pedestrians believe that traffic will be released during the flashing DON'T WALK interval.

5. Pedestrian-actuation devices are used too infrequently by pedestrians and, therefore, the use and respect for pedestrian signals may be minimized at such locations. One study showed that they are used by less than 35 percent of the pedestrians in crossing at many sites.

The results of this analysis, although they raise questions about the effectiveness of pedestrian signalization, are not believed to justify the elimination of pedestrian signals. We recommend that city and state agencies take a closer look before indiscriminately installing pedestrian signals at all traffic signalized locations. Such pedestrian signals are expensive to install and maintain (for a large number of sites), and they may not be justified at many locations. Based on the findings of this study, further research may be desirable to further quantify the optimal use of pedestrian signals, including the following topics:

1. Determine the effect of intersection type on pedestrian safety by considering differences in functional classifications, lane configuration, crosswalk length, and special signal phasing;
2. Assess the effect of regional differences in pedestrian behavior, accident reporting, and pedestrian enforcement policies;
3. Investigate further the influence of pedestrian activities related to accident experience by type of pedestrian signal timing; and
4. Assess the impacts of general pedestrian compliance and understanding of signal indications on accident experience.

Only after the completion of such additional research can revised policies and practices be implemented.

Also, further efforts should be made to determine means to improve the effectiveness of standard pedestrian signals by making them more understandable, particularly in terms of the flashing WALK and the flashing DON'T WALK intervals. Also, efforts should be undertaken to determine the appropriateness of the pedestrian signal warrants currently given in the Manual on Uniform Traffic Control Devices (7) to determine whether more-realistic warrants are justified.

ACKNOWLEDGMENT

We acknowledge the support provided by the Federal Highway Administration in making this research possible. In addition, we acknowledge the cooperation and assistance provided by the traffic engineers in each of the cities used in this study. Their help was invaluable in compiling the data base used in this analysis. The opinions and viewpoints expressed in this paper are our own and do not necessarily reflect the viewpoints, programs, or policies of the U.S. Department of Transportation or of any state or local agency.

REFERENCES

1. BioTechnology, Inc. Urban Intersection Improvements for Pedestrian Safety. Federal Highway Administration, 5 vols., Dec. 1977, NTIS: PB-286496-SET/ST.
2. P. Fleig and D.J. Duffy. A Study of Pedestrian Safety Behavior Using Activity Sampling. Traffic Safety, Dec. 1967.
3. C.M. Abrams and S.A. Smith. Selection of Pedestrian Signal Phasing. TRB, Transportation Research Record 629 1977, pp. 1-6.
4. R.G. Mortimer. Behavioral Evaluation of Pedestrian Signals. Traffic Engineering, Nov. 1973.
5. J. Inwood and G.B. Grayson. The Comparative Safety of Pedestrian Crossings. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, TRRL Rept. 895, 1979.
6. M. Williams. Pelican Crossings, Myth or Miracle. Joint Australian Road Research Board - U.S. Department of Transportation Pedestrian Conference, Sydney, Australia, Nov. 1978.
7. Manual of Uniform Traffic Control Devices. Federal Highway Administration, 1978.

*Publication of this paper sponsored by Committee on Pedestrians.*

# Pedestrian Flows at Signalized Intersections

MARK VIRKLER

**Early techniques for dealing with pedestrian flows at signalized intersections were concerned with the minimum green time needed for crossing a street and often did not treat green time as a function of the number of people who cross. Recently, new knowledge has been gained about characteristics of pedestrian flow, including relations among speed, flow, and density. In the Interim Materials on Highway Capacity, a method is presented for pedestrian flows and queues at intersections. Some flaws in the method are examined here and a different approach for analyzing the problem is presented.**

The presence of pedestrians can have important effects on the operation of signalized intersections. Pedestrian crossing times can often determine minimum green times, and, therefore, minimum cycle lengths (1, p. 810). If insufficient crossing time is provided, pedestrians in crosswalks may adversely affect vehicular capacity and, of course, their own safety. Various methods have been proposed for ensuring adequate pedestrian crossing times (1-3). Three of these methods are discussed below.

