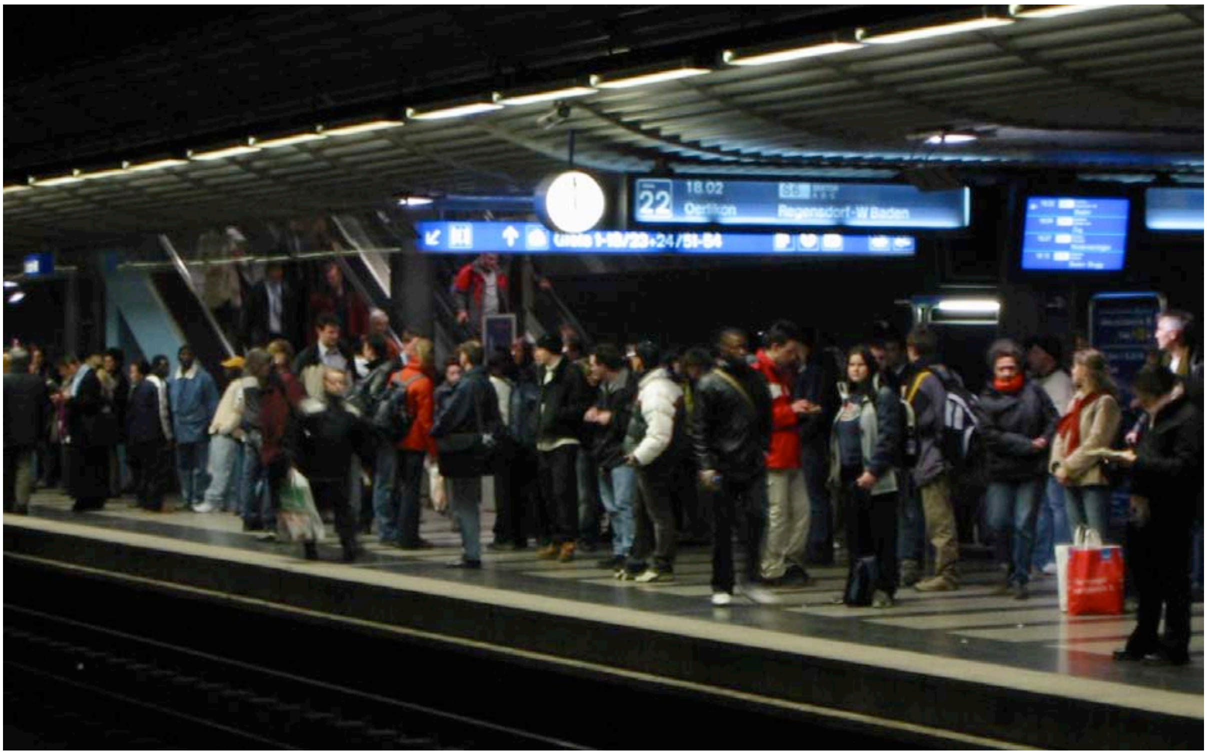

Pedestrian and Transport Facility Attributes as Input Parameters for Microscopic Pedestrian Simulations

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1 Introduction

This document will give you a short overview of pedestrian movement, pedestrian traffic and pedestrians themselves. Goals of this study are to get the parameters and principles of pedestrian traffic to the reader and/or the user of microscopic pedestrian simulation tool SIMWALK.

Based on the IVT-report no. 90 (Weidmann 1993) inquiries were made to amend and to update the cognitions of pedestrian traffic to the most recent state of research.

This work of reference is structured as follows:

Chapter 2 intends to give an overview of relevant pedestrian attributes for foot traffic: dimensions, energy consumption for pedestrian movement, walking speed and the influence factors on it and maximum empirical flow rates.

Chapter 3 explains the principles of pedestrian movement, which is given basically by the fundamental diagram. There is to differentiate between one- and bidirectional pedestrian flows and diverse parts of pedestrian facilities, i. e. walkways, inclined walkways, stairs etc.

Chapter 4 handles the analysis of pedestrian flows. In the first part the level of service concept is explained in order to evaluate pedestrian traffic. Different LoS-definitions are listed. In the second part some evidences are given regarding dimensioning of walkways, i.e. minimum width of walkways and recommended levels of service.

2 Pedestrians

2.1 Dimensions

2.1.1 Human body dimensions

Considering the outline of pedestrians, the typical human body has a width of about 50 cm and a depth of 30 cm. The average body ellipse of an adult person includes a minimum elbowroom for different body postures and is about 60 cm wide and 50 cm deep.

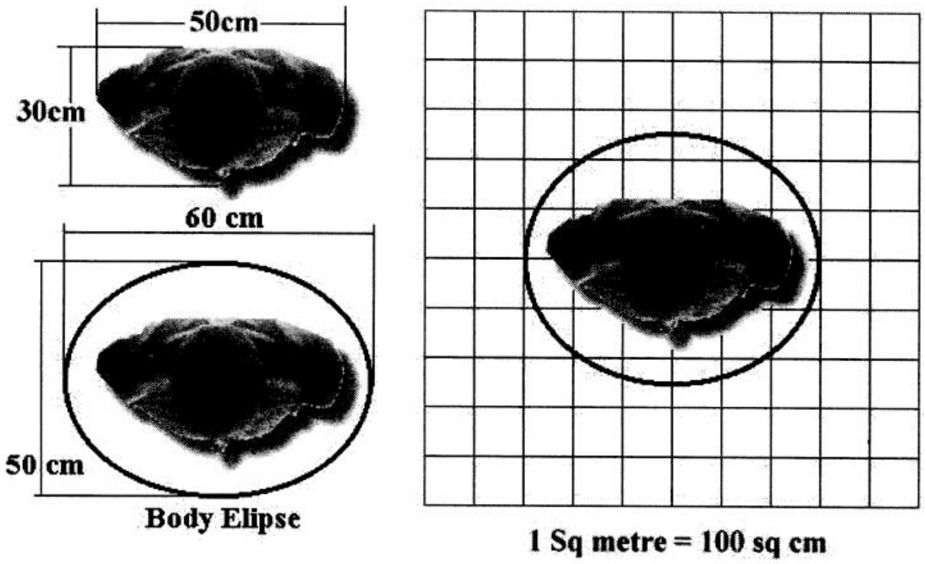


Figure 1 Body ellipse of pedestrians (Crowd Dynamics 2005)

The minimum dimensions of human bodies are varying from country to country depending on racial differences, customs of working and alimentation etc. Typical values for human bodies for different populations are shown in Table 1.

Population		Width [cm]	Depth [cm]	Area (Rectangle) [m^2]	Area (Ellipse) [m^2]
Switzerland	Male	47.50	29.50	0.14	0.11
	Female	45.50	32.50	0.15	0.12
France	Male	51.50	28.00	0.14	0.11
	Female	47.00	29.50	0.14	0.11
Great Britain	Male	51.00	32.50	0.17	0.13
	Female	43.50	30.50	0.13	0.10
Hong Kong	Male	47.00	23.50	0.11	0.09
	Female	43.50	27.00	0.12	0.09
India	Male	45.50	23.50	0.11	0.09
	Female	39.00	25.50	0.10	0.08
Japan	Male	41.00	28.50	0.12	0.09
	Female	42.50	23.50	0.10	0.08
Poland	Male	47.50	27.50	0.13	0.10
	Female	41.00	28.50	0.12	0.09
Sweden	Male	51.00	25.50	0.13	0.10
	Female	42.50	30.00	0.13	0.10
USA	Male	51.50	29.00	0.15	0.12
	Female	44.00	30.00	0.13	0.10
Elderly People	Male	48.00	29.00	0.14	0.11
	Female	41.50	30.50	0.13	0.10
Average		45.58	28.20	0.13	0.10
Maximum		51.50	32.50	0.17	0.13

Table 1 Average dimensions of pedestrians for different countries (Crowd Dynamics 2005)

The average human body over all considered countries has a width of about 45.6 cm and a depth of 28.2 cm.

These values lead to a minimum surface for an average pedestrian (without bulky clothes or luggage) of about 0.10 m^2, considering the elliptical form of the body. As pedestrian forms are taken as ellipses, they can not fill completey the rectangle (width multiplied with depth), which has an average area size of 0.13 m^2 and a maximum value of 0.17 m^2.

2.1.2 Dynamic width of walking pedestrians

While pedestrians are walking their balance point is wavering around an ideal line. Therefore they require more space in cross direction than an immobile person.

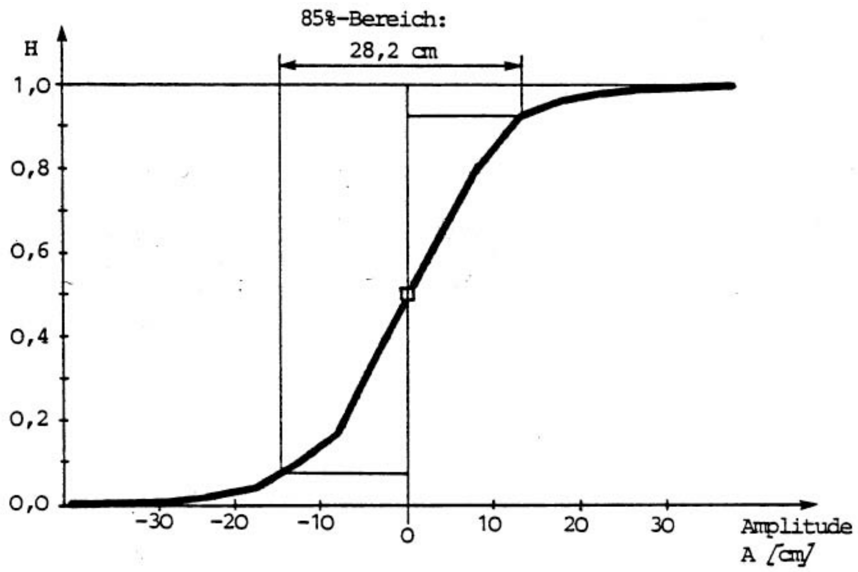


Figure 2 Wavering movements of pedestrians during walking (Schopf 1985)

The amplitude of the wavering movement reaches 14.1 cm (85%-percentil). Therefore the additional required space during walking in cross-direction amounts about 28.2 cm. This is about 62% of the average width of pedestrians.

2.1.3 Pedestrians with luggage

Pedestrian carrying any kind of luggage with them need again more space than normal pedestrians. In public pedestrian facilities only a small part of the pedestrians are walking free of luggage. Measurements in urban pedestrian walkways are showing the percentage Table 2 for people with different kind of luggage or people taking pets or children with them.

		First Hand							
		Empty	Small	Middle	Big	Child	Pram	Stick	Dog
Second hand	Empty	25.8	37.1	20.8	1.6	0.7	1.2	0.6	0.6
	Small		2.8	3.3	0.2	0.5	0.2	0.7	0.3
	Middle			1.5	0.2	0.4	0.1	0.4	0.2
	Big				0.1	0.1	0.0	0.0	0.0
	Child					0.2	0.2	0.0	0.0
	Pram						0.0	0.0	0.0
	Stick							0.0	0.1
	Dog								0.0

Table 2 Proportion of pedestrians with luggage. Values in [%], (Schopf, 1985)

Only 26% of the pedestrians are walking empty-handed, about 58% are carrying a small- or middle-sized piece of luggage. The remaining 16% are charged otherwise.

Table 3 shows the 50%- and 85%-fractile of pedestrian width of persons taking luggage, pets or children with them.

		First Hand							
		Empty	Small	Middle	Big	Child	Pram	Stick	Dog
Second hand	Empty	64 73	73 81	73 80	89 100	107 120	63 70	69 74	108 122
	Small		75 83	72 80	78 84	107 120	68 76	69 74	108 122
	Middle			74 81	85 95	107 120	68 76	69 74	108 122
	Big				79 84	107 120	-	-	-
	Child					141 160	97 110	-	-
	Pram						-	-	-
	Stick							-	108 122
	Dog								-

Table 3 50%- and 85%-fractiles of pedestrian width depending on luggage. Values in [cm], (Schopf, 1985)

Taking the luggage of pedestrians into account, the width of pedestrians is distributed as shown in Figure 3 with a mean width of 68.5 cm.

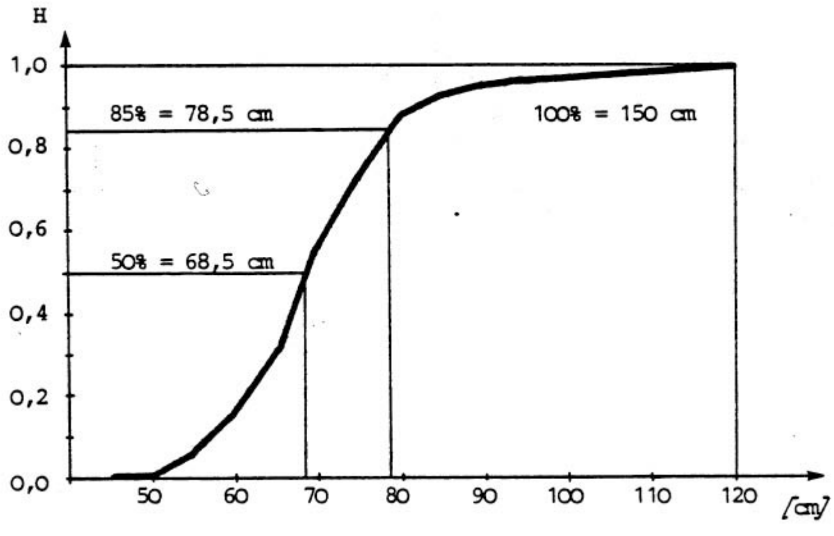


Figure 3 Width of pedestrians considering the luggage (Schopf 1985)

2.1.4 Pedestrian pairs

Pedestrians walking side by side in pairs need more space in lateral direction than just twice the body width. Schopf (1985) examined pedestrian pairs in urban areas and found the following distribution of width.

