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Experimental Research of Pedestrian Walking Behavior

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Abstract. 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 is 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 the 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.

INTRODUCTION

The traditional way of designing transfer stations is based on rules of thumb. These rules convey experience concerning the behavior 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, or 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 traveler's comfort and the timetable's reliability.

To support the design and planning process, Delft University of Technology, in association with Holland Railconsult, has developed the simulation tool SimPed to estimate both mean and variability of walking times incurred by transferring passengers and to visualize walking patterns inside transfer stations and other pedestrian areas [*1*]. Also, the microscopic simulation model NOMAD has been developed, which predicts pedestrian behavior in general walking facilities using microscopic behavioral rules [*2*].

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 behavior exist and most of these data sets have been gathered in Asia (Japan, Hong Kong [*3*]). However, pedestrian characteristics in Asia differ significantly from those of Western European pedestrians (for example pedestrian figure, 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 behavior. 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 organizing walking behavior 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 behavior 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 [*4*].

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.

STATE OF THE ART OF EMPIRICAL RESEARCH ON PEDESTRIAN BEHAVIOR

This section presents a very brief (and therefore non-exhaustive) overview of some of the empirical facts regarding pedestrian walking behavior 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-organization, and cooperation between pedestrians.

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. Weidmann [*5*] 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. 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

$$A(V) = A_{jam} - 0.52 \ln\left(1 - \frac{V}{V_f}\right) \tag{1.1}$$

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 ($A_{jam} \approx 0.19$ m^2). Note this relation implicitly defines the speed density relation presented in [*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* [*6*]. 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%; see [*5*]). 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 [*7*], albeit in the form of strips or moving clusters composed of pedestrians walking in the same direction.

Walking behavior and interaction

Goffman [*8*] describes how the environment of the pedestrian is observed through a mostly subconscious process called *scanning* in order to sidestep small obstructions on the flooring. Golson and Dabbs [*9*] observe that women spend more time scanning the sidewalk than men. Wolff [*10*] argues that a *high degree of cooperation between pedestrians* is an intrinsic part of pedestrian behavior, without which walking would be impossible: pedestrians expect others to be cooperative 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.

Wolff [*10*] 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 cooperates*. Nevertheless, even when the step-and-slide movement is correctly executed by both pedestrians, some body contact may occur. Experimental studies of Sobel and Lillith [*11*] 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 cooperate.

Dabbs and Stokes [*12*] have studied the extent in which pedestrian *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. On the contrary, Sobel and Lillith [*11*] observed that woman are often granted more room than men. Willis *et al*. [*13*] suggested that power may not be so 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; women do not tend to move for men, nor do blacks tend to move for whites. They indicated that besides power, and gallantry, also maneuverability may play a decisive role.

RESEARCH OBJECTIVES

We have already discussed the importance of gaining more insight 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 process variables (or factors) are deliberately changed in order to observe the effect the changes have on one or more response variables. We begin with determining the objectives of an experiment and selecting the process factors for the study. Well-chosen experimental designs maximize 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 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.

The aim of this experimental research on pedestrian behavior is also gaining insight in the relation between several process variables and depending variables describing the process. Both the behavior of the individual pedestrian (microscopic) as the behavior of pedestrian flows are 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.

ESTABLISHING PROCESS VARIABLES

Process variables include both inputs and outputs - i.e., factors and responses. The selection of these variables is best done as a team effort. The team should

- Include all relevant factors (based on engineering judgment).
- Be bold, but not foolish, in choosing the low and high factor levels.
- Check the factor settings for impractical or impossible combinations - i.e., very low pressure and very high gas 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.

Brainstorm process variables

To determine the (relevant) process variables, we set up a brainstorm session, in which several experts have been invited. During the brainstorm we created a list of all variables, which we thought would have some influence on the process:

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

The ranges 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 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 twelve.

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 free 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 flows in these circumstances. It seems reasonable to use percentages of 5%, 25%, 50%, 75% en 95% in this research.

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.

Choice of process parameters

Over all, seven process variables have been distinguished. When we combine these variables in all possible ways, 54000 experiments are possible. This is impossible for one day, so the number of process 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 process variables are:

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

Also, ranges of values process variables can have are restricted.

