Study of movement on stairs during evacuation using video analysing techniques

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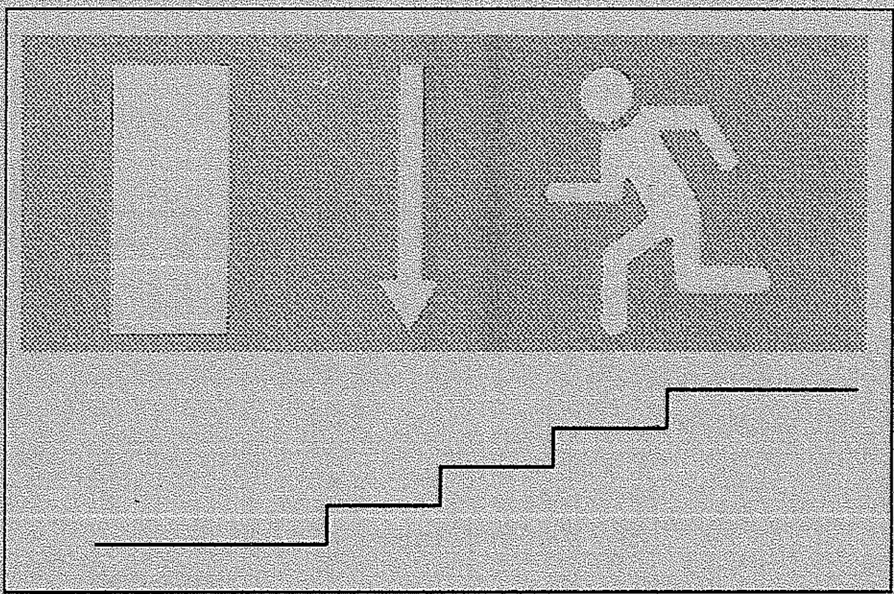

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Summary

The present report investigates the velocity of people on stairs using experiments. The purpose of the study is to derive design values for the walking velocities for people moving up or down a stair. This study presents the data as a function of the interperson distance between people on the stair. The interperson distance is the distance between the centres of bodies, seen from above, in the route. Traditionally the velocity assessment of people moving on stairs is based on a function of the population density in the passage. This measure makes it somewhat difficult to use the data presented by other researchers, as it forces the designer to choose a population density. This chosen density may then not be valid in the real case as the circumstances change with time.

New computer software make it possible to assess the velocity using the interperson distance. It is now possible to model the dynamics of the evacuation process. Data from other studies can be translated to fit this new approach which makes the suggested design parameter more robust.

The experiments were conducted using students as test persons. The students walked on different types of stairs and the sequences were videofilmed. The film was then analysed using a software developed for this purpose. The resulting data can be saved on a standard spreadsheet format.

The results indicate a constant velocity, independent of the interperson distance above a certain distance. Below this point the velocity decreases rapidly to zero. The relationship between the velocity and the interperson distance is very similar to a stepfunction. The design velocities for stairs were derived for movement both up and down staircases. The mean velocity upstairs was 0.55 m/s until the breakpoint in interperson distance was reached. The velocity downstairs was 0.7 m/s until the same breakpoint in interperson distance was attained.

The velocity for spiral stairs was also measured and a design value was derived as 0.55 m/s for downstairs movement. No measurements were made for upstairs movement on spiral stairs. As the movement pattern is very different on spiral stairs compared to straight stairs a decrease in velocity was not observed. On spiral stairs the people are moving after eachother in a line, which is not the condition on straight staircases. If the interperson distance decreases on spiral stairs the probability of falling increases and therefore only a few observations were made at low interperson distances. The presented

design value for spiral stairs is valid until an interperson distance of 0.7 m. Shorter distances are not likely to occur. Instead a crowd will form on the landing before the staircase.

Foreword

This work is part of a project with the objective of deriving means for the planning of escape routes in buildings. The two other parts composing this project cover areas of both basic fundamental research and technical implementation of existing and new knowledge from the remaining parts of the project. The three parts are

- Deriving data on movement on stairs (this report)
- Studying human behaviour related to choosing escape route (Benthorn et al, 1996)
- Producing an escape model for design purposes (not published)

The main outcome of the project from the designers point of view is the evacuation model, Simulex. This is the result from the third part. The necessary information for calculations in the model is provided from the two first parts. From a scientific point of view the two first parts will also provide new information to be used for other purposes.

The work on this project has been carried out by researchers at Lund University (parts 1 and 2) and at the University of Edinburgh (part 3). Project coordinator has been MSc Robert Jönsson at Lund University.

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1 Introduction

1.1 Design methods available

In designing the evacuation routes in a building, at least two methods are available, Frantzich, 1994. These design methods are

- simple handbook method
- analytical method.

When using the first of these, the designer only uses tables handbooks to find out the required widths and walking distances which are stipulated in the national building code. This method is very simple to use. The only thing the designer has to know is more or less the intended use of the building. The designer does not have to know very much about evacuation behaviour of people subjected to a fire situation. Using the second method, the designer compares the evacuation time with the time to reach untenable conditions in the escape route. It is then possible to choose different design alternatives in deriving safe escape routes. This method is usually referred to as an analytical method. The second method is increasingly being used in designing complex buildings where there are major drawbacks in using a simple handbook method.

It should be stated that neither method is better than the other in all cases. Both methods have their advantages and disadvantages. It has to be the designer who makes the choice which method he/she wants to use. The handbook-method is simple to use and costs little in design time. This makes it an inexpensive method in the design phase of the building project. The flexibility is however limited. To arrive at a design solution that avoids expensive design or is oversafe, the analytical method could be used. The design cost is probably higher but the total cost of the evacuation system might be lower, or at least the building owner will have a more tailormade system. The need for information on the evacuation behaviour is usually higher for the designer when he/she decides to use the analytical method.

1.2 The evacuation process

The events in an evacuation process take time, and the less time evacuation takes, the less a person is exposed to the consequences of fire in the form of toxic gases, heat etc. The evacuation process is continuous with new impulses, and new decisions being taken on the course of action. Using the analytical method of design, with engineering based calculation methods, this process has to be simplified. One way of simplifying the process, in a way which is acceptable from an engineering point of view, is to regard the process as taking place in three phases:

- awareness or detection
- behaviour and response
- movement.

The time elapsed in each phase can be calculated, with assumptions based on the fact that there are interactions between the phases as in a real evacuation. The sum of the durations of each phase must be less than the time taken to reach a critical situation. This procedure is repeated for every part of the building.

The dimensioning expression is

$$t_a + t_b + t_m < t_{crit} \qquad (1)$$

1.2.1 Awareness

The phase denoted awareness consists of the time elapsed from the start of the fire until the person experiences the external stimulus or signal which tells him or her that something abnormal has happened. The stimulus may be the discovery of the smell of smoke, hearing or seeing the fire, information via an automatic warning system or through another person. In many cases, the awareness time can be long, especially if no automatic warning system is installed.

1.2.2 Behaviour and response

The behaviour and response phase is equivalent to the time elapsed from becoming aware of the situation to taking some action, i.e. movement. Firstly, the signal must be identified and interpreted as something which is not expected. The signal then gives the impulse to take some action, i.e. the person decides to do something. The action chosen may be to investigate what has happened, i.e. seek further information, to try to fight the fire, help others, save material property, call the fire brigade, leave the building or even to ignore the danger. It should be observed that the time elapsed during the behaviour and response phase is often longer than in the awareness and movement phases, which means that it is important to be able to predict and control this phase.

1.2.3 Movement

The final phase of the evacuation process in the model proposed is concerned with an action, leaving the building. The movement time is the sum of the times consumed in walking through the different routes to the final exit. To be able to calculate the movement time it is necessary to know typical walking speeds and crowd behaviour in the various components forming the escape route like stairs, horizontal corridors and doorways. As movement on stairs plays a very important role during evacuation this report will cover some related problems and derive data on walking velocities on stairs.

1.3 Limitations

Users of the material presented in this report should be aware of its limitations. The prediction of walking velocities down stairs can vary quite significantly as shown in the resulting figures. Observations of both high and low velocities were made even if the proposed design value is a constant velocity value.

Also the subjects used in this study presented no physical disabilities. They were also familiar with the experimental position. The designer therefore has to carefully judge whether or not the assumptions can be justified. Using the present information for example in a building designed for the elderly may jeopardize the safety of the occupants. For many other cases the information can be used as design values.

2 Definition of the problem

Stairs are one of the more important components forming an escape route. It is therefore necessary to be able to predict the movement behaviour on stairs as accurately as possible. There have been many investigations performed during the last 30 years with the purpose of collecting data describing the different movement velocities on various kinds of stairs. In Frantzich, 1993 a survey of these previous investigations is made and also identifies that there are some problems to be addressed despite all the previous investigators results. The problems can be divided into separate areas;

- variation in the experimental data
- walking on spiral stairs and
- high population density situations

Because of the shortage of data on movement on stairs during evacuation an experimental study was set up with the purpose to obtain more information about movement on stairs. Studies were made observing people as they moved down or up on the stairs as a function of the interperson distance between the people. Another purpose was to see how the movement behaviour is affected by different circumstances such as the presens of a slower person on the stair. This was done for straight stairs. For spiral stairs the only variable observed was the walking velocity for people descending the staircase.

2.1 Variation in the data

There is a rather large scatter in the results from earlier investigations and there seem to be variations depending on how the results were obtained. This is most obvious when looking at persons moving upstairs. Most evacuation stairs are used as downward communication routes leading down to the ground level. Therefore, most of the investigators have looked at evacuation down stairs with a considerably amount of data as a result. For movement upstairs, however, only a few investigations have been performed and the scatter is therefore more visible and no clear trend is evident.