The Interim Materials on Highway Capacity (4, pp. 115-147) contain a more-comprehensive procedure for the analysis of pedestrian requirements at signalized intersections. The procedure provides for the analysis of space requirements (for queuing and circulation) on the sidewalk at intersections and for determining needed crosswalk widths. Unfortunately, the procedure has some severe shortcomings. The purpose of this paper is to review the above procedures critically and to provide insight to the analysis of the problem.

EARLIER PROCEDURES

The 1976 Transportation and Traffic Engineering Handbook (1, p. 810) contains a simple equation for determining the minimum green time needed for pedestrians:

$$G = D/v_p \quad (1)$$

where

- G = minimum green time (s),
- D = length of the longest crosswalk in use during the phase (ft), and
- $v_p$ = pedestrian walking speed (ft/s).

The handbook states that a walking speed of 4 ft/s is a value frequently used.

Pignataro (2) has suggested a somewhat similar procedure that can be described by the following equation:

$$G + Y = t + (D/v_p) \quad (2)$$

where Y is the vehicle clearance interval (yellow or yellow plus all red time) in seconds and t is the pedestrian starting time, also in seconds.

Pignataro suggests that the pedestrian starting time be not less than 5 s. Where pedestrian (WALK-DON'T WALK) signals are used, the starting time would be 7 s and the vehicle clearance interval (Y) would not be included on the left side of Equation 2. Pignataro does not explain why this difference occurs. The 7-s starting time is in agreement with the 1971 Manual on Uniform Traffic Control Devices (5, p. 245). The 1978 edition of the manual calls for a walk interval of at least 4-7 s so that pedestrians will have adequate opportunity to leave the curb (6) before the DON'T WALK clearance interval is shown. Both the 1971 and 1978 manuals suggest a pedestrian walk speed of 4.0 ft/s; Pignataro suggests 3.5-4.0 ft/s.

A common weakness of the above procedures is that they do not explicitly consider the number of people who cross during a particular phase. A pedestrian toward the back of a queue must wait for the pedestrians in front to perceive and react to the signal change and then wait for them to proceed. The procedures do not guarantee an adequate starting time for those toward the back of the queue.

The Institute of Traffic Engineers developed a recommended practice, A Program for School Crossing Protection, which considers the number of pedestrians that cross at a given time (3). The procedure to determine an adequate gap uses the following equation:

$$\text{Gap time} = (W/3.5) + 3 + (N-1)2 \quad (3)$$

where W is the width of roadway to be crossed, in feet, and N is the number of five-person rows crossing the street (rounded up). The 3.5 was the assumed walk speed in feet per second, 3 was the assumed perception or reaction time (in seconds), and 2 was the assumed time interval between rows (in seconds). Children were assumed to walk in rows of five, with a two-second headway between rows. The obvious weaknesses of the procedure lie in use of the assumed parameters and the assumed orderliness of crossing.

INTERIM MATERIALS ON HIGHWAY CAPACITY

Recent knowledge of how pedestrians react to space availability and to the presence of other pedestrians provided the impetus for developing a more-comprehensive procedure for analyzing pedestrian characteristics at intersections. Level-of-service descriptions allow one to determine the quality of pedestrian flow if volume and walkway characteristics are known.

## Pedestrian Flow Characteristics

Pedestrian flow has been described in terms of speed, flow, density, and pedestrian space module (the inverse of density). As in highway-traffic-flow theory, these variables can be related to one another through the fluid-flow analogy:

$$q = k\,u \quad (4)$$

or

$$q = u/M \quad (5)$$

where

- q = pedestrian flow volume (pedestrians/foot-width of walkway/min);
- k = pedestrians per square foot of walkway;
- u = pedestrian space mean speed (ft/min); and
- M = pedestrian space module ($ft^2$/pedestrian).

