same layer). The correlation between passage times of a pedestrian and a pedestrian in the adjacent layer are small, although the pedestrian in the adjacent layer may be closer then the leading pedestrian in same layer.

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