Free speed

- Normal situation (100% normal speed).
- Stations with hurried pedestrians (60% normal speed, 40% high speed; pedestrians are told they are in a hurry to catch a train).
- Shopping environments with window-shoppers (40% low speed, 60% normal speed; pedestrians are told they walk quietly, to behave as if they are walking in a shopping area).

Walking directions

- One-directional flow (100% direction west – east).
- Equal two directional flow (50% direction west – east, 50% direction east – west).
- Unequal two directional flow (90% direction west – east, 10% direction east – west).
- Equal crossing flows (50% direction west – east, 50% direction north - south).
- Unequal crossing flows (90% direction west – east, 10% direction north – south).
- Equal four directional flows (25% direction west – east, 25% direction east – west, 25% direction birth – south, 25% direction south – north).

Bottlenecks

- No bottlenecks.
- One large bottleneck with a width of 2 meters.
- One small bottleneck with a width of 1 meter.

The density varies between an almost empty area and a fully occupied area. The density is then measured in a percentage, where 0% indicates the 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, the density is increased by adding new groups of pedestrians. 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 around 12.5%, 25%, 37.5%, 50%, 62.5%, 75%, 87.5% and 100%.

Determining the final experiments

An important aid for the final determination of the experiments is the 'analysis matrix'. This matrix describes the experiments in a structured way. The columns of the matrix contain the different process variables, while the rows describe the different experiments. Each cell contains the value of the variable. Combining these variables leads to the different experiments, which are then given a priority value.

Variables playing a part in the determination of the experiments are free speed, direction, density and bottlenecks. Three out of four variables are constant during an experiment, while the density can be varied by adding and removing groups of pedestrian. The following analysis matrix therefore only contains the 'fixed' variables (free speed, direction and bottlenecks) during the experiment. This leads to 54 (= 3 * 6 * 3) experiments.

However, it is not possible to use bottlenecks when pedestrian flows have more directions. Experiments with conflicting parameter values are therefore removed. Even after removing these 'conflicting' experiments, 36 experiments have left. Therefore, additional priorities have been set:

- Different free speeds of pedestrians are only relevant in the one-directional flow without bottlenecks. In this basic variant the influences of these free speeds are determinant and can later be added in the rest of the experiments.
- The first variant (all pedestrians keep normal free speed, one directional flow and no bottlenecks) will be the 'basic' variant. To compare the influence of the process variables, only one of the variables will deviate from the values in the basic variant.

Application of these additional priorities leads to the final experiments indicated by Table 1. Figure 1 provides a graphical overview of the experiments, where the arrows indicate the pedestrian flows; the dashed arrows show the directions in which pedestrians will return towards their starting point or the starting point of another flow. For the experiments, two areas are used: a rectangular area (10 meters × 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 × 8 meters. The areas valid for each experiment are indicated by the thick lines in Figure 1.

CARRYING OUT THE EXPERIMENTS

The walking experiments were conducted in a large hallway in the faculty building of Civil Engineering in Delft, the Netherlands. The number of pedestrians for the morning experiments was 60, while 80 pedestrians took part in the evening experiments. In the morning, 56.7% of the participants was female; in the evening, this percentage decreased to 52.5%. the pedestrians have been divided into three age categories: young persons (< 20 years), middle aged (20 – 65 years) and seniors (>= 65 years). In the morning, the division of pedestrians over the groups was: 6.7% young persons, 85.4% middle aged and 8.9% seniors. In the evening, more young persons and less seniors were present: 12.0% students, 84.6% middle aged and 3.4% seniors.

Statistics on the Dutch population reveal that it consists for 49.5% of men and 50.5% of women. Furthermore, 24.4% of the population is under 20 years, 62.0% is middle-aged (20 – 65 years old) and 13.6% is senior (>= 65 years) [*14*]. The group lacking in our experiments are 'children' under 18. The percentage of seniors is less in our experiments than in Dutch practice, but when we lower the age barrier to 60 years, the morning percentage is 28.4%, meaning that we have a significant number of pedestrians between 60 and 65 years old. The simulation models we developed are especially used for peak hours in transfer stations, when less juveniles and less seniors are present. For station circumstances, our experiments are thus representative.

Due to the fact that it is impossible to manage all these pedestrians at the same time, groups were formed. A group leader was assigned to each group. This group leader has been informed in advance of the experiments. This group leader is then responsible for the pedestrians in his group and among others takes care of the right moment his group can join the experiment.

