CAPACITY OF WALKWAYS

Boris Pushkarev and Jeffrey M. Zupan, Regional Plan Association

Flow and space standards for walking facilities and their application are focused on. Consistency is shown in a comparison of work done by various researchers on speed, flow, and density relationships. Levels of comfort at different fractions of maximum capacity are defined. The effect of short-term fluctuation of flow, known as platooning, is evaluated and related to average conditions. Levels of service for platooning are postulated based on available space per pedestrian. Key flow rates for defining walkway service levels are 2, 4, 6, and 10 pedestrians/min/ft (7, 13, 20, and 33 pedestrians/min/m) of walkway width corresponding to 130, 65, 40, and 24 ft^2/pedestrian (12.08, 6.04, 3.72, and 2.23 m^2/pedestrian) respectively.

•CAPACITY of pedestrian facilities, like capacity of vehicle facilities, usually means maximum ability of a facility to accommodate a flow, but, more often than not in vehicle traffic design, operation at maximum capacity is undesirable. So as not to establish imminent congestion as a design standard, researchers have defined levels of service that characterize the quality of traffic flow at various fractions of maximum capacity. Similarly, several pedestrian levels of service can be defined by indicating what kind of behavior is possible, or impossible, at various degrees of spaciousness or crowding. The selection of any particular level of service as a desirable design standard is, to a large extent, a matter of judgment and policy.

SPACE RELATED TO SPEED AND FLOW

Pedestrian travel requires enough room to allow for pacing and a buffer zone large enough to permit anticipating potential collisions and taking evasive action. For example, because of the angle the human eye encompasses, one has to be at least 7 ft (2.1 m) away from someone to be seen from head to toe and to have one's speed and direction of movement accurately judged. Pedestrians have been found to take evasive action anywhere from 2 to 17 ft (0.6 to 5.2 m) ahead of a stationary or moving obstacle. The longer the distance is, the less violent the evasion and the less likely a collision is. The spacing between pedestrians, like the spacing between vehicles, is related to the speed at which the objects are moving. More space is required for faster movements. The relationship of space requirements (density), speed of movement, and rates of flow in pedestrian streams has been studied by a number of investigators. Among the more recent ones are Fruin (1), Oeding (2), Older (3), and Navin and Wheeler (4). Their findings are generally consistent with those of several other researchers (5, 6, 7, 8).

The traditional equation describing traffic flow is (9)

$$\text{Flow} = \text{Speed} \times \text{Density} \tag{1}$$

where

flow = number of moving objects crossing a unit of channel width in a unit of time,
speed = number of units of distance the moving objects pass in a unit of time, and
density = number of moving objects per unit of channel area.

When the units by which channel area is measured are relatively small, such as square feet (m^2), density becomes an inconvenient concept that forces us to deal with fractions of pedestrians. Moreover, a density scale shrinks rapidly in the range in which we are most interested. The range is the one that has less than 0.1 pedestrians/square ft (1.0 pedestrians/m^2) and where varying degrees of comfort prevail. So the reciprocal of density, or available space per pedestrian, is a more useful unit for trying to arrive at comfort criteria. With that in mind, and by adding dimensions, we can rewrite equation 1 as follows:

$$\text{Space} = \frac{\text{Speed}}{\text{Flow}} \qquad (2)$$

The relationship between speed and flow can be approximated by a parabolic curve that is familiar from motor-vehicle flow analysis. Figure 1 shows a family of 5 speed-flow curves abstracted from measurements by the investigators cited previously and converted to common units.

The formula for the parabolas in Figure 1 is a quadratic equation:

$$\text{Speed} = \frac{A \pm A^2 - 4B \text{ Flow}}{2} \qquad (3)$$

where A and B are constants. These constants can be calculated for any set of observations statistically by means of the least squares technique, or they can be estimated by inspection of a plot of speed versus density. Plotting density rather than space per pedestrian is useful in this case because the resulting relationship can be represented as a linear one. The straight-line form has been shown to represent a reasonable approximation of reality. It takes the form of the equation

$$\text{Speed} = A - B \times \text{Density} \qquad (4)$$

A represents the intercept on the y axis (speed in this case), and B represents the slope of a straight line or the rate at which speed declines with density as shown in Figure 2. The meaning of these 2 constants also can be interpreted as follows: A represents the theoretical speed attained by a traffic stream under conditions of completely free flow and an unlimited amount of space per pedestrian; B is a factor that, when divided by A, yields the theoretical minimum space allocation per pedestrian at a point where all movement in a traffic stream stops and speed is zero. The constants A and B for the curves in Figure 1 and 2 are given in Table 1.

To determine the maximum or capacity pedestrian flow and at what speed it occurs, all we have to do is find the maximums on the curves defined by equation 4. These calculated maximums are given in Table 2 along with extremes observed by the different investigators.

It is evident that the findings of Older (3), Oeding (2), and Fruin (1) on maximum pedestrian flow are in close agreement. In fact, Fruin's (1) calculated maximum of 24.7 pedestrians/min/ft (81 pedestrians/min/m) of walkway width at a speed of 134 ft (40.8 m)/min falls exactly halfway between the maximums derived by Older (3) and Oeding (2). The extremes observed by Older (3) in England and Oeding (2) in Germany are also in close agreement although speeds differ. These extreme flow rates are high and come close to those attainable in highly organized military formations as given in Table 3. The behavior of Navin and Wheeler's (4) student population is different; it has greater spacing between individuals and, accordingly, a lower flow at comparable speeds. One may speculate that the higher interpersonal distances adopted by the

Figure 1. Speed-flow relationships.