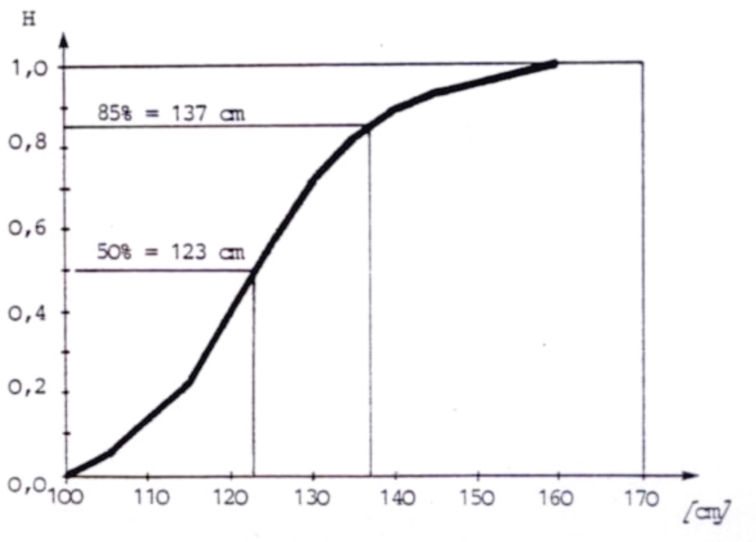


Figure 4 Width of pedestrian pairs (Schopf 1985)

The mean width of pedestrian pairs in urban areas measures about 123 cm, the 85%-fractile about 137 cm.

2.1.5 Handicapped people

Handicapped people often need more space than normal pedestrians depending on their equipment for moving or escorting persons. People with prams can be considered as handicapped because of their restricted walking speed, difficulty passing stages and the additional required space. Ackermann (1997) specifies the following dimensions for handicapped people.

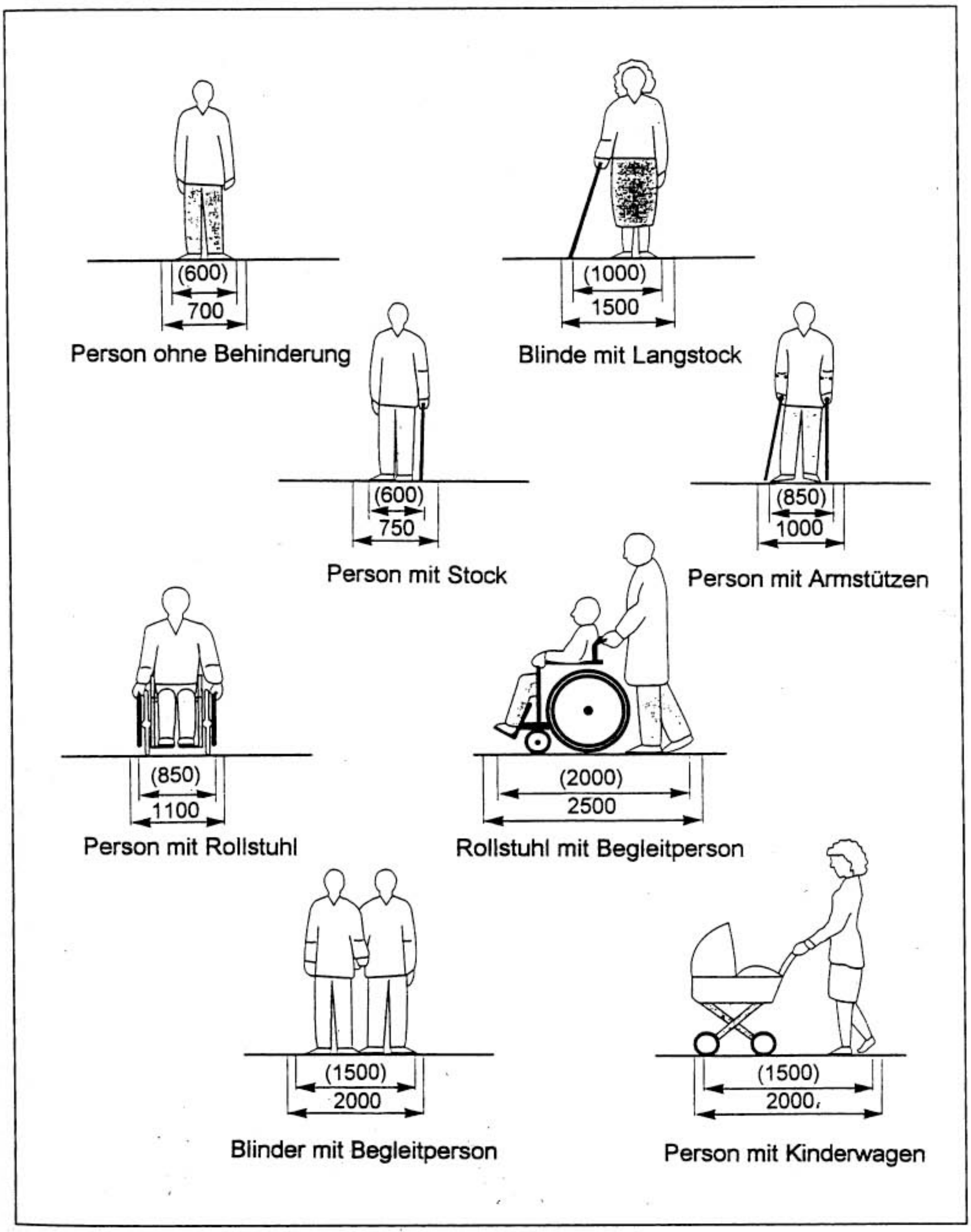


Figure 5 Dimensions of handicapped people (Ackermann 1997)

People moving by wheelchair require space for the dimensions of the wheelchair itself and a dynamic additional space for turning.

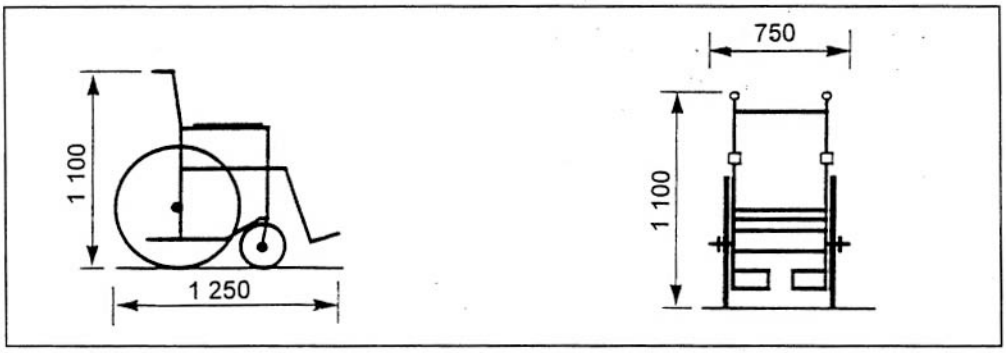


Abb. 4-1: Rollstuhl nach Normmaßen [49]

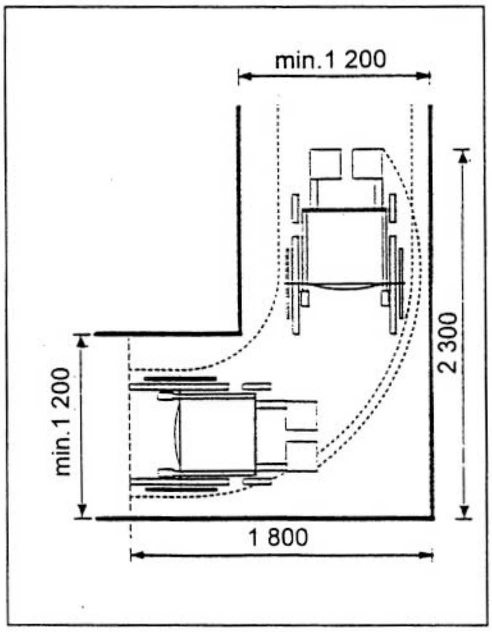


Abb. 4-2: Flächenbedarf für einen Rollstuhl bei Kurvenfahrt

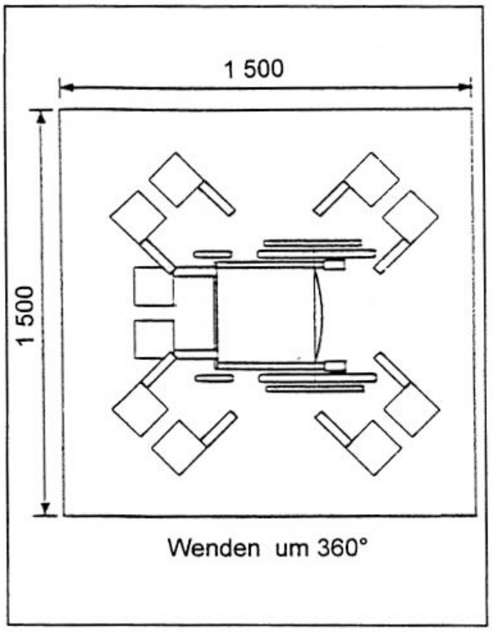


Abb. 4-3: Bewegungsfläche für einen Rollstuhl beim Wenden [73]

Figure 6 Basic dimensions and dynamical required space of wheelchairs

2.1.6 Body height

The average body height in Central Europe is 178.5 cm for male, 166.0 cm for female persons. The mean value for both gender is 172.3 cm. Body height is Gaussian distributed with a standard deviation of 3.3% of the average value, i.e. +/- 5.9 cm for men and +/- 5.5 cm for women.

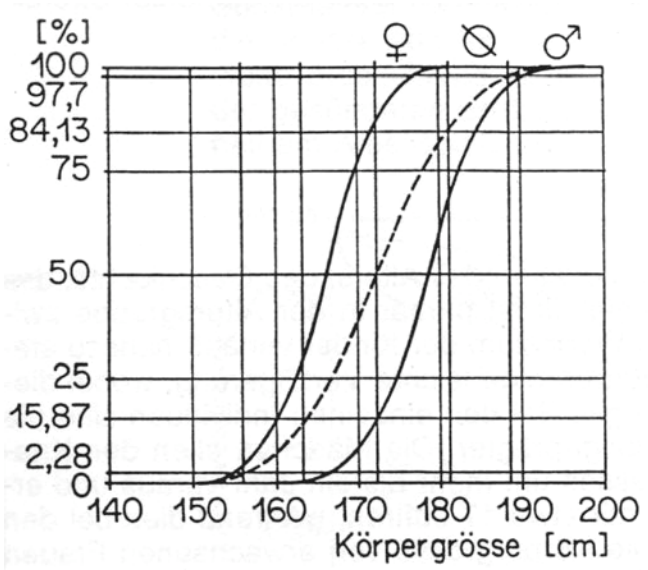


Figure 7 Distribution of body height for adult persons in Central Europe

The average body height is varying for different countries and populations. Table 4 shows differences of body height compared to the mean value of Central Europe.

Country	Relative Body Height
France	-3%
Italy	-2%
Japan	-6%
Thailand	-8%
Vietnam	-9%

Table 4 Relative body height compared to the average in Central Europe

Because of the period of growth body height is also a function of age. Figure 8 shows relative body height for male and female persons during the first two decades of life.

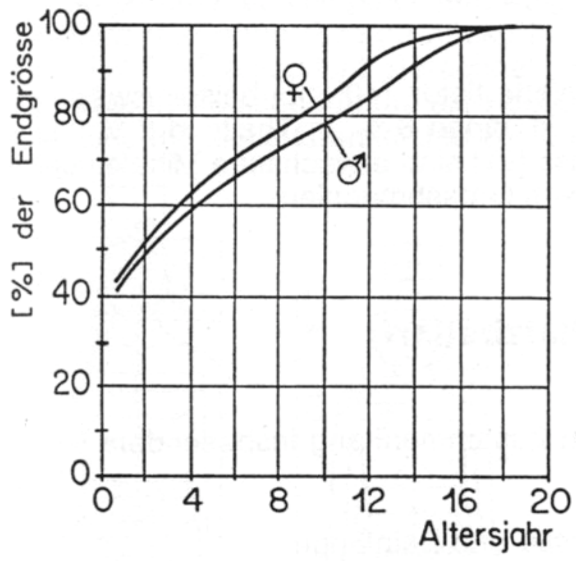


Figure 8 Relative body height for the adolescence (Weidmann 1993)

2.2 Energy consumption

2.2.1 Flat walkways

Pedestrian need for moving energy which has to be provided by physical processes of the human body. Therefore walking speed is limited by the physical capabilities of the individual organism. The energy consumption for moving depends on pedestrian speed and is different for walking and running. Energy minimum for walking is about 274 kJ/km at a walking speed of 1.39 m/s and about 250 kJ/km at 3.89 m/s for running.