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 behavior 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.

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 stabilized during two minutes, after which a group left the experiment. After the removal of a group, the situation was stabilized 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. For the admission of a pedestrian, the traffic light was green during 0.5 second and red during 1.0 second. The first time a pedestrian enters the area (he starts being part of the experiment), his starting position is a standstill. Afterwards, the pedestrian continues walking and enters the area while walking.

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 could be admitted, followed by the rest of the group. Because of the presence of eight groups, it took 480 seconds until all pedestrians joined the experiment. At this moment, the maximum density was reached and the situation was stabilized 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 480 seconds, so the total duration of the experiment was 2 * 480 + 120 = 1080 seconds = 18 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 = 10 minutes).

PRELIMINARY RESULTS FOR NARROW BOTTLENECK EXPERIMENT

All experiments took place on Thursday May 17th and video data were collected for all described experiments. Until now, we have only analyzed the data of one of the experiments: experiment number 10 with the narrow bottleneck. In this experiment, all pedestrians walked from the right to the left (one directional flow) with a normal walking speed. On the left, a small bottleneck (width = 1.0 m) is situated. 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 consists of trajectories of individual pedestrians that were determined from digital video. The trajectories of each pedestrian are described at a resolution 0.02 cm per 0.1 s. Each pedestrian has a unique ID. The velocities of the pedestrians are thus easily determined from the trajectory information. More information on the conversion of the video data into data can be found in [*4*].

Microscopic pedestrian characteristics

Figure 2 shows the trajectories of 10 pedestrians for varying traffic conditions. To make the deviations of the straight line of the pedestrians more clear, the y-axis is scaled differently from the x-axis. The time dimension has hereby omitted for the clearness of the pictures. Figure 2a shows trajectories in case the density is low and pedestrians are free to choose their paths. The trajectories shown are from 10 successive pedestrians, when the situation in the current density was stable. Figure 2b shows similar results, but in this case, densities are higher, and pedestrians were somewhat restricted in their freedom of movement. Figure 2c shows trajectories in a congested situation, in which speeds have dropped and pedestrians have to wait to do a step forward.

Figure 2 shows that low pedestrian speed reduces the pedestrian's the 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 in used.

Figure 2 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 however 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 ped/m^2, the histogram of these free speeds is shown in Figure 3. 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.

Macroscopic flow characteristics

This section discusses another way of showing the distribution of pedestrians over the walking area, namely by considering the densities. To determine the densities, new calculation approaches to determine two-dimensional flow characteristics have been determined. More specifically, the generalized definitions of flow, density, and speed of Edie [*15*] were adapted to suit analysis of two-dimensional traffic flows.

Generalized 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 traveled 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 traveled 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 generalized definition of density and flow in the x and y direction are given by the following equations:

Generalized definition of density k (in P/m^2):

$$k = \frac{\sum_{i \in C} TT_i}{XYT} \tag{1.2}$$

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

$$q_x = \frac{\sum_{i \in C} D_i}{XYT} \text{ and } q_y = \frac{\sum_{i \in C} Z_i}{XYT} \tag{1.3}$$

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 generalized definition of the density k yields the classical (instantaneous) definition of the density:

$$k = \frac{\sum_{i \in C} TT_i}{XYT} \overset{TT_i = T}{=} \frac{nT}{XYT} = \frac{n}{XY} \tag{1.4}$$

where n equals the number of pedestrians on area $X \times Y$ at a certain time instant; the same holds for the generalized 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:

$$v_x = \frac{q_x}{k} = \frac{\sum_{i \in C} D_i}{\sum_{i \in C} TT_i} \text{ and } v_y = \frac{q_y}{k} = \frac{\sum_{i \in C} Z_i}{\sum_{i \in C} TT_i} \tag{1.5}$$

Distribution of density and speed over walking area

Figure 4 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 generalized approach discussed in the previous section.

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 ped/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 generalized Edie definition to determine average densities, flows, and speeds. We have chosen $X = Y = 0.5$ m, and $T = 60$ s.

Figure 5 depicts the three fundamental relations. 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 (¼ 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 are higher that the densities upstream of the bottleneck, contrary to what would be expected from shockwave theory. In part, this can be explained by the discretization of the area in 1 m × 1 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.