In recent years more buildings are constructed under ground. These are typically train or underground stations, tunnels or assembly buildings where people have to evacuate up to the ground level. Difficulties then arise in how to choose valid design values for the different parameters controlling the movement. But still, the variability in the existing data is large and more data is needed to obtain a robust prediction of the velocity. Figures 1 and 2 show some results from earlier investigations. The lines indicate the equations derived by the various researchers and the grey area gives an approximate position of where the data points are situated. The darker circle indicates where the majority of the data points are situated. The varying parameter in the figures below are the population density defined as number of persons per square metre. The velocities are presented as slope velocities parallel to the staircase direction. As one can see the lines are extrapolated out from the region where the data points are situated. In section 3 a brief description of some more important investigations is given, also showing the authors original figures with the data. In the figures 1 to 4 the following investigations are presented; Khisty E and Khisty N from Khisty 1985, Pauls 28 and Pauls 32 from Pauls 1995, Fruin from Fruin 1971, Kendik E from Kendik 1984, Galbreath from Galbreath 1969, Togawa from Togawa 1955 and LTB from London Transport Board 1958 and Melinek and Booth 1975.

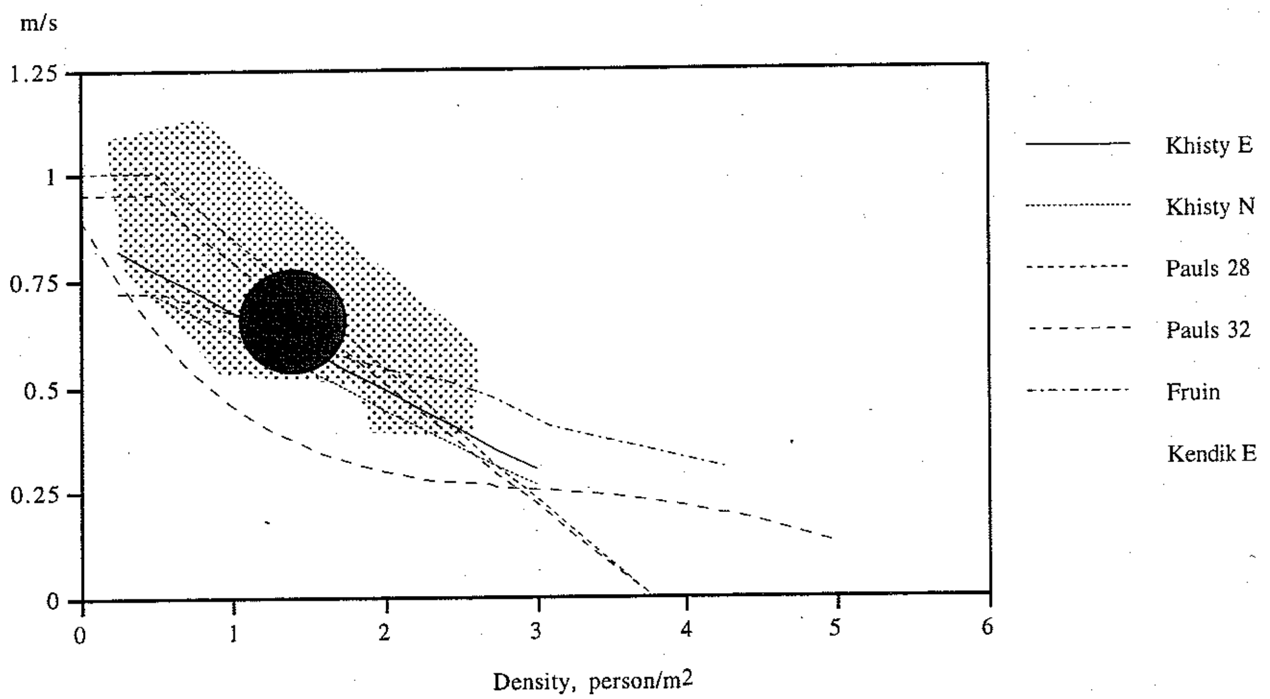

Figure 1. Walking velocity down stairs. In the legend E = Emergency, N = Normal and number indicate the degree of the slope.

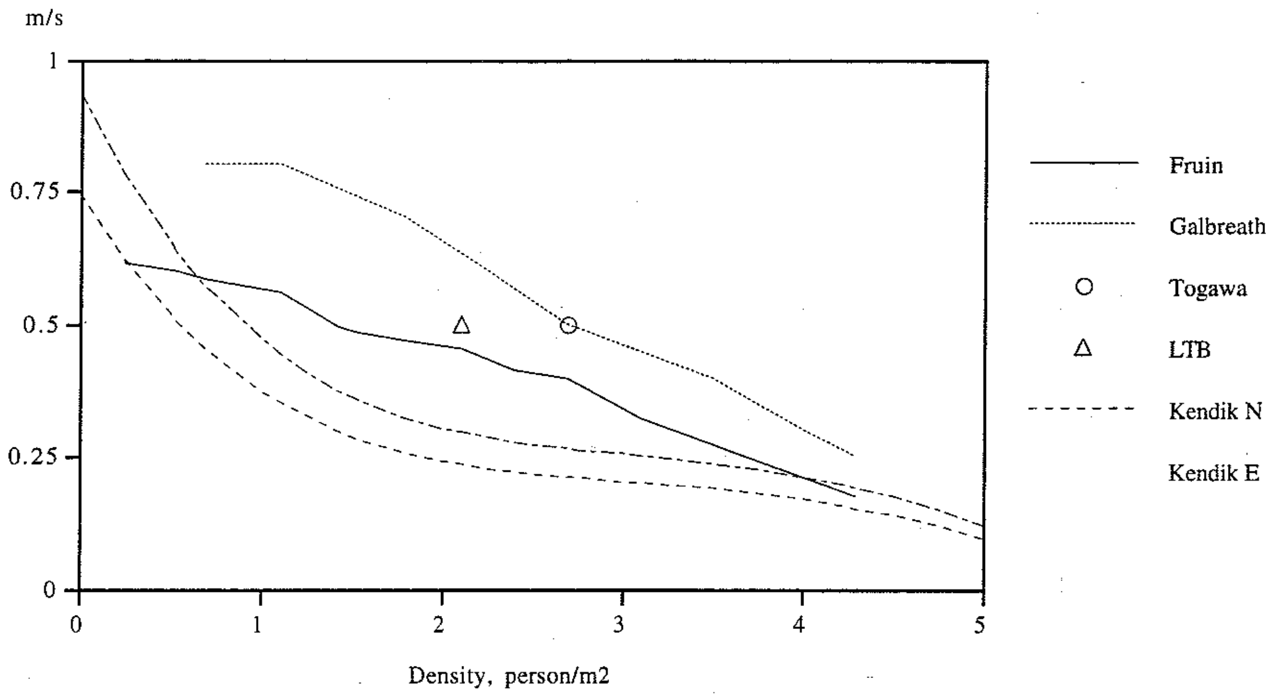

Figure 2. Walking velocity up stairs. E = Emergency, N = Normal.

2.2 Spiral stairs

Another problem in designing the escape routes according to the analytical method is if the designer wants to use spiral stairs as part of the evacuation route. Spiral stairs are used quite frequently when a new exit has to be installed in an existing building. The movement capacity for spiral stairs has not been examined to any larger extent. The movement pattern is totally different comparing normal straight stairs to spiral stairs. On spiral stairs people are walk in a line after eachother and data from the former stair type cannot be applied to the latter.

2.3 High population density

In many investigations it is assumed that the population density can reach very high values i.e. people are standing very close. This assumption is in some cases also adopted for stairs, Fruin, 1971, but the assumption may not be valid because of differences in movement patterns between stairs and horizontal surfaces. The stair threads might have an influence on how the movement pattern will develope when the population density increases. When looking at figures 1 and 2 not many experiments have been performed at high population densities but the data has been extrapolated to form simple equations describing the relationship between velocity and population density.

In handbooks covering escape route design, SFPE, 1995, BSI, 1995, NKB, 1994, the population density is usually one of the parameters given high priority for design. The reason for using the population density as the varying parameter has probably to do with the simplicity of deriving the parameter. Investigations are usually interpreted from film sequences of people movement. It is then simple to count the number of persons on a certain measuring area to obtain the density. Crowdidness is then expressed in population density. Studies have, however, shown that there is another parameter that is more suitable in describing the movement conditions. That is the distance between persons in a queue or escape route, Thompson, 1994. The interperson distance seems to be a more realistic parameter to be used in describing the changes in velocity for persons in various situations.

There is a second reason for changing to interperson distance as the varying parameter. With todays computer power, it is possible to construct evacuation models that can use this parameter in assessing a persons velocity. Previous models like the Evacnet+, described in Kisko et al, 1984, assumes that the people in a building can be treated as a homogenous crowd using simple flowrate relationships. The calculation of flow rates through the different routes then becomes rather rough. The designer also has to make assumptions on the population density throughout the whole building and for every timestep as this is needed for a proper calculation. That is a rather difficult task. The circumstances in one part of a room can be different than in another part but the Evacnet-type of models execute the calculation on average values. Recent models, Thompson et al, 1995, treat each person as a specific individual with its own characteristics and speed assessment depending on the local circumstances close to that individual.