Various researchers have collected data that relate these variables to one another. Figure 1 shows some of these findings in terms of speed versus density (7). Fruin (8) has also gathered data that relate the probability of a pedestrian being able to freely choose a path to the space module [see Figure 2 (8)].

The Interim Materials on Highway Capacity (4, pp. 115-147) include a section on pedestrians that incorporates these findings on pedestrian flow characteristics. The interim materials also recommend definitions for level of service for walkways [Table 1 (4, pp. 115-147)] and for queuing areas [see table below (4)].

| Level of Service | Avg Pedestrian Area Occupancy ($ft^2$/person) | Avg Interperson Spacing (ft) |
|---|---|---|
| A | $\geq 13$ | $\geq 4$ |
| B | 10-13 | 3.5-4.0 |
| C | 7-10 | 3.0-3.5 |
| D | 3-7 | 2-3 |
| E | 2-3 | $\leq 2$ |
| F | $\leq 2$ | Close contact |

A procedure for analyzing the performance of an intersection for handling pedestrian flow is then given.

## Intersections Analysis with the Interim Materials Method

The interim materials method (4, pp. 115-147) considers two critical conditions for a street corner at a two-phase signalized intersection. Each condition would occur when the signal is changing to a phase that will allow pedestrians at the corner to begin to cross the street [see Figure 3 (4, pp. 115-147)].

In Figure 3, each approach is designated by the letters A, B, C, and D. A and B are sidewalk approaches. The subscripts of the volume vectors (V) identify the movement on each approach. The designation 1 in a subscript indicates pedestrians walking toward the intersection, and the designation 2 indicates pedestrians leaving the intersection. Total signal cycle length (TS), curb radius (r), cross time (CT), and queue time (QT) for each signal must be known. All volumes are for 15-min peaks only.

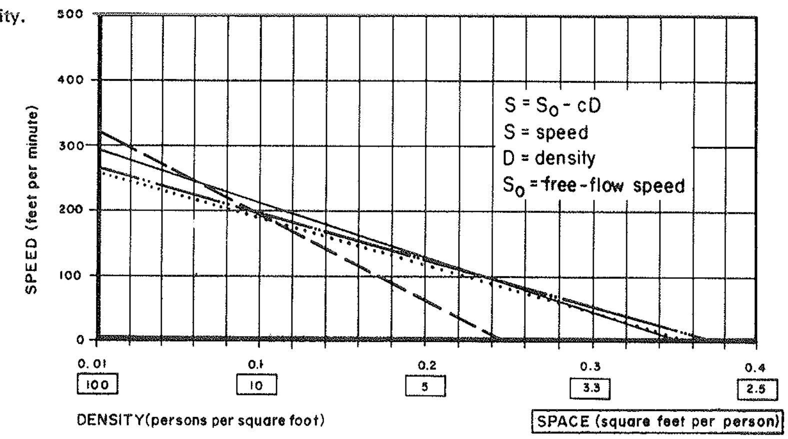
In step 1 the circulation areas (for pedestrians who are not waiting to cross) are computed for each condition. Step 1a involves conversion of 15-min pedestrian volumes for platooning (micropeaks within the 15-min design period).

In step 1b incoming pedestrian volumes $V_{C1}$ and $V_{D1}$ (people that reach the corner after crossing the street) are converted to peak volume. For example,

$$V_{D1(p)} = V_{D1} \times [TS/(CT_2 - 3)] \quad (6)$$

where TS is the total signal time (cycle length) in seconds, and $CT_2 - 3$ is the total cross time

Figure 1. Pedestrian speed versus density.




| $S_0$ ft./min. | c | $\frac{S_0}{c}$ ped./ft.² | $\frac{c}{S_0}$ ft.²/ped. | PEDESTRIAN TYPES (RESEARCHERS) |
|---|---|---|---|---|
| 268 | 714 | 0.36 | 2.77 | ·········· SHOPPERS (Older) |
| 267 | 722 | 0.37 | 2.70 | —··—··— COMMUTERS (Fruin) |
| 295 | 835 | 0.35 | 2.83 | ——— MIXED URBAN (Oeding) |
| 320 | 1280 | 0.25 | 4.00 | — — — STUDENTS (Navin and Wheeler) |

Figure 2. Cross flow traffic--probability of conflict.

