

Controlled Experiments to Derive Walking Behaviour

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To assess the design of walking infrastructure such as transfer stations, shopping malls, sport stadiums, etc., as well as to support planning of timetables for public transit, tools to aid the designer are needed. To this end, microscopic and macroscopic pedestrian flow models can and have been applied. To calibrate and validate such models, as well as to gain more insight into the characteristics of pedestrian flows under a variety of circumstances, very detailed pedestrian flow data are required. This is why Delft University of Technology has recently carried out experimental pedestrian flow research.

This paper describes the experimental design (determination of process variables, measurement set-up, etc.), the resulting microscopic pedestrian data, as well as some first results for the narrow bottleneck experiment. Both microscopic and macroscopic characteristics of pedestrian flows are presented. Interesting first results pertain to the way in which the narrow bottleneck is used under saturated flow conditions, and the use of the space (or rather, width) upstream of the bottleneck in case of congestion.

1. Introduction

The traditional way of designing transfer stations is based on rules of thumb. These rules convey experience concerning the behaviour of passengers in transfer stations. However, they only consider static situations. Furthermore, a scientific foundation for these rules has yet to be provided. Similar arguments hold for the planning of timetables, which involves approximating the time people actually need to transfer. Different types of passengers, such as elderly people and parents with children, need different transfer times. Adopting accurately estimated transfer times will both remove excessive waiting times from a timetable as well as reduce the probability for passengers to miss their connection, thereby increasing the traveller's comfort and the timetable's reliability.

To support the design and planning process, Delft University of Technology, in co-operation with Holland Railconsult, has developed the simulation model SimPed to estimate both mean and variability of walking times incurred by transferring passengers and to visualise walking patterns inside transfer stations and other pedestrian areas (Daamen, 2002). Also, the microscopic simulation model NOMAD has been developed, which predicts pedestrian behaviour in general walking facilities using microscopic behavioural rules (Hoogendoorn and Bovy, 2002).

Before these models can be applied, they need to be calibrated and validated. This can be achieved by comparing model results with empirical data. However, little data on pedestrian behaviour exist and most of these data sets have been gathered in Asia (Japan, Hong Kong (Lam, Morral and Ho, 1992)). However, pedestrian characteristics in Asia differ significantly from those of Western European pedestrians (for example length and width of the pedestrians, as well as cultural differences). Furthermore, the data are generally macroscopic, meaning that they describe the characteristics of the flow rather than of the individual pedestrians. Although these data may be adequate to roughly validate the model, they will generally not suffice to calibrate the model parameters or to test the underlying theoretical hypotheses of walking behaviour. Therefore, new data sets need to be gathered for the validation of the software tools. Preferably, data are collected in stations (for that is one of the specific application areas of SimPed), but the required approval has been refused because of privacy matters. Among the disadvantages of gathering data in railway stations are the expected problems in the automatic tracking of pedestrians. Because of the low ceilings, video cameras cannot be placed in ideal positions (right above the pedestrian flows) in order to collect exact locations of pedestrians. On top of these technical problems, the data will contain traffic conditions that occur under specific non-controllable circumstances. As a result, whether the data will include all situations that are deemed relevant is highly unlikely. If we are for instance interested in observing crossing flows, where the composition of the two directions is 50-50%, the probability that this situation will occur and last for a considerable period of time is very slim.

To overcome these problems, the Transportation and Traffic Engineering Section of Delft University of Technology has performed unique experimental research by organising walking behaviour experiments. The advantage of performing experiments is the total control of the circumstances and the flexibility to vary each of the influencing variables one by one to see effects of these variables on the behaviour of the individual pedestrians and of the total pedestrian flow. From the gathered video data both macroscopic and microscopic relations can be derived. For more information on the transformation of video data to information, we refer to Hoogendoorn and Daamen (2002).

This paper describes the performed experiments and the first macroscopic results from the research. First, we give a short overview of the state of the art of pedestrian observations. Then, we formulate the research objectives and we derive the experiments to be carried out. After a short report of the day of the experiments itself, we show some preliminary results, we got from one of the experiments. Finally, we end with some conclusions.

2. State of the art of empirical research on pedestrian behaviour

This section presents a very brief (and therefore non-exhaustive) overview of some of the empirical facts regarding pedestrian walking behaviour and flow characteristics. These facts concern among other things the relation between walking speed and energy consumption, the factors influencing walking speeds, and the use of space by pedestrians. Other important features of pedestrian flows are discussed, such as self-organisation, and co-operation between pedestrians.

2.1 Macroscopic flow characteristics

Several authors have considered macroscopic pedestrian flow properties empirically. For instance, recent work of Lam and Cheung (2000) investigate collective walking behaviour for different types of pedestrian facilities (commercial areas, shopping areas, etc.) in Hong Kong and compare results (eg. walking speeds) to other countries. Speed-density-flow models developed for Hong Kong are similar to those developed for Singapore for similar facilities (Lam, Morrall and Ho, 1992). However, no single model fits all pedestrian facilities, indicating that more data collection is required for a larger range of flow conditions. Other studies are due to Navin and Wheeler (1969), Older (1968), Pushkarev and Zupan (1975), and Weidmann (1993). For sake of illustration, Weidmann (1993) presented the following relation between walking speed and density for one-directional flow

$$V_e(k) = 1.34 \left[1 - e^{-1.913 \left(\frac{1}{k} - \frac{1}{k_{jam}} \right)} \right] \quad (1)$$

where k is the density in P/m², and where k_{jam} denotes the jam-density of 5.4 P/m². The free speed of the pedestrians with different purposes of walking (where $k \rightarrow 0$ P/m²) equals 1.34 m/s. Shopping pedestrians have a free speed of 1.04 m/s, commuters of 1.45 and the free speed for tourists is 0.99 m/s (Weidmann, 1993). Clearly, eqn. (1) can be used to determine the relation between the density and equilibrium flow as well.

2.2 Walking speeds and spatial use

Different factors 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. At some traffic condition beyond free flow, pedestrians are limited in forward movement by people to the front and side. Weidmann (1993) provides a comprehensive overview of the most important studies.