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 process variables were considered, namely free-speed, walking direction, density, and the effect of bottlenecks. To study the process variables and their effect on walking behavior and flow characteristics, 10 walking experiments were prepared and carried out.

Approximately 80 pedestrians participated in the experiment. 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 building in which the experiments were carried out. The resulting video footage was analyzed using specially designed pedestrian detection and tracking software, yielding detailed microscopic pedestrian data (i.e. pedestrian trajectories).

Although a full description of the results is beyond the scope of this paper, several interesting preliminary results were found. Having considered 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 center of the bottleneck, thereby maximizing 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 headways and thus maximizing 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 analyzing 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 behavior of crowds and the pedestrians of which they consist.

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FIGURES AND TABLES

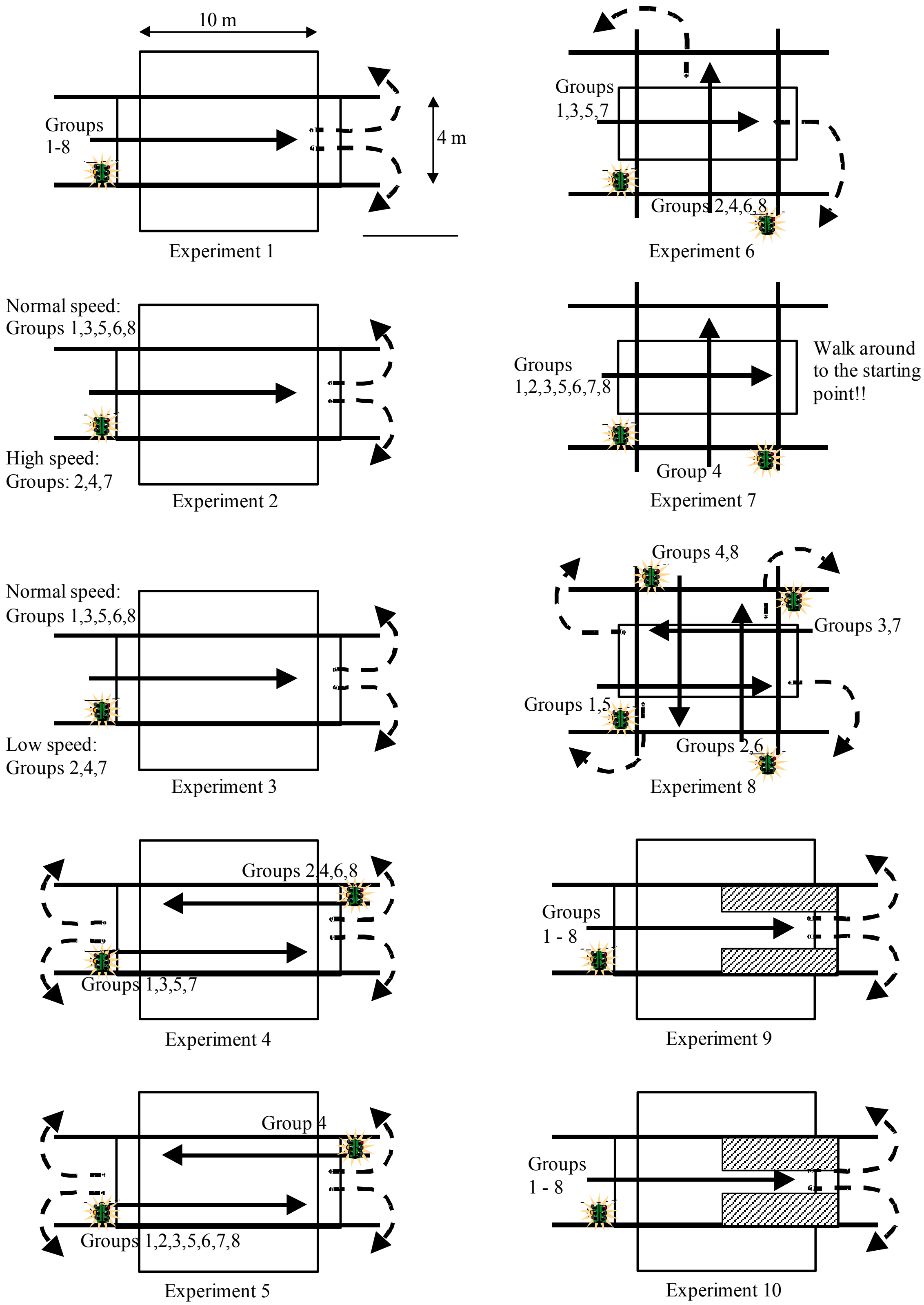

Figure 1 Overview of experiments.