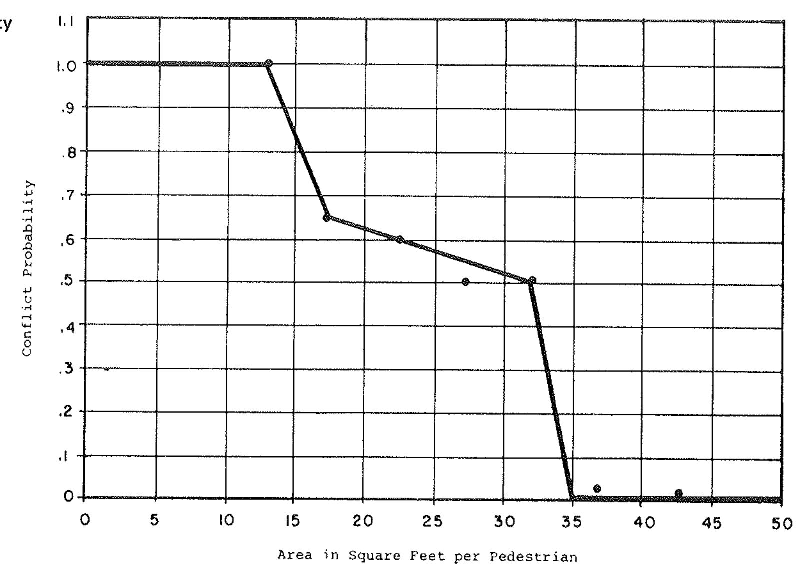



Table 1. Levels of service on walkways.

| Level of Service | Space (ft²/pedestrian) | Avg Flow Rate[a] (pedestrians/min/ft) | Mean Speed[b] (ft/min) | Volume/Capacity Ratio[c] |
|---|---|---|---|---|
| A | >40 | <6 | >250 | <0.24 |
| B | 24-40 | 10-6 | 240-250 | 0.24-0.40 |
| C | 16-24 | 14-10 | 224-240 | 0.40-0.56 |
| D | 11-16 | 18-14 | 198-224 | 0.56-0.72 |
| E | 6-11 | 25-18 | 150-198 | 0.72-1.00 |
| F | <6 | 0-25 | 0-150 | 0.00-1.00 |

[a]Flow rate relative to effective walkway width.
[b]Speeds are calculated based on space and flow rate variables.
[c]Assumed capacity is 25 pedestrians/min/ft.

Figure 3. Curb areas for pedestrian movements.