With respect to the pedestrian's spatial use, both 'lateral spatial use' and 'longitudinal spatial use' are important. For one, pedestrians will generally not be able to walk in a straight line; the required walkway width theoretically depends on the walking speed. These deviations are however rather small (i.e. approximately 5 cm). Pedestrians will also need more space in the longitudinal direction with increasing walking speeds. This is in part caused by the additional

space needed to take a step. Empirical studies have shown that the relation between the longitudinal space used and the speed is given by the following relation

$$A(V) = A_{jam} - 0.52 \ln \left(1 - \frac{V}{V_f} \right) \quad (2)$$

where V is the walking speed, V_f is the average free walking speed ($V_f \approx 1.34$ m/s), $A = LW$ denotes the required area (i.e. longitudinal spatial use L multiplied by the lateral spatial use W), and A_{jam} is the largest area for which walking is impossible ($A_{jam} \approx 0.19$ m²). Note this relation implicitly defines the speed density relation presented in (Weidmann, 1993).

2.3 Collective behaviour and self-organisation

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 relative small loss of capacity in case of bi-directional pedestrian flows (in the range of 4% to 14.5% (Weidmann, 1993). It is interesting to note that the structure of the lanes that are formed are equal for countries where traffic regulations are left-hand or right-hand based: it turns out that for walkways of moderate width, the lanes are formed on the right-hand side. Similar results have been established for crossing flows (Toshiyuki, 1993), albeit in the form of strips or moving clusters composed of pedestrians walking in the same direction.

2.4 Walking behaviour and interaction

Goffman (1971) describes how the environment of the pedestrian is observed through a mostly subconscious process called *scanning* in order to side-step small obstructions on the flooring. Golson and Dabbs (1974) observe that women spend more time scanning the sidewalk than men. Wolff (1973) argues that a *high degree of co-operation between pedestrians* is an intrinsic part of pedestrian behaviour, without which walking would be impossible: pedestrians expect others to be co-operative rather than obstructive in the completion of their walking tasks.

Goffman's notion of scanning the infrastructure is also applicable to describe the interaction with other pedestrians. He describes how pedestrians assume that the pedestrians, who are in a small closed circle around him, are those pedestrians that he must check up on. Pedestrians who are a person or two away are neglected. The scanning area is not a circle, but an ellipse, which is narrow to either side of the individual and longest in front of him. Moreover, the area of the ellipse changes constantly according to the prevailing traffic density.

Two special moments occurring during an encounter can be distinguished:

1. Emission of critical sign. Pedestrians communicate to let each other know what they will do next. Frequently, these communications consist of very subtle movements (e.g. small movement of the shoulder).
2. Establishing moment. This point describes the recognition by both parties that they have exchanged critical signs.

Only after both moments have passed, actual changes in the courses of the pedestrians are 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*. This movement occurs mostly between members of equal gender and conveys that interacting pedestrians do not take a total detour or attempt to avoid physical contact at all cost. Rather, there is a slight angling of the body, shoulder turn and an almost imperceptible side step. Neither of the pedestrians will move enough to guarantee contact avoidance or bumping into each other, *unless the other pedestrian co-operates*. Nevertheless, even when both pedestrians correctly execute the step-and-slide movement, some body contact may occur. Experimental studies of Sobel and Lillith (1975) report a relatively high number of *brushes* in situations where interactions were one-sided, even at low densities. 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 co-operate.

Dabbs and Stokes (1975) have studied the extent in 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. They also reported that culturally defined beautiful women were given more space than unattractive women were. On the contrary, Sobel and Lillith (1975) observed that women are often granted more room than men. Willis *et al.* (1979) suggested that power may not be so important as gallantry in deciding who moves where during collision avoidance manoeuvres. They found that persons or groups moved for larger groups; younger groups tended to move for older groups; women do not tend to move for men, nor do blacks tend to move for whites. They indicated that besides power, and gallantry, also manoeuvrability may play a decisive role.

2.5 Experimental approaches

In this paper, we describe controlled experiments on walking behaviour. We are not acquainted with any other research also using experiments to study pedestrian behaviour. Most research until now uses video data out of practice to describe and study pedestrians. This way, independent variables cannot be influenced, but are set by the external circumstances.

3. Research objectives

In the introduction, we have stressed the importance of gaining more insights into both the microscopic and macroscopic characteristics of pedestrian flows, and the use of experimental research in achieving such insights. In an experiment, one or more experimental variables (factors or stimuli) are deliberately changed in order to observe the effect the changes have on one or more response variables. We begin to determine the objectives of an experiment and to select the process factors for the study. Well-chosen experimental designs maximise the amount of 'information' that can be obtained for a given amount of experimental effort.

It is common to begin with a process model of the 'black box' type, with several discrete or continuous input factors that can be controlled – that is, varied at will by the experimenter –

and one or more measured output responses. The output responses are assumed continuous. Experimental data are used to derive an empirical (approximation) model linking the outputs and inputs.

Often there are many possible factors, some of which may be critical and others, which may have little or no effect on a response. It may be desirable, as a goal by itself, to reduce the number of factors to a relatively small set (2-5) so that attention can be focused on controlling those factors with appropriate specifications, control charts, etc. Screening experiments are an efficient way, with a minimal number of runs, of determining the important factors.

A common experimental design is one with all input factors set at two levels each. These levels are called 'high' and 'low', respectively. A design with all possible high/low combinations of all the input factors is called a full factorial design in two levels (Statistics Engineering Handbook).

The aim of this experimental research on pedestrian behaviour is also gaining insight in the relation between several experimental variables and dependent or response variables describing the process. Both the behaviour of the individual pedestrian (microscopic) as the behaviour of pedestrian flows (macroscopic) is of interest. For example, the relation between the macroscopic magnitudes density, composition of the flow (with regard to the walking direction of the pedestrians) and mean speed can be investigated.

4. Walking process variables

The process variables are both the input and output variables that are found relevant. In an early phase of the research, a clear distinction has been made between primary and secondary factors. Hoogendoorn and Daamen (2002) give an overview of the different factors that have been determined, from expert knowledge and literature surveys, for the walking experiments. In this paper, we have distinguished between *experimental variables* and *context variables*: while the former were influenced during the experiments, the latter are specific for different pedestrians.

The selection of these variables is best done as a team effort. The team should

- Include all relevant factors (based on engineering judgement).
- Be bold, but not foolish, in choosing the low and high factor levels.
- Check the factor settings for impractical or impossible combinations - i.e., the presence of a bottleneck and multi directional pedestrian flows.
- Include all relevant responses.
- Avoid using only responses that combine two or more measurements of the process. For example, if interested in selectivity (the ratio of two etch rates), measure both rates, not just the ratio.
- Be careful when choosing the allowable range for each factor. We have to choose the range of the settings for input factors, and it is wise to give this some thought beforehand rather than just try extreme values. In some cases, extreme values will give runs that are not feasible; in other cases, extreme ranges might move one out of a smooth area of the response surface into some jagged region, or close to an asymptote.