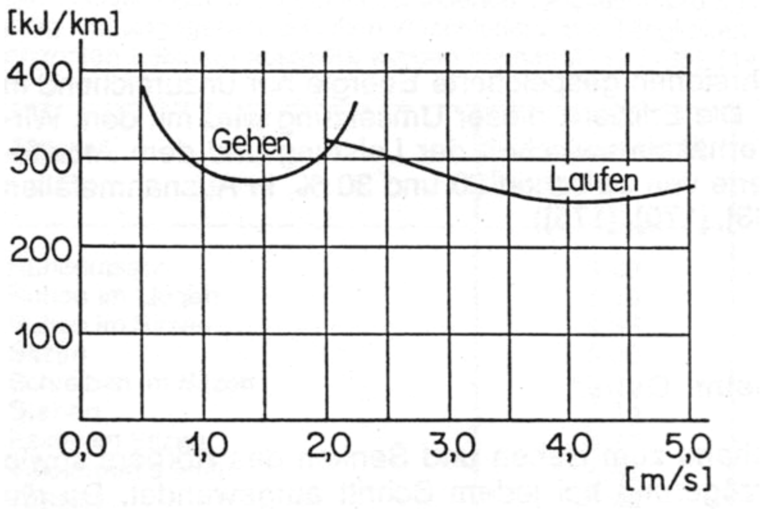


Figure 9 Total energy consumption for walking (left curve) and running (right curve) over a distance of 1000 metres (Weidmann 1993)

2.2.2 Inclined areas

On inclined areas energy consumption is very sensitive to the angle of inclination. At a gradient of 12% energy consumption is twice the value for flat areas. For declined areas up to 25% energy consumption is lower than on flat areas.

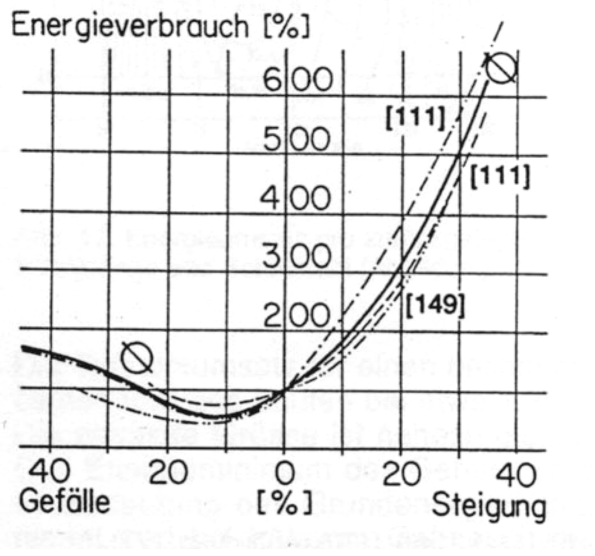


Figure 10 Relative energy consumption for walking on inclined areas (Weidmann 1993)

Combining the correlation between energy consumption and walking speed and the correlation of Figure 10, horizontal walking speed is directly related to the inclination (see section 2.3.5.1).

2.2.3 Energy consumption on stairs

On stairs additional energy has to be expended for the ascending movement. Therefore, total energy consumption for moving on stairs is mucher higher compared to walking on flat areas.

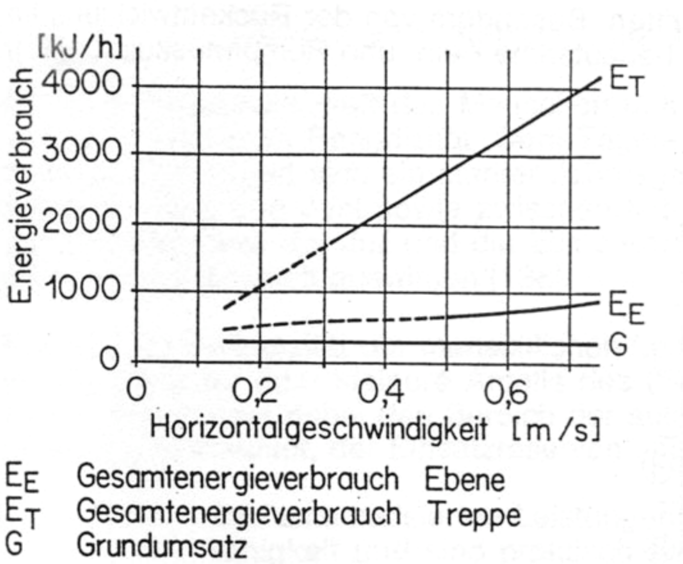


Figure 11 Energy consumption for moving upwards on stairs (E_T) compared to walking movement on flat areas (E_E), (Weidmann 1993)

2.3 Walking speed

2.3.1 Overview

The walking speed of individuals in unimpeded pedestrian flows appears to follow a normal distribution with an estimated mean of 1.34 m/s and a standard deviation of 0.37 m/s being calculated as a mean of Table 5. Under specific circumstances, the distribution can be as-symmetric. The median speed in these studies was 1.2 m/s (Fruin 1971).

Source	Mean speed [m/s]	Standard deviation [m/s]	Location
Crow (1998)	1.40		The Nederlands
Daly et al. (1991)	1.47		UK
FHWA (1988)	1.20		US
Fruin (1971)	1.40	0.15	US
Hankin & Wright (1958)	1.60		UK
Henderson (1971)	1.44	0.23	Australia
Hoel (1968)	1.50	0.20	US
Institute of Transportation Engineers (1969)	1.20		US
Knoflacher (1995)	1.45		Austria
Koushki (1988)	1.08		Saudi-Arabia
Lam et. al. (1995)	1.19	0.26	Hong Kong
Morrall et al. (1991)	1.25		Sri Lanka
Morrall et al. (1991)	1.40		Canada
Navin & Wheeler (1969)	1.32		US
O'Flaherty & Parkinson (1972)	1.32	1.0	UK
Older (1968)	1.30	0.30	UK
Pauls (1987)	1.25		US
Roddin (1981)	1.60		US
Sarkar & Janardhan (1997)	1.46	0.63	India
Sleight (1972)	1.37		US
Tanariboon et al. (1986)	1.23		Singapore
Tanariboon & Guyano (1991)	1.22		Thailand
Tregenza (1976)	1.31	0.30	UK
Virkler & Elayadath (1994)	1.22		US
Young (1999)	1.38	0.27	US
Estimated all average	1.34	0.37	

Table 5 Mean speed and standard deviation of unimpeded pedestrian flows (Daamen 2004)

Figure 12 Cumulative curve for normal distributed walking speeds (average = 1.34 m/s; standard deviation = 0.37 m/s)

The specific walking speed for pedestrians is determined by a lot of influencing factors. Some of them are listed in Table 6 and described in details in the following chapters.

Physical conditions of pedestrians	Cultural and racial differences (Section 2.3.2.1) Age (Section 2.3.2.2) Gender (Section 2.3.2.3) Body Height/Step Length (Section 2.3.2.4) Handicaps Luggage
Travel Purpose	(Section 2.3.3)
Environmental Conditions	Temperature (Section 2.3.4.1) Weather Daytime (Section 2.3.4.2)
Walkways attributes	Inclined Areas (Section 2.3.5.1) Stairways (Section 2.3.5.2) Escalators (Section 2.3.5.3)

Table 6 Influence factors on walking speed of pedestrians

2.3.2 Physical conditions

2.3.2.1 Cultural and racial differences

Most studies have been performed in Northern America, Europe and Asian countries. Walking behaviour in Northern America and Europe appears to be similar, whereas walking behaviour in the Asian countries is significantly deviant.

Taking the studies of Table 5 the following mean speeds can be derived: 1.41 m/s for European countries, 1.35 m/s for the US, 1.44 m/s in the Australian study and 1.24 m/s for the Asian countries.

2.3.2.2 Age

Walking speed is closely related to the physical capabilities of the pedestrian. Therefore, walking speed differ with the age of pedestrian. In fact, several studies (Daamen 2004) report an average walking speed for people over 60 of 1.06 m/s and a larger variance than for adults.

Only one author reports a speed-curve over all ages (Weidmann 1993) shown in Figure 13. This curve comports to the curve of physical capability.

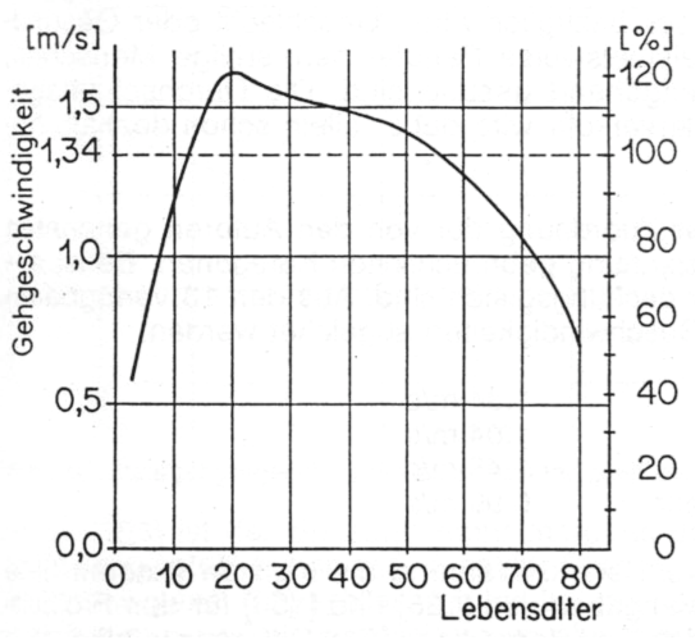


Figure 13 Correlation between walking speed and age (Weidmann 1993)

2.3.2.3 Gender

Men's walking speed is about 10.9% higher than the walking speed of women according to Weidmann (1993).

Source	Men	Women
	[m/s]	[m/s]
Weidmann (1993)	1.41	1.27
Hoel (1968)	1.55	1.45

Table 7 Mean walking speeds for men and women (Daamen 2004)

The walking speed differences between men and women could be explained by the specific physical characteristics, which lead to a larger step lengths and higher step frequencies for men.

The differences between the found values may be caused by different trip purposes. The values of Hoel (1968) are based on a data collection in a business district in Philadelphia.

2.3.2.4 Body height

A correlation between body height and walking speed is evident, but no data could be found. If we take into account, that body height and step length are correlated variables, walking speed can be derived from Figure 14.

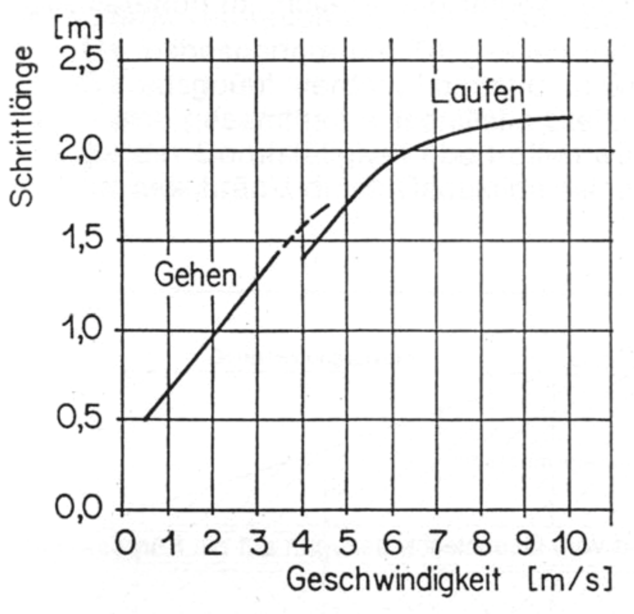


Figure 14 Correlation between step length and walking speed for walking (left curve) and running (right curve), (Weidmann 1993)

2.3.3 Travel purpose

According to the travel purposes, different walking speeds can be measured as shown in Table 8.

Travel Purpose	Walking speeds [m/s]	Standardized Values [m/s]
Business districts	1.45	1.61
Commuters	1.34	1.49
Shoppers	1.04	1.16
Leisure	0.99	1.10
Overall average	1.20	1.34

Table 8 Mean walking speeds for different trip purposes (Weidmann 1993)

If we assume an equal share for each travel purpose the calculated mean value for walking speed is 1.2 m/s, which is significantly lower than the mean value of section 2.3.1. In the third column of Table 8 the walking speeds for the different travel purposes are standardized on a overall mean value of 1.34 m/s.

Other studies found free walking speeds for commuters of 1.5 m/s and for students of 1.75 m/s (see Daamen 2004).