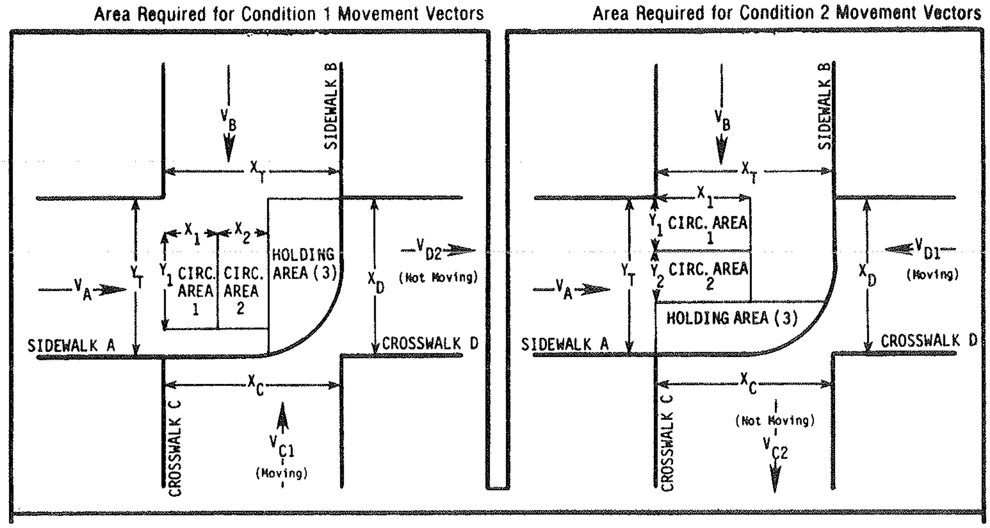
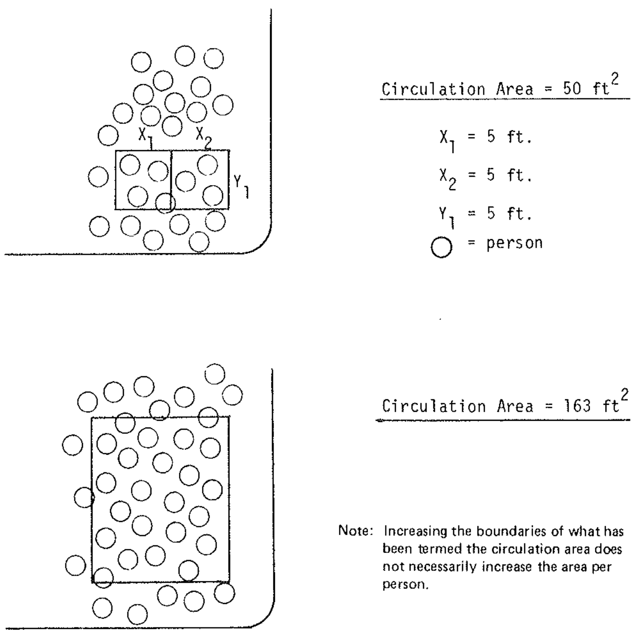



Figure 4. Effect of increasing circulation area.




(i.e., green time) less 3-s start-up delay. In the interim materials example,

$$V_{D1(p)} = 400 \times [80/(32 - 3)]$$

A flow of 400 pedestrians/15 min is converted to an equivalent 1100 pedestrians/15 min. The implicit assumption is that the pedestrian flow will be uniform for 29 s per 80-s cycle. For this to be true, the time required to cross the street would have to be zero and queued pedestrians would have to spread themselves out to achieve the uniform flow rate. The interim materials example does not include street width, but if one were to assume a width of 70 ft and a walk speed of 3.5 ft/s, it would take 20 s for a pedestrian to cross. With the 3-s start-up delay, a time band of only 9 s would be available for crossing (anyone waiting would have to leave the curb at between 3 and 12 s after the initial green indication in order to reach the opposite curb before the signal turned). Perhaps a more-appropriate pedestrian rate $[V'_{D1(p)}]$ would be

$$V'_{D1(p)} = V_{D1} \times [TS/(CT_2 - 3 - W)] \qquad (7)$$

where W is the walk time to cross the intersection.

$$V'_{D1(p)} = 400 \times [80/(32 - 3 - 20)] = 3556 \text{ pedestrians/15 min.}$$

With the assumptions used, the equivalent flow rate would be more than three times that found through the interim materials method. (A later procedure in the interim materials for calculating needed crosswalk width is based on the same faulty reasoning.)

In step 1c effective walkway widths for circulation on the street corner are determined. In step 1d the number of pedestrians in the circulation area is determined. This information is then misused in step 1e, determination of circulation area requirements. In Figure 3 (4, p. 135) the variables $X_1$, $X_2$, and Y are determined. These define the area assumed to be available for circulations, $Y_1 \cdot (X_1 + X_2)$. Then, the number of people within the circulation area at a given time is found. In the interim materials example (4), $X_1$, $X_2$, and $Y_1$ all equal 5 ft. Therefore 50 ft² are available in the defined circulation area. The number of people found to be in the area is 6.8. To have a probability of conflict equal to 0.5, 24 ft² per pedestrian are needed. The interim materials then calculate the needed circulation area, A $circ_1$:

$$A\ circ_1 = 6.8 \text{ pedestrians} \times 24 \text{ ft}^2\text{/pedestrian} = 163 \text{ ft}^2.$$