4.1 Process variables

The following variables having influence on the process appeared to be relevant:

- Free or desired speed.
- Direction.
- Formation of groups.
- Extent in which the free speed is maintained (indicator of aggressiveness).
- Density.
- Bottlenecks.
- Presence of obstacles.

Implications for each of these variables are described in the following paragraphs.

Free speed

Free speed is the speed pedestrians like to keep during undisturbed circumstances. A pedestrian can not walk at a predefined (exact) speed. During this experiment we will, therefore, use subjective walking speeds, ordered in three classes: slow, normal and fast.

Direction

Basically, a pedestrian can walk in any arbitrary direction in an area. Since this will lead to an infinite number of combinations of directions, the number of directions will be restricted to eight. These directions are shown in Figure 1.

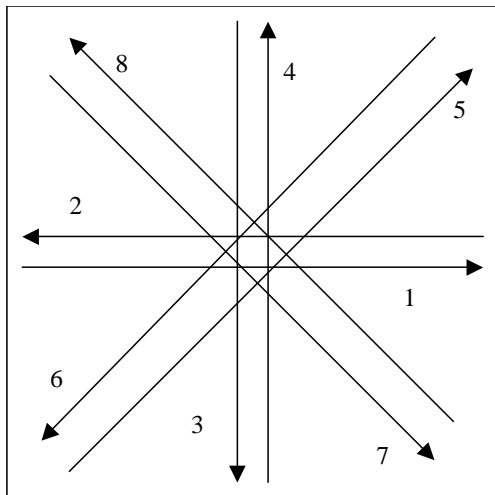


Figure 1. Directions of a pedestrian in an area.

During the final experiments, combinations of these flows are chosen to investigate the interaction between individual pedestrians in the flow, but also the interaction between flows as a whole.

Group formation

Especially during shopping or on trips groups are formed: two or more pedestrians try to stay together in a pedestrian flow. In this experiment we will distinguish three types of groups:

individuals, pairs and large groups, where the number of ‘members’ depends on the number of pedestrians being in the area during an experiment.

Extent in which the free speed is maintained (indicator of aggressiveness)

At higher densities it becomes more difficult to keep a speed higher than the speed of most of the pedestrians. Depending on external circumstances (for example for someone trying to catch a train), the mental pressure to maintain free speed will rise and this person will take much trouble to find a path overtaking others. Ultimately, he will nudge or even push away pedestrians walking in the way. In this experiment we distinguish two classes: pedestrians easily adapting their free speed and pedestrians maintaining their free speeds as long as possible.

Density

Density varies between an almost empty area and a fully occupied situation. Density is indicated by a percentage, where 0% indicates an empty area and 100% a fully occupied area. These limits will not be taken into account in this research, because of the lack of pedestrian flow in these circumstances.

Bottlenecks

To observe the congestion part of the fundamental diagram as well, we need to consider bottlenecks by placing obstructions in the controlled walking area. These bottlenecks will narrow the area, leading to congestion upstream of the bottleneck.

Presence of obstacles

The following characteristics of obstacles are important:

- Size (length, width and surface area).
- Shape (in both horizontal and vertical direction).
- Sight (material, cleanliness).
- Number of obstacles.
- Location (inside or outside the flow).

Types of obstacles can hardly be changed during this experiment. Only the number, the size and the location of obstacles will be changed.

4.2 Choice of process parameters

Over all, seven experimental variables have been distinguished. When we combine these variables in all possible ways, about 54000 experiments are possible. This is impossible for one day, so the number of experimental variables is reduced, the variable ranges are restricted and also the number of combinations of variables is decreased.

The aspect ‘formation of groups’ is left out of the experiment. Especially during morning peak hours, most train passengers travel alone and do not have any attraction towards other passengers. Then, the variable regarding the adaptability of the free speed is combined with free speed. We assume that pedestrians with a (significantly) higher free speed are in a hurry and therefore they are more willing to maintain this free speed. Slowly walking pedestrians

have all time and will therefore sooner adapt their speed. The remaining experimental variables are:

- Free speed.
- Direction.
- Density.
- Bottlenecks.

Also, ranges of values of experimental variables are restricted.

Free speed

- A. Normal situation (100% normal speed).
- B. Stations with hurried pedestrians (60% normal speed, 40% high speed).
- C. Shopping environments with window-shoppers (40% low speed, 60% normal speed).

Walking directions

- A. One-directional flow (100% direction 1).
- B. Equal two directional flow (50% direction 1, 50% direction 2).
- C. Unequal two directional flow (90% direction 1, 10% direction 2).
- D. Equal crossing flows (50% direction 1, 50% direction 3).
- E. Unequal crossing flows (90% direction 1, 10% direction 3).
- F. Equal four directional flow (25% direction 1, 25% direction 2, 25% direction 3, 25% direction 4).

Bottlenecks

- A. No bottlenecks.
- B. One bottleneck with a width of 2 meters.
- C. One bottleneck with a width of 1 meter.

Density

The density varies between an almost empty area and a fully occupied area. The density is then measured in a percentage, where 0% indicates an empty area and 100% an area fully occupied. These limits will not be taken into account in these experiments because of the lack of pedestrian flows in these circumstances.

In the experiments, adding new groups of pedestrians increases the density. The exact densities (= number of pedestrians on the controlled area) during the experiment depend on the sizes of the pedestrian groups and the number of pedestrians walking back towards the starting point of each group. The size of each group is between 8 and 10 pedestrians and there are eight groups. Measured densities will then be about 12.5%, 25%, 37.5%, 50%, 62.5%, 75%, 87.5% and 100%.