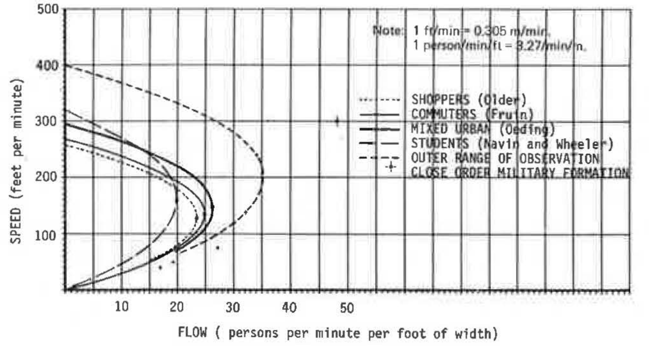


Figure 2. Speed-density relationships.

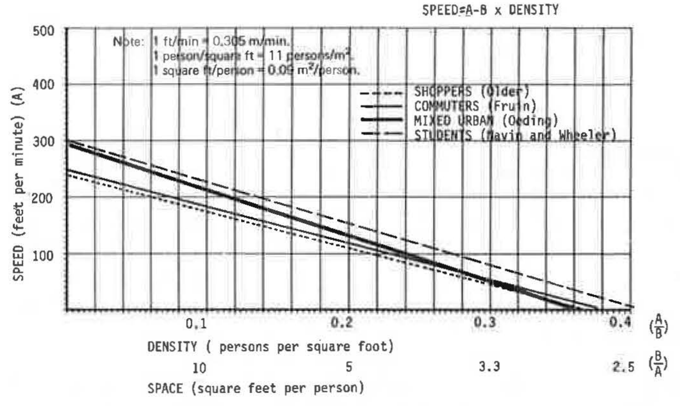


Table 1. Coefficients of pedestrian flow equations.

Type of Flow	Source	A (ft/min)	B	B/A (square ft)
Shoppers, average[a,b]	Older (3)	258	714	2.77
Commuters, average[a]	Fruin (1)	267	722	2.70
Mixed traffic, average[c]	Oeding (2)	295	835	2.83
Students, average[c]	Navin and Wheeler (4)	320	1,280	4.00
Mixed traffic, outer boundary[c]	Oeding (2)	400	1,132	2.83

Note: 1 ft/min = 0.305 m/min. 1 square ft = 0.09 m².

[a]Calculated.

[b]Extreme observations suggest a minimum space allocation of 2.1 square ft (0.2 m²)/pedestrian at zero speed.

[c]Estimated.

Table 2. Maximum pedestrian flow.

		Maximum Flow (pedestrians/ft)		Mean Speed at Maximum Flow (ft/min)	
Type of Flow	Source	Calculated Average	Observed Extreme	Calculated Average	Observed Extreme
Shoppers	Older (3)	23.3	33.0	129	170
Commuters	Fruin (1)	24.7	–	134	–
Mixed traffic	Oeding (2)	26.1	34.0	148	246
Students	Navin and Wheeler (4)	20.0	26.4	160	240
Close-order military drill		–	48.0	–	300

Note: 1 pedestrian/ft = 3.27 pedestrians/m. 1 ft/min = 0.305 m/min.

Table 3. Space per pedestrian at maximum flow.

Type of Flow	Source	Maximum Flow (pedestrians/ min/ft)	Space per Pedestrian at Maximum Flow (square ft)
Average			
Students	Navin and Wheeler (4)	20.0	8.0
Shoppers	Older (3)	23.3	5.5
Commuters	Fruin (1)	24.7	5.4
Mixed traffic	Oeding (2)	26.0	5.5
Extreme			
Students	Navin and Wheeler (4)	26.4	9.1
Shoppers	Older (3)	33.0	5.2
Mixed traffic	Oeding (2)	34.0	7.2
Close-order military drill		48.0	6.3

Note: 1 pedestrian/min/ft = 3.27 pedestrians/min/m. 1 square ft = 0.09 m².

students are more representative of a comfortable situation than are the close spacings found by Older (3), Oeding (2), and Fruin (1) in forced downtown flows.

To be able to make an evaluation for comfort, we must take a look at the relationship between flow and space per pedestrian. Following equation 3, if we take the speed at any point on the curves in Figure 1 and divide it by the flow at that point, we obtain the amount of space available per pedestrian at that point. For example, at a speed of 200 ft (61 m)/min and a flow rate of 20 pedestrians/min, the average space allocation is 10 square ft (0.93 m^2)/pedestrian. In this manner, the speed-flow diagrams shown in Figure 1 are converted into the flow-space diagrams shown in Figure 3. The formula for the flow-space curves is:

$$\text{Flow} = \frac{A \times \text{Space} - B}{\text{Space}^2} \tag{5}$$

where A and B are the constants given in Table 1. The available space per pedestrian at maximum flow is given in Table 3.

It is apparent from Figure 3 and Table 3 that all the different observations of maximum flow previously listed fall in a very narrow range of density—that in which space allocation varies between 5.2 and 9.1 square ft (0.48 and 0.85 m^2)/pedestrian. As space is reduced to less than 5 square ft (0.46 m^2)/pedestrian, flow rate declines precipitously; all movement comes to a standstill at space allocations between 2 and 4 square ft (0.2 to 0.4 m^2) as the data given in Table 1 have shown.

Thus, if our objective is to maximize pedestrian flow, regardless of speed or comfort, the space allocation per pedestrian should be between 5.2 and 9.1 square ft (roughly 0.5 to 0.9 m^2). Letting space allocations drift below that level will lead to a crush; the crowd will grow in size as long as the number of incoming pedestrians is greater than what the bottleneck can release.