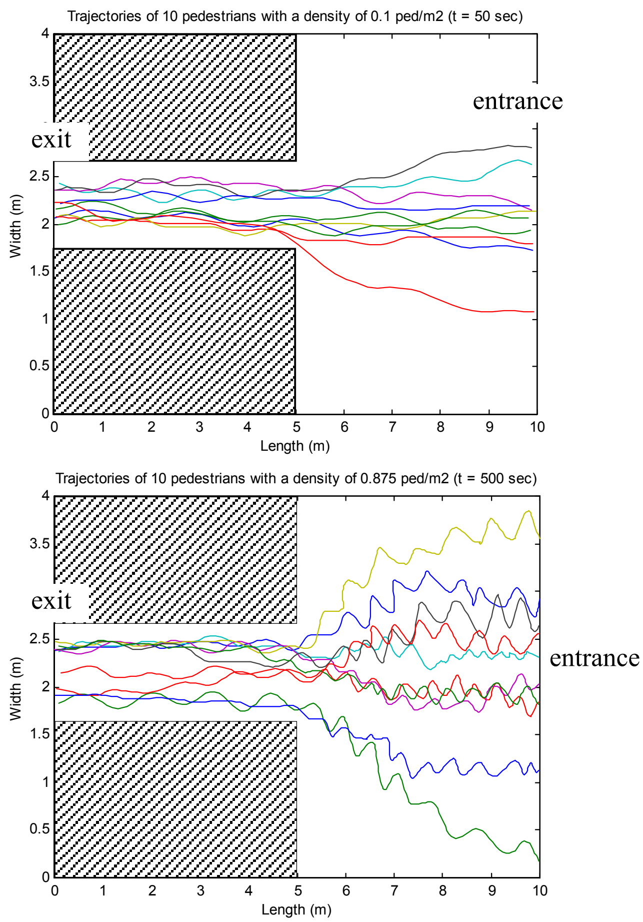

Figure 2a-c Example trajectories of pedestrians for three different situations (a : density = 0.1 P/m^2; b : density = 0.325 P/m^2; c : density = 0.875 P/m^2). Pedestrians walk from right (x = 10 m) to left (x = 0 m).

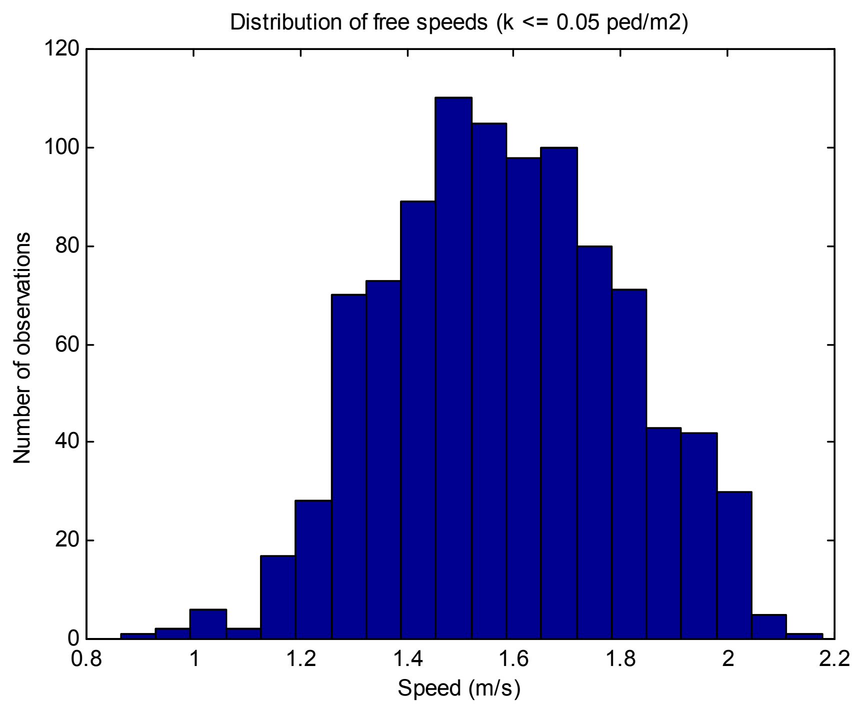

Figure 3 Pedestrian free speed distribution for narrow bottleneck experiment.

