High-Volume Pedestrian Crosswalk Time Requirements

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Existing methods to determine pedestrian crossing times at signalized intersections are described. These approaches have significant shortcomings under high-volume conditions. They can indicate that adequate crossing time is present when a high volume of pedestrians would not be able to clear the intersection in the time provided. Alternative shock wave approaches are developed to provide a more appropriate means of estimating flow characteristics when pedestrian volumes are high. The results can be used to determine crosswalk capacity, to assist in developing signal timing plans, and to determine desirable crosswalk widths and lengths.

A variety of methods have been developed for determining appropriate pedestrian crossing times at signalized intersections. Although many of these methods have useful applications, all have significant shortcomings when estimating the crossing time required under high-volume conditions. Existing methods are described. A shock wave approach is then used to develop a more appropriate means of estimating flow characteristics when pedestrian volumes are high. This approach is then adapted to allow one to estimate parameters required for operation or design.

BACKGROUND

Crossing Time

Many crossing time recommendations have been based on assumed start-up delay and walking speed. The Manual on Uniform Traffic Control Devices [MUTCD (*1*)], Pignataro (*2*), and the Signalized Intersection Chapter of the Highway Capacity Manual (HCM) (*3*) have formulations similar to those in Equation 1. The parameters of each model are indicated in Table 1. A time-space diagram of the model appears in Figure 1.

$$T = D + L/u \tag{1}$$

where

- T = time required for crossing (sec),
- D = initial start-up delay to step off curb and enter crosswalk (sec),
- L = walking distance (m), and
- u = walking speed (m/sec).

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If only a small number of pedestrians use the crosswalk during a given phase, this time should be sufficient. However, if the number of people crossing is large, the time D may not be sufficient for everyone to leave the curb. If the platoon uses the assumed walking speed, the crosswalk will not be cleared of pedestrians within the time T.

The 1962 Institute of Traffic Engineers (ITE) School Crossing Guidelines (*4*) consider platoon size. The crossing time can be described as

$$T = D + L/u + 2[(N/5) - 1] \tag{2}$$

where N is the number of pedestrians crossing during an interval. It is assumed that the students walk in rows, five abreast, with a 2-sec headway between rows. Figure 2 shows a one-way platoon flow to correspond to this equation.

Virkler and Guell (*5*) recommended an equation for one-directional flow that also considers platoon size. The equation takes the following form:

$$T = D + L/u + x(N/W) \tag{3}$$

where

- x = average headway (sec/pedestrian/m of crosswalk width) and
- W = crosswalk width (m).

The first term, D, is perception/reaction time. The third term equals the time required for the platoon to pass a point. Figure 2 also can be used to represent this equation. Although the above two formulations consider platoon size, they do not address the problem of two opposite-direction platoons meeting in a crosswalk.

Platoon Flow Rate

The Interim Materials on Highway Capacity (*6*) provided a procedure to estimate crosswalk level of service by converting the pedestrian flow rate to a "platoon" flow rate. The platoon flow rate was calculated as

$$q_{\text{platoon}} = q[C/(G - 3)] \tag{4}$$

where

- q_{platoon} = platoon flow rate (pedestrians/min),
- q = actual pedestrian flow rate (pedestrians/min),
- C = cycle length (sec), and
- $G-3$ = green time minus 3 sec of start-up delay (sec).

The platoon flow rate assumes that, when pedestrians are in the crosswalk, a uniform rate of flow exists during the green phase

TABLE 1 Crossing-Time Parameters of Three Models

	Parameters	
Method	Initial Start-up Delay (sec)	Walking Speed (m/sec)
MUTCD (*1*)	4 to 7	1.22
Pignataro (*2*)	5 or more	1.07 to 1.22
HCM Ch. 9 (*3*)	7	1.22