On the other hand, increasing space allocations above 10 square ft (0.9 m^2)/pedestrian will lead to declines in flow. It can be deduced from Figure 3 that at 40 square ft (3.7 m^2)/pedestrian, the flow rates are, depending on which curve one chooses, between 24 and 32 percent of maximum flow. At 100 square ft (9.3 m^2)/pedestrian, the flow rates are down to about 10 percent of maximum flow. Our concern is, of course, with quality of flow, not quantity. This leads us to look at average speed in relation to space per pedestrian.

Going back to equation 2, if we multiply the flow at any point of Figure 1 by the space per pedestrian at that point, we obtain the speed at which the flow is occurring. Thus, the flow-space diagram in Figure 3 can be transformed into the speed-space diagram shown in Figure 4. The equation of the speed-space curve is

$$\text{Speed} = A - \frac{B}{\text{Space}} \tag{6}$$

A and B again are constants from Table 1. The form of equation 6 makes it clear why A equals B divided by the space allocation at zero speed. It also makes it clear that, as space per pedestrian increases toward infinity, speed increasingly approaches A, previously defined as the theoretical maximum speed at free flow for a given type of traffic stream. Thus, for example, at 100 square ft (9.3 m^2)/pedestrian, the average speed is between 96 and 97 percent of the theoretical speed at an infinite space allocation per pedestrian. At 40 square ft (3.7 m^2)/pedestrian, average speed drops to between 90 and 93 percent of this theoretical level. From then on, the reduction becomes sharper, and at 11 square ft (1 m^2)/pedestrian, average speed is down to between 64 and 75 percent of the theoretical maximum. In the range where flow is maximized to somewhere between 9 and 5 square ft (0.9 and 0.5 m^2) /pedestrian, speed drops drastically to between 27 and 50 percent of its theoretical level and then keeps declining to reach zero at space allocations between 2 and 4 square ft (0.18 and 0.36 m^2)/pedestrian.

Reductions in average speed come about as available space per pedestrian shrinks. Fewer people have the freedom to select their own rate of movement because of the interference from others in the traffic stream. The fastest walkers are slowed down first, but, eventually, even slow walkers are affected. Thus, the range of observed speeds shrinks as space per pedestrian is reduced. Some indication of this is given by the dotted lines shown in Figure 4 that portray the upper and lower limit of speeds observed by Oeding (2).

SERVICE LEVELS

Studies concerning the distribution of pedestrian speeds under conditions of free choice have been carried out by numerous observers, among them Fruin (1), MacDorman (10), Gehl (11), and Hoel (12). Biological limits govern both how fast and how slowly people can walk. The various investigators agree that virtually no one will voluntarily select speeds faster than 400 ft (122 m)/min, or slower than 145 ft (44 m)/min. Speeds below that range can be classified as shuffling. Oeding (2) points out that speeds in the shuffling range do not occur under unobstructed conditions because they require cramped movements, which are unnatural in terms of body balance.

On this basis we may note two things. First, average speeds on all the curves in Figure 4 are depressed into the unnatural shuffling range of less than 150 ft (46 m)/min at space allocations between 6 and 8 square ft (0.56 and 0.74 m^2)/pedestrian. Second, those who choose to walk at the minimum speed of about 150 ft (46 m)/min when space per walker is ample cannot maintain even that speed when space shrinks below 15 to 18 square ft (1.4 to 1.7 m^2). The fast walkers lose the ability to maintain their chosen speed as space drops below 30 to 40 square ft (2.8 to 3.7 m^2)/pedestrian.

There are other indicators of congestion, besides the inability to maintain a freely selected speed. An important one is the inability to choose one's path freely across the traffic stream. Fruin (1) studied pedestrian crossing conflicts in relation to available space per pedestrian. He defined conflicts as "any stopping or breaking of the normal walking pace due to a too close confrontation with another pedestrian" that requires adjustments in speed or direction to avoid collision. He found such situations inevitable when flow is dense—less than 15 square ft (1.4 m^2)/pedestrian. As gaps between pedestrians widen, crossing movements become easier and the probability of conflict drops to between 65 and 50 percent. However, the probability of conflict does not drop to zero until the space allocation reaches about 45 square ft (4.2 m^2)/pedestrian.

A related indicator is ability to pass slow-moving pedestrians, which Oeding (2) found to be relatively unrestricted at space allocations of more than 36 square ft (3.3 m^2)/pedestrian. He found the ability to pass to be considerably restricted in the range between 18 and 36 square ft (1.7 to 3.3 m^2)/pedestrian. At lower space allocations, he found passing to be possible only by physically pushing the slow-walking person aside.

Finally, an important consideration is the ability to maintain flow in the reverse direction. All of the data presented here, except some extreme observations by Oeding (2), refer to bidirectional flow. Bidirectional flow is not substantially different from 1-directional flow as long as the directional distribution is relatively balanced. Pedestrians spontaneously form directional streams that minimize conflict with the opposing flow. Each stream occupies a share of the walkway that is proportional to its share in the total flow, and reduction in speed or capacity is minimal—Fruin (1) found it to be less than 6 percent under maximum flow conditions. However, Navin and Wheeler (4) have shown that reduction in capacity increases as directional imbalance increases. Thus for directional distributions of 25 to 75 or better, reduction in capacity approaches 10 percent. For a 10 to 90 distribution, reduction in capacity rises to 14.5 percent, given a space allocation of 10 square ft (0.93 m^2)/pedestrian. As space allocations are reduced, maintaining a small flow in the opposite direction becomes more difficult (a problem acute on some rapid transit stairways) and effect on capacity becomes more pronounced. A summary of the different kinds of pedestrian behavior that are possible or impossible at different densities is given in Table 4 (1, 2). Fruin (1) brands space

Figure 3. Flow-space relationships.