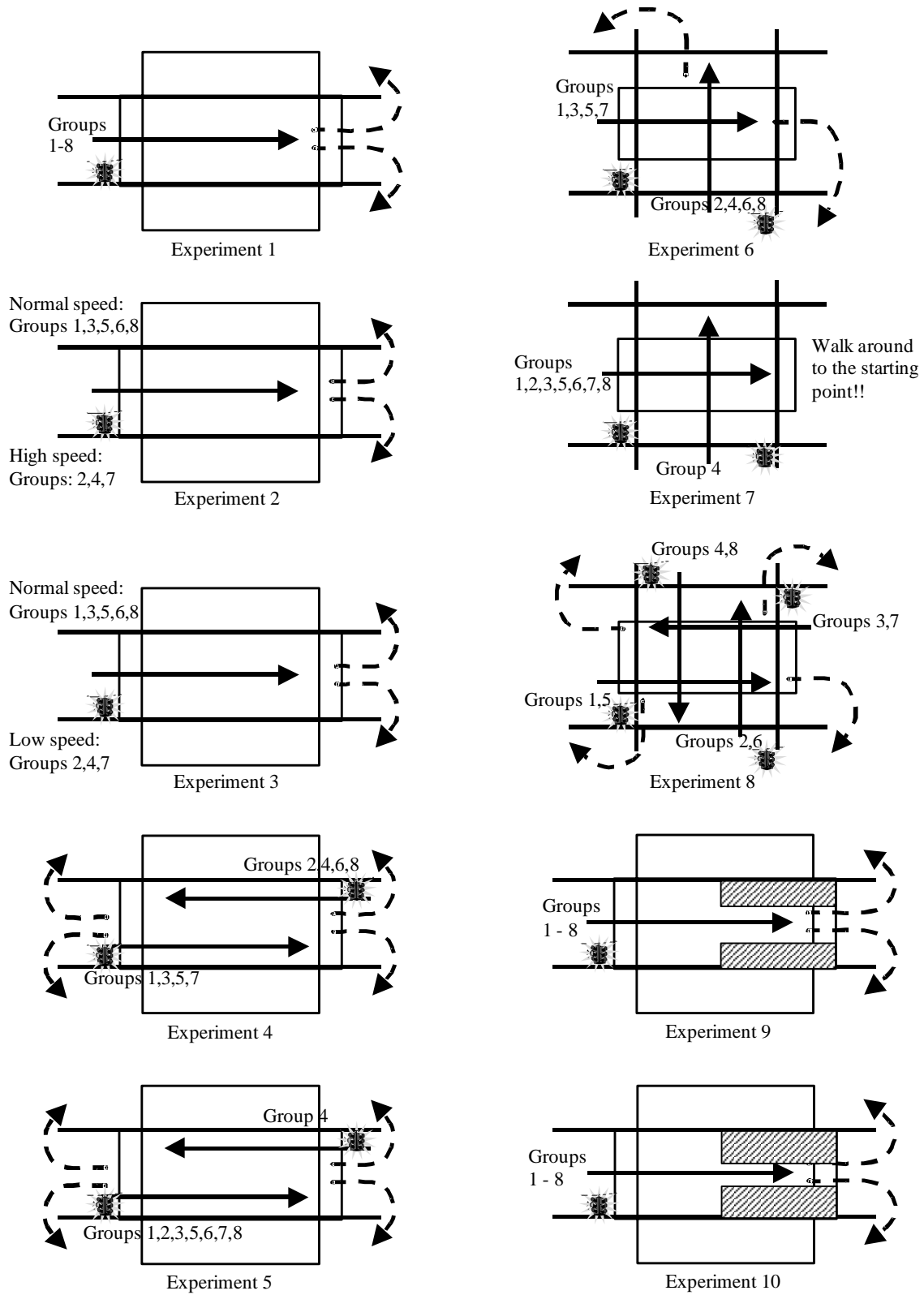


Figure 2. Overview of experimental set-up.

5. Carrying out the walking experiments

5.1 Measurement set-up

For the experiments, we used two areas. One rectangular area (10 meters x 4 meters) was used for the unidirectional and two directional experiments and the experiments with the bottlenecks (experiments 1, 2, 3, 4, 5, 9 and 10). For the experiments with crossing flows, a square is used of 8 meters \times 8 meters. Both areas are taped on the floor: the rectangular area in blue; the square area in white. Cones indicate corners of both areas. To make pedestrians walk as straight as possible over the area (without deviation towards the corners while turning back towards their starting point), more cones are set joined by red-white tape. Bottlenecks are made of green boards, built up in triangles to increase stability. These bottlenecks are heavy and stable enough to not being pushed away by the pedestrians in an accidental contact and light enough to be moved in case of emergencies. To give signals to the pedestrians to enter the area the first time, traffic lights are used.

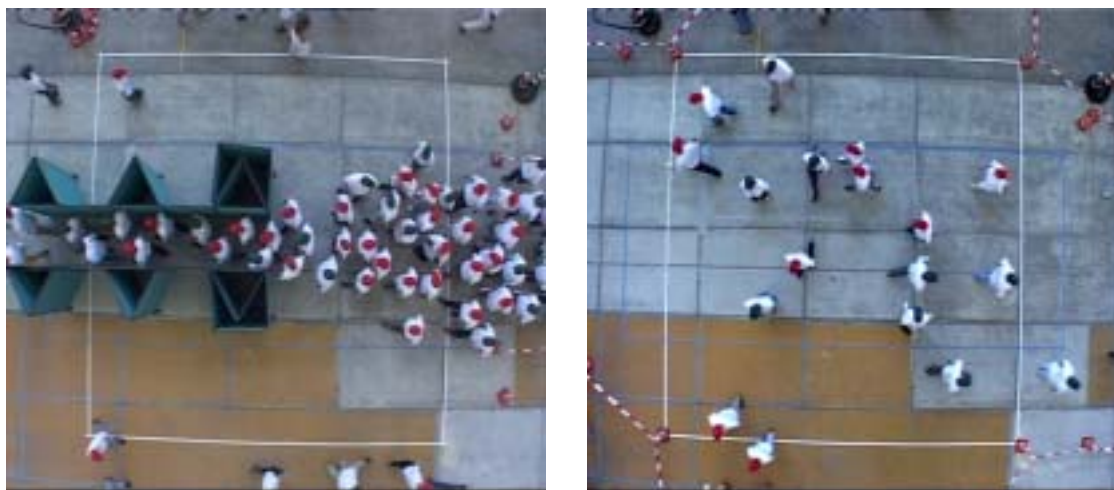


Figure 3. Examples of pedestrian experiments; a) narrow bottleneck experiment, and b) four-directional crossing flow experiment.

The walking experiments have been conducted in a large hallway. The ambient conditions were favourable (reasonably constant light intensity, few shadows, smooth surface), although there was some influence of the sun shining through the windows. The 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, and was attached to a digital video recorder. The quality of the collected video footage was very high.