(minus 3 sec for start-up delay). For instance, consider a crosswalk serving 30 pedestrians per minute with a 27-sec green indication (for vehicles and pedestrians) and a 60-sec cycle length. The platoon flow rate would be

$$q_{\text{platoon}} = 30[60/(27-3)]=30[60/24] = 75 \text{ pedestrians/min}$$

One advantage of this procedure is that it can be applied to estimate walkway width requirements for two-way pedestrian flow. Unfortunately, an implicit assumption is that a uniform platoon flow rate will exist throughout the crosswalk for all but 3 sec of the green time. For this to be a realistic estimate of the flow rate, the crossing time for the crosswalk would have to be 0. Virkler (*7*) suggested that this equation would be appropriate for one-way flow if the crossing time were also deducted from the available green time, as shown below:

$$q_{\text{platoon}} = q[C/(G - T - 3)] \tag{5}$$

where T is walking time for one individual to cross in seconds.

For instance, using the previous example with a crosswalk length of 13 m and a walking speed of 1.3 m/sec, the walking time for one individual would be 10 sec, and the flow rate within the platoon would become

$$q_{\text{platoon}} = 30[60/(27 - 10 - 3)] = 30[60/14]$$
$$= 129 \text{ pedestrians/min}$$

Time-Space Concept

The pedestrian chapter of the HCM (*3*) uses a time-space approach to deal with crosswalk level of service but suffers from a flaw similar to that in the interim materials. The entire area of the crosswalk is assumed to be available to pedestrians during all but 3 sec of the walking phase (on a typical crosswalk with concurrent vehicular

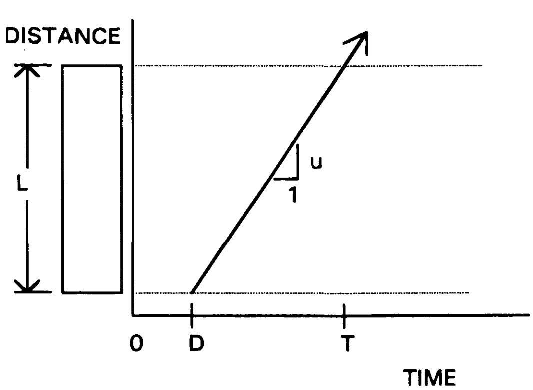

FIGURE 1 Time-space diagram for a single pedestrian.

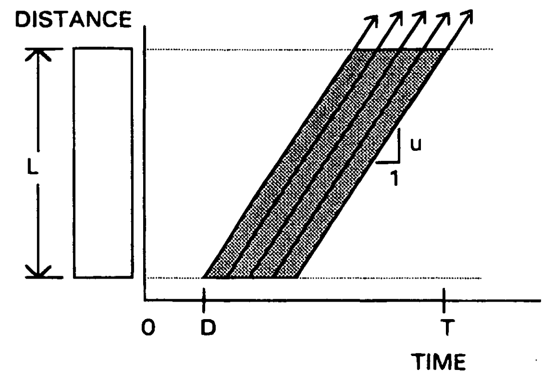

FIGURE 2 Time-space diagram for a one-way platoon.

green, the walking phase equals the vehicular green plus yellow time). For example, the HCM has an example with a cycle length of 80 sec and two walk phase times of 48 and 32 sec. For the latter walk time

Crosswalk width = W_d = 5 m,
Crosswalk length = L_d = 15 m,
WALK phase time = G_w = 32 sec − 3 sec = 29 sec = 0.48 min, and
Time-space = TS = [(5 m)(15 m')](0.48 min) = 36 m/min²

The time-space diagram for this approach is shown in Figure 3. If 100 pedestrians (total from both directions) required 10 sec each to cross, then the average space per pedestrian would be

$$\frac{2175 \text{ m}^2 \cdot \text{sec}}{(100 \text{ pedestrians})(10 \text{ sec})} = 2.175 \text{ m}^2/\text{ped}$$

A level of service would then be associated with the average space per pedestrian (2.175 m²/pedestrian). Although this technique has the advantage of dealing with two-directional walking, there are two problems with the approach:

1. The available time-space is overstated and
2. The approach does not ensure that adequate walking time is provided.

Overestimation of Time-Space

As indicated in Figure 3, the entire space of the crosswalk is assumed to be available to pedestrians during the walk phase time. However, if pedestrians are to cross safely, the space in the middle of the street is not available during the beginning of the walk phase (because pedestrians could not yet have reached it) or near the end of the walk phase (if pedestrians are to reach the curb before the walk phase time ends). Figure 4 illustrates that the available time space has been overestimated by 20 percent.