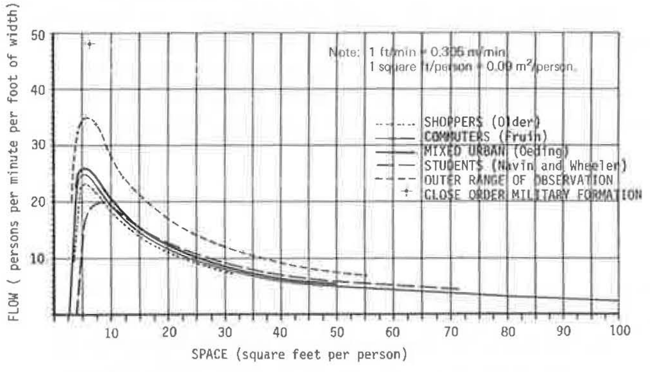


Figure 4. Speed-space relationships.

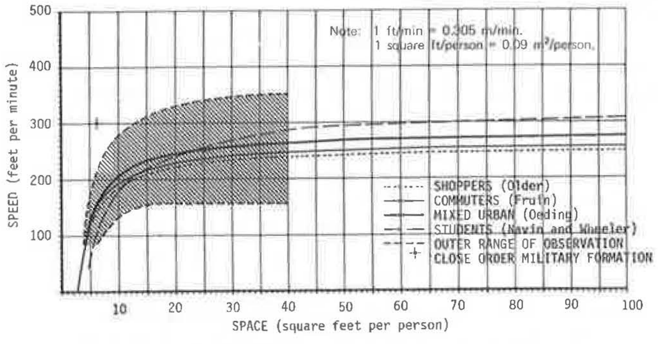


Table 4. Pedestrian behavior related to available space.

Average Area per Person (square ft)	Flow	Average Speed	Choice of Speed	Crossing or Reverse Movement	Conflicts	Passing
2 to 5	Erratic, on the verge of complete stoppage	Shuffling only	None	Impossible	Physical contact unavoidable	Impossible
5 to 7	Attains a maximum in traffic streams under pressure	Mostly shuffling	None, movement only with crowd	Most difficult	Physical contact probable, conflicts unavoidable	Impossible
7 to 11	Attains a maximum in more relaxed traffic streams	About 67 percent of free flow	Practically none	Severely restricted with collisions	Physical contact probable, conflicts unavoidable	Impossible
11 to 15	65 to 80 percent of maximum capacity	About 75 percent of free flow	Restricted, constant adjustments to gait necessary	Severely restricted with conflicts	Unavoidable	Rarely possible without touching
15 to 18	56 to 70 percent of maximum capacity	About 80 percent of free flow	Restricted except for slow walkers	Restricted with conflicts	Highly probable	Rarely possible without touching
18 to 25	Roughly 50 percent of maximum capacity	More than 80 percent of free flow	Partially restricted	Possible with conflicts	Highly probable	Difficult without abrupt maneuvers
25 to 40	Roughly 33 percent of maximum capacity	Approaching free flow	Occasionally restricted	Possible with occasional conflicts	Probably 50 percent of the time	Possible with interference
More than 40	20 percent of maximum capacity or less	Virtually as chosen	Virtually unrestricted	Free	Maneuvering needed to avoid conflicts	Free with some maneuvering

Note: 1 square ft = 0.09 m².

allocations of less than 5 square ft (0.5 m^2) completely unacceptable; Oeding (2) brands those of less than 7 square ft (0.66 m^2) completely unacceptable. Both (1, 2) agree that space allocations below 10 or 11 square ft (1 m^2) can easily lead to flow stoppages and a buildup of crowds; pedestrians should not be required to endure this degree of congestion. Yet it is at this level that the maximum flow of 25 to 28 pedestrians/min/ft (82 to 93 pedestrians/min/m), which is frequently accepted as design capacity, occurs. Oeding (2) and Fruin (1) point out, however, that such crush loads can, on occasion, be difficult to avoid in short-term bulk situations, such as when a crowd leaves a sports stadium.

Oeding (2) calls space allocations between 18 and 36 square ft (1.7 and 3.3 m^2)/pedestrian tolerable. Fruin (1) subdivides the range between 15 and 35 square ft (1.4 and 3.3 m^2) into 2 service levels, B and C, which he recommends conditionally for transportation terminals and similar heavily used facilities. Fruin's (1) B and C levels represent respective flow volumes of up to 10 and 15 pedestrians/min/ft (33 and 49 pedestrians/min/m) of walkway. Oeding (2) cites similar flow volumes—14 pedestrians/min/ft (45 pedestrians/min/m) for shoppers and 18 pedestrians/min/ft (60 pedestrians/min/m) for commuters—as the upper limit of his tolerable range.

Although they are tolerable occasionally in tight circulation areas, space allocations of 15 to 35 square ft (1.4 to 3.3 m^2)/pedestrian still impose serious restrictions on pedestrian flow, as evident from the data given in Table 4.

Both Oeding (2) and Fruin (1) characterize only space allocations greater than 35 or 36 square ft (3.3 m^2)/pedestrian as permitting free flow. Stramentov, based on observations in Moscow, suggests in effect a similar range between 25 and 55 square ft (2.3 and 5.1 m^2)/pedestrian. Thus 40 square ft (3.7 m^2)/pedestrian, corresponding to a flow rate of 6 pedestrians/min/ft (20 pedestrians/min/m) of walkway width, can be accepted as a reasonable threshold, beyond which pedestrian behavior no longer is constrained physically by the traffic stream.

One should note, however, that a space allocation of 40 square ft (3.7 m^2)/pedestrian, although it allows a relatively free choice of speed and direction of movement, does not really represent an uncrowded situation. The lateral spacing adopted by people under conditions approaching free flow was found by Fruin (1) to be roughly 3.5 ft (1 m); if one assumes this, the longitudinal spacing on the threshold of Oeding's (2) and Fruin's (1) comfortable density is a little over 11 ft (3.5 m). At such close spacing, people, although they are able to avoid physical collisions or restrictions in speed, are acutely aware of others in the traffic stream and must continuously interact with them.