In pedestrian flows with different travel purposes, the standard deviation of walking speed increases up to 0.5 – 1.0 m/s (Daamen 2004).

2.3.4 Environmental conditions

2.3.4.1 Temperature

The physical capabilities of the human organism is a function of the environmental temperature, air humidity and the heat emission of the human body. Several studies were performed to analyze a possible correlation temperature and walking speed. The results are combined to the curve of Figure 15.

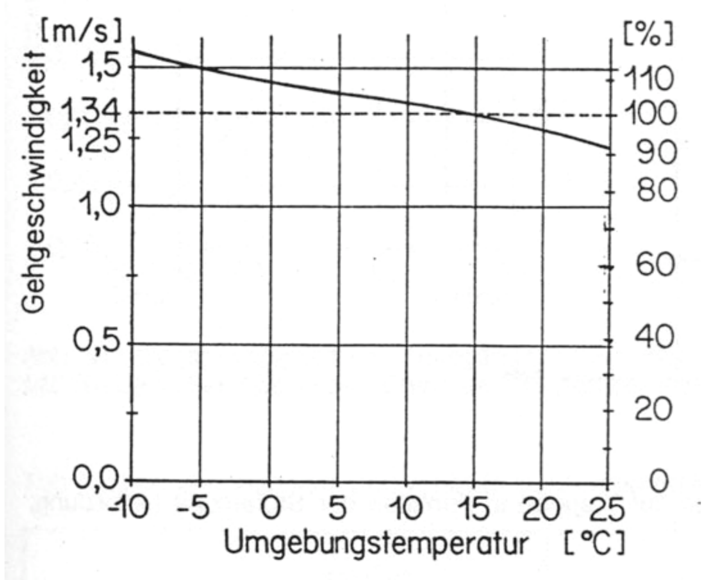


Figure 15 Correlation between walking speed and temperature (Weidmann 1993)

2.3.4.2 Daytime

Walking speed is probably influenced by the actual daytime corresponding to the varying physical capability of pedestrians over the day. There were only few studies performed about this correlation. Figure 16 shows a hypothesis for walking speed over the day.

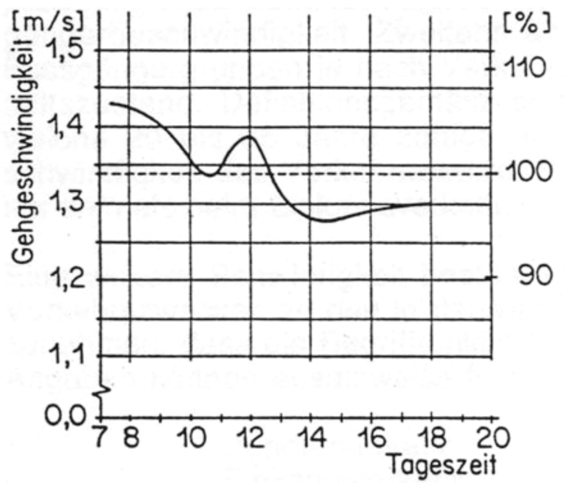


Figure 16 Varying walking speed over the day (Weidmann 1993)

2.3.5 Walkway attributes

2.3.5.1 Inclination of walkways

With an inclination of walkways walking speed of pedestrians is changing. In upward direction pedestrians are getting slower. Downwards, for declinations below 20%, walking speed is increasing. Inclinations over 20% are seldom used for walkways. For this field of application in pedestrian facilities, stairs, escalators or elevators are used.

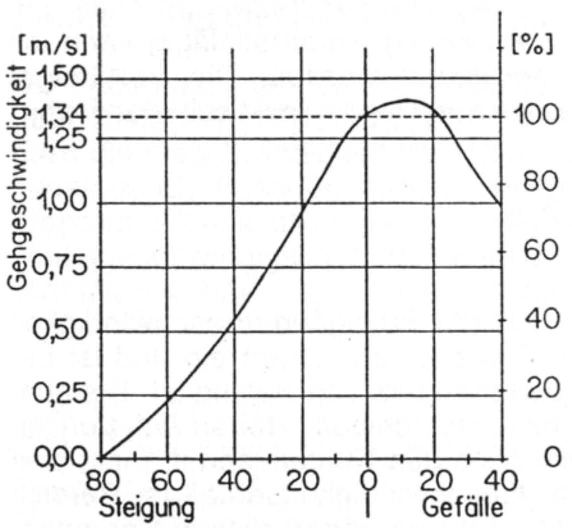


Figure 17 Mean horizontal walking speed on inclined areas (Weidmann 1993)

Inclination	Upward direction		Downward direction	
	$v_{horizontal}$	$v_{vertical}$	$v_{horizontal}$	$v_{vertical}$
	[m/s]	[m/s]	[m/s]	[m/s]
0%	1.34	0.00	1.34	0.00
5%	1.29	0.06	1.38	0.07
10%	1.19	0.12	1.40	0.14
15%	1.07	0.16	1.40	0.21

Table 9 Mean walking speeds of pedestrian on inclined areas (Weidmann 1993)

2.3.5.2 Stairs

Stairs are used to connect different levels in walking facilities, especially in cases where ramps would be to steep or the required space for ramps is not available. Typical angles of inclination for stairs are between 30% and 45%.

Walking speeds on stairs are lower than on walkways, in both directions. The mean horizontal walking speed on stairs decreases to 48% in upward and 54% in downward direction compared to the free-flow speed on flat walkways.

	$v_{horizontal}$	$v_{vertical}$	v
	[m/s]	[m/s]	[steps/s]
Upward	0.610	0.305	1.97
Downward	0.694	0.347	2.24

Table 10 Mean walking speeds of pedestrian on inclined areas (Weidmann 1993)

Different studies found that walking speed is going down with increased length of stairways.

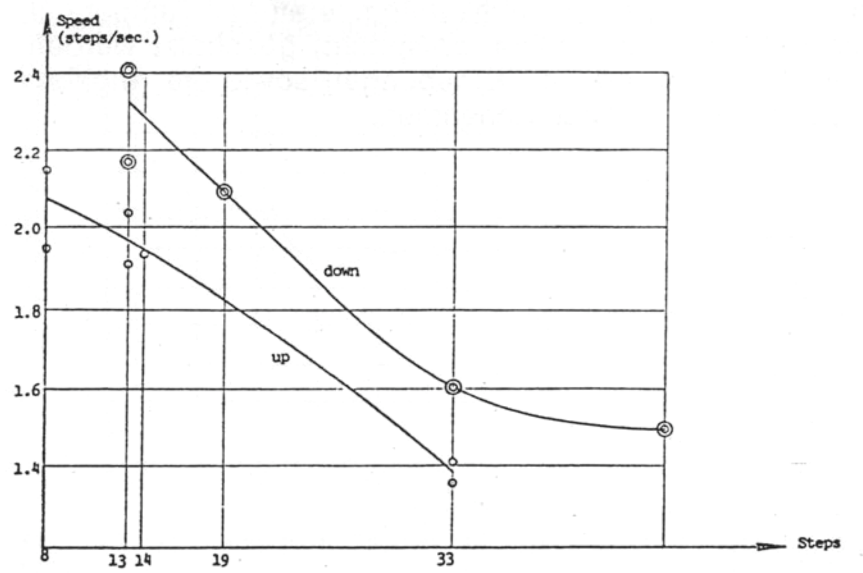


Figure 18 Deceleration of pedestrian on long stairways (Weidmann 1993)

Therefore for big level differences stairs are amended or replaced by escalators or elevators.

2.3.5.3 Escalators

Escalators are used instead or as amendment of stairways to provide more comfort or to connect higher level differences. Typical escalators have a inclination angle of 30°. The maximum inclination in Europe is restricted to 35° (EN 115; *[10]*).

The inner width of escalators starts at a minimum of 600 mm and goes up to 1000 mm, which represents a two-lane-stair and allows bypassing of pedestrians. The steps are about 400 mm deep.

Most of the escalators have a travel speed of about 0.5 m/s. Other common travel speeds are 0.65 m/s or 0.75 m/s, which is the maximum value after EN 115.

At both ends of escalators horizontal runout areas of 800 – 1200 mm (2 or 3 steps long) have to be placed. They ensure a smooth passage between walkways and escalators.

2.3.5.4 Moving walkways

Moving walksways are providing more pedestrian comfort for long walking distances. They can be placed horizontal or can have an inclination up to a maximum of 12°.

In most cases maximum speed is restricted to 0.75 m/s. Travel speed for moving walkways can be increased up to 0.9 m/s, if the inner width is lower than 1000 mm and horizontal runout areas have a minimum length of 1600 mm.

2.4 Flow rates

2.4.1 Empirical values

The flow rate is defined as number of persons passing a section within a period of time and is measured in [P/sm]. The maximum flow rates measured in pedestrians flows is varying with different countries. In Asia pedestrian flows of about 1.50 P/ms are observed. These values exceed those in American or European facilities caused by smaller Asian body buffer zone.

Region	Maximum flow rates [P/ms]
Asian countries	1.48 – 1.53
Europe, America	1.00 – 1.29

Table 11 Maximum flow rates for different regions (Daamen 2004)

Values of maximum flow rates derived from speed-density-relations are of the same size (see section 3.1.1, 3.2).

2.4.2 Flow rates and pedestrian speed

The flow rates of pedestrian flows depends on the speed-density-condition. Pedestrians can choose their preferred walking speed at low pedestrian volumes, i.e. if pedestrian density is lower than approximately 0.5 P/m^2 (unimpeded pedestrian flow). But under more crowded conditions pedestrian density and walking speed are correlated variables (see section 3.1).

Under normal conditions, pedestrians intend to avoid physical contacts, which is possible for pedestrian densities lower than 3.0 - 3.5 P/m^2. In waiting areas, where pedestrians can choose their waiting position, densities between 2.0 and 2.9 P/m^2 can be observed.

At densities over 5.0 P/m^2 people can't hardly move. But if pedestrians are forced, much higher densities can be reached. The maximum pedestrian density can be derived from the minimum dimension of the human body. The minimum body surface of an average pedestrian measures about 0.15 m^2, which leads to a maximum density of 6.7 P/m^2.

In literature different values for unimpeded and jammed pedestrian flows can be found.

Source	**Unimpeded Flows**	**Jammed Flows**
	Pedestrian density [P/m^2]	Pedestrian density [P/m^2]
Fruin (1971)	< 0.5	> 5.0
Pauls (1987)	< 0.5	4.0 – 5.0
Pushkarev & Zupan (1975)		2.5 – 5.0
Sarkar & Janardhan (1997)		> 4.2
Weidmann (1993)	< 0.5	> 5.4

Table 12 Pedestrian densities of unimpeded and jammed pedestrian flows (Daamen 2004)

3 Principles of pedestrian flows

3.1 Walking on flat areas

3.1.1 One-directional flow

In unimpeded flows pedestrians can choose their walking speed freely unattending to other pedestrians. The values of free-flow speed can be observed. At densities higher than 0.5 P/m^2 the walking speed of pedestrians is decreasing. At a densities over 5 P/m^2 pedestrians can't hardly move.

The relation between walking speed and pedestrian density was described through the Kladek formula by Weidmann (1993).

$$v(d) = v_0 \cdot \left[1 - e^{-1.913 \cdot \left[\frac{1}{d} - \frac{1}{d_{jam}} \right]} \right] \qquad (1)$$

v: *walking speed [m/s]*
v_0: *free-flow walking speed [m/s]*
d: *pedestrian density [P/m^2]*

Other authors used linear or exponential formulas, two- or three regime approaches to describe speed-density-relation.

Source	Location	Relation	
Fruin (1971a)	Peak-hour flows at commuter bus terminal	$v = 1.43 - 0.35d$ $f = 1.43d - 0.35d^2$ $f = 4.08v - 2.86v^2$	
Older (1968)	Shopping streets	$v = 1.31 - 0.34d$ $f = 1.32d - 0.34d^2$ $f = 3.85v - 2.94v^2$	
Sarkar & Janardhan (1997)	Calcutta Metropolitan transfer area	$v = 1.46 - 0.35d$ $f = 1.46d - 0.35d^2$ $f = 4.17v - 2.86v^2$	
Tanariboon et al. (1986)	Singapore	$v = 1.23 - 0.26d$ $f = 1.23d - 0.26d^2$ $f = 4.73v - 3.85v^2$	
Virkler & Elayadath (1994)	Pedestrian tunnel after University of Missouri football games	$d < 1.07$ [P/m^2] $v = 1.01 \exp(-k/4.17)$ $f = 4.17\ v \ln(1.01/v)$ $f = 1.01\ d \exp(-d/4.17)$	$d > 1.07$ [P/m^2] $v = 0.61 \ln(4.32/d)$ $f = 4.32\ v \exp(-v/0.61)$ $f = 0.61\ d \ln(4.32/d)$
Weidmann (1993)	Kladek formula	Equation 1	
Variables: v: walking speed [m/s], d: pedestrian density [P/m^2], f: flow [P/ms]			

Table 13 Speed-density-relations (Daamen 2004, Virkler & Elayadath 1994, Weidmann 1993)

The formulas of Table 13 are derived from measurements in different pedestrian facilities. They were performed in everyday situations, where people aren't forced to walk at a certain speed. The differences in the described formulas are based on different measurement situations (location, pedestrian attributes, trip purposes).