Adequacy of Walking Time

The HCM methodology does not ensure that adequate walking time exists for a platoon of pedestrians to cross the street. In the first

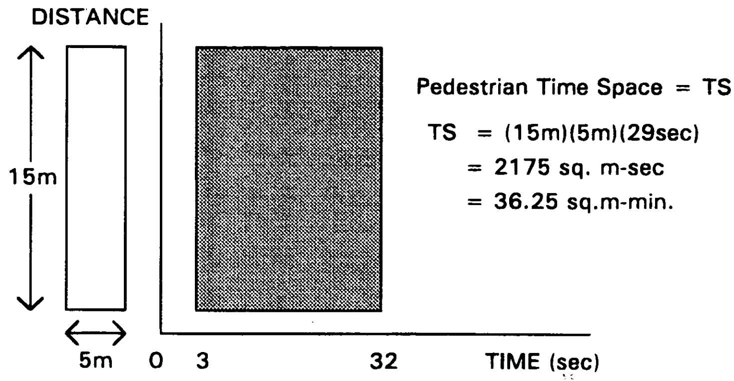

FIGURE 3 Time-space diagram for HCM approach.

example, the pedestrian space available (2.175 m²/pedestrian) would be the same whether the walkway was 5 × 15 m or 1 × 75 m. In the latter case no one could safely cross during the green. A different formulation is necessary to ensure that adequate space and time exist at crosswalks. A proposed method is developed in the next section.

PROBLEM FORMULATION

Equation 1 [$T = D + L/u$] is appropriate when pedestrian flow rates are low. When pedestrian flow rates are high and in one direction only, the Virkler and Guell formulation of Equation 3 [$T = D + L/u + x(N/W)$] appears appropriate. This form, with a 3-sec start-up time and the parameters for LOS B (associated with the flow rate found by Virkler and Guell) would be

$$T = 3 \text{ sec} + L/(1.27 \text{ m/sec}) + (2.61 \text{ sec/pedestrian/m})(N/W) \quad (6)$$

This approach could also be modeled as shown in the shock wave analysis of Figure 5. Figure 5 shows low-density pedestrians arriving on an approach (Flow State A) and forming a high-density queue (Flow State B) while the signal is effectively red (actual red plus start-up delay plus crossing time). When the signal turns effectively green for pedestrians (i.e., when pedestrians can safely leave the curb), a moderate-density platoon moves over the crosswalk (Flow State C). The largest possible platoon for the given red time and cycle length is shown in the figure. The maximum depth of the standing queue is shown as L_q.

The distance traveled by the last pedestrian in the queue would be $L_q + L$. Ignoring the start-up delay, the time to clear all pedestrians would be the time between when the front of the queue begins to move and when the rear of the queue begins to move (t_0) plus the time (t_1) for the last pedestrian to travel $L_q + L$. The required effective green time, derived from shock wave theory (*8*) would therefore be

$$G_{\text{req}} = t_0 + t_1 \quad (7)$$

$$G_{\text{req}} = R \cdot \left(\frac{\omega_{AB}}{\omega_{BC} - \omega_{AB}} \right) + \frac{[(k_A)(N/W)] + L}{U_C} \quad (8)$$

where

G_{req} = required effective green time (sec),
R = effective red time (sec),
$\omega_{AB} = -q_A/(k_B - k_A)$,
$\omega_{BC} = -q_C/(k_B - k_C)$,
q_A = flow rate of pedestrians approaching the queue (pedestrians/min),
q_C = flow rate of the pedestrians leaving the queue (pedestrians/min),
k_B = density of platooned pedestrians (pedestrians/m²),
k_A = density of arriving pedestrians (pedestrians/m²).