The problem is that almost all previous investigations uses some kind of population density measure. The translation into interperson distance is not easy even if there is a relation between the two parameters. Figures 3 and 4 shows the same data as in figures 1 and 2 but with the interperson distance as the varying parameter. The transformation can be done if one assumes that the distances between people are the same in all directions and between all people, see figure 5. It is not completely correct to make the translation like that. The reason is that the population is not so even and well distributed in reality. But it is a simple way to change the varying parameter. The interperson distance can then be derived using the following expression which also is presented graphically in figure 6.

$$\text{Distance} = \frac{1}{\sqrt{\text{Density}}} \qquad (2)$$

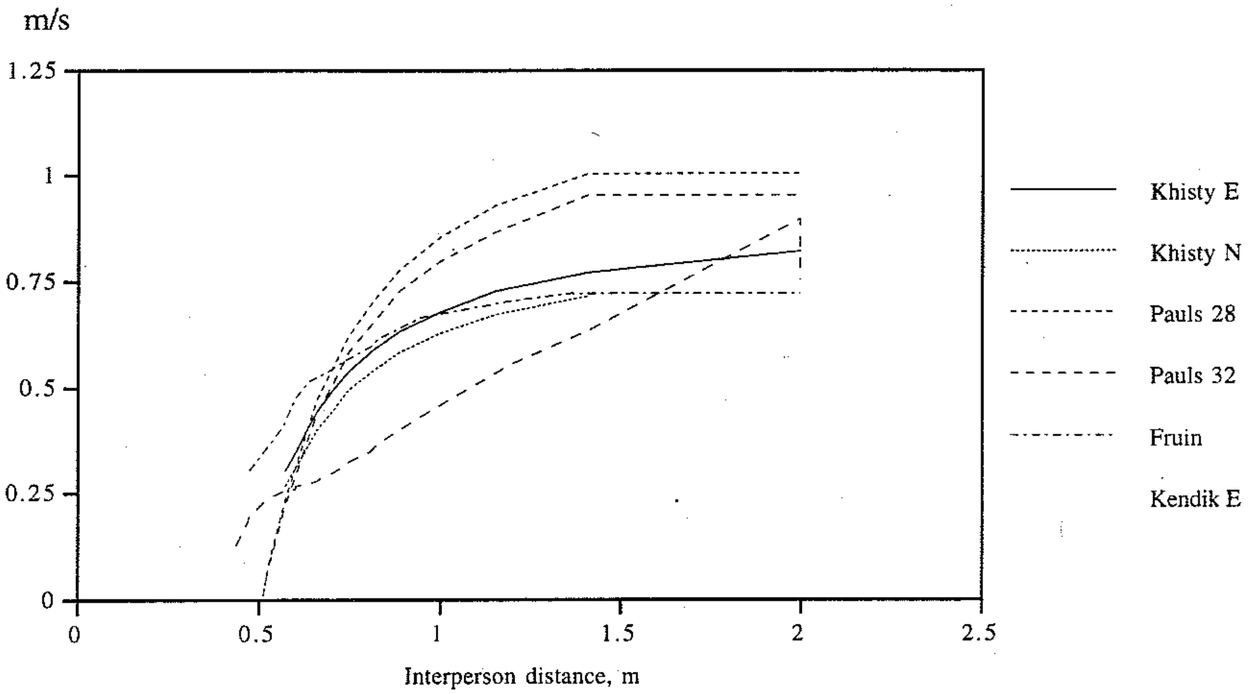

Figure 3. Walking velocity down stairs.

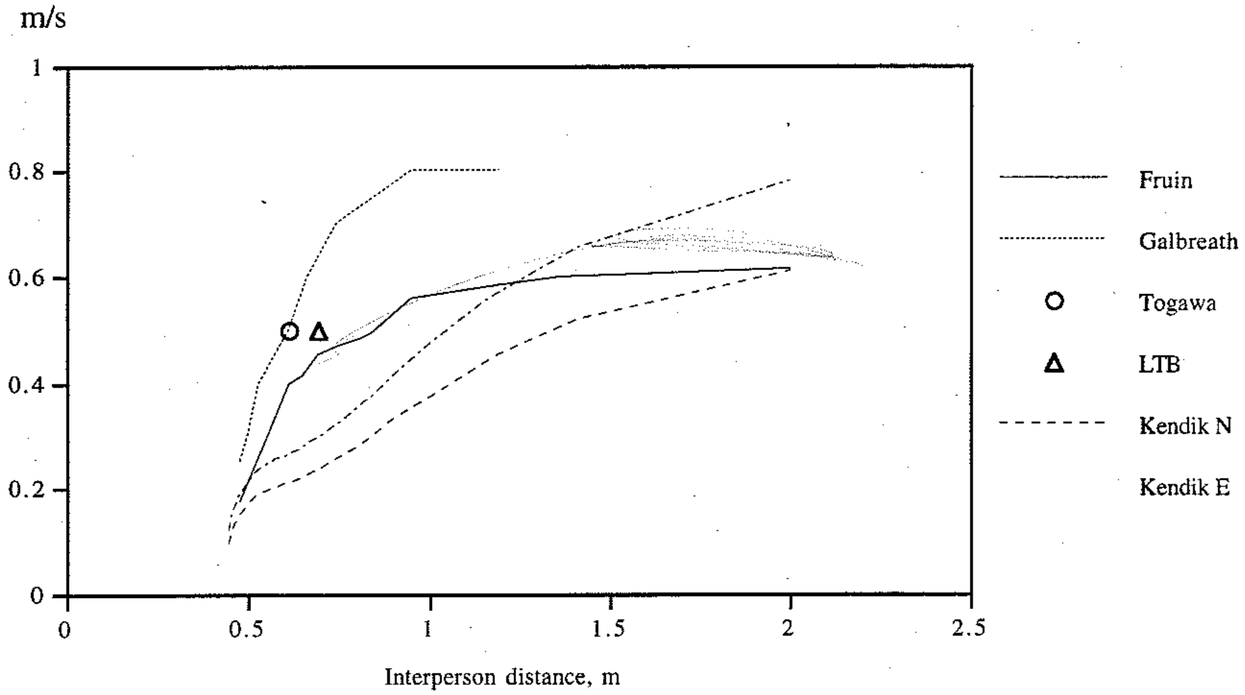

Figure 4. Walking velocity up stairs.

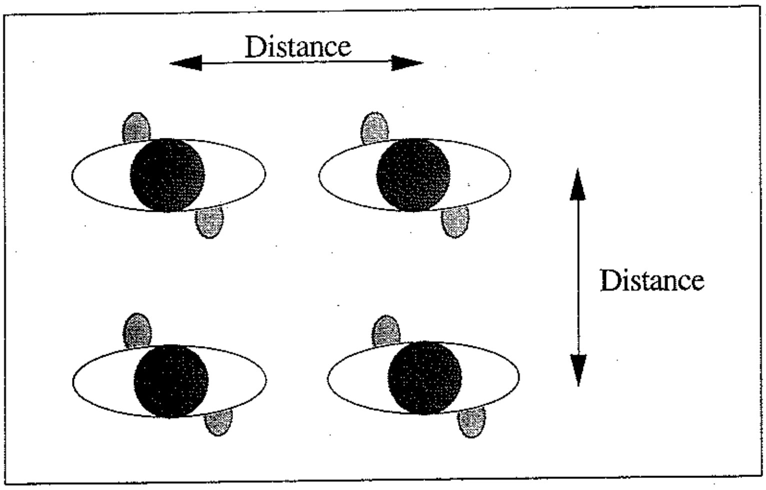

Figure 5. Assumption for using equation 2 regarding the distances between people.

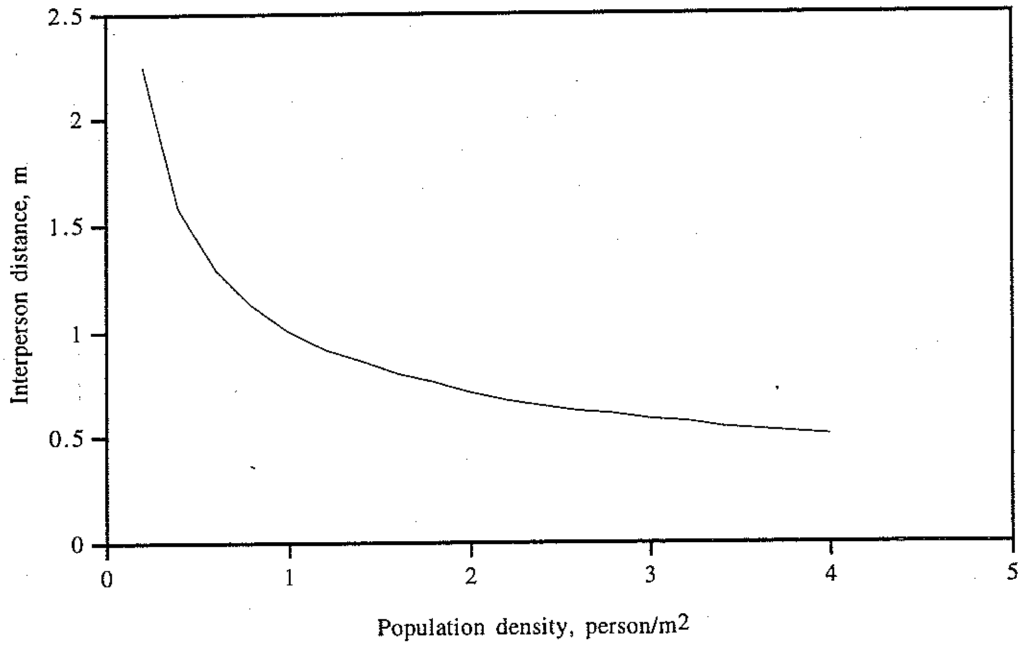

Figure 6. Relationship between the interperson distance and population density.

3 Earlier studies

During the last 30 years there have been a number of investigations performed with the purpose of deriving experimental data on people movement on stairs. Some of them are made to simulate real fire evacuations conducting the experiments during fire drills. In Frantzich, 1993 a survey of results from nine research groups is presented. Four of them will be briefly referenced here. The presented investigations are:

- Predtetschenski and Milinski, 1971
- Kendik 1984, 1988
- Fruin 1971
- Pauls 1980, 1984, 1987, 1988

3.1 Predtetschenski and Milinski, Kendik

The two russian researchers, Predtetschenski and Milinski, have studied movement on horizontal surfaces and on stairs. A rather extensive investigation resulted in a huge amount of data and expressions of the movement velocities for different situations were derived. The expressions are derived using a density measure defined as the ratio of the horizontally projected area of the people to the floor area. The density then becomes dimensionless. Predtetschenski and Milinski presented information on different horizontally projected areas for people during various situations for example for adults with and without children. Kendik has performed an investigation to see how the russian data on the horizontal area differ from an austrian population. Her data differs from the russian, usually giving higher values. An evacuation velocity can be obtained using an compensation expression multiplied to the expression giving the normal velocity. The evacuation expression predicts values which are lower than values presented by other researchers. In figure 7 the resulting expressions are plotted for the different movement conditions. The expressions are evaluating the mean values of the velocities from the observations.