5.2 Pedestrians

During the morning session 60 pedestrians joined the experiments while 80 pedestrians were present during the evening session. Each pedestrian got a white TU Delft T-shirt and a red or

green cap. Both cap and T-shirt were used to be sure of a sufficient contrast between the pedestrians and the background. Cap and T-shirt could be kept as souvenirs.

Due to the fact it is impossible to manage all pedestrians at the same time, groups were formed. A group leader was assigned to each group. This group leader was in advance informed of the experiments, was responsible for the pedestrians in his group and took among others care of the right moment for his group to join the experiment. All members of one group had the same cap colour. In the experiments 2 and 3, the colour of the cap was used to indicate the fast and the slow pedestrians (red = normal speed; green = adapted speed).

Groups consisted of 8-10 pedestrians, so a maximum of 8 group leaders was needed. The composition of each group was uniform to have a conform behaviour for all groups. To achieve this, all pedestrians were divided into pedestrian types (child, male student, female student, male, female and senior). Each of these types was equally divided over the different groups.

5.3 Course of the experiments

During an experiment, pedestrians were added group by group. To add the pedestrians of a group to the experiment we used traffic lights. After a group joined the experiment, a stable situation was reached and remained during one minute. After this time period a next group was added and the process was repeated until all groups (or as many groups as capacity allowed) joined the experiment. This 'capacity' situation was then stabilised during two minutes, after which a group left the experiment. After the removal of a group, the situation was stabilised once more during one minute, until the next group could leave the experiment. This continued until all groups left.

The traffic light turned green the moment one pedestrian could enter the area. After a short time period the traffic light turned red. The length of the area was about 10 meters and afterwards, the pedestrian had to return to his starting point. In total he walked about 25 m, which took 16.67 seconds at a speed of 1.5 m/s. During these 16.67 seconds 10 persons entered the area, leading to one pedestrian per 1.5 second. For the admission of a pedestrian, the traffic light was green during 0.5 second and red during 1.0 second.

The admission of a group of pedestrians took somewhat less than 20 seconds. Then, the situation needed to be stable. In total this took one minute, so 60 seconds after the first pedestrian of the preceding group joined the area, the first pedestrian of the next group was admitted, followed by the rest of the group. Because of the presence of eight groups, it took 720 seconds until all pedestrians had joined the experiment. At this moment, the maximum density was reached and the situation was stabilised during 120 seconds. As a next step, the density was decreased by removing groups one by one from the area, in the same order as they entered the area. Removing all groups from the area also took 720 seconds, so the total duration of the experiment was $2 * 720 + 120 = 1560$ seconds = 26 minutes. In some experiments two groups were added at the same time. These experiments therefore took less time ($4 * 60 + 120 + 4 * 60 = 600$ seconds).

6. Preliminary results for narrow bottleneck experiment

Until now, we have only elaborated one of the experiments: experiment number 10 with the narrow bottleneck. Since traffic demand exceeded the capacity of the narrow bottleneck, congestion occurred during the experiment. Thus, also part of the congested branch of the fundamental diagram can be determined from these data.

The data used in this section consist of trajectories of individual pedestrians that have been determined from digital video. The trajectories of each pedestrian are described with an accuracy of 0.02 cm at each 0.1 s. Each pedestrian has a unique ID. The velocities of the pedestrians are thus easily determined from the trajectory information. Hoogendoorn and Daamen (2002) give more information on the conversion of the video data into data.

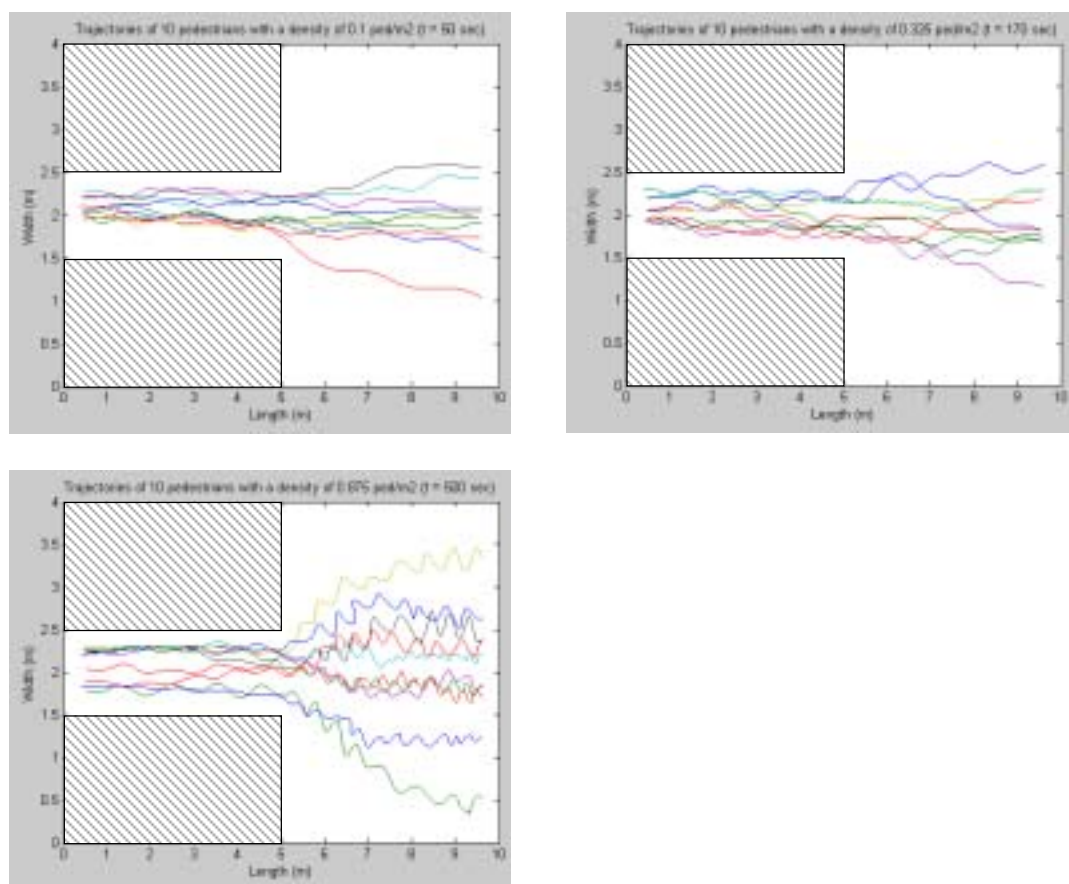


Figure 4a-c. Example trajectories of pedestrians for three different moments (narrow bottleneck experiment). Pedestrians walk from right ($x = 10$ m) to left ($x = 0$ m).