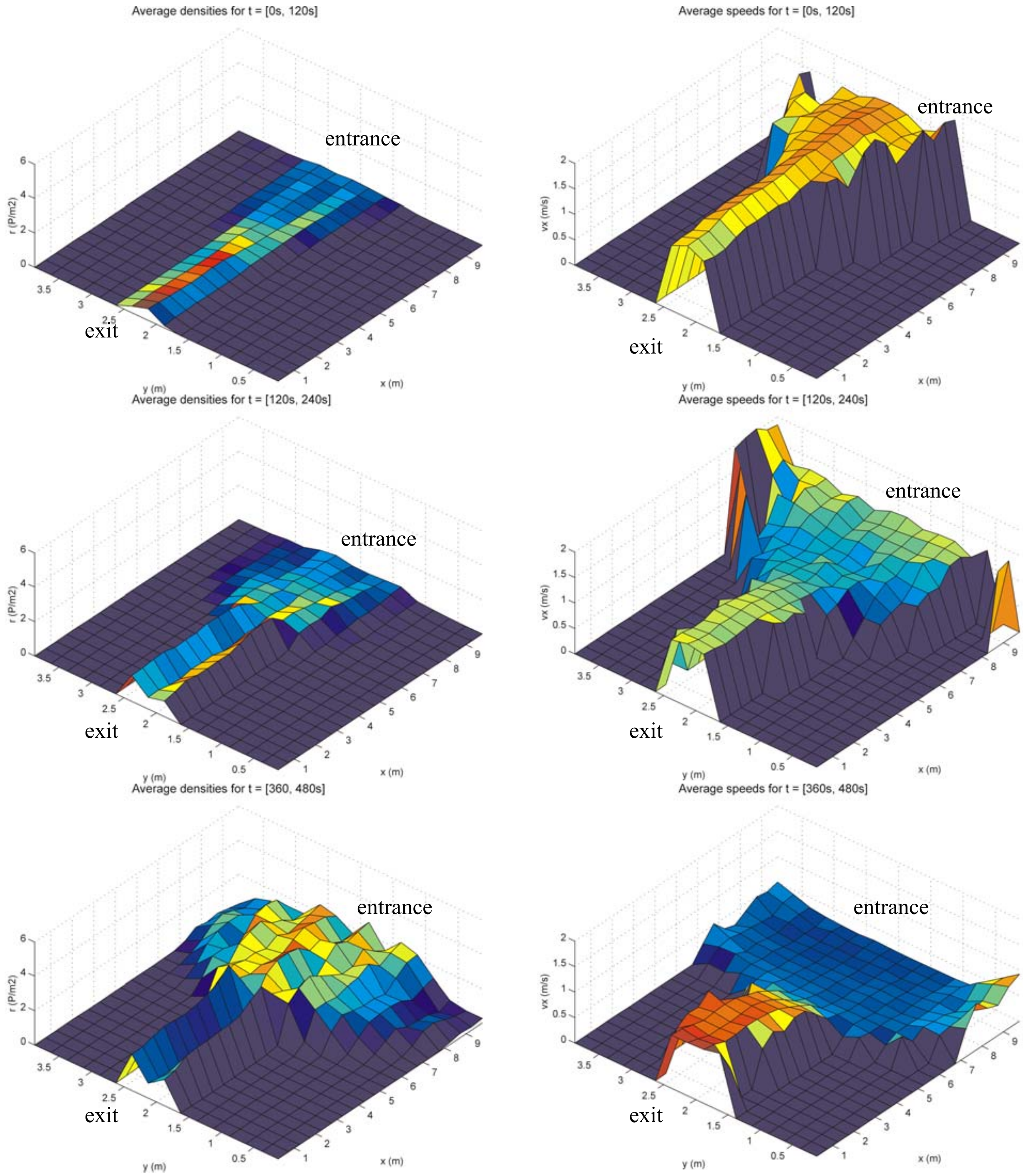

Figure 4a-f Densities and mean speeds (in *x* direction) for narrow bottleneck example for different time periods during the experiment. Pedestrians walk from right (x = 10 m) to left (x = 0 m).