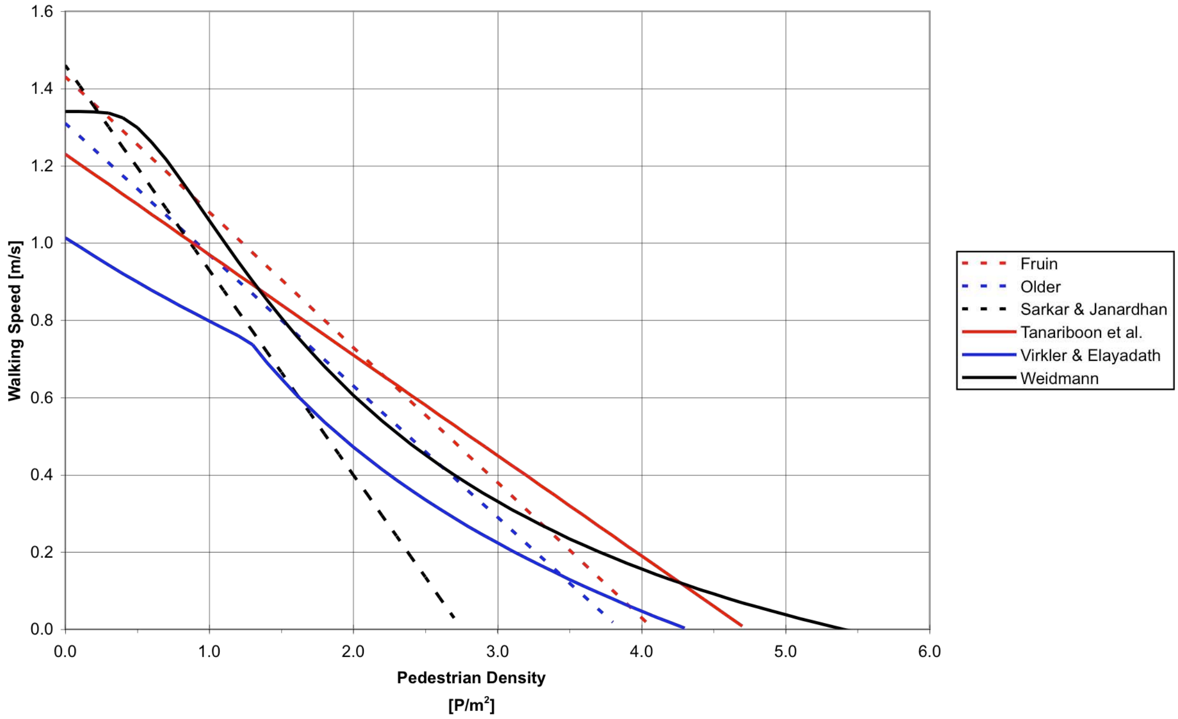


Figure 19 Definition of Speed-Density-Relations (Daamen 2004, Virkler & Elayadath 1994, Weidmann 1993)

Out of the speed-density-relation, the pedestrian flow can be calculated with Equation 2.

$$f = d \cdot v(d) \tag{2}$$

f: *pedestrian flow [P/ms]*
d: *pedestrian density [P/m²]*
v: *walking speed [m/s]*

For the speed-density-relations of Table 13 the resulting pedestrians flows are shown in Figure 20.

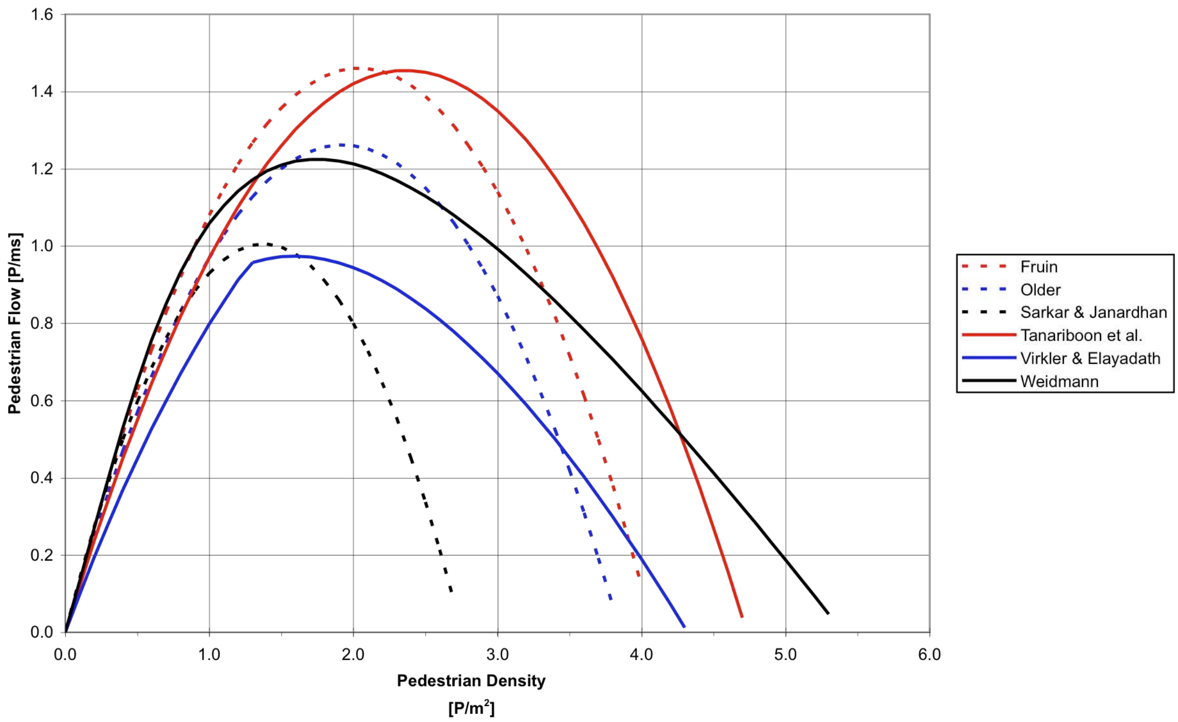


Figure 20 Pedestrian flows derived of the speed-density-relations (Daamen 2004, Virkler & Elayadath 1994, Weidmann 1993)

Out of the pedestrian flow curves the maximum flow rate and the corresponding walking speed and pedestrian density can be read off.

	Maximum Pedestrian Flow	Corresponding Walking Speed	Corresponding Density
	f_{max}	v_{fmax}	d_{fmax}
	[P/ms]	[m/s]	[P/m^2]
Fruin	1.46	0.72	2.04
Older	1.26	0.65	1.93
Sarkar & Janardhan	1.01	0.73	1.38
Tanariboon et al.	1.45	0.61	2.37
Virkler & Elayadath	0.97	0.61	1.59
Weidmann	1.22	0.70	1.75

Table 14 Maximum pedestrian flows on walkways (Daamen 2004, Virkler & Elayadath 1994, Weidmann 1993)

These values of maximum flow rates represent the theoretical capacity of walkways under normal conditions.

Taking the kladek-formula (Weidmann 1993) the following diagramm shows the relation between speed, density and pedestrian flow for a average free-flow walking speed of 1.34 m/s

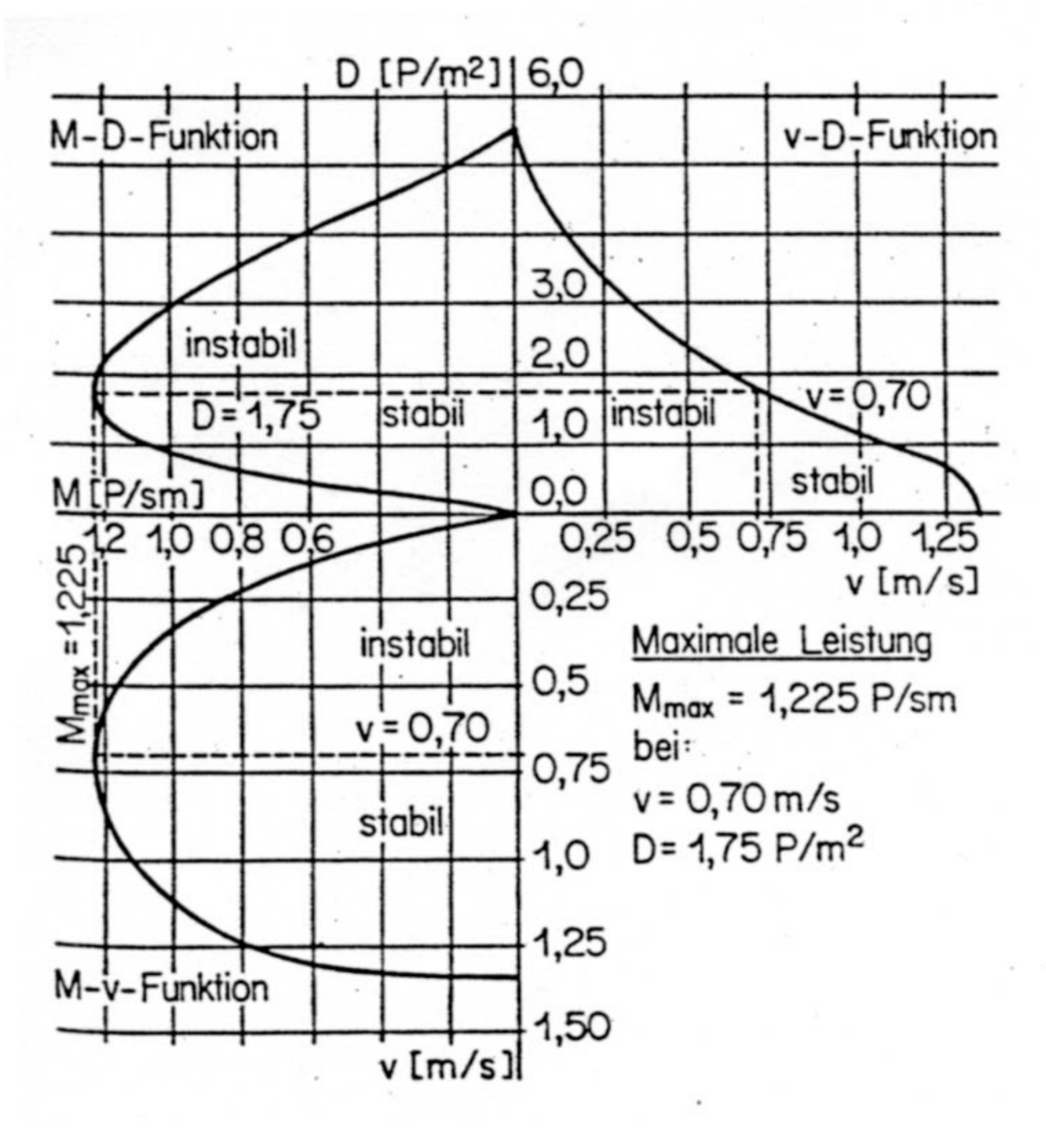


Figure 21 Fundamental diagram for walking pedestrians on flat walkways (Weidmann 1993)

Starting with a pedestrian density of nearly 0 P/m^2, people are walking with free-flow speed. With increased pedestrian density pedestrians are slowing down due to reduced headway distances. Nevertheless, the pedestrian flow is still increasing. So far, the flow is stable and no congestion occurs. At a density of about 1.75 P/m^2 the maximum pedestrian flow is reached. If more pedestrians arrive, density increases further, but the flow rate is going down again.

The situations gets unstable and congestion occurs. The capacity of the walking facility is exceeded.

3.1.2 Bypassing pedestrians

Schopf (1985) studied the process of bypassing pedestrians. At the beginning of this ordinary, frequent situation there are two pedestrians approaching each other. At a certain distance they sidestep off the ideal line. After bypassing, they return back on the ideal line (see Figure 22).

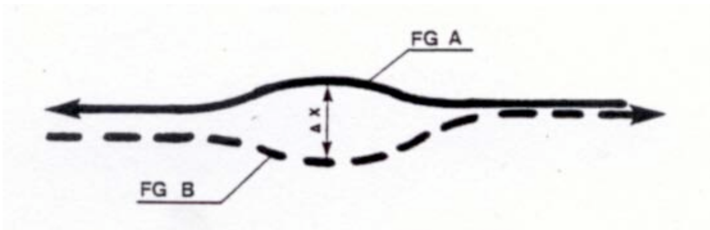


Figure 22 Movement of bypassing pedestrians (Schopf 1985)

Figure 23 shows the distribution of the minimal lateral distance between bypassing pedestrians.