6.1 Microscopic pedestrian characteristics

Figure 4 shows the trajectories of 10 pedestrians for varying traffic conditions. The time dimension has hereby omitted for the clearness of the pictures. Figure 4a shows trajectories in case the density is low and pedestrians are free to choose their paths. Figure 4b shows similar results, but in this case, densities are higher, and pedestrians were somewhat restricted in their

freedom of movement. Figure 4c shows trajectories in a congested situation, in which speeds have been dropped and pedestrians have to wait to do a step forward.

Figure 4 also shows that low pedestrian speed reduces the pedestrian's ability to walk in a straight line. Furthermore, the use of the available walking space depends on the prevailing traffic conditions: when traffic conditions deteriorate, more of the available walking space is used.

Figure 4 also shows interesting results inside the narrow bottleneck. It turns out that at low densities, pedestrians tend to walk in the middle of the bottleneck. When density increases, two lanes are formed, implying that the bottleneck space is used more efficiently. Because the bottleneck is narrow (width is 1.0 meter) it is impossible for pedestrians to walk next to each other. Therefore, they start walking diagonally after each other. This can be seen in the trajectories at high density, when two paths can be distinguished in the bottleneck.

Let us also consider the free (or desired) speeds of the pedestrians. We assume that pedestrians walk at their free speed when not hindered by other pedestrians, i.e. when densities are very small. Having recorded all pedestrian speeds at densities lower than 0.05 P/m^2 , the histogram of these free speeds is shown in Figure 5. The minimum free speed we measured is 0.86 m/s , the maximum free speed is 2.18 m/s . The mean speed is 1.58 m/s . These results are comparable to earlier results of other researches.

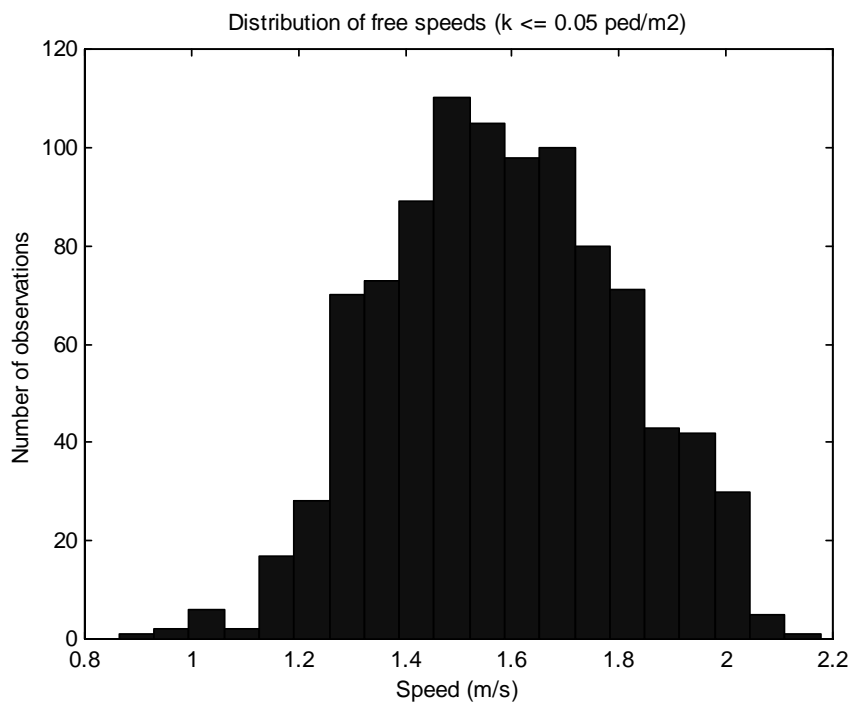


Figure 5. Pedestrian free speed distribution for narrow bottleneck experiment.

6.2 Macroscopic flow characteristics

This section discusses another way of showing the distribution of pedestrians over the walking area, namely by considering densities. To determine the densities, new calculation approaches to determine two-dimensional flow characteristics have been elaborated. More

specifically, the generalised definitions of flow, density, and speed of Edie were adapted to suit analysis of two-dimensional traffic flows (Edie, 1963).

Generalised definition of macroscopic variables

Before continuing, let us briefly describe the approach. We consider a small, three-dimensional cell C with dimensions $X \times Y \times T$. For all pedestrian trajectories passing through the cell, we determine three quantities, namely:

1. The travel time $0 < TT_i \leq T$ defined by the duration pedestrian i is in cell $X \times Y \times T$;
2. The travelled distance $0 < D_i \leq X$ in the x -direction, defined by the distance pedestrian i walks in the x direction during his stay in cell $X \times Y \times T$;
3. The travelled distance $0 < Z_i \leq X$ in the y -direction, defined by the distance pedestrian i walks in the y direction during his stay in cell $X \times Y \times T$

From these quantities, the generalised definition of density and flow in the x and y direction are given by the following equations:

Generalised definition of density k (in P/m²):

$$k = \frac{\sum_{i \in C} TT_i}{XYT} \quad (3)$$

Generalised definition of flow in x and y direction respectively (in P/ms)

$$q_x = \frac{\sum_{i \in C} D_i}{XYT} \quad \text{and} \quad q_y = \frac{\sum_{i \in C} Z_i}{XYT} \quad (4)$$

Similar to the one-dimensional definition of Edie, it can be easily shown that upon taking the limit $T \downarrow 0$ (implying $TT_i = T$), the generalised definition of the density k yields the classical (instantaneous) definition of the density:

$$k = \frac{\sum_{i \in C} TT_i}{XYT} \stackrel{TT_i=T}{=} \frac{nT}{XYT} = \frac{n}{XY} \quad (5)$$

where n equals the number of pedestrians on area $X \times Y$ at a certain time instant; the same holds for the generalised flow definitions q_x and q_y for taking the limit $X \downarrow 0$ and $Y \downarrow 0$ respectively.