With high-volume two-way flow a more intricate approach is necessary. The assumptions are as follows:

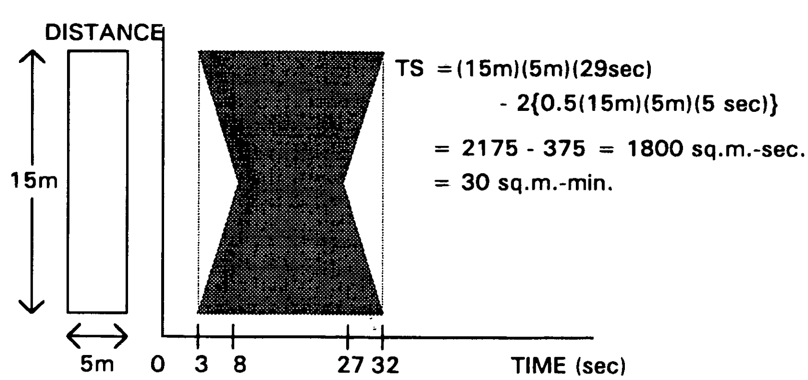

FIGURE 4 Time-space available considering walking speed.

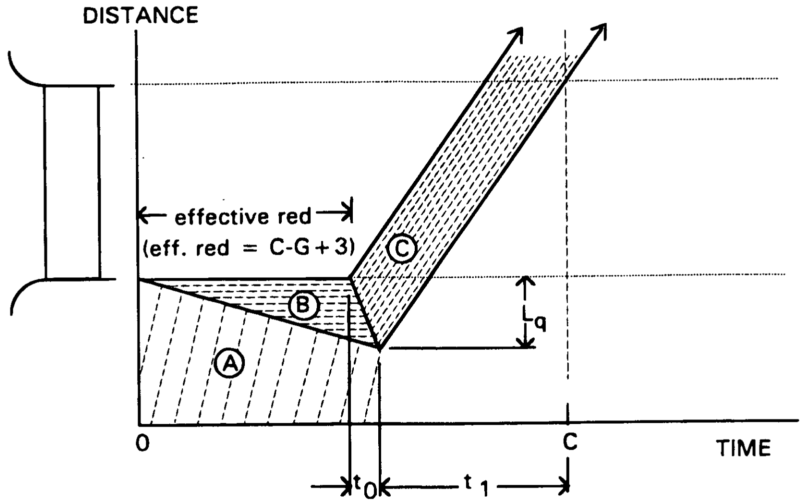

FIGURE 5 Time-space diagram for largest one-way platoon.

1. Before the flows meet, each flow occupies the full walkway width.
2. Until flow from the opposite direction is encountered, pedestrian walk speed is u_C and density is k_C. When the flows meet, the density increases to k_D and the speed reduces to u_D. The low speed of u_D will continue after the flows separate.
3. When the flows meet, each opposing flow will occupy one-half of the walkway width.

The speed and density assumptions are based on the work of Virkler and Guell (*5*) and the authors' experience. The assumptions are illustrated in Figure 6, where the higher flow rate is moving upward. The authors' experience suggests that Flow State C would be in LOS B (with u_C = 1.27 m/sec and k_C = 0.269 pedestrians/m^2). Flow state D would be at capacity (u_D = 0.762 m/sec and k_D = 1.794 pedestrians/m^2).

One might expect that the assumption that the low speed of u_D will continue after the flows separate is too conservative. On the other hand it is likely that pedestrians will anticipate downstream high-density conditions by reducing their speed while their own density is still low. Therefore the assumed low-density speed (u_C) may be too high (or unconservative).