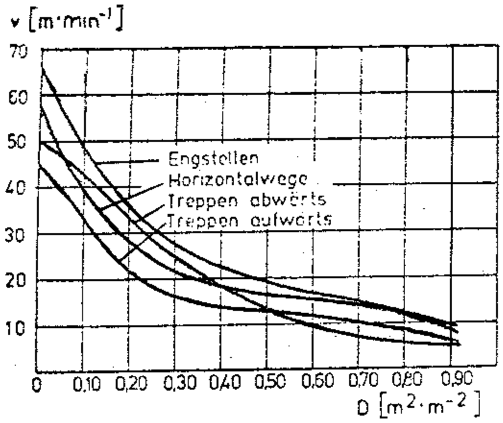

Figure 7. The walking velocity as a function of the dimensionless density for different communication routes.

3.2 Fruin

Fruin made most of his studies in bus and train terminals and on streets. The main purpose was to obtain information on movement during normal conditions. The information was then to be used for design of stairs and common pathways in terminal buildings where a considerable number of persons are present. The data is however often used as a basis for design of evacuation routes as well. Data from his investigations on stairs are presented in figures 8 and 9, showing movement down and up staircases. There is also in this data a large scatter, specially as the population density is increasing. In those conditions the movement is controlled by the specific individual behaviour and not by crowd movement. There are however no collected data in the region of low population density and Fruin has extrapolated the curves down to a zero velocity. The justification of a decrease in velocity is not that evident. The reason for making this assumption has probably to do with observations from movement on horizontal surfaces. On such a pathway a more clear trend of the decrease in velocity is observed, see figure 10. But still, the lowest observed population density is 6 sq ft per person for horizontal surfaces (1.8 persons/m^2).

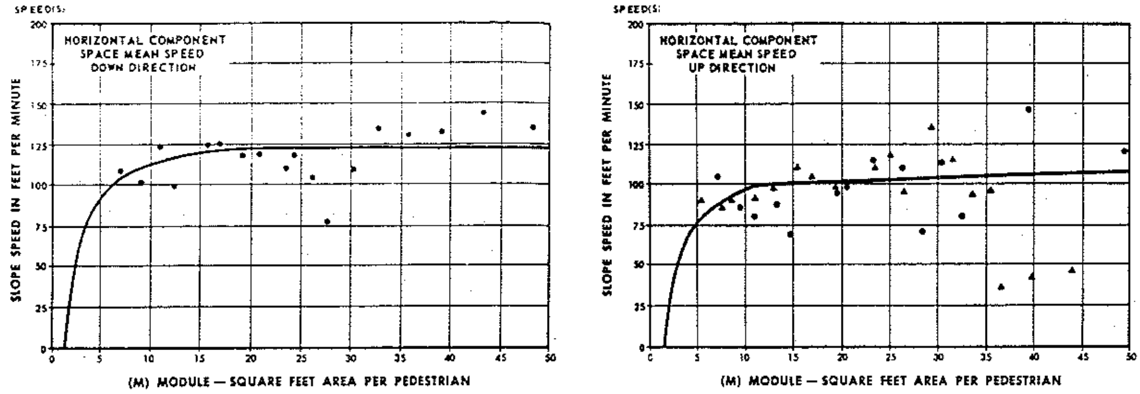

Figure 8 and 9. Walking velocity on stairs. The velocity is represented by the horizontal component of the velocity vector. 1 sq ft = 0.093 m^2.

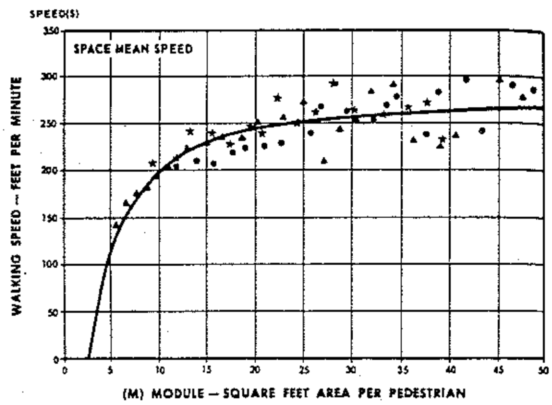

Figure 10. Observation of the velocity on horizontal surfaces made by Fruin.

3.3 Pauls

Jake Pauls is the researcher that probably has contributed most to background data for design methods based on engineering calculations. Pauls has studied emergency evacuations from high office buildings in Canada. This means that the populations in Pauls experiments can be assumed to represent a standard population for offices. Also people with minor physical disabilities participated i the experiments. The results can be used for design under emergency conditions. Most stairs in Pauls experiments had raisers of 18 cm and tread sizes of 28 cm. If other sizes is used a correction could be done. The correction has to be "... based on opinion...",Pauls, 1984.

One major finding from Pauls experiments is the justification of using the effective width on stairs. People tend to move with a little distance from walls and railings due to body-sway and friction to walls. This means that when performing calculations on flow on stairs the effective width should be used.

Data on how to calculate the effective width can be found in, Pauls, 1980. The distance which should be subtracted from the real width on each side of the stair is in the interval between 0 and 15 cm.

The data from the experiments is presented in figure 11 showing the slope velocity as a function of the population density in persons per square meter.

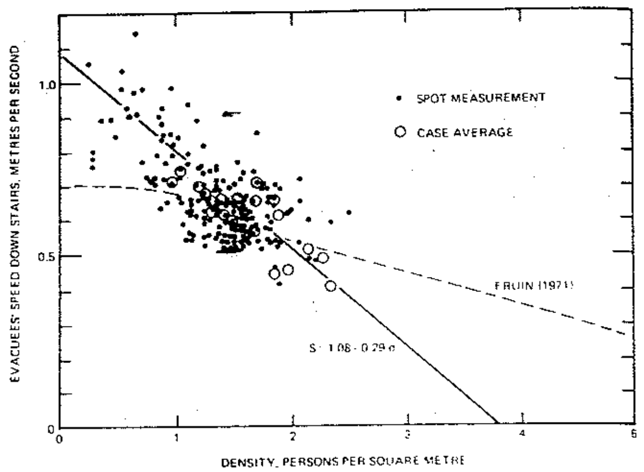

Figure 11. Velocity down stairs from Pauls, 1995. Also Fruins average measurement is displayed in the figure.

4 Method

4.1 Experimental setup

The method to obtain the velocity versus interperson distance information was to use a video image analysis technique. A video sequence is filmed during the experiment and that film is then analysed frame by frame with an image analysing computer software. This technique has been developed at the University of Edinburgh, Thompson 1994.

In the stair a test area is set out in which the measuring will take place. The corners of the test area are recorded on the video film for later use in the analysis software. The angle between the test area and the camera does not have to be considered as the analysis software only needs to know the four corners of the test area and the size of it. For observation reasons it is advisable to choose a position from where the test persons are well visible. For practical reasons looking at people evacuating it is convenient to have the test area at the shoulder height level on the stair and not on the floor level. The analysis of movement will then take place at that height using the shoulders of the individual as the place of the marker defining the individual. This elevated test area, the perspective rectangle, for stairs will then be a slope rectangle parallel to the stair slope and situated at approximately 1.5 m above the stair level, see figure 12.

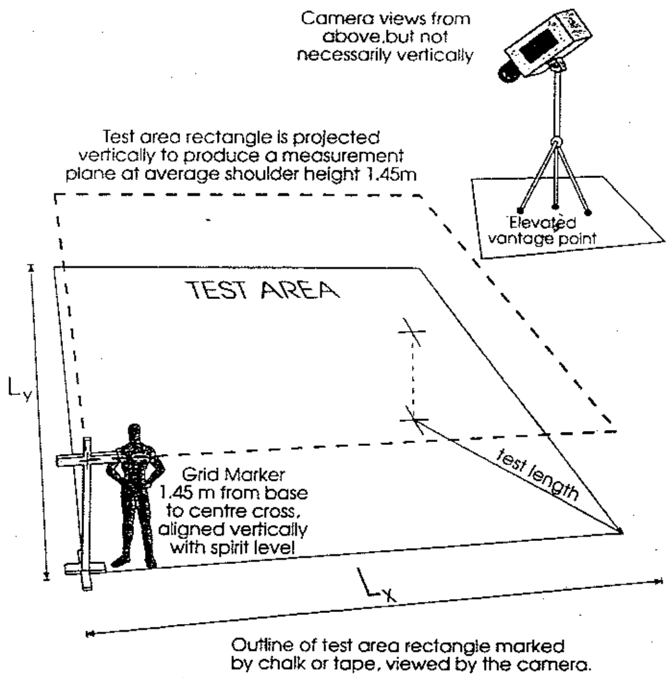

Figure 12. Test area and the perspective plane for a horizontal test position. A vertical marker is used to identify the corners of the perspective plane. Thompson, 1994

The video camera used was a standard VHS PAL camera and it was placed approximately 3 m above the stair level covering the test area. After the perspective rectangle is recorded on the video film the camera position must not be changed. When filming stairs it is difficult to position the camera so that a large test area is covered because of limitations in the building. Stairs above the test stair usually block any a good camera position and a rather small test area has to be accepted. For the later analysis it is recommended that the camera be positioned somewhat aside from the stair so the view will not be from straight above.

After the coordinates of the perspective rectangle are recorded the actual experiment can start. People are filmed as they proceed up or down the stair passing the test area. In the current experiments the test people went through the stair several times but with different conditions each time.