Furthermore, the pedestrian speeds in x and y directions can be determined from the definitions easily as follows:

$$v_x = \frac{q_x}{k} = \frac{\sum_{i \in C} D_i}{\sum_{i \in C} TT_i} \quad \text{and} \quad v_y = \frac{q_y}{k} = \frac{\sum_{i \in C} Z_i}{\sum_{i \in C} TT_i} \quad (6)$$

Distribution of density and speed over walking area

Figure 6 shows overviews of densities and speeds in the x direction for three different moments. The area has been divided into rectangles of 0.5 m length and 0.25 m width. For each rectangle, average density and mean speed have been determined for periods of 2 minutes using the generalised approach discussed in the previous section.

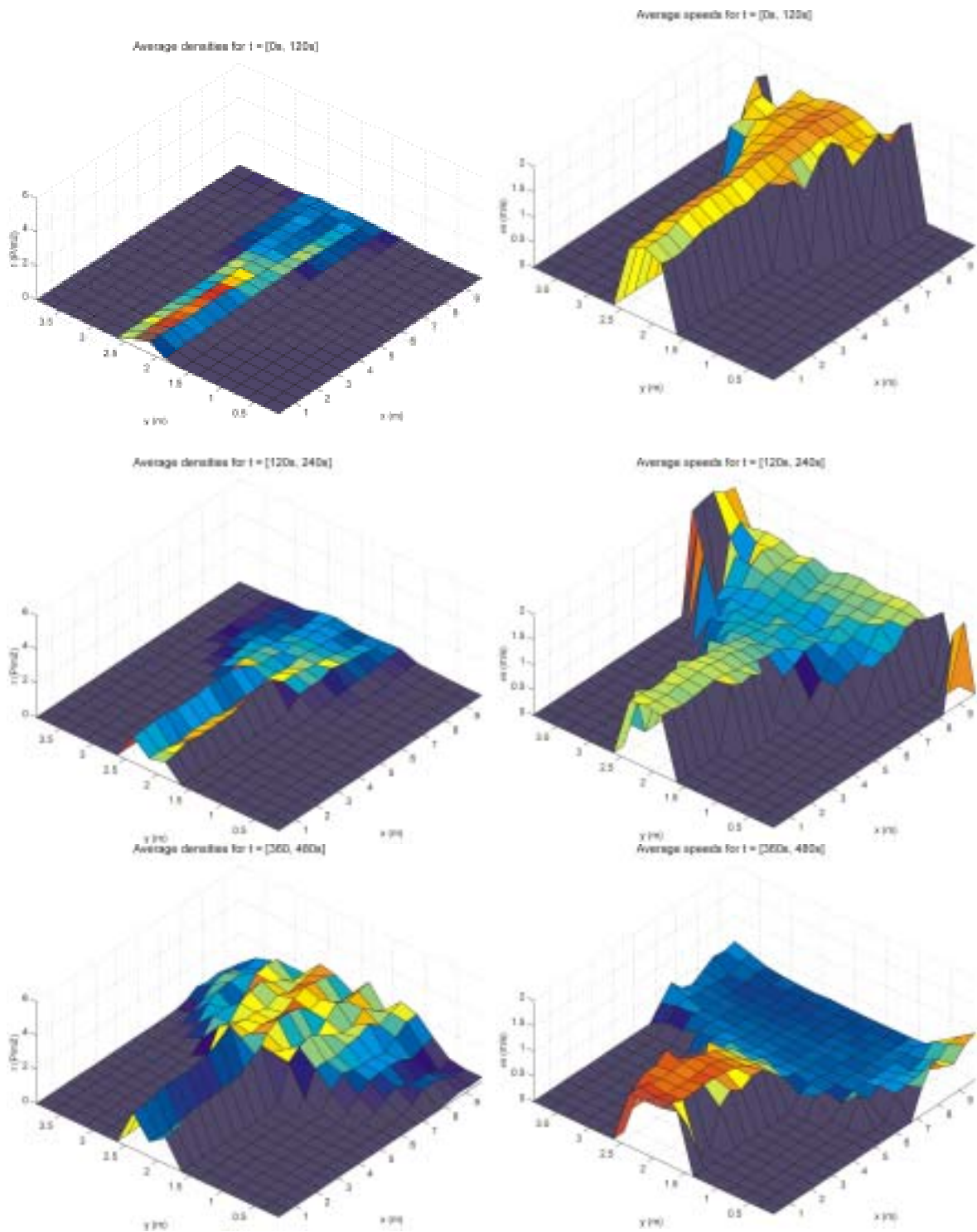


Figure 6 a-f. Densities and mean speeds (in x direction) for narrow bottleneck example for different time periods during the experiment. Pedestrians walk from right ($x = 10$ m) to left ($x = 0$ m).

In the first period, we see low densities and relatively high speeds (free speeds). The figure clearly shows how only a small portion of the walking area is used. In the second period [120 s, 240 s], about half of the groups have entered the area. 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.

In the period [360 s, 480 s], congestion is present upstream of the bottleneck. We also observe that a larger portion of the walking area upstream of the bottleneck is used. The used walkway width increases with the distance to the bottleneck. Density rises to 2.5 P/m^2 , while the mean speed in the bottleneck is around 1 m/s . The mean speed upstream of the bottleneck has decreased to about 0.3 m/s .

Fundamental diagrams

This final section discusses the relation between density, flow, and speed for the narrow bottleneck experiment. To this end, we have again applied the generalised Edie definition to determine average densities, flows, and speeds for each individual square XY . We have chosen $X = Y = 0.5 \text{ m}$, and $T = 20 \text{ s}$.

Figure 7 depicts the three fundamental relations. Each dot is an observation in a square XY during a time period T . Note that in each of the different diagrams, two distinct sets of points can be distinguished. Further inspection revealed that one set reflects the flow conditions inside the bottleneck, whereas the other set reflects the conditions upstream of the bottleneck. In the bottleneck, both densities and flows are high, while the speeds are approximately 1 m/s . On the contrary, in the congested region upstream of the bottleneck, densities are high and flows are low. The speeds are also low (approximate 0.3 m/s). The capacity of the bottleneck is approximately 1.5 P/ms . The flows upstream of the bottleneck are approximately 0.38 m/s ($1/4$ of the capacity). This suggests that the pedestrians use the entire width of the area efficiently during congested flow operations.