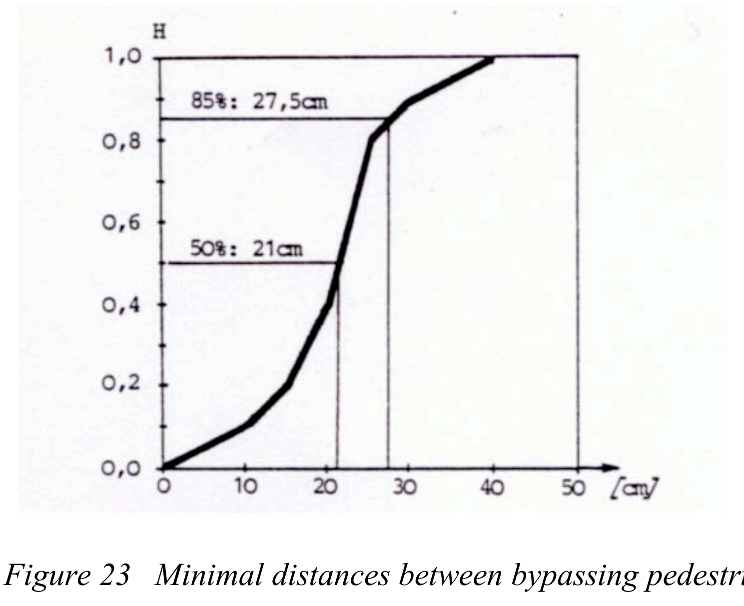


Figure 23 Minimal distances between bypassing pedestrians (Schopf 1985)

3.1.3 Bi-directional flows

In bi-directional pedestrian flows there are in addition to the density-related effects interactions between bypassing pedestrians leading to a capacity loss for the walkway.

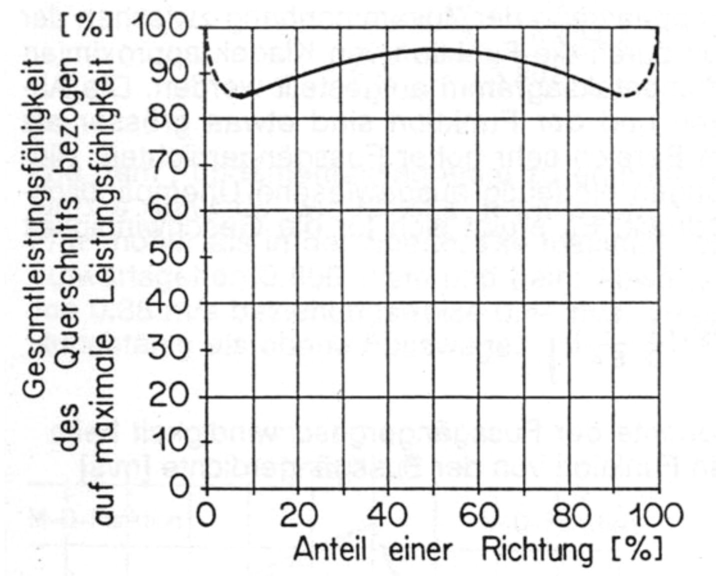


Figure 24 Capacity loss for bidirectional pedestrian flows in function of the proportion of the directional flows

In case of equal flows in both directions (50/50%), a small loss of capacity of about 4% occurs. The capacity loss increases, if the percentage of the weaker pedestrian stream gets lower. For a directional ratio of 10/90%, a loss of 14.5% could be observed. This phenomen could be explained by the following consideration: Studies showed that the smaller pedestrian stream in bi-directional pedestrian flows needs relatively more space as shown in Figure 25. Therefore for the bigger stream remains less space leading to the capacity loss.

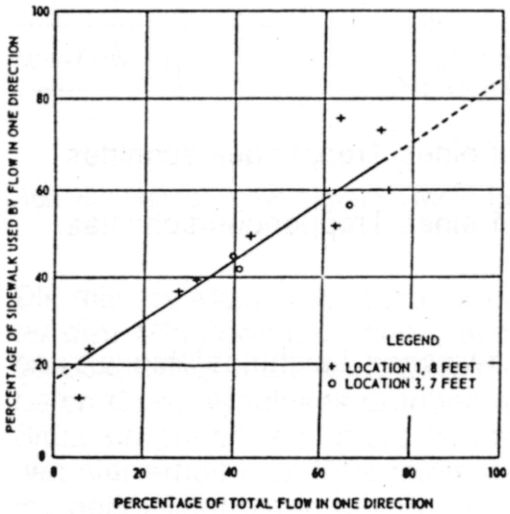


Figure 25   Required width for the in bidirectional pedestrian flows

In recent studies pedestrian simulations are used to model multi-directional. The above described phenomen was confirmed by the simulation models, which provided the following results.

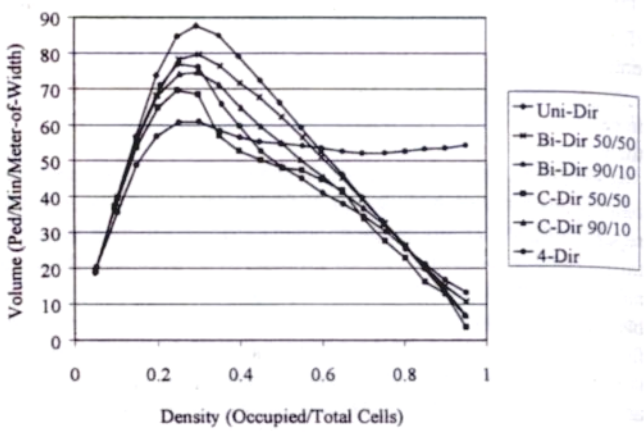


Figure 26   Simulation results of different multidirectional pedestrian flows (Blue 1999)

The maximum flows of the simulation results are shown in Table 15.

Pedestrian flow	Maximum flow	Capacity loss
	[P/ms]	[%]
Uni-directional Flow	1.47	
Bi-directional (50%/50%)	1.33	-9.1
Bi-directional (90%/10%)	1.28	-12.5

Table 15 Simulation results for bi-directional pedestrian flows (Blue 1999)

The empirical and simulation results for a directional ratio of 90/10% are about the same size. There is a capacity loss of about 12 to 14%.

In case of equal flows in both direction the resulting capacity loss is varying from 4 to 9%. The particular capacity loss depends on the separation of the pedestrian streams. In case of well separated streams in opposite directions the capacity loss is lower than with disperse streams. In everyday situations in pedestrian facilities the level of separation is influenced by many pedestrian- or facility-specific factors and has to be quantified for the particular situation.

3.2 Walking on stairs

For walking movements of pedestrians on stairs the speed-density relation for walkways can be adapted to a fundamentaldiagram for stairways. Equation 3 describes the horizontal walking speed on stairs in upward direction, Equation 4 in opposite direction.

$$v_{h,up} = 0.610 \cdot \left[1 - e^{-3.722 \cdot \left[\frac{1}{d} - \frac{1}{5.4}\right]}\right] \tag{3}$$

$$v_{h,down} = 0.694 \cdot \left[1 - e^{-3.802 \cdot \left[\frac{1}{d} - \frac{1}{5.4}\right]}\right] \tag{4}$$

$v_{h,up}$: *horizontal speed in upward direction [m/s]*
$v_{h,down}$: *horizontal speed in downward direction [m/s]*
d: *pedestrian density [P/m²]*

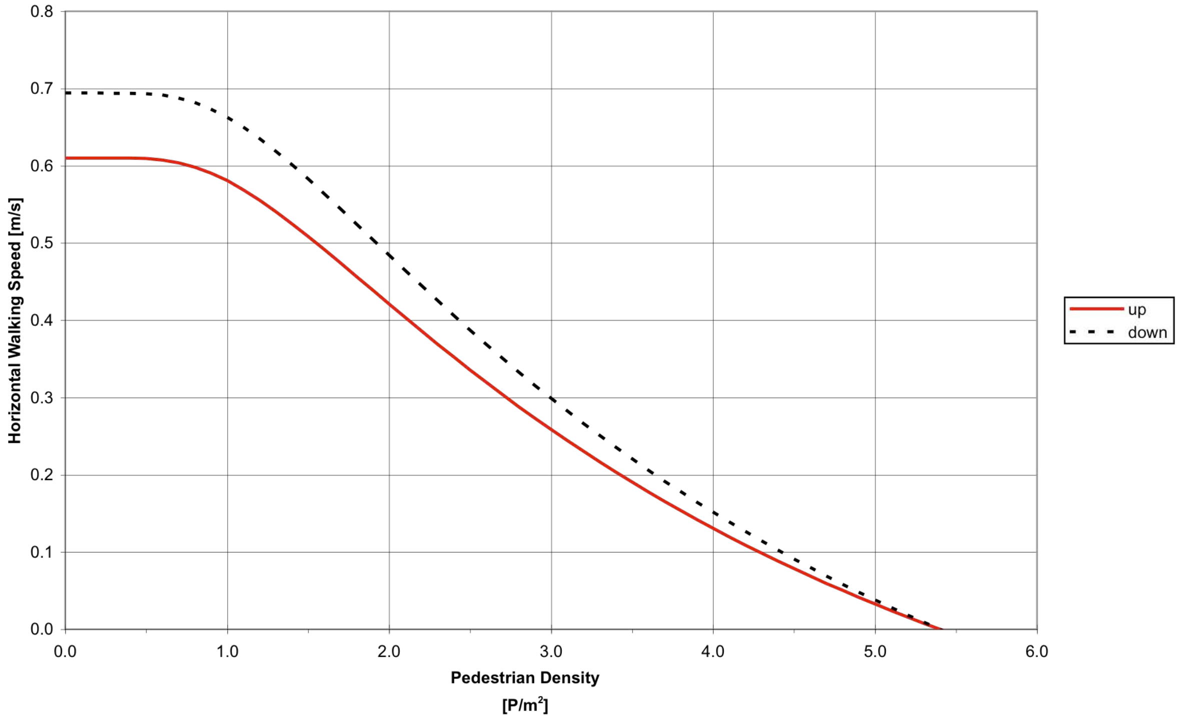


Figure 27 Speed-density-relation for pedestrian movement on stairs for both directions (Weidmann 1993)

Using the speed-density-relation of Figure 27 and Equation 2, the pedestrian flows on stairways can be defined.

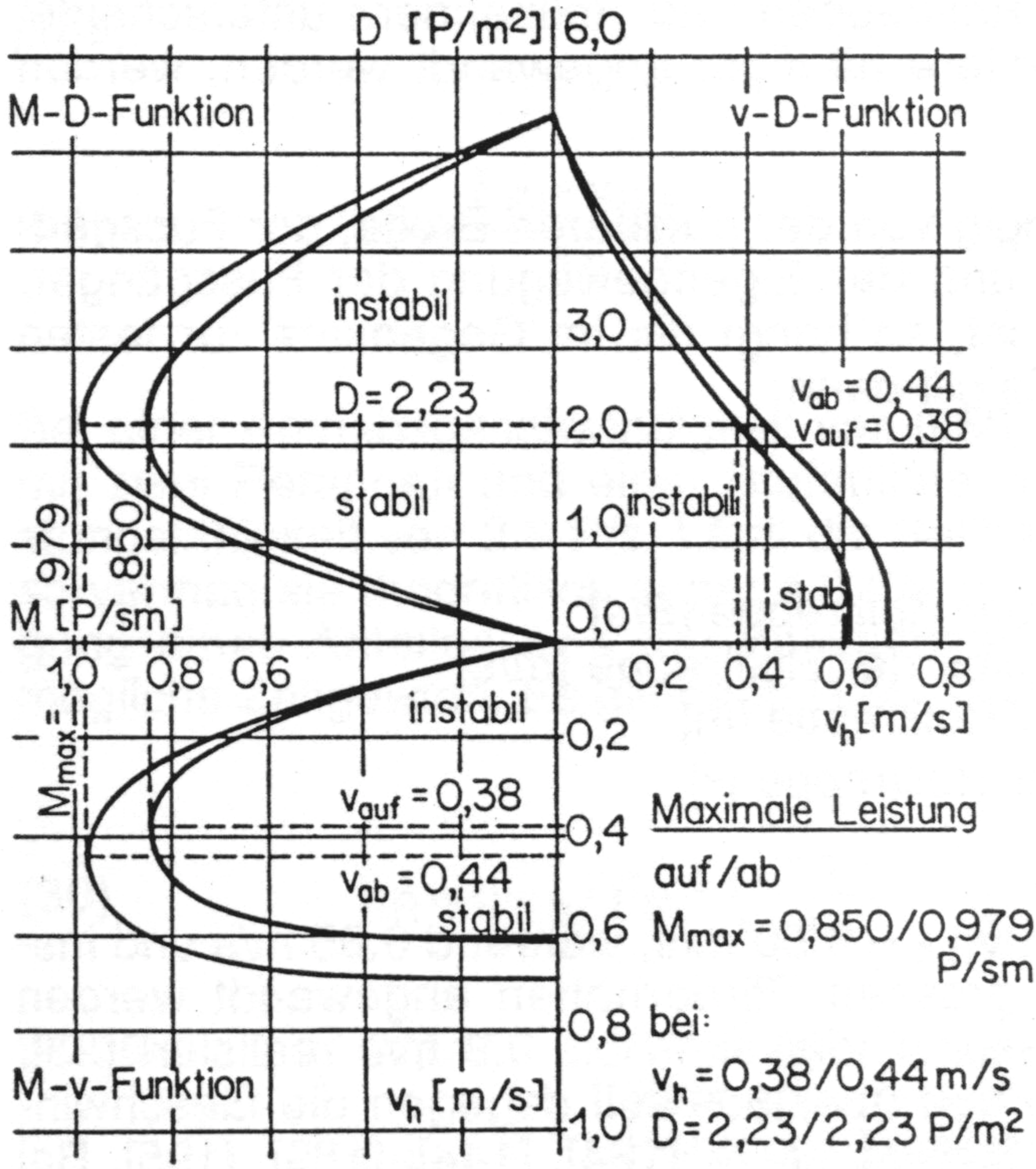


Figure 28 Fundamental diagram for pedestrian flows on stairs (Weidmann 1993)

Evaluating the maximum pedestrian flows for both directions separately lead to the capacity of stairways.