Following the assumptions of Figure 6, the total time required can be derived as

$$G_{\text{req}} = t_0 + t_1 + t_2 \tag{9}$$

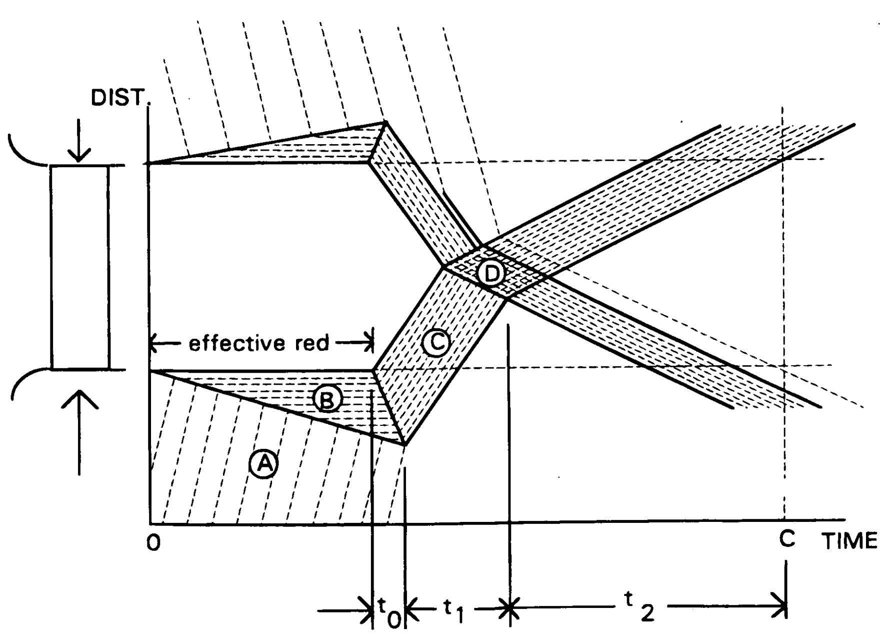

FIGURE 6 Time-space diagram for two-way platoons.

where

$$t_0 = R \cdot \left(\frac{\omega_{AB}}{\omega_{BC} - \omega_{AB}} \right) \tag{10}$$

$$t_1 = \frac{L_q + \dfrac{L}{2} - \left[u_D \cdot \dfrac{L_q + u_C \cdot t_0}{u_C + u_D} \right]}{u_C} \tag{11}$$

$$t_2 = \frac{(L/2) + u_D \cdot \left[\dfrac{L_q + u_C \cdot t_0}{u_C + u_D} \right]}{u_D} \tag{12}$$

However, if the opposing stream passes the last pedestrian before he or she begins to move, the required green time would be

$$G_{\text{req}} = t_0 + (L + L_q)/u_D \tag{13}$$

APPLICATIONS

This shock wave approach could be used to

1. Determine the capacity of a crosswalk,
2. Assist in developing a signal timing plan adequate for pedestrians, and
3. Determine a desirable crosswalk width or length,

Figures 7 through 9 provide a broad range of required crossing times for crosswalks while varying the demand, cycle length, and crosswalk length. The crosswalk LOS predicted by the HCM is shown in the cell, below the crossing time. The first letter represents the LOS and the second letter represents the surge LOS. The surge occurs when "the two lead platoons from opposite corners . . . are simultaneously in the crosswalk" (3).

In Figures 7 through 9 several cells (which are shaded) have crossing times greater than the crossing time available (i.e., the green time is not sufficient for demand. Note that none of the cells with inadequate crossing times are identified as being over capacity by the HCM. Many are reported to operate at the relatively high quality LOS B or C, even though pedestrians would not have sufficient time to clear the crosswalk before the onset of red. This occurs because the HCM does not consider whether crossing time is adequate. LOS is based solely on the average space available per pedestrian.

OTHER CONSIDERATIONS

The HCM considers the effects of turning vehicles by reducing the time-space available to pedestrians by the time-space used by each turning vehicle. A similar treatment for crossing time would require that the crossing time be increased by the number of seconds that each turning vehicle would delay the major pedestrian platoon. An alternative view would be that the vehicular green time for turning vehicles should provide for the number of seconds that the crosswalk space is not available to the turning vehicles because of the presence of pedestrians.