Note finally that the densities inside the bottleneck appear higher than the maximum densities upstream of the bottleneck, contrary to what would be expected from shockwave theory. In part, this can be explained by the discretisation of the area in $0.5 \text{ m} \times 0.5 \text{ m}$ cells: a cell may be occupied by a single pedestrian, whose speed is low as a result of pedestrians in downstream cells. In that case, the pedestrian speed is low, while the density is also low. Also, pedestrians are waiting to walk into the bottleneck. While they are waiting, they try to maintain their level of comfort by keeping distance to other pedestrians, thus not increasing the (local) density. This is possible, because the time it takes to reach the bottleneck is independent of the distance between the pedestrians (pedestrians close to each other do not come faster in the bottleneck than pedestrians maintaining some distance). This observation has important implications for the applicability of a single speed – density diagram to describe pedestrian traffic flows.

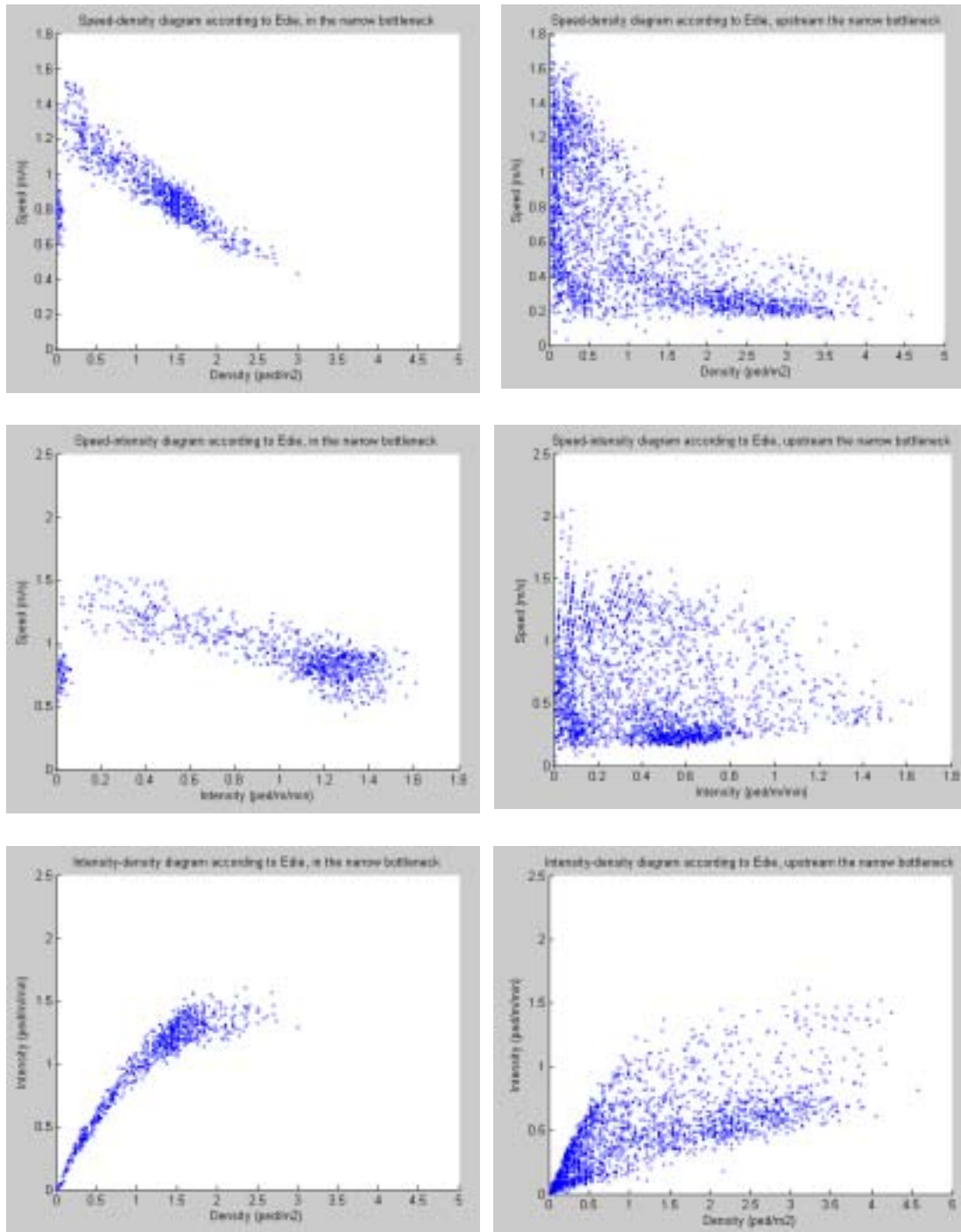


Figure 7a-f. Fundamental diagrams in (left) and upstream (right) of the narrow bottleneck.

7. Conclusions

This contribution presented experimental research to study microscopic and macroscopic pedestrian flow characteristics. The paper discussed the experimental design, given the identification of the process variables of interest. In the end, four experimental variables were considered, namely free speed, walking direction, density, and the effect of bottlenecks. To study the experimental variables and their effect on walking behaviour and flow characteristics, 10 walking experiments were prepared and carried out.

Approximately 80 pedestrians participated in the experiments. In order to manage the experiments, the pedestrians were divided into 8 groups of which the group leader received instructions how the group members had to behave. The pedestrians entered the experimental area gradually, using dedicated traffic signals.

The pedestrians were observed using a digital video camera mounted at the ceiling of the hall in which the experiments were carried out. The resulting video footage was analysed using specially designed pedestrian detection and tracking software, yielding detailed microscopic pedestrian data (i.e. pedestrian trajectories).

Considering the narrow bottleneck situation only, it was found that during near-capacity and capacity flow situations, the bottleneck is used differently than in case of free flow conditions. While at free-flow conditions, pedestrians will walk in the centre of the bottleneck, thereby maximising the distance between themselves and the walls. During capacity conditions, two trails or lanes are formed: pedestrians tend to walk diagonally behind each other, thereby reducing the headway and thus maximising the use of the infrastructure supply. Another interesting result pertains to the use of the available space in case of congestion. It turns out that only a small amount of the width is used at the location of the bottleneck (namely, the width of the bottleneck itself). Further upstream, the pedestrian stream ‘spreads out’ covering more or less the entire available width.

Future research is aimed at further analysing the wealth of data that has been collected for the other experiments. To this end, new approaches to data analysis applicable to two-dimensional flows are deemed necessary. When data analysis is finished, the research findings will serve as a basis for model calibration and validation, as well as new theories regarding the behaviour of crowds and the pedestrians of which they consists.

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