For example, Wolff (13) points out that at distances of less than 15 ft [which represents a space of at least 60 square ft (5.6 m^2)] people normally do not walk behind each other but rather walk in a checkerboard pattern, looking over the shoulder of the person in front. Thus, if any person in a group of walkers changes his or her lateral position, others are forced to accommodate to maintain the checkerboard spacing. A similar phenomenon also can be observed in the lateral direction. People prefer not to walk side-by-side with a stranger for any length of time, and they either accelerate or slow down if someone else is walking next to them. Navigating in the fluid, dense pedestrian stream thus requires constant attention and interaction with others. Psychologists suggest that it is this kind of effort that makes walking in crowded places tiresome, especially if other walkers are uncooperative, as shoppers with bags tend to be.

Exactly at what point flow on a walkway becomes sufficiently sparse to induce no stress is a good subject for further study. Only fragmentary pieces of evidence are available. Wolff (13) shows that the distance at which evasive action is taken in the face of an imminent collision increases from about 2 ft (0.6 m) at a space allocation of 40 square ft (3.7 m^2)/pedestrian to an average of about 7 ft (2.1 m) at 100 square ft (30 m^2)/pedestrian and then stays constant, suggesting that evasion at that distance may be sufficiently smooth. However, Wolff (13) cautions that the latter distance may have been foreshortened by the conditions of the experiment; he found 16.5 (5 m) to be the distance at which evasive maneuvers from fixed objects began.

Another method for analyzing the quality of flow in the lower density range, into which neither Fruin (1) nor Oeding (2) ventured, is the maximum pedestrian technique. The maximum pedestrian sets out to walk as fast as he or she can. Both the speed and the number of conflicts (sharp evasive maneuvers or near collisions) that he or she encounters at different flow rates are observed. In one experiment on Fulton Street in Brooklyn (14), the maximum pedestrian generally was unable to walk faster than 300 ft (91 m)/min, which is at the threshold of Oeding's (2) and Fruin's (1) comfortable density [about 5 pedestrians/min/ft (16 pedestrians/min/m)], and encountered an average of 12 conflicts/250 ft (76 m) of walking distance. As average hourly flow declined to less than 3 pedestrians/min/ft (10 pedestrians/min/m), the number of conflicts declined linearly to about 4, and the maximum possible speed increased to 380 ft (116 m)/min, at an average space allocation on the order of 90 square ft (8.4 m^2)/pedestrian in the traffic stream.

Qualitative observations as a part of this study, both in transit corridors and on outdoor walkways, suggest that a space allocation on the order of 130 square ft (12 m^2)/pedestrian may be a reasonable minimum limit for truly unimpeded walking; only negligible influence will come from the traffic stream. That represents a flow rate of 2 pedestrians/min/ft (6.5 pedestrians/min/m) of walkway, which feels comfortable yet retains a busy appearance. However, involuntary bunching or platooning still occurs at this flow rate and does not disappear until flow falls below 0.5 pedestrians/min/ft (1.6 pedestrians/min/m) and space allocation increases to roughly 500 or 600 square ft (50 m^2)/pedestrian. When space allocations are beyond this range, one can no longer talk about pedestrian flow, but only about isolated pedestrians.

Let us now define walkway width. Some people in the past have described a pedestrian "lane" as a strip as narrow as 22 in. (56 cm) (15). However, the lane is irrelevant to capacity calculations. The lane can only be meaningful if one wishes to calculate how many people can walk abreast or pass each other simultaneously along a walkway of a given width. The lateral spacing to avoid interference with a passing pedestrian, according to Oeding (2) and the observations of this study, is at least 30 in. (75 cm). Pedestrians who know each other and are walking together will walk as close as 26 in. (65 cm) center-to-center; at this distance there is considerable likelihood of touching. Lateral spacing of less than 24 in. (60 cm) between strangers occurs, as Fruin (1) has shown, under jammed conditions, when there is less than about 5 square ft (0.5 m^2)/pedestrian. [In contorted evasive maneuvers on narrow stairs, people, if necessary, can squeeze by in about 20 in. (50 cm) of space.] Under normal conditions, even the 2.5-ft (0.75-m) lateral spacing is tolerated only momentarily to pass a person or to walk alongside a person through a stairway. Otherwise, a spacing of 3 to 4 ft (0.9 to 1.2 m) or more is adopted by walking in a checkerboard pattern.

Multiples of about 2.5 ft (0.75 m) can be used to calculate clear walkway width for a given number of people to walk abreast in a voluntary group and to be able to pass a group, but clear walkway width deserves more emphasis. People shy away from walking along the very edge of a curb or against building walls. Therefore, dead space along the edges of a walkway must be excluded from effective width when one calculates design flow. Also excluded must be a strip preempted by physical obstructions, such as light poles, mail boxes, and parking meters, although their exact effect on pedestrian flow has not been sufficiently investigated. The area preempted by standing pedestrians also is not available for walking.

In a study of shopping walkways in Leeds, O'Flaherty and Parkinson (8) found that a speed-density relationship calculated on the basis of curb-to-wall sidewalk width could not be meaningfully converted into a flow-space relationship because of a large number of standing pedestrians who occupied space but did not contribute to flow. Only by subtracting the space occupied by those standing from total sidewalk space could a useful relationship be obtained. The width preempted by window shoppers was between 1.6 and 2.5 ft (0.5 and 0.75 m), and that by standees at a bus stop, about 3.6 ft (1.1 m). The implicit space allocations per window shopper were roughly between 5 and 7 square ft (0.5 and 0.7 m^2). These findings are in agreement with the lateral clearances from building walls suggested by Oeding (2). The clearance from the curb suggested by him is 1 to 1.5 ft (0.3 to 0.5 m).