Direction	Maximum Pedestrian Flow	Corresponding Walking Speed	Corresponding Density
	f_{max}	v_{fmax}	d_{fmax}
	[P/ms]	[m/s]	[P/m²]
Upward	0.85	0.38	2.23
Downward	0.98	0.44	2.23

Table 16 Maximum pedestrian flows on stairs (Weidmann 1993)

3.3 Walking on escalators

Pedestrian behaviour on escalators is different from pedestrians on stairways. Most of them are using escalators without moving. Therefore, capacity of escalators is restricted (only) by the attributes of the facility.

$$c = v_{esc} \cdot \cos\alpha \cdot b_{st} \cdot d \tag{5}$$

c: *escalator capacity [P/s]*
v_{esc}: *travel speed of the escalator [m/s]*
a: *inclination angle of the escalator [-]*
b_{st}: *width of steps [m]*
d: *pedestrian density [P/m²]*

$$d = \frac{P_{st}}{b_{st} \cdot a_{st} \cdot \cos\alpha} \tag{6}$$

$P_{st:}$ *Number of pedestrians per step [P]*
a_{st}: *depth of escalator steps [m]*

Combining Equation 5 and 6 the capacity of escalators is defined as Equation 7.

$$c = \frac{P_{st} \cdot v_{esc}}{a_{st}} \tag{7}$$

Equation 7 suggests that capacity of escalator is linear increasing with the travel speed. But studies in real-life situations (Westphal 1974) showed that the number of pedestrians per step is decreasing with higher travel speeds of escalators. This is due to the inflow conditions at the beginning of escalatorsor the lacking acceptance of high travel speeds by the users of escalators. The following analyses are valid for two-lane-escalators with a width of 1.0m, which is the most common type.

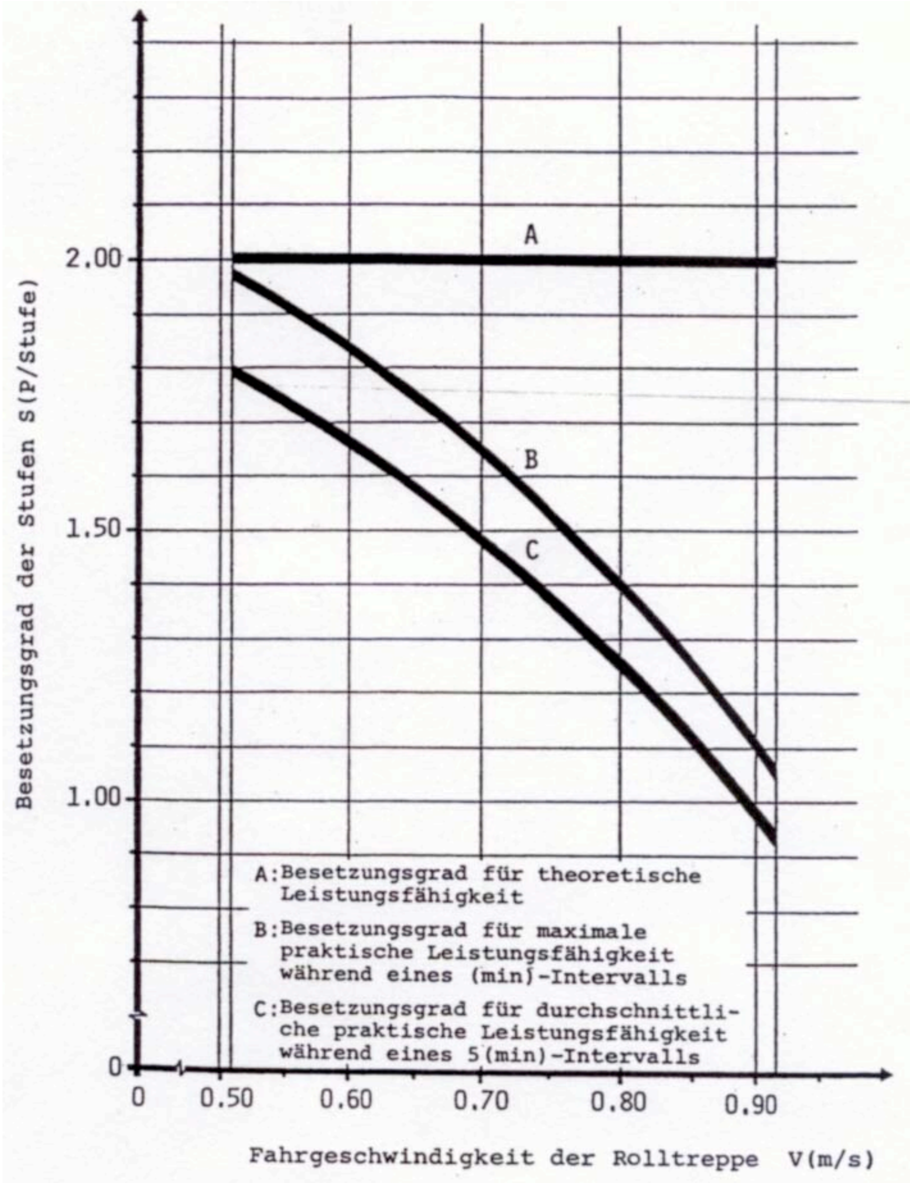


Figure 29 Occupancy of escalator steps dependent on escalator travel speed (Westphal 1974)

Due to this effect, there is an optimal travel speed for escalators, where capacity limit is rea-ched.

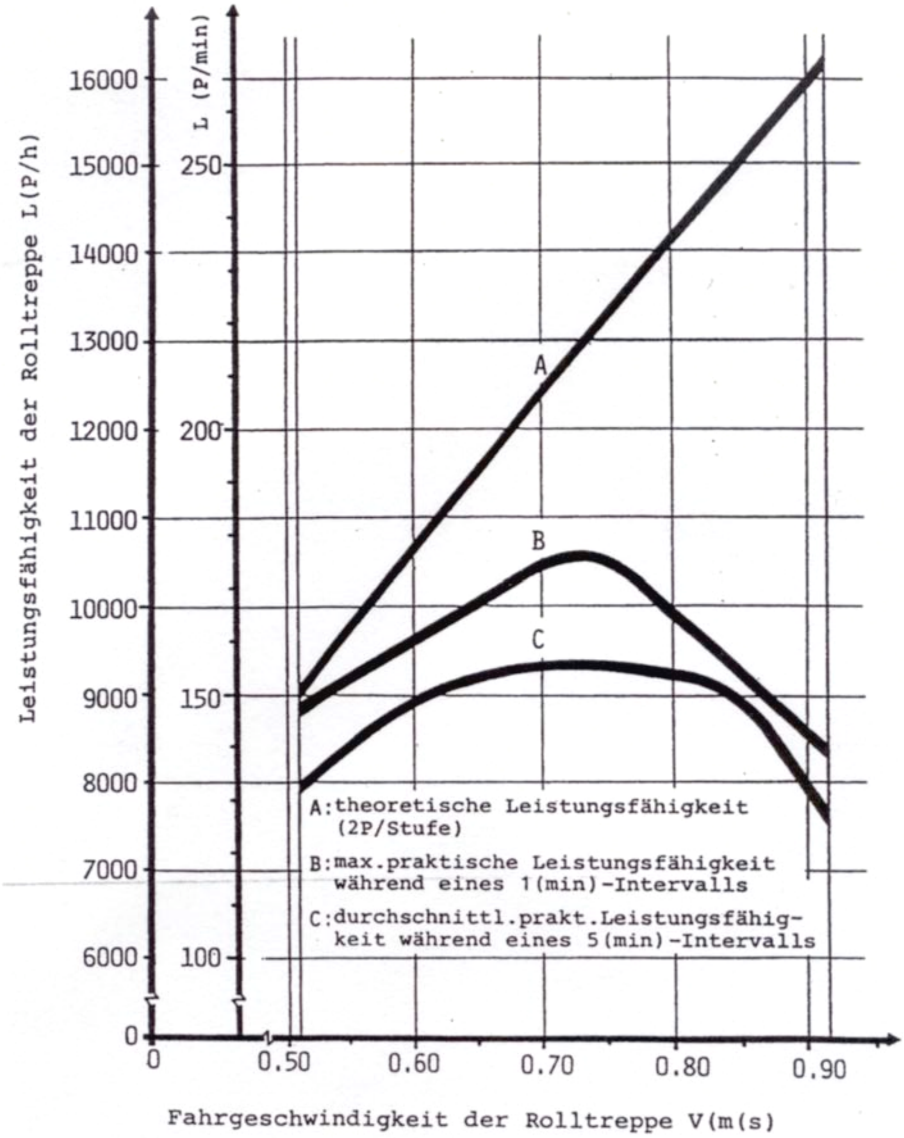


Figure 30 Capacity curves for escalators: theoretical values (Curve A), practical values: for 1 min intervals (Curve B) and 5 min intervals (Curve C), (Westphal 1974)

Interval	Travel speed	Capacity		Occupancy of steps
	[m/s]	[P/h]	[P/s]	[P/step]
1 min Interval	0.50	8900	2.47	1.98
	0.73	10650	2.95	1.62
5 min Interval	0.50	8000	2.22	1.78
	0.71	9300	2.58	1.46

Table 17 Practical values for capacities of escalators for different travel speeds and intervals (step width 1.0 m; step depth 0.4 m)

For long-term-intervals, e.g. one hour, the influence of inflow conditions is getting more important. For a 1 hour interval the transport performances of Table 18 should be exceeded for capacity analyses.

Step width [m]	Travel speed [m/s]	Capacity [P/h]	[P/s]	Occupancy of steps [P/step]
0.6	0.50	3600	1.00	0.80
	0.65	4400	1.22	0.75
	0.75	4900	1.36	0.73
0.8	0.50	4800	1.33	1.07
	0.65	5900	1.64	1.01
	0.75	6600	1.83	0.98
1.0	0.50	6000	1.67	1.33
	0.65	7300	2.03	1.25
	0.75	8200	2.28	1.21

Table 18 Practical values for capacities of escalators for 1 hour intervals (step depth 0.4 m; DIN EN 115; [10]*)*

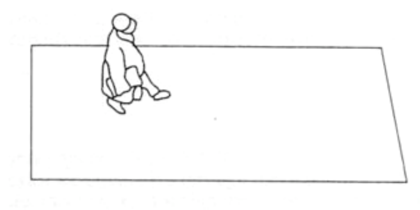
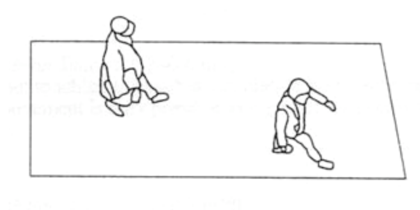
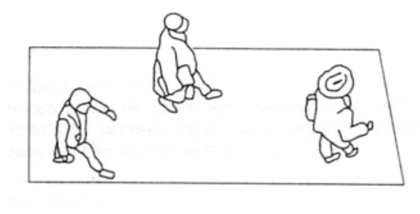
4 Analysing pedestrian flows in walking facilities

4.1 Evaluation of pedestrian flows (level of service concept)

To evaluate the quality of traffic conditions for pedestrians and to control the layout and dimensions of pedestrian facilities the Level of Service concept can be applied. Recent standards define 6 quality levels from A to F. They are representing comfort levels for the user of infrastructure and are based on pedestrian densities. For different parts of the infrastructure specific LoS definitions exist.

4.1.1 Walkways

In the following table there is a description of Levels A to F for walkways according to the Highway Capacity Manual (2000; [27]).

Level of Service	Description of the walkway conditions	
A	At LOS A, pedestrians move in desired paths without altering their movements in response to other pedestrians. Walking speeds are freely selected, and conflicts between pedestrians are unlikely.	
B	At LOS B, there is sufficient area for pedestrians to select walking speeds freely, to bypass other pedestrians, and to avoid crossing conflicts. At this level, pedestrians begin to be aware of other pedestrians, and to respond to their presence when selecting a walking path.	
C	At LOS C, space is sufficient for normal walking speeds, and for bypassing other pedestrians in primarily unidirectional streams. Reverse-direction or crossing movements can cause minor conflicts, and speeds and flow rate are somewhat lower.	