4.2 Processing the video film

The movement analysis is carried out using the software Persias, developed at the University of Edinburgh. Persias reads input files containing the video film in a standard Video for Windows AVI format. Therefore, the filmed video sequences have to be converted to computer files in this format. The video signal was run through a video film capturing package called Fast Movie Machine Pro from Fast Electronics in Germany. This capturing package makes it possible to catch a complete 25 frame per second video sequence and convert it and store it into a computer file. The Movie Machine Pro captures the sequence in nearly full PAL resolution, 736 x 560 pixels and in approximate 2 million colours. As the size of such a file is rather large the images are compressed using a Motion JPEG compression system allowing storage of this great amount of data quickly enough on the hard disk during the capturing. Using the M-JPEG makes it possible to play the video on screen in full 25 frames per second and in full screen size.

As the purpose of this video film is to analyse people movement the sequence capture rate was set to four frames per second trying to further minimize the file sizes on the hard disk.

4.3 Using Persias

With the AVI-files containing the video sequences of the different experiments the movement analysis can begin. Persias is a software tool which can analyse the movement of points on a computer screen defined by the user, Thompson, not published. T-shaped markers on the computer screen are used to define the different points of interest. The markers are used to follow a motive on the film and different parameters such as the actual velocity of the motive, in this case people velocity, can be calculated from information of the marker positions. The data is stored onto a spreadsheet compatible file which can be used in, for example, MS Excel to produce graphs etc.

First the elevated test area or perspective rectangle must be defined with the test area corners first filmed on the video film. The perspective rectangle, visible with lines on the computer screen, can be adjusted with the mouse to fit the video filmed corner markers. As the perspective rectangle is defined and assigned the correct size the motion analysis can begin. The T-shaped markers used to identify each individual are now movable with the mouse on the perspective rectangle plane. There are two different kinds of markers, a base marker and obstructing markers. The base marker tracks the person of interest and the obstructing markers are used to identify persons close to the base person. In the data file, distances from the base marker to the other markers are stored together with other relevant data.

Analysing the information on the video film is fairly simple. The markers are adjusted to the shoulders of the persons to be analysed and their positions are stored. The base marker and at least one obstructing marker should be used. The film is advanced to the next frame, 0.25 second later, and the markers are moved by the user to the new positions on the screen for the same individuals. As this is repeated the position data of the markers are recalculated to real distances and velocities and stored on the data file. The data can then be analysed and examined using, for example, MS Excel.

The accuracy of the measurements using Persias is in the range of +/- 5 % of the real value. This accuracy is derived from experiments in, Thompson, 1994.

4.4 Subjects

The experiments presented in this report are controlled laboratory experiments. The persons used for the tests are students, males and females, at a technical university in the age interval approximately 20-30 years. This means that there are no individuals showing any movement disabilities among this test group. Other advantages in using students are that they are usually walking with a uniform velocity minimizing the age-dependant scatter in the data. The test was assumed to determine the normal walking speed for the test group and not a simulated evacuation speed or conditions assumed to be valid during evacuation. It is generally assumed that evacuation velocities are higher than a normal situation velocity. One can therefore roughly assume that the velocities measured in these tests could be treated as a standard evacuation velocity valid for the group of people representing the average adult population. The horizontally projected bodysizes of the subjects are subjectively determined as approximately representative to the population as a whole.

4.5 Movement conditions

Two different stair setups were used with different widths and tread sizes, denoted wide stair and narrow stair. Also different test groups were used for the two stairs. Most of the experiments were performed on the wide stair. The experiments were performed in the same manner for all cases and tests were performed in both up and down directions. It is then possible to make the following division of experiments.

Table 1. Experiments performed.

Experiment no	Stair width	Description of experiment	Direction
1	1.3 m	Normal to high density.	Up and down
2	0.9 m	Normal to high density.	Up and down
3	1.3 m	Normal to very high density.	Up and down
4	1.3 m	Slower individual on stair, overtaking.	Up and down

In the experiments the test persons walked in different configurations from a single person on a stair to all the test persons acting like a crowd. This was done in all the four experiments both for upstairs and downstairs movement. In experiment number 3, a further study was made to see what happens when the population density is very high. The test persons were then forced to pass the stair provided with a restriction. The restriction was simulated using two test persons standing on the stair on both sides resulting in a narrower section in the middle of the stair. This procedure was repeated for both upstairs and downstairs. Different restriction widths were used. In the last experiment overtaking of slower individuals was investigated. Observations were made to see how the movement changes as a person is overtaking another and to see how that person is actually changing its direction to accomplish the overtake.

4.6 Geometrical description of the stairs

4.6.1 Wide stair

The stair is a normally used stair in an office close to the department of fire safety engineering. The horizontal surfaces on the stair consists of hard burnt bricks. The stair is open on one side, except from a handrail, and limited by a painted concrete wall on the other side. The free width is 1360 mm between the railings, see figure 13. The tread size is 280 mm and the raiser is 175 mm giving a slope of 32 °. The test area and perspective rectangle is 1305 mm wide and 1930 mm in the direction of movement. This distance is real walking distance and not the horizontally projected distance.

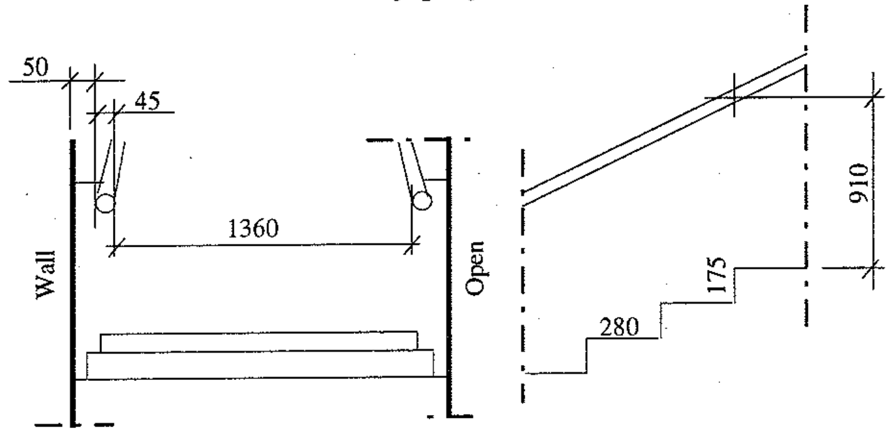

Figure 13. Drawing of the wide stair. Dimensions in mm.

4.6.2 Narrow stair

This stair is a internal stair in a large laboratory hall. The stair is constructed totally of steel and the treads are made by steel grating plates. The stair is open on one side, except from a handrail, and limited by a gypsum board wall on the other side. The free width is 920 mm between the railings, see figure 14. The tread size is 225 mm and the raiser is 205 mm which gives a slope of nearly 45 °. The test area in this case is 840 mm wide and 5710 mm in the walking direction.

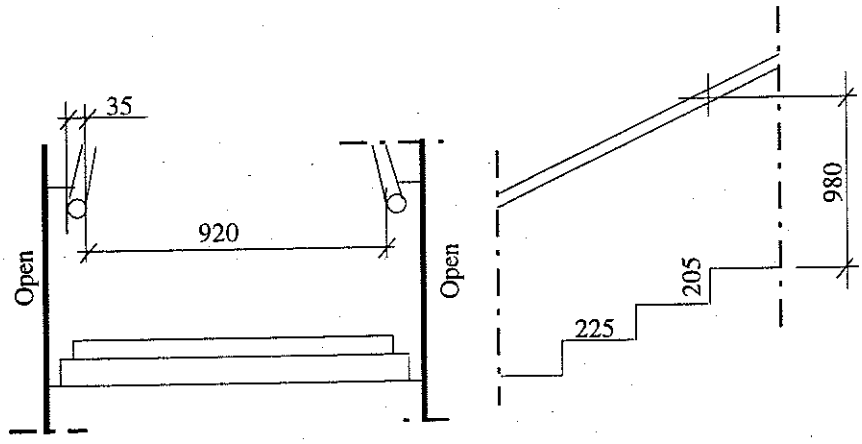

Figure 14. Drawing of the narrow stair.

4.6.3 Spiral stairs

Two different spiral stairs were used in this study. Both are situated outside of a building and constructed by steel grating plates. The weather conditions during the experiments were sunny and warm. The experiments are earlier presented in a licentiate thesis, Frantzich, 1994, but the results are also given here for completeness. The intention was to carry out further experiments in this type of stairs. However, it became apparent that it was not possible to use the above described video analysis method in deriving the velocity of evacuees. The measuring plane in the software Persias must be a two dimensional hyperplane i.e. a curved plane cannot be used. As the walking area on spiral stairs changes direction in the line of walking, the measuring plane for Persias would only be valid for a very short distance. Actually, it is only valid on one point on the stair, in the tangent point between the plane and the stair. The measurement can therefore only take place on a very short distance and it would not be possible to track a person for more than one or two frames which is not enough. Also the long distances between the camera and the two stairs made the use of video recording for Persias uncertain.

Walking speed down spiral stairs were derived by simply measuring the time spent on a certain distance on the stair. The walking distance was measured in the line of walking. The two stairs used differ in dimensions and figure 15 and table 2 display the respective dimensions.