On the basis of these observations we can now proceed to summarize the characteristics of pedestrian flow at different levels of spaciousness. This is given in Table 5, which goes beyond the range investigated by Oeding (2) and Fruin (1); the boundaries of the various conditions are slightly adjusted for arithmetical convenience. These data in Table 5 assume that the pedestrian flow is even, or homogeneous, in time. The flow rate is expressed in terms of 1 min and should not be extrapolated to longer periods of time until the considerations presented in the next section are taken fully into account.

Essentially no interaction among pedestrians occurs at the open flow level. At the unimpeded level some bunching begins to occur, but an individual is generally not influenced by others in the traffic stream, and walking is carefree. At the impeded level progress is possible only by constant interaction with the movement of others. At the constrained level interaction turns into physical restrictions on freedom of movement, speed is limited, and conflicts occur. The crowded level is rarely reached except for short periods of time on urban sidewalks and is more typical of heavily used transportation terminals where movement may still be fluid but has a lot of friction and depressed speed.

SPACE FOR PLATOONS

To have defined possible flow rates at different levels of pedestrian comfort will do us little good unless we know what time spans these rates should be applied to. Flow is uneven so a flow rate of 10 pedestrians/min does not necessarily equal 600 pedestrians/hour.

Platoon Effect

A good picture of minute-by-minute variation can be obtained from data collected by Okamoto and Beck (16) in their time-lapse photography studies of 2 walkways in Lower Manhattan. These data, shown in Figure 5, cover the morning rush hour on Nassau Street and the morning rush hour and lunch hour at the entrance to the Chase Manhattan Plaza. The maximum 15-min flow rate at the Nassau Street location averaged 10 pedestrians/min/ft (32.8 pedestrians/min/m). The maximum 15-min flow rate at the Chase Plaza entrance during the morning rush hour averaged 1.4 pedestrians/min/ft (4.6 pedestrians/min/m); during the lunch hour it averaged 1.9 pedestrians/min/ft (6.2 pedestrians/min/m).

The diagrams indicate that flow during 1 minute can, on occasion, be more than twice as high as flow during the next minute, particularly when overall volume is low. Even during the peak 15-min periods, 1 minute can be 1½ times different from another minute even during what would appear to be, on the average, an unimpeded flow to the plaza and a constrained flow on Nassau Street. Relating the scatter in the diagrams to the 15-min average, we find that the highest minute within a 15-min period exceeds the average by at least 20 and up to 75 percent. The 3rd highest minute exceeds the average by at least 10 and up to 30 percent. Even the 7th highest minute can be up to 20 percent higher than average. In general, at least 6 and up to 9 min of every 15-min period experience an above-average rate of flow. As a result, more than 50 percent (up to 73 percent) of the people walk during minutes when flow exceeds the 15-min average. For them, the flow on Nassau Street is no longer constrained, but rather is crowded, and the lunch-hour flow in the Chase Manhattan Plaza entrance is not unimpeded but impeded.

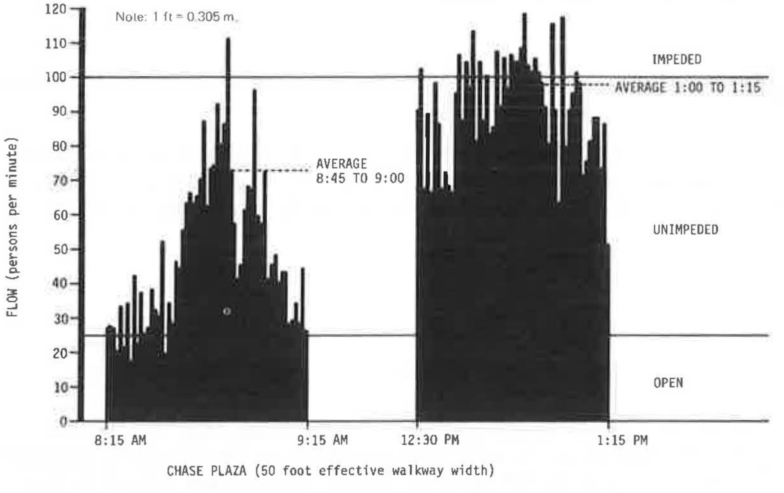
These findings are supported by manual minute-to-minute counts in Midtown Manhattan that fall in the same range. It is clear that any facility designed for the average flow in a 15-min period will be underdesigned for a sizable portion of the pedestrians using it. At the same time, it would be extravagant to design a facility for 1 peak minute that may be 150 percent of the average but that may occur with only a 1 or 2 percent probability. To resolve that dilemma and to find a relevant time period, we must take a closer look at short-term fluctuation.

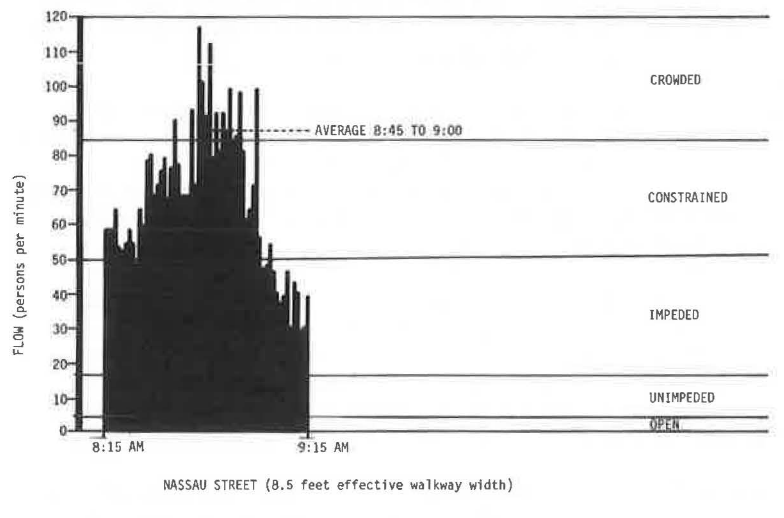
Table 5. Characteristics of pedestrian flow in a homogeneous stream.