This would indicate that the area available of 50 ft² is not sufficient (with 7.35 ft²/pedestrian, the probability of conflict equals 1.0). Instead of recognizing this, the interim materials tell one to see whether 163 ft² are available (4) (e.g., could the circulation area be 16.3 ft x 10). This ignores that, if the boundaries of the circulation area are increased, the number of people within the area is increased (see Figure 4). The remaining steps of the procedure involve determination of the holding (queuing) area required for people waiting to cross, then comparison of the total space requirements with the total space available at the corner.

## ANOTHER APPROACH FOR ANALYZING PEDESTRIAN FLOW AT INTERSECTIONS

The purpose of this section is to (a) analyze how

Figure 5. Time required for herd to cross street at various levels of service.

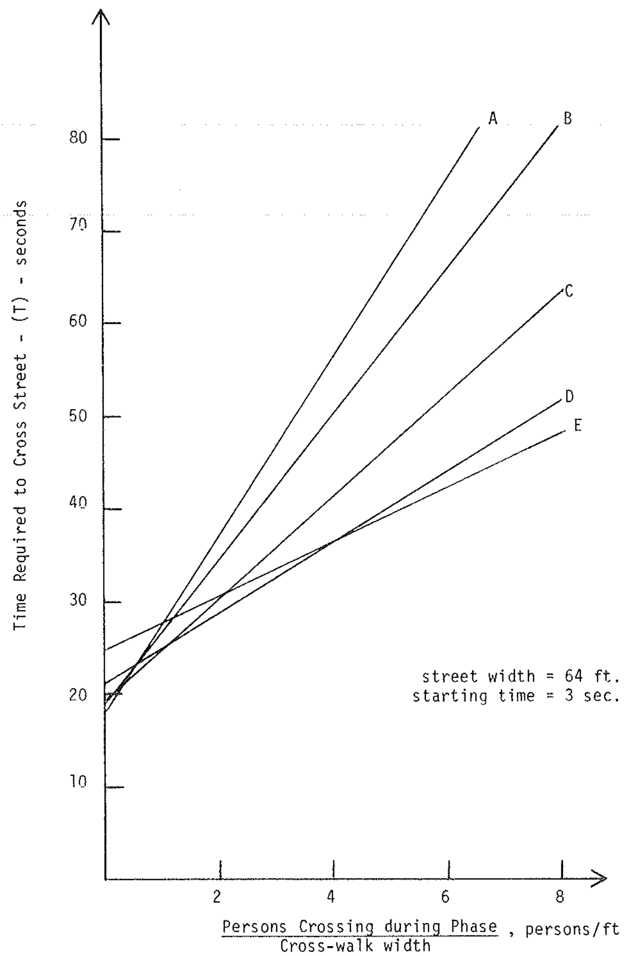
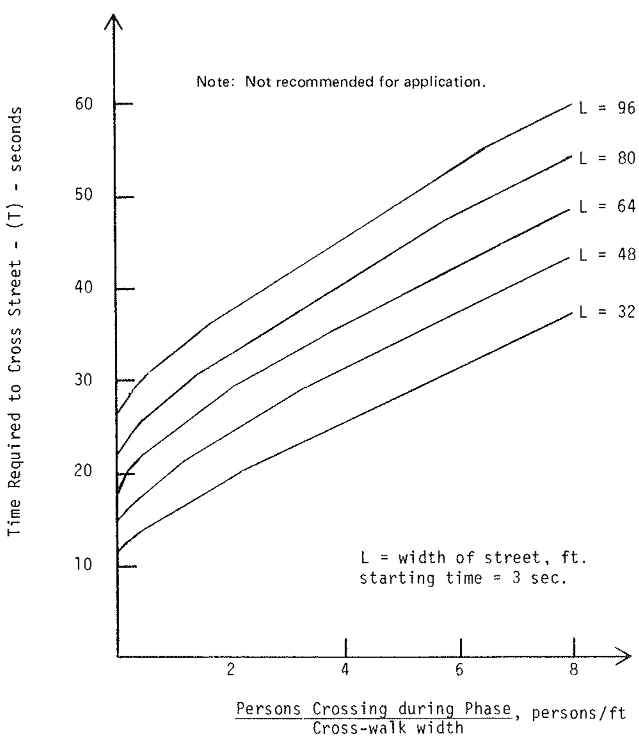