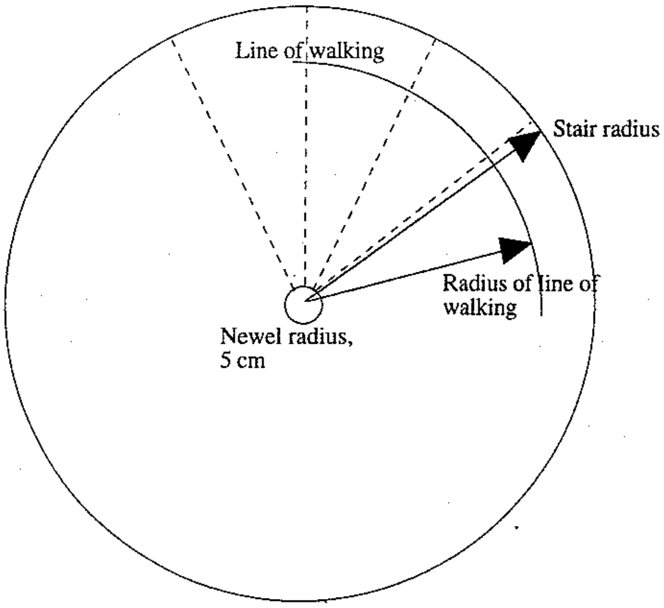

Figure 15. Spiral stair used in the experiments.

Table 2. Dimensions of the stairs.

Stair	Raiser m	Tread m	Radius m	Radius of line of walking m
Wide	0.18-0.21	0.18	0.85	0.55
Narrow	0.20	0.21	0.65	0.40

5 Result and discussion

5.1 General

The main results from this series of experiments are the velocities of persons moving on stairs as a function of the distance to an individual in front, the interperson distance. This relationship is necessary for the prediction of time spent on stairs for people evacuating down or up stairs. A second parameter of interest for evacuation is the twisting rate. This parameter is important for the prediction of how fast a person can turn to seek for a new direction. The reason for turning can be to seek a quicker direction of travel if the current one is blocked by for example a slower person. This parameter is however not as relevant for stairs as for other communication routes like horizontal corridors. On stairs, people do not tend to move in other directions than in the straight parallel direction of the stair. If a person has to move aside to, for example, pass another person in front, this person will not turn the body in choosing a new direction of movement. The person will simply move sidewise, without twisting. Gain of travel time is usually the reason for changing direction if the population density is small. At high population densities this movement to one side is likely to occur to decrease the body pressure, but usually not to change direction. Passing was not observed in any of the first three experiments, the people moved with almost the same velocity. In experiment number four, passing was observed when a slower person used the stair. The persons passing a slower person moved sidewise, without twisting, to change direction and accomplish the overtake.

A third parameter that could be of interest is the speed reduction close to walls. If persons are moving close to walls, a friction effect could be assumed to reduce the velocity. No such tendencies were observed, not even in experiment three at high densities. All the persons on the stairs moved in the same manner independent of their position on the stair. In none of the two first experiments was the interperson distance so small that people were forced to walk with their shoulders touching the walls. The walls in the experimental staircases were rather smooth. If the walls have rough surfaces, the wall friction effect would probably be more evident. Pauls, Pauls, 1980, has presented a solution to be able to take this effect into account in calculations. He assumes that the width used in the calculations should be the effective width. Another solution is to reduce the velocity for persons moving close to walls.

The minimum interperson distance measured for experiments one and two was 0.37 m which gives a small distance of air between two succeeding persons. In experiment three, simulating high population density, the shortest distance was 0.25 m which resulted in body contact.

5.2 Velocity on stairs

One would expect that persons travelling on stairs adjusted their velocity according to the closeness to other persons on the stair. This means that when persons decreased the distance between them, the velocity would also decrease. This behaviour has been reported by earlier researchers who in their average results indicate a drastic decrease in velocity as the interperson distance is decreased, see figures 3, 8 and 11. These assumptions are made even if the data points do not always justify this. The data in this study is, on the contrary, rather well defined around a constant velocity, independent of the interperson distance even down to very short interperson distances, at least for the two first experiments. Figures 16 - 19 show the results from experiment one and two. The very high velocities, above 1.5 m/s in figure 16, probably have to do with measuring errors.

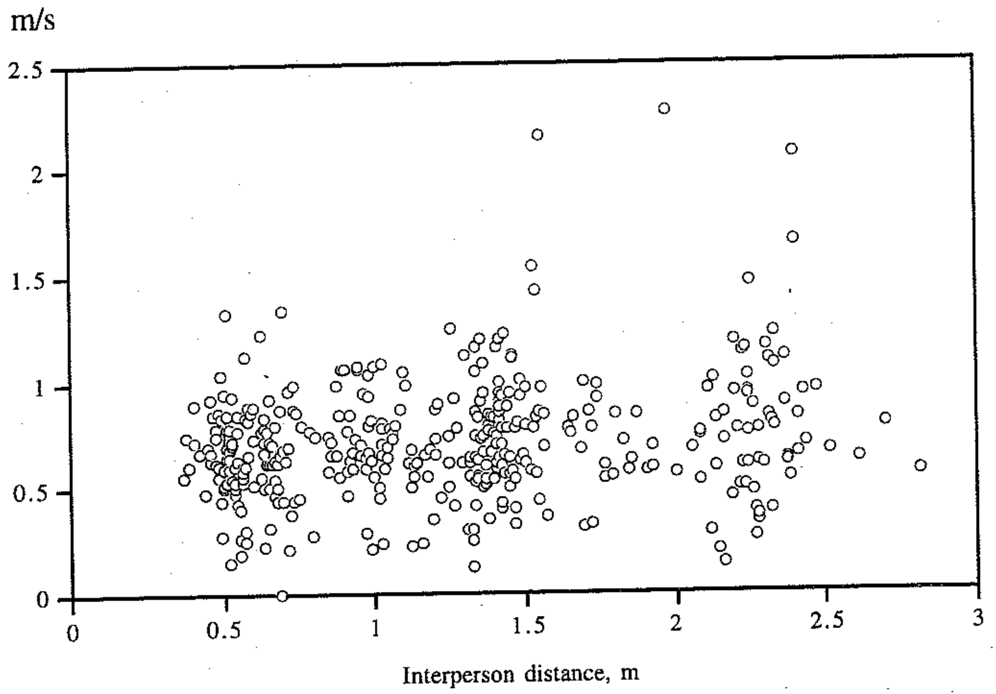

Figure 16. Velocity downstair on the narrow stair.

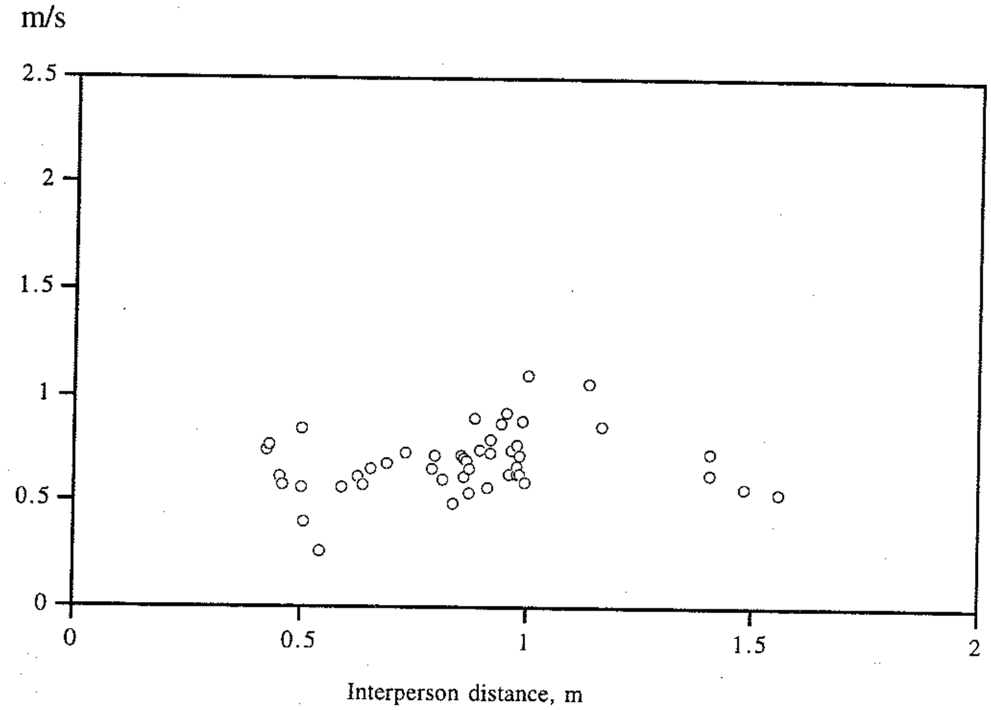

Figure 17. Velocity downstair on the wide stair.

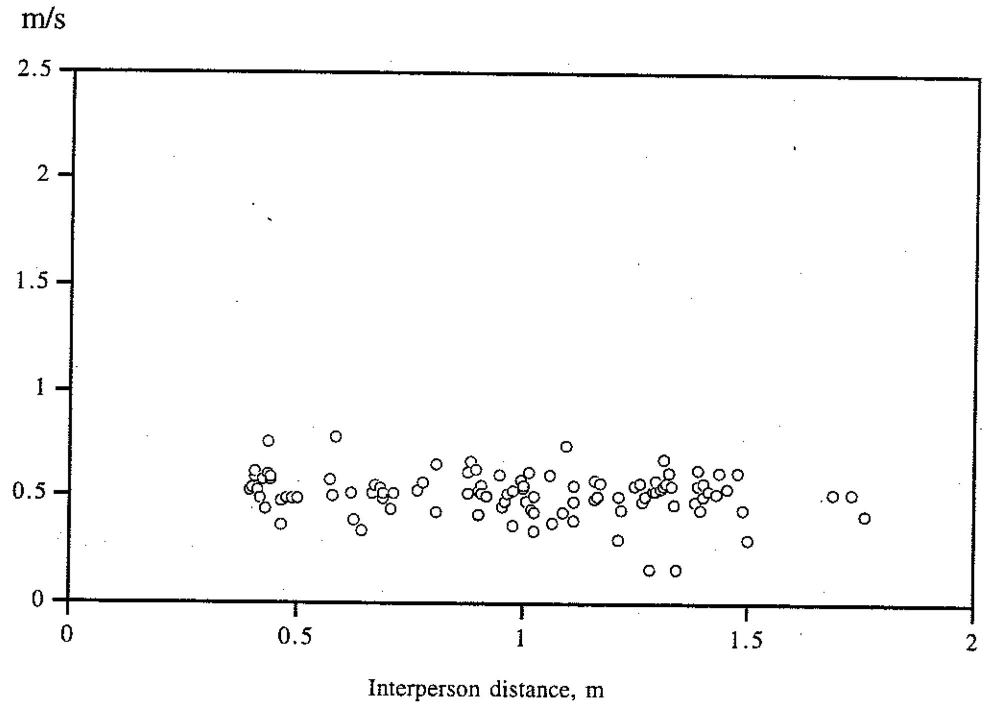

Figure 18. Velocity upstair on the narrow stair.