The HCM also provides an LOS measure for the corner through a similar time-space analysis. The time-space (in square meters per second) available on the corner is compared with the time-space demand required by queued pedestrians, crosswalk users passing through the corner area, and other pedestrians using the same space but not using a crosswalk. Because the shock wave method developed earlier can find the space occupied by queued pedestrians, it appears likely that a shock wave approach could be used to analyze corner operations. Shock wave analysis could determine the adequacy of the corner throughout the signal cycle. Time-space analysis only examines average conditions during the cycle. Critical situations may exist that could not be identified by the time-space approach.

	REQUIRED CROSSING TIME (sec) & AVERAGE LOS/SURGE LOS							
	One-way Flow in Major Direction (ped/hr)							
Length	250	500	750	1000	1250	1500	1750	2000
8.5m (28')	11.6 A/B	14.1 B/B	16.7 B/C	19.25 B/C	21.8 B/D	24.3 C/D	26.7 C/D	29.2 C/E
12.2m (40')	15.4 A/A	18.0 B/B	20.6 B/B	23.1 B/C	25.6 B/C	28.1 C/D	30.6 C/D	33.0 C/D
15.8m (52')	19.3 A/A	21.9 B/B	24.4 B/B	27.0 B/B	29.5 B/C	32.0 C/C	34.5 C/D	36.9 C/D
19.5m (64')	23.1 A/A	25.7 B/B	28.2 B/B	30.8 B/B	33.3 B/C	35.8 C/C	38.3 C/C	40.7 C/D
23.2m (76')	26.9 A/A	29.5 B/B	32.1 B/B	34.6 B/B	37.1 B/B	39.6 C/C	42.1 C/C	44.5 C/C
26.8m (88')	30.8 A/A	33.3 B/B	35.9 B/B	38.5 B/B	41.0 B.B	43.5 C/C	45.9 C/C	48.4 C/C

ASSUMPTIONS: Cycle Length = 40 sec, Effective Green Time = 20 sec,
67/33 directional split, no turning vehicles, Crosswalk Width = 3.0m (10.0')
INADEQUATE CROSSING TIME INDICATED BY SHADING

FIGURE 7 Required crossing time and LOS with 40-sec cycle.

	REQUIRED CROSSING TIME (sec) & AVERAGE LOS/SURGE LOS							
	One-way Flow in Major Direction (ped/hr)							
Length	250	500	750	1000	1250	1500	1750	2000
8.5m (28')	12.9 A/B	16.7 B/C	20.6 B/C	24.4 B/D	28.2 B/D	31.7 C/E	35.1 C/E	38.5 C/E
12.2m (40')	16.7 A/B	20.6 B/B	24.4 B/C	28.2 B/C	32.0 B/D	35.8 C/D	39.5 C/E	43.1 C/E
15.8m (52')	20.6 A/B	24.5 B/B	28.3 B/B	32.1 B/C	35.9 B/C	39.7 C/D	43.3 C/D	47.0 C/D
19.5m (64')	24.4 A/A	28.3 B/B	32.1 B/B	35.9 B/C	39.7 B/C	43.5 C/D	47.1 C/D	50.8 C/D
23.2m (76')	28.2 A/A	32.1 B/B	35.9 B/B	39.8 B/C	43.6 B/C	47.3 C/C	51.0 C/D	54.6 C/D
26.8m (88')	32.0 A/A	35.9 B/B	39.8 B/B	43.6 B/B	47.4 B/C	51.1 C/C	54.8 C/C	58.5 C/D

ASSUMPTIONS: cycle length = 60 sec, effective green time = 30 sec,
67/33 directional split, no turning vehicles, crosswalk width = 3.0m (10.0')
INADEQUATE CROSSING TIME INDICATED BY SHADING

FIGURE 8 **Required crossing time and LOS with 60-sec cycle.**

RECOMMENDATIONS

It has been shown above that when a large number of pedestrians cross an intersection the required crossing time is greater than that currently required by the methods commonly used. The platoon size to consider as large and the walking time to provide are addressed next.

Determining When Platoon Is Large

Four alternative guidelines are discussed below, as they relate to the present, provided by Chapter 9 of the HCM.