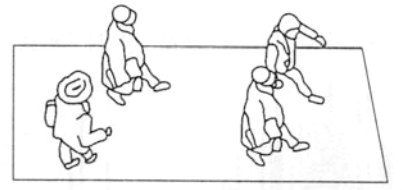
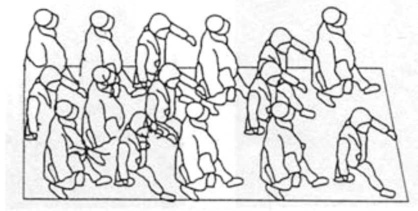
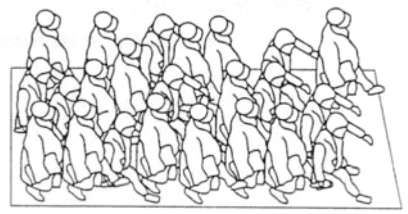
D	At LOS D, freedom to select individual walking speed an to bypass other pedestrians is restricted. Crossing or reverse-flow movements face a high probability of conflict, requiring frequent changes in speed and position. The LOS provides reasonably fluid flow, but friction and interaction between pedestrians is likely.	
E	At LOS E, virtually all pedestrians restrict their normal walking speed, frequently adjusting their gait. At the lower range, forward movement is possible only by shuffling. Space is not sufficient for passing slower pedestrians. Corss- or reverse-flow movements are possible only with extreme difficulties. Design volumes approach the limit of walkway capacity, with stoppages and interruptions to flow.	
F	At LOS F, all walking speeds are severely restricted, and forward progress is made only by shuffling. There is frequent, unavoidable contact with other pedestrians. Cross- and reverse-flow movements are virtually impossible. Flow is sporadic and unstable. Space is more characteristic of queued pedestrians than of moving pedestrian streams.	

Table 19 Description of the Level-of-Service for walkways (HCM 2000)

Standards of level-definitions for the US and for Germany and definitions of Fruin (1971) are listed in Table 20.

Level of Service	Highway Capacity Manual (2000), [27]	Handbuch für Bemessung von Strassenverkehrsanlagen (2001), [11]	Fruin
	[P/m^2]	[P/m^2]	[P/m^2]
A	< 0.18	< 0.10	< 0.31
B	0.18 – 0.27	0.10 – 0.25	0.31 – 0.43
C	0.27 – 0.45	0.25 – 0.40	0.43 – 0.71
D	0.45 – 0.71	0.40 – 0.70	0.71 – 1.11
E	0.71 – 1.33	0.70 – 1.80	1.11 – 2.00
F	> 1.33	> 1.80	> 2.00

Table 20 LoS-definitions for walkways (HCM 2000, HBS 2001, Fruin 1971)

4.1.2 Stairs

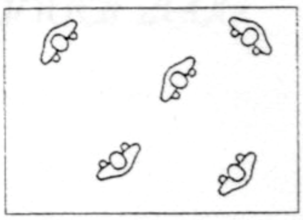
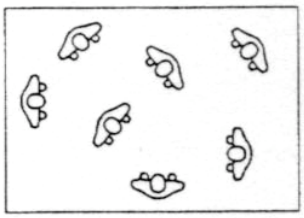
For pedestrian flows on stairways there are adapted LoS-definitions in the Highway Capacity Manual (2000) and by Fruin (1971). The defined pedestrian densities on each quality level are higher than for walkways (see Table 21).

Level of Service	Highway Capacity Manual (2000) [P/m²]	Fruin [P/m²]
A	< 0.53	< 0.53
B	0.53 – 0.63	0.53 – 0.72
C	0.63 – 0.91	0.72 – 1.08
D	0.91 – 1.43	1.08 – 1.54
E	1.43 – 2.00	1.54 – 2.69
F	> 2.00	> 2.69

Table 21 LOS-definition for stairs (HCM 2000, Fruin 1971)

4.1.3 Waiting areas

For waiting and queuing situations and areas specific levels of service are to be applied. The conditions at each quality level are described in Table 22.

Level of Service	Description of the walkway conditions	
A	Standing and free circulation through the queuing area is possible without disturbing others within the queue.	
B	Standing and partially restricted circulation to avoid disturbing others in the queue is possible.	

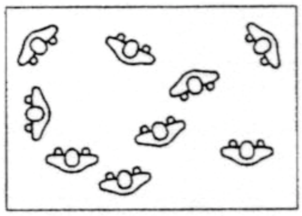
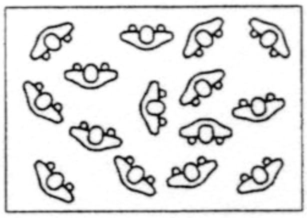
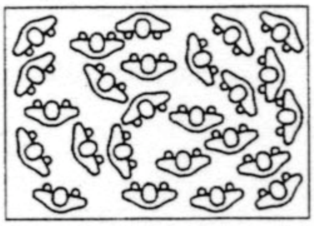
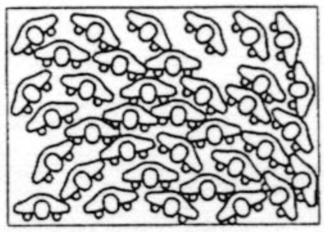
C	Standing and restricted circulation through the queuing area by disturbing others in the queue is possible; this density is within the range of personal comfort.	
D	Standing without touching is possible; circulation is severely restricted within the queue and forward movement is only possible as a group; long-term waiting at this density is uncomfortable.	
E	Standing in physical contact with others is unavoidable; circulation in the queue is not possible; queuing can only be sustained for a short period without serious discomfort.	
F	Virtually all persons within the queue are standing in direct physical contact with others; this density is extremely uncomfortable; no movement is possible in the queue; there is potential for panic in large crowds at this density.	

Table 22 Description of the level-of-service for waiting areas (HCM 2000, [27])

Level of Service	Highway Capacity Manual (2000) [P/m^2]	Handbuch für Bemessung von Strassenverkehrsanlagen (2001) [P/m^2]
A	< 0.83	< 1.00
B	0.83 – 1.11	1.00 – 1.50
C	1.11 – 1.67	1.50 – 2.00
D	1.67 – 3.33	2.00 – 3.00
E	3.33 – 5.00	3.00 – 6.00
F	> 5.00	> 6.00

Table 23 LoS-definition for waiting areas (HCM 2000, [27]; HBS, [11])

4.2 Dimensioning

4.2.1 Influence of obstacles

In pedestrian facilities it can be observed that pedestrian are walking in a certain lateral distance to obstacles or boundaries (walls, balustrade etc.). In everyday situations pedestrians intend to keep lateral distances. These distances are decreasing in enforcing situations (see Figure 31).

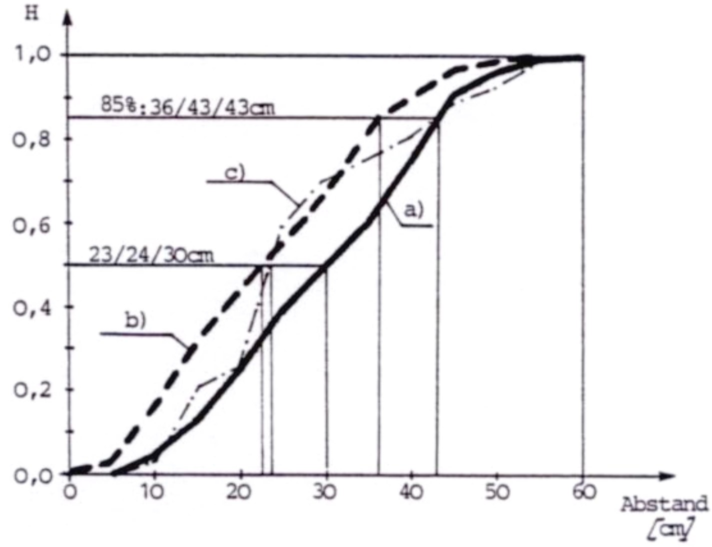


Abb. 27: Seitenabstandsverhalten zu seitlichen Hindernissen [1]
a) freiwilliger Mindestabstand
b) erzwungener Mindestabstand
c) Abstand zu Person bei b)

Figure 31 Lateral distances of pedestrians to obstacles under normal conditions (Curve a), under enforcing situations (Curve b), to other pedestrians in enforcing situations (Curve c), (Schopf 1985)

The lateral distances are varying with different kind of objects.

Object	Distance [cm]	Source
Concrete walls	30 – 45	CROW (1998)
	45	De Neufville & Grillot (1982)
	50	HBS (2001)
	15	Pauls (1987)
	40	Van Soeren (1996)
	25	Weidmann (1993)
Metal walls	20	Weidmann (1993)
Shop windows	100	HBS (2001)
Fence, plantings	60	HBS (2001)
Single obstacles	40	Van Soeren (1996)
	10	Weidmann (1993)
Handrail of stairways	0	HBS (2001)
	30	Weidmann (1993)
Platform edges	80	Van Soeren (1996)
Distance to roadways	35	Weidmann (1993)

Table 24 Shy away distances of obstacles for pedestrians (Daamen 2004, HBS 2001 [11], Knoflacher 1987, Weidmann 1993)

These shy away distances will have to be deducted from the width of walkways for dimensioning or for level of service evaluation.

4.2.2 Minimum width of walkways

To choose or to check the minimum width of walkways, the regime (number of lanes) and the dimension of pedestrians have to be taken in account. Pedestrians require beyond the static width (see section 2.1.1, 2.1.3, 2.1.5) additional space for the dynamic width (see section 2.1.2). In case of opposite pedestrian flows the bypassing distances have to be added (see section 3.1.2). Around obstacles or near boundaries the shy away distances should appended (see section 4.2.1).

In the following sections the minimum width of walkways are calculated according to the SN-Norms (SN 640201; [23]). The width of walkways is composed by the width of the different, intended lanes, which are determined by the static width of pedestrians and the additional, dynamic and safety width on both sides of each lane.

4.2.2.1 Minimum width of 2 lane walkways

The width of 2 lane walkways is laid out on the bypassing incident of two pedestrians (one person with luggage, the other one without luggage).

	Lane 1		Lane 2		Total width
	Basic width	Addition for dynamic and safety width	Basic width	Addition for dynamic and safety width	
	[m]	[m]	[m]	[m]	[m]
Standard	0.80	0.40	0.60	0.40	2.20
Minimum	0.80	-	0.60	-	1.40

Table 25 Standard and minimum width of 2 lane walkways (SN 640201; [23])

The minimum width of 1.40 m should only be used on short section near bottlenecks. Pedestrians would have to reduce walking speed bypassing other pedestrians.

In pedestrian facilities used by many travellers (e.g. railway stations, airports), the most common bypassing incident will be pedestrians with luggage in both directions (basic static width of 80 cm). Therefore the total width of such walkways should be at least 2.40 m.

Additionally the specific shy away distances will have to be added to the walkway width.

4.2.2.2 Minimum width of 3 lane walkways

The following dimension of 3 lane walkways is laid out on the bypassing incident of three pedestrians (one person with luggage, the other two without luggage).

	Lane 1		Lane 2		Lane 3		Total width
	Basic width	Additional width	Basic width	Additional width	Basic width	Additional width	
	[m]	[m]	[m]	[m]	[m]	[m]	[m]
Standard	0.80	0.40	0.60	0.40	0.60	0.40	3.20
Minimum	0.80	-	0.60	-	0.60	-	2.00

Table 26 Standard and minimum width of 3 lane walkways (VSS 2005)

The minimum width of 2.00 m should only be used on short section near bottlenecks. Pedestrians would have to reduce walking speed bypassing other pedestrians.

In pedestrian facilities used by many travellers (e.g. railway stations, airports), the most common bypassing incident will be pedestrians with luggage in both directions (basic width of 80 cm). Therefore the total width of such walkways should be at least 3.60 m.

Additionally the specific shy away distances will have to be added to the walkway width.

4.2.2.3 Minimum width of bottle necks (single lane)

At bottle necks (most narrow passages for pedestrians) a minimum width of 1.0 m should be kept. This allows passing pedestrians with luggage or wheelchairs.

The length of such bottle necks should be kept at a very minimum in order to avoid dead-locked pedestrians or congestion at the inflow of bottle necks.

4.2.3 Recommended minimum LoS

For dimensioning or evaluating pedestrian facilities minimum level of services can be used to verify pedestrian comfort. For short-term periods a higher level of service (lower comfort) is proposed than for long-term intervals.

		Minimum Level of Service	Density	Walking Speed	Pedestrian Flow
			[P/m^2]	[m/s]	[P/ms]
Walkways					
	Normal	B	0.22	1.34	0.30
	Rush hour	D	0.58	1.27	0.74
	Bottle necks	E	1.02	1.05	1.07
Stairs				(up / down)	(up / down)
	Normal	B	0.58	0.61 / 0.69	0.35 / 0.40
	Rush hour	D	1.31	0.54 / 0.62	0.71 / 0.81
	Bottle necks	E	2.12	0.40 / 0.46	0.85 / 0.98
Waiting Areas					
	Normal	B	0.87	-	-
	Short-term	D	2.50	-	-

Table 27 Minimum level of services for pedestrian facilities (Weidmann 1993, HCM 2000; [27])

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