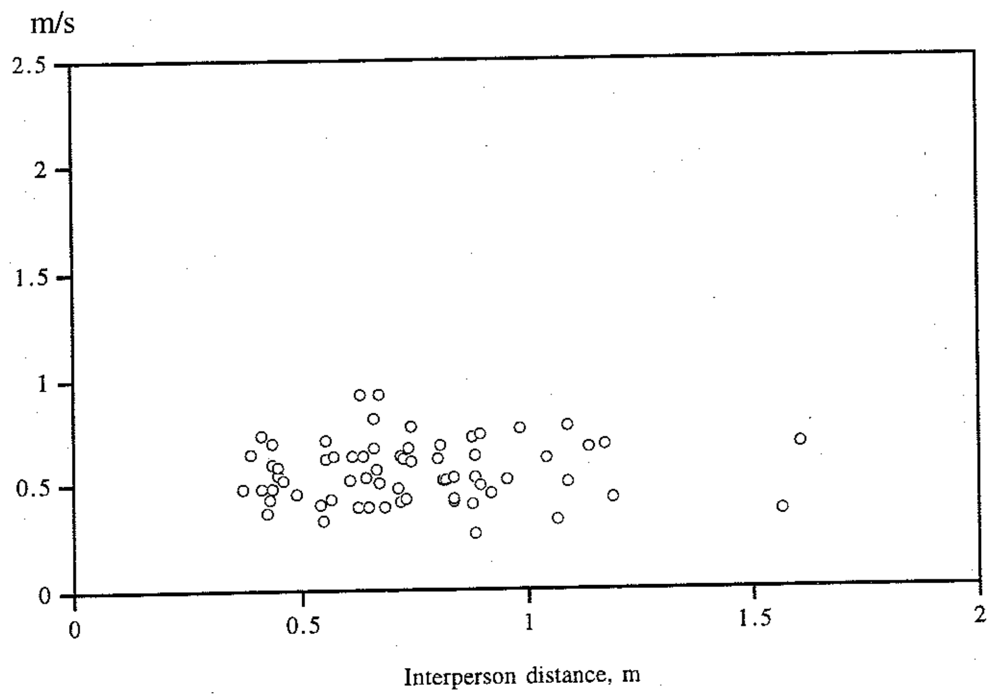

Figure 19. Velocity upstair on the wide stair.

The data from figures 16 - 19 can be extracted to simplify the comparison between the different experiments which are summarized in table 3.

Table 3. Data from the four diagrams 16 - 19. W = wide stair, N = narrow stair.

Width and direction	Mean velocity m/s	Standard deviation m/s	Number of observations	Min value m/s	Max value m/s	Shortest inter-person distance m
W, Down	0.69	0.15	47	0.27	1.09	0.42
N, Down	0.72	0.27	381	0	2.27	0.37
W, Up	0.56	0.14	67	0.26	0.92	0.37
N, Up	0.51	0.10	105	0.16	0.78	0.40

Obviously the velocity is higher when the walking direction is downwards but the difference between the two examined stair widths is not very large. In neither case, up or down, is there any difference at the confidence level of 95 %. Therefore one can assume that the stair width is not a parameter controlling the velocity on stairs. The flowrate, however, is of course depending on the width of the stair.

The data points are fairly well normally distributed around the mean value of the velocity. An example of the distribution of datapoints and a fitted normal distribution curve is presented in figure 20. The figure represents data from downward movement in the narrow stair. It is assumed in this figure that the velocity does not vary with the interperson distance i.e. the mean value is constant. This seems to be the case for the two first experiments. Better approximations to the data with other distributions than the normal distribution can be obtained. The normal distribution is chosen for simplicity and the agreement is good if the number of observations is large. The frequency of the observed velocity data points is displayed on the vertical axis and the velocity on the horizontal.

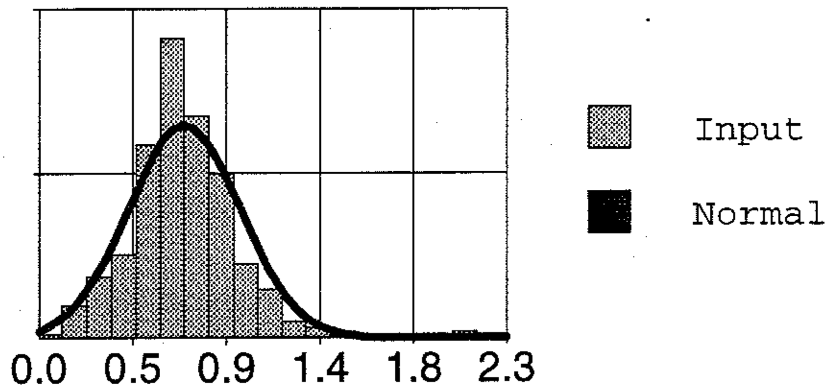

Figure 20. Distributions of results and the approximated normal distribution for velocity downstairs on the narrow stair.

From the two first experiments only a small tendency of decreasing velocity can be observed as the interperson distance in decreasing. Earlier studies indicate that a decrease in velocity is to be found as the distance between individuals are decreasing. If such a decrease in velocity can be assumed, it is not obvious how the shape of the curve will look. The curve can look like curve A in figure 21 relating to predictions made by other researchers. It can be probably be assumed that the decrease in velocity will not be going from the average velocity down to zero directly following a step function, but rather like curve B illustrating a linear decrease, see figure 21.

A validation for any of these curves cannot be made because of the variation in the data and the not so clear trend of a decreasing velocity for the shorter interperson distances. According to the data from experiments one and two the decrease cannot be observed. From a logical point of view there ought to be some kind of decrease. As the distance is getting shorter the velocity should also decrease.

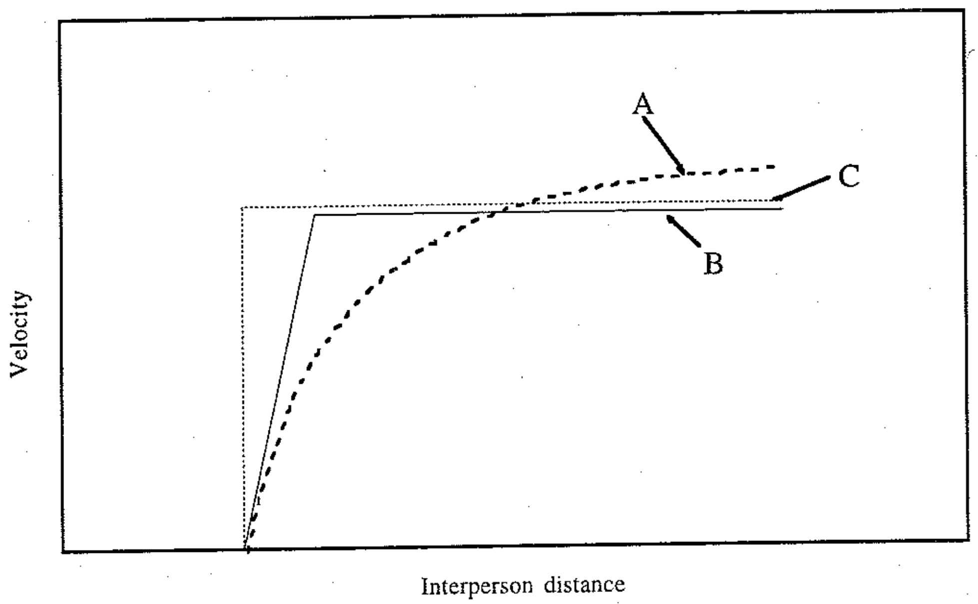

Figure 21. Suggested result curve approximations.

This assumption was actually the reason for performing the third experiment. In this experiment movement behaviour at very short interperson distances was to be observed. The subjects were told to walk with short distances to the person in front simulating a very dense crowd. The persons in this experiment walked with bodily contact to each other in a way which they would not do in a real situation. Studies of real evacuations and in the experiments described earlier in this report show that contact between persons is avoided. This means that the current experiment is trying to simulate a situation that is not likely to occur in reality but still not impossible.

The dense conditions were created using a restriction in the width on the stair forcing the people together. As the width is smaller, the flow capacity is smaller creating a queue in front of the restriction. The persons were told to walk towards the restriction in various manners. This with the purpose of creating different interperson distance circumstances at the restriction. The test persons were in some cases told to walk as they would do naturally and in some cases force themselves through the narrower section on the stair. In no case were they supposed to act as they knew each other or to advance in the crowd hurting the other persons.

The results from the experiments are presented in figures 22 and 23 showing persons moving both downstairs and upstairs. As the interperson distance is decreasing towards very short distances the movement velocity is showing a tendency to decrease. The distance between persons in the most left part of the observations is as low as 0.25 m which results in body contact. It is then possible to make some conclusion about how the velocity is decreasing.

It seems that the shortest interperson distance should be around 0.25 m for both upstairs and downstairs. We now assume that at that point the velocity will be zero. From experiments one and two we can obtain the mean velocities. These velocities will be valid down to the shortest interperson distances indicated in table 3. The result of this assumption is that the velocity on stairs could follow the relationships shown in figure 24 for up- or downwards movement on straight stairs.