Daamen, W, & Hoogendoorn, SP (2003). Experimental research of pedestrian walking behaviour, Transportation Research Record 1828, pp. 20-30.

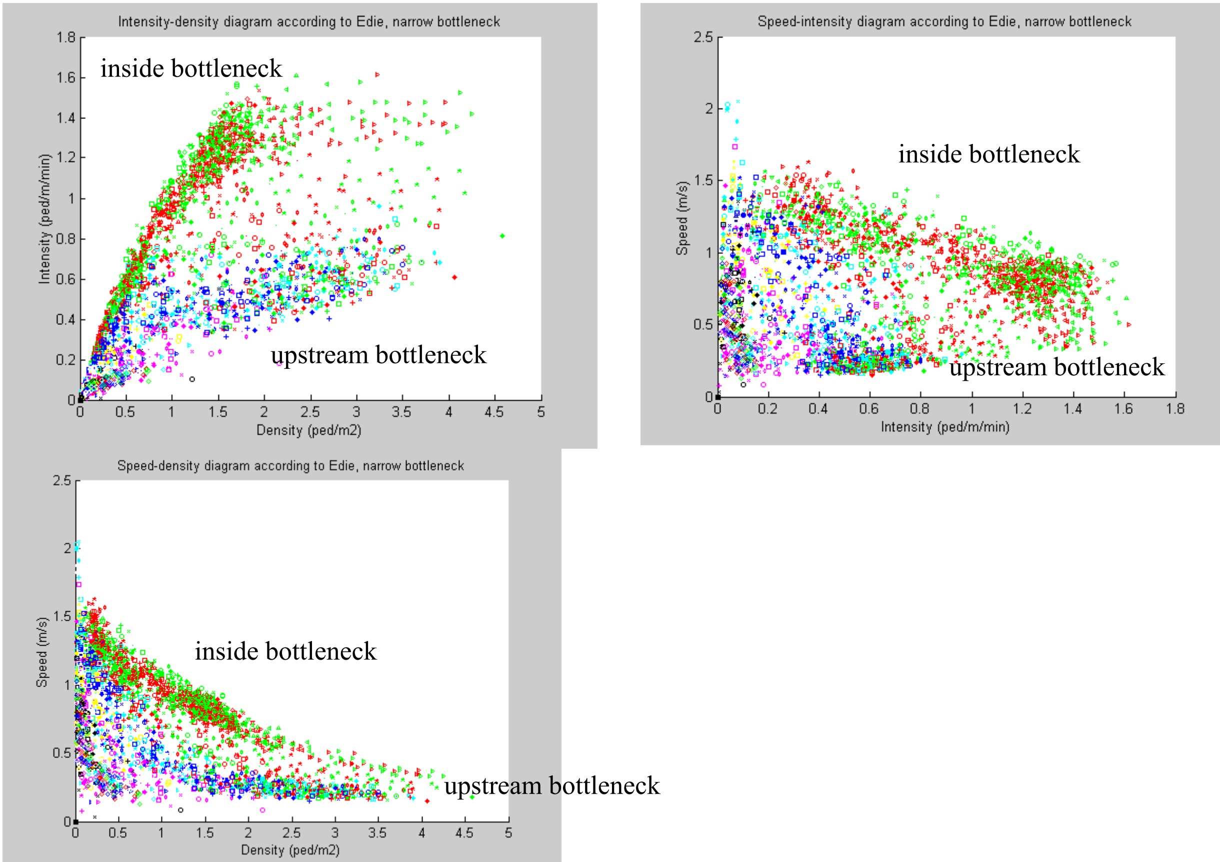

Figure 5a-c Fundamental diagrams for narrow bottleneck experiment.

Daamen, W, & Hoogendoorn, SP (2003). Experimental research of pedestrian walking behaviour, Transportation Research Record 1828, pp. 20-30.

Table 1 Overview of considered experiments.

Experiment	Free speed			Direction						Bottlenecks		
	A	B	C	A	B	C	D	E	F	A	B	C
1	X			X						X		
2		X		X						X		
3			X	X						X		
4	X				X					X		
5	X					X				X		
6	X						X			X		
7	X							X		X		
8	X								X	X		
9	X			X							X	
10	X			X								X