Quality of Flow	Space per Pedestrian (square ft)	Flow Rate (pedestrians/ min/ft)
Open	More than 530	Less than 0.5
Unimpeded	530 to 130	0.5 to 2
Impeded	130 to 40	2 to 6
Constrained	40 to 24	6 to 10
Crowded	24 to 16	10 to 14
Congested	16 to 11	14 to 18
Jammed	2 to 11	0 to 25

Note: 1 square ft = 0.09 m².
1 pedestrian/min/ft = 3.27 pedestrians/min/ft.

Figure 5. Minute-by-minute variation in pedestrian flow.





Short-term fluctuation is generally present in any traffic flow that is not regulated effectively by a schedule, and its underlying cause is that participants in a traffic stream arrive at a given spot at random. Thus, purely by chance, one minute a section of sidewalk may receive many pedestrians, and the next minute it may receive few. In an urban situation, this random unevenness is exaggerated by 3 additional factors. First, if passing is impeded because of insufficient space, faster pedestrians will slow down behind slow-walking ones, and a random bunch of pedestrians will snowball into a platoon. Second, subway trains and, to a lesser extent, elevators and buses release groups of people in very short intervals of time with pauses during which no flow may occur. Until they have a chance to dissipate, these groups proceed together more or less as a platoon. Finally, and most importantly, traffic signals release pedestrians in groups that tend to proceed as groups along a sidewalk.

Platoons represent involuntary groupings of pedestrians, and, as such, should be distinguished from groups who walk together by choice. Of course, a voluntary group of people strolling leisurely together and chatting can cause others to form a platoon when opportunities for passing are limited.

One of the reasons why platoons have been neglected by previous researchers may be that they are hard to define. In this exploration, we have tried both a positive and a negative definition. In the positive definition, platoons were timed and counted when it appeared to the observer that a wave of above-average density was swelling up in the traffic stream. In the negative definition, gaps in flow were timed and the stragglers walking during these lulls were counted; then the nonplatoon time and flow were subtracted from total time and flow to determine performance in platoons. The total time of an observation was generally 5 to 6 min except at subway exits, where hourly counts were taken. The platoons were timed in seconds to avoid the arbitrary mixing of periods of flow with periods of no flow that results from choosing longer units of time. Some 58 observations are summarized in the scatter diagram in Figure 6. The symbols in Figure 6 distinguish between observations that defined platoons positively and those that defined them negatively. The duration of platoons defined either way generally ranged from 5 to 50 s, but the average time in platoons was shorter for the positive definition. According to the positive definition, 53 percent of the flow occurred in platoons roughly 20 percent of the time. By the negative definition, 84 percent of the flow occurred in platoons 63 percent of the time. The flow rate in platoons was about 2.5 times greater than the average flow rate for the positive definition and about 1.3 times greater than that for the negative definition. Platooning tends to be more pronounced during the morning and evening rush hours than during midday.

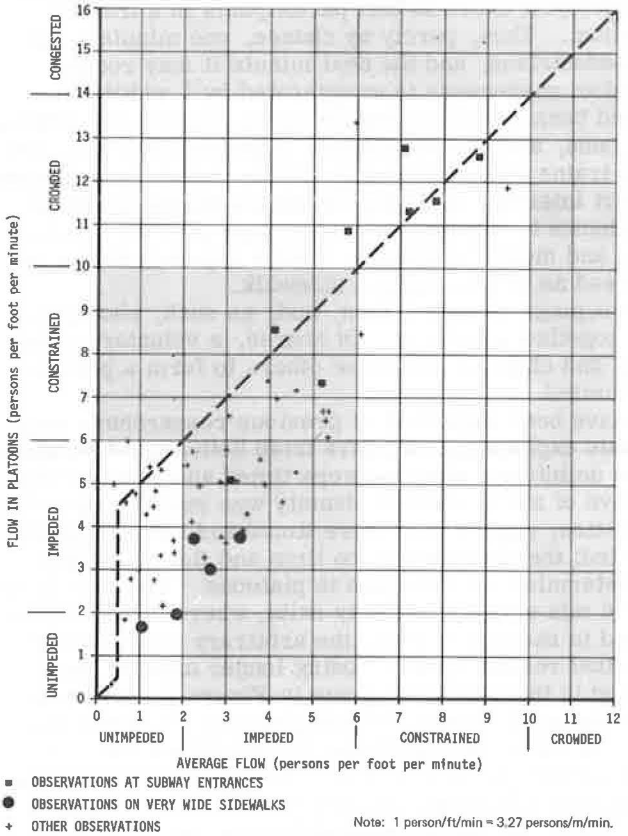
The most important influence on platoons at the street surface is traffic signals. Platoons generally follow signal cycles. To explore a different situation, counts also were taken during the morning arrival period at light-flow subway station exits. When platoons were strictly defined, 75 percent of the flow occurred in platoons 47 percent of the time, which is about 1.6 times the average flow rate. When platoons were more loosely defined, 95 percent of the flow occurred in platoons 60 percent of the time, which also is about 1.6 times the average flow rate.