Figure 6. Time required for herd to cross street at optimal levels of service.




people are capable of crossing intersections and (b) shed some light on how one might determine space requirements on a street corner. A basic consideration is that a herd (or group) of people will be already queued up waiting to use a crosswalk. The herd will walk across at some average speed and some average density. If one knew the average speed and average density, then determination of the green time required would be a simple task.

$$T = t + (L/v_p) + P \quad (8)$$

where

- T = cross time, from when signal allows pedestrians to begin crossing until the last person clears the intersection,
- t = pedestrian starting time,
- L = length of the crosswalk,
- $v_p$ = pedestrian walking speed, and
- P = time headway from front to back of herd.

Note that

$$ab = NM \quad (9a)$$

or

$$a = NM/b \quad (9b)$$

where

- a = length of herd,
- b = width of herd (effective walkway width),
- N = number of people in herd, and
- M = pedestrian module in herd.

Also,

$$P = a/v_p \quad (10)$$

Therefore,

$$T = t + (L/v_p) + [(NM/b)/v_p] \quad (11)$$

One might assume that people would select to walk at a combination of speed and density that one could expect to find on a normal walkway. Then, the pedestrian walk speed and module would be related to pedestrian level of service, as in Table 1. A graphical representation of crossing time versus number of people crossing per effective crosswalk width is given in Figure 5. The combinations of speed and module were taken from Table 1.

One would have to know the level of service to determine the appropriate crossing time. However, one might make a further assumption: The herd will select a combination of speed and density (that could exist on a normal walkway) in order to minimize the time it takes for the last person to cross the intersection. A graphical representation of this is given in Figure 6.

The relation between speed and density in Figure 1 can be used with Equation 11 to develop an expression for pedestrian module in the herd to minimize crossing time.

$$M = [C + \sqrt{C^2 + S_0\, CL\, (b/N)}]/S_0$$

where $S_0$ is the free-flow speed and C is the negative of the slope in Figure 1, speed versus density. Equation 11 can then be used to find crossing time.

As the number of persons per foot of width of crosswalk increases, the lower level of service becomes more attractive for minimizing crossing time.

One might say that, for a large number of people crossing, the benefit of the high density (low module) of a poorer level of service more than outweighs the benefit of higher speed associated with a better level of service. As the length of the crosswalk increases, the break-even points (the points at which the poorer levels of service provide the lower cross time) move to the right, due to the greater importance of walk speed.

Some obvious problems with the above approach are as follows:

1. People may not choose to walk at a combination of speed and density that they would on a normal walkway,
2. People may not choose to walk at the optimum combination of speed and density, and
3. The presence of turning vehicles may disrupt pedestrian flow.

The lack of an optimum combination would tend to make Figure 5 overly optimistic. On the other hand, people may be willing to walk at a higher density for a given speed in a crosswalk than they would on a much longer walkway. This condition would be similar to the experience observed near highway on-ramps, where a particular lane can carry a volume higher than its expected capacity, apparently because people are willing to put up with a higher combination of speed and density for a short period of time. Further, the herd consists of a relatively small number of people. The people in front will not have their speed constrained by others. This may tend to reduce the time required for crossing.