1. *A Large One-Way Platoon Can Be Found by the ITE School Crossing Protection Philosophy*—Chapter 9 of the HCM (*3*) allows 7 sec for pedestrians to leave the curb. The ITE School Crossing Protection formulation (*4*) assumes that a 3 sec start-up delay is required before students move in rows of five, with a 2-sec headway between rows (i.e., the rows enter the intersection at 3,5,7, and 9 sec, and so forth after the signal turns green). Because the fourth row would enter the intersection after the HCM's initial 7-sec period, a large platoon can be defined as 16 pedestrians.

2. *A Large One-Way Platoon Can Be Found by the Virkler and Guell Formulation*—Virkler and Guell found that a one-way platoon requires 2.61 sec/(pedestrians/m) to pass a point. With a 3-sec start-up delay, the HCM allows 4 sec for a platoon to leave the curb. In 4 sec the volume would be 4 sec/[2.61 sec/(pedestrian/m)] or 1.53 pedestrian/m. For walkway widths of 3, 4, and 5 m, the volumes that could leave the curb would be 4.6, 6.1, and 7.6 pedestrians, respectively. A large one-way platoon might be defined as 7 or more pedestrians.

3. *A Large Two-Way Platoon Can Be Found by the Virkler and Guell Formulation*—With two-way flows, the two platoons must pass each other on the crosswalk. Using the same platoon headway of 2.61 sec/(pedestrian/m) to pass a point, a large two-way volume can be defined as 7 or more pedestrians (total for both directions) when the walkway is 4 m wide.

4. *A Large Two-Way Platoon Can Be Found by Equation 9*—One could use Equation 9 (required green time for two-way flow) to determine when the needed green time exceeded that provided by Chapter 9 of the HCM. Because of the reduced walking speed after the platoons meet, it is likely that a large platoon would be somewhat less than seven pedestrians. The exact number would depend on the crosswalk length and width.

Equation 9 has not been tested with field data. The authors therefore support alternative Guideline 3 because it appears rational and incorporates two-way flow. Recognizing that the pedestrian volume at which Chapter 9 of the HCM crossing time would be exceeded depends on the assumed walking speed, crosswalk length, and crosswalk width, the authors recommend that seven pedestrians crossing during a phase be considered as a large platoon. The hourly demand that would be expected to have a design volume (e.g., perhaps the 85th percentile volume) per cycle of 7 pedestrians would depend on the cycle length and peaking characteristics but might be roughly estimated as 300 pedestrians per hour.

Recommended Crossing Time

Three alternative guidelines for determining adequate crossing times are discussed.

Provide Crossing Time for Large One-Way Platoon

Virkler and Guell found that a one-way platoon requires 2.61 sec/(pedestrian/m) to pass a point. With the conservative HCM walking speed of 1.22 m/sec rather than 1.27 m/sec, Equation 6 can be modified to become

	REQUIRED CROSSING TIME (sec) & AVERAGE LOS/SURGE LOS							
	One-way Flow in Major Direction (ped/hr)							
Length	250	500	750	1000	1250	1500	1750	2000
8.5m(28')	14.2 A/B	19.3 B/C	24.5 B/D	29.3 B/D	33.9 B/E	38.5 C/E	43.1 C/E	47.7 C/E
12.2m(40')	18.0 A/B	23.2 B/C	28.3 B/C	33.4 B/D	38.4 B/D	43.3 C/E	47.9 C/E	52.5 C/E
15.8m(52')	21.9 A/B	27.0 B/B	32.2 B/C	37.3 B/C	42.3 B/D	47.2 C/D	52.0 C/E	56.7 C/E
19.5m(64')	25.7 A/B	30.8 B/B	36.0 B/C	41.1 B/C	46.1 B/D	51.1 C/D	56.0 C/D	60.9 C/E
23.2m(76')	29.5 A/B	34.7 B/B	39.8 B/B	44.9 B/C	50.0 B/C	54.9 C/D	59.9 C/D	64.7 C/D
26.8m(88')	33.4 A/A	38.5 B/B	43.7 B/B	48.8 B/C	53.8 B/C	58.8 C/C	63.7 C/D	68.6 C/D