It is clear that an average flow rate, even if it refers to a period as short as 1 min, is of little relevance to defining the condition of most of the pedestrians in a traffic stream. The time period truly relevant for design does not appear to be 15 min, 1 min, or any other arbitrary time span, but rather it appears to be that period during which flow in platoons occurs. Because time in platoons is composed of short spans of variable length, the most convenient way to deal with it is to take a time interval that is appropriate from the viewpoint of cyclical variation, say 15 to 30 min, and then design not for the average, but for the platoon flow rate during that period.

Revised Service Levels

Our task thus becomes one of showing those flow rates in platoons that occur at certain average flow rates so that the characteristics given in Table 6 can be applied to platoons. A comprehensive way of going about this would be to plot distributions for a range of

Figure 6. Flow in platoons related to average flow.



Note: 1 person/ft/min = 3.27 persons/m/min.

Table 6. Characteristics of average flow and flow in platoons.

Quality of Flow	Average Flow: Space per Pedestrian (square ft)	Average Flow: Flow Rate (pedestrians/min/ft)	Possible Flow in Platoons: Space per Pedestrian (square ft)	Possible Flow in Platoons: Flow Rate (pedestrians/min/ft)
Open	More than 530	Less than 0.5	More than 530	Less than 0.5
Unimpeded	530 to 130	0.5 to 2		
Impeded	130 to 40	2 to 6	60 to 40	4.5 to 6
Constrained	40 to 24	6 to 10	40 to 24	6 to 10
Crowded	24 to 16	10 to 14	24 to 16	10 to 14
Congested	16 to 11	14 to 18	16 to 11	14 to 18
Jammed	2 to 11	0 to 25	Less than 11	More than 18

Note: 1 square ft = 0.09 m². 1 pedestrian/min/ft = 3.27 pedestrians/min/m.

pedestrian densities by type of facility and time of day showing the percentage of people that have to walk at densities exceeding the average and by what amount the average is exceeded. Then a cutoff level can be chosen to serve a specified percentage of the walkers at a specified level of service. This detail, however, could not be attained, so a shortcut method was used.

In Figure 6 a time was drawn approximating the upper limit of all the platoon observations for 51 out of the 58 cases. Above it are 3 observations typifying small platoons during periods of light flow. One observation shows extreme conditions on an approach to the Port Authority bus terminal shortly after 5:00 p.m.; 3 of the 8 observations were at subway exits. The equation of this line relating maximum platoon flow to average flow is:

$$\text{Platoon Flow} = 4 + \text{Average Flow} \tag{7}$$

Application of this equation shows that an average flow rate of 6 to 10 pedestrians/min/ft (20 to 33 pedestrians/min/m) of walkway width, which we have previously described as constrained, will result in a crowded flow of 10 to 14 pedestrians/min/ft (33 to 46 pedestrians/min/m) in platoons. A flow between 2 and 6 pedestrians/min/ft (6.5 and 20 pedestrians/min/m), which all preceding authors have unanimously categorized as free flow and which we have called impeded flow, can result in platoon flow of between 6 and 10 pedestrians/min/ft (20 and 33 pedestrians/min/m), which by common consensus, is constrained.

To ensure a platoon flow rate of less than 6 pedestrians/ft (20 pedestrians/m) or a space allocation of more than 40 square ft (3.7 m^2)/pedestrian in platoons, the average flow rate must drop below 6.5 pedestrians/ft (21.2 pedestrians/m) and the average space allocation must rise above 130 square ft (12 m^2)/pedestrian, especially when sidewalks are narrow. An average of more than 500 square ft (46 m^2)/pedestrian would prevent formation of platoons on sidewalks 12 to 15 ft (3.7 to 4.6 m) wide, but this criterion would be impossible to meet in downtown areas. However, average space allocations between 80 and 200 square ft (7.4 and 18.5 m^2)/pedestrian on sidewalks wider than 30 ft (9 m) cause platoons to be substantially attenuated. Four such observations are shown separately in Figure 6.

The form that equation 7 takes (constant added to average flow) indicates that platooning has a much greater impact on light flow volumes than heavy flow volumes. Thus for an average flow rate of 2 pedestrians/min/ft (6.5 pedestrians/min/m), the additional margin necessary to accommodate platoons is 200 percent; at a flow rate of 10 pedestrians/min/ft (33 pedestrians/min/m) it is 40 percent. This pattern is not illogical because gaps between platoons tend to fill up as flow increases. It does, however, point to the following design conclusion: Minimum walkway standards that can be applied regardless of actual flow volume are necessary when flows are small because large platoons could arise suddenly. For example, an entrance to an apartment house may experience zero flow for many minutes until an elevator arrives with a platoon. As average flow increases space requirements do not grow proportionally but rather at a retarded rate, which is fortunate for the design of such high-intensity pedestrian facilities as shopping malls or transportation terminals. There are clear economies of scale in providing walkway space. Table 6 gives a comparison of average flow and platoon flow.

If the designer wants to attain for platoons what Oeding calls free flow and what Fruin calls service level A then 130 square ft (12 m^2)/pedestrian is the minimum average space allocation and 2 pedestrians/min/ft (6.5 pedestrians/min/m) of walkway width is the maximum flow except for wide walkways or where the absence of platooning can be demonstrated.

If unusual cost limitations are present, such as for underground passageways, or if a degree of crowding is desirable, such as in intensive shopping areas, then the average space allocation can be lowered and the flow rate can be raised accordingly. But, if overcrowding and congestion in platoons are to be avoided, space allocation should never fall below 40 square ft (3.7 m^2)/pedestrian on the average [below 24 square ft/ pedestrian (2.2 m^2/pedestrian) for platoons], and flow rate should never rise above 6 pedestrians/min/ft (20 pedestrians/min/m) on the average [above 10 pedestrians/ min/ft (33 pedestrians/min/m) for platoons].

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