The interim materials procedure (4, pp. 115-147) implicitly assumes that people would desire the best level of service possible. However, over a relatively short distance (e.g., 20-100 ft), pedestrian level of service might not be as relatively important to the pedestrian as would level of service over a much longer walkway. Further, some researchers (9,10) have reported higher average walk speeds at intersections and in the middle of city blocks than is indicated in Table 1 for level of service A.

Figure 6 is a coarse representation of how a herd is capable of negotiating a crosswalk. It should be thought of as a starting point for further investigation.

A related problem is providing a sufficient circulation area at a corner. The most-critical condition would occur when we have a herd of people just leaving a crosswalk and reaching the corner, some people seeking to use the same circulation area as will be used by the herd, and a queue waiting to use an adjacent crosswalk (e.g., $V_{C1}$, $V_A$, and $V_{D2}$ in Figure 3). If the herd ($V_{C1}$) were at level of service E, then anyone wishing to cross the herd (for instance, someone from $V_A$) would be unable to do so. This problem might be slightly improved by increasing the effective width of the herd's path on reaching the corner. Also, since the herd would be using the space for a relatively short period of time, anyone wishing to cross the herd's path could wait until the herd has passed. If the herd were at a level of service better than E, the people wishing to cross the path might be able to weave their way through the herd. The most-severe problems would, of course, occur if one large group of people needed to cross the path of another large group.

Another related problem is providing a sufficient crosswalk width so that two herds that pass each other in the middle of the street would have sufficient space to avoid delay. If the effective crosswalk width is not increased, the assumed crosswalk width would not be appropriate when two relatively large herds pass. To deal with this problem, one would have to determine the needed reduction in effective crosswalk width due to the presence of the opposing herd. This might be done in proportion to the expected size of each herd. Otherwise, herds would be forced to walk outside of the crosswalk in order to reach the opposite curb within the signal phase.

## SUMMARY

Recent studies of pedestrian movement can provide aid for dealing with pedestrian movement at signalized intersections. The procedure given in the Interim Materials on Highway Capacity (4, pp. 115-147) uses this relatively new knowledge of pedestrian movement, but faults within the procedure make it inappropriate for use. A different application of the principles of pedestrian flow was presented to provide a more-realistic starting point for the analysis of pedestrian flows at intersections and for ways to determine required walkway widths and lengths of signal phase. Still, some assumptions used might need to be modified when new information becomes available.

## REFERENCES


1. S. Cass. Traffic Signals. In Transportation and Traffic Engineering Handbook (J.E. Baerwald, ed.), Institute of Traffic Engineers, Prentice Hall, Inc., Englewood Cliffs, NJ, chapter 17, 1976.
2. L.J. Pignataro. Traffic Engineering: Theory and Practice. Prentice Hall, Inc., Englewood Cliffs, NJ, 1973.
3. A Program for School Crossing Protection--A Recommended Practice of the Institute of Traffic Engineers. Traffic Engineering, Oct. 1962, pp. 51-52.
4. Development of an Improved Highway Capacity Manual. In Interim Materials on Highway Capacity, Transportation Research Circular 212, TRB, June 1980, pp. 3-147.
5. Federal Highway Administration. Manual on Uniform Traffic Control Devices. U.S. Government Printing Office, 1971.
6. Federal Highway Administration. Manual on Uniform Traffic Control Devices. U.S. Government Printing Office, Section 4D-5, 1978.
7. B. Pushkarev and J.M. Zupan. Capacity of Walkways. TRB, Transportation Research Record 538, 1975, pp. 1-15.
8. J.J. Fruin. Pedestrian Planning and Design. New York Metropolitan Assn. of Urban Designers and Environmental Planners, New York, 1971, 206 pp.
9. L.A. Hoel. Pedestrian Travel Rates in Central Business Districts. Traffic Engineering, Jan. 1968, pp. 10-13.
10. F.P.D. Navin and R.J. Wheeler. Pedestrian Flow Characteristics. Traffic Engineering, June 1969, pp. 30-36.


*Publication of this paper sponsored by Committee on Pedestrians.*