ASSUMPTIONS: cycle length = 80 sec, effective green time = 40 sec,
67/33 directional split, no turning vehicles, crosswalk width = 3.0m (10.0')
INADEQUATE CROSSING TIME INDICATED BY SHADING

FIGURE 9 Required crossing time and LOS with 80-sec cycle.

$$T = 3 \text{ sec} + L/(1.22 \text{ m/sec}) + (2.61 \text{ sec/pedestrian/m})\,(N_{1\text{-way}}/W) \quad (14)$$

where

T = time required for crossing (sec),
L = walking distance (m),
$N_{1\text{-way}}$ = larger one-way pedestrian volume during a phase, and
W = crosswalk width (m).

Because of the slightly lower walking speed, this equation is more conservative than Equation 6. The form of the equation has been derived from field data on one-way flow (*5*).

Provide Crossing Time for Two-Way Platoons with Constant Headways

Equation 14 would be extended to recognize that the larger of the two one-way volumes using the crosswalk would require more time to cross the intersection if an opposite direction flow is using the same crosswalk. The same platoon headway of 2.61 sec/pedestrian/m) to pass a point is used, but the volume to pass the point includes both the larger one-way flow and the smaller, opposite-direction, one-way flow.

$$T = 3 \text{ sec} + L/(1.22 \text{ m/sec}) + (2.61 \text{ sec/pedestrian/m})(N_{2\text{-way}}/W) \quad (15)$$

where

T = time required for crossing (sec),
L = walking distance (m),
$N_{2\text{-way}}$ = two-way pedestrian volume during a phase,
W = crosswalk width (m).

The point on the crosswalk that both platoons must pass could be imagined as a doorway or bottleneck. The same number of seconds would be required to allow N people through the doorway whether the directional split was 50:50, 60:40, or 100:0. Because two-way pedestrians would be walking under higher-density conditions over a significant length of the crosswalk, rather than just at a point, the assumed walking speed is probably high, making the crossing time unconservative (too short). However this crossing time is more conservative than that presently provided.

Provide Crossing Time Called for in Equation 9

The authors view Equation 9 as a rational interpretation of two-way flow conditions on the basis of the shock wave theory and personal observation. It would provide the most conservative (longest) crossing times under two-way flow conditions.

Because Equation 9 has not been tested with field data, the authors do not recommend it for implementation. The speed used in Equation 15 is accepted in current practice, and the headway was derived from field data, although that headway was limited to one-way flow. Under high-volume two-way flow conditions, Equation 15 is probably somewhat unconservative, but it is more conservative than Equation 14 and would be a significant improvement on current practice. For these reasons, Equation 15 is recommended for use where high-volume conditions are present (i.e., seven or more pedestrians in a phase).

CONCLUSIONS

Adequate methods exist to determine low-volume pedestrian crossing times. When high pedestrian volumes are present, the existing methods are inadequate to ensure safe operation. A shock wave approach, as developed earlier, can be used to ensure that adequate crossing time is present for large one-way or two-way platoon flows. The authors recommend that a shockwave approach (i.e., Equation 15) be used in the procedure from the HCM chapter on pedestrians as a check on whether adequate crossing time is present. Without such a check, an analysis could indicate a high-quality LOS when inadequate crossing time could yield unsafe conditions.

SUGGESTIONS FOR FURTHER RESEARCH

The approaches developed earlier need to be tested by field data. A field study could refine the assumptions used for start-up delay, walking speeds, pedestrian densities, queue depth, and crosswalk widths used. Such a study could also examine the effects of turning vehicles on individual pedestrians and on platoon operations. For example, do all turning vehicles conflict with platoons, or does the time of the vehicle movement within the green phase alter the effect?

Examination of corner operations could assist in the development of an alternative means to examine corner operations. A study could examine whether the various flows that occur on a corner follow predictable patterns that could be modeled by shock wave analysis, simulation, or some other method.

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