One may suspect that the tread size may affect the lowest observed interperson distance. In this experiment the tread size was 0.28 m which then should equal one person on each step standing in a line. Probably, the body sizes of the persons are more important. If the density increases, people are not standing after each other in a line but more like in a zig-zag pattern to reduce the body pressure.

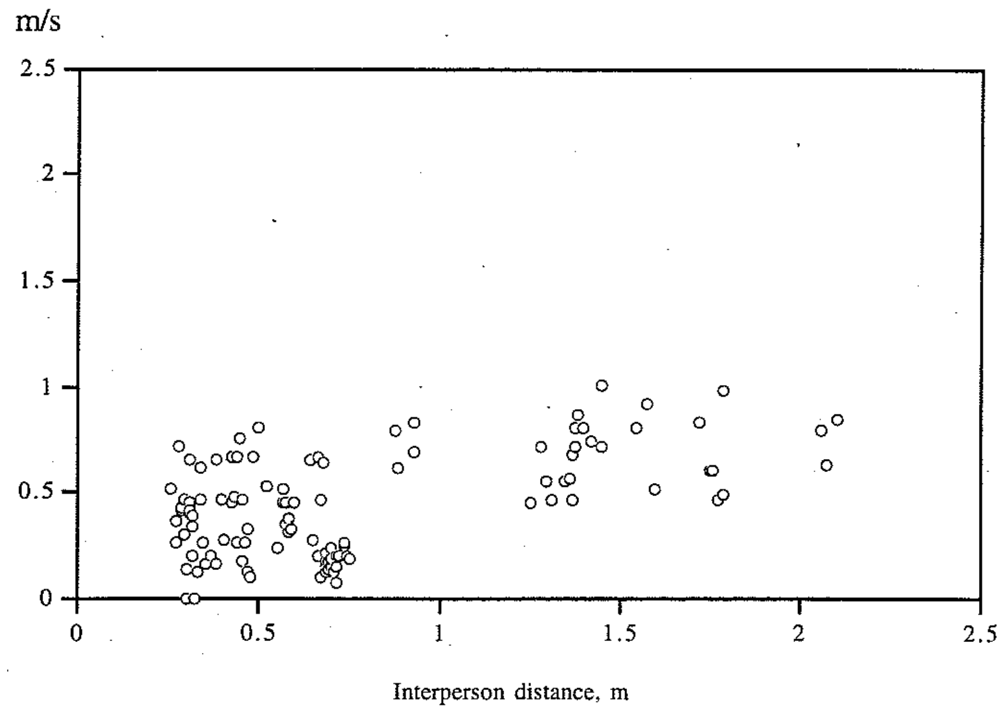

Figure 22. Velocity downstair from experiment three.

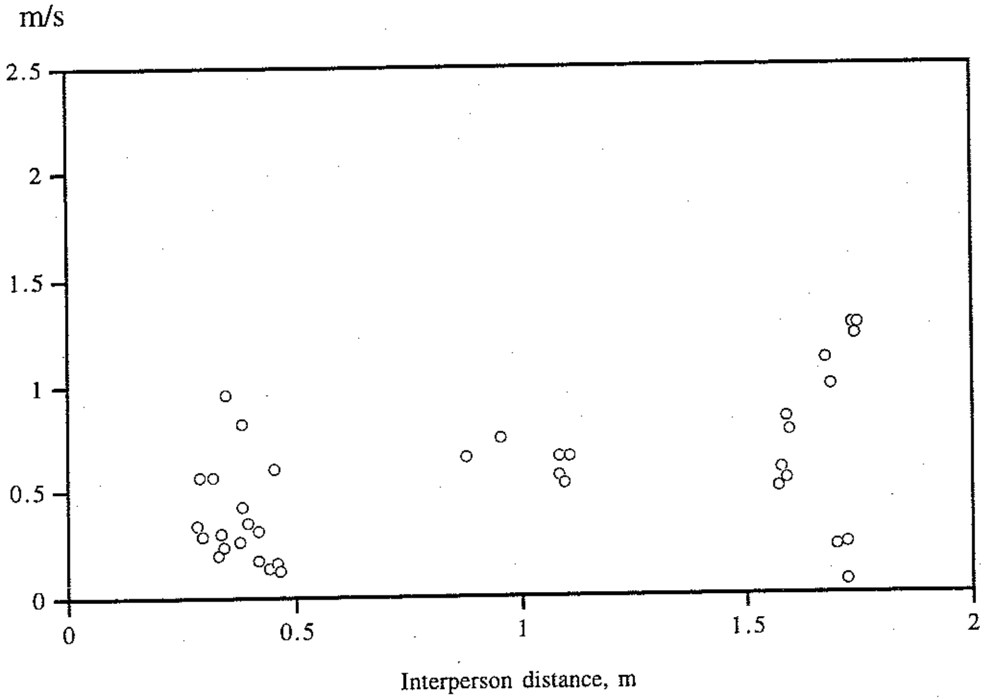

Figure 23. Velocity upstair from experiment three.

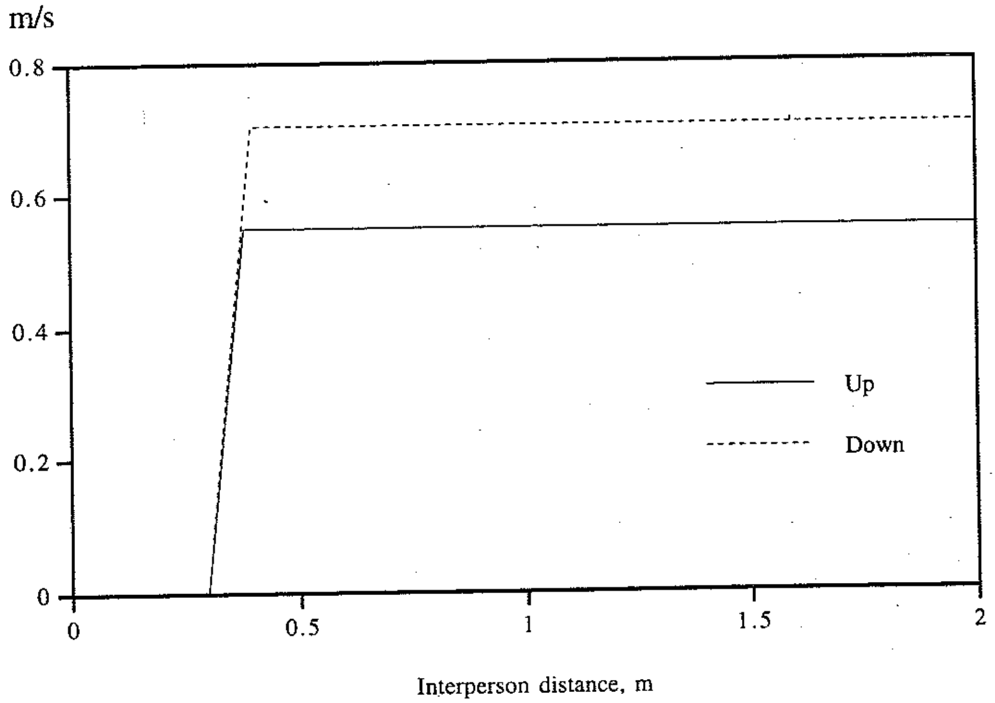

Figure 24. Resulting design velocities for stairs.

5.3 Spiral stairs

What distinguishes the walking pattern on spiral staircases from that on normal straight staircases is that in the former case, people follow each other in single file. Not once in any of the experiments did anyone try to overtake the person in front. In all cases, the handrail on the outside of the staircase was used, while the other hand rested against the newel (central pole). The subjects said that it was easier to use the wider staircase as the radius was greater and the curvature in the walking direction less.

The horizontal distance between people was between 0.7 and 1 m in the walking direction. The shortest interperson distance observed was approximate 0.5 m. The walking velocity down the stair was between 0.5 to 0.55 m/s depending on the width of the stair. The former value is for the narrow spiral stair. Higher values were observed but many of the subjects tripped at those velocities. The difference in flow on the two staircases was very small.

The flow measured was on average 0.55 people per second, regardless of the width of the staircase. Because of the rather rough measuring techniques the uncertainty in variability in velocity is unknown. For design purposes the following can be used. People on a spiral staircase move with a constant velocity of 0.5 m/s and with interperson distances longer than 0.7 m. This gives a restriction of the inflow of people at the entrance of the spiral staircase of 0.7 person per second. If the flow of people arriving at the spiral staircase exceeds 0.7 persons per second a queue will form in front of the staircase. The movement on the staircase will then take place with a constant velocity of 0.5 m/s. The movement can be seen as a quasi-steady flow.

6 Future studies

It seems that the prediction of the mean velocities up and down stairs are rather well determined. There is a variation in the data that is inherent but now addressed. But the basis for deriving the velocity curves at short interperson distances is not too good. A more detailed study with the purpose of looking at short interperson distances should be made. Also the effect of different tread sizes should then be included. Concerning spiral staircases, not much can be done to improve the information for downward movement. There is little to gain in having more detailed studies performed. However, investigating the use of spiral staircases for upward movement, could be an area of interest. It is though presently not very common to use spiral staircases for movement upwards because the poor movement capacity compared to straight stairs.

The present study has focused on persons moving in one direction and is restricted to the staircase area only. Another situation of interest is to study the change in movement pattern as one or more persons are moving in the opposite direction of that of the main stream. This could be the case when firefighters are entering the building at the same time as people are evacuating using the same communication route. Some information indicates that the flow of people then will decrease to half. To be able to make a better prediction of the evacuation, other situations should also be studied. For example merging flows of people from different directions and movement through doorways. The method used in this project to extract information from a video sequence has proven to be very efficient. It is rather easy to obtain more information from other evacuation situation with a minimal work effort, as the technique is working.

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