Recommended Procedures
Chapter 13, "Pedestrians,"
of the *Highway Capacity Manual*

Capacity Analysis of Pedestrian and Bicycle Facilities
Task Order 8: Pedestrian-Bicycle Research Program

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The University of North Carolina
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for:
United States Department of Transportation
Federal Highway Administration
Turner-Fairbank Highway Research Center
McLean, Virginia

Final Report
February 1998

Technical Report Documentation Page

1. Report No. FHWA-RD-98-107	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle RECOMMENDED PROCEDURES FOR CHAPTER 13, "PEDESTRIANS," OF THE HIGHWAY CAPACITY MANUAL		**5. Report Date** February 1998
		6. Performing Organization Code
7. Author(s)		**8. Performing**

9. Performing Organization Name and Address

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10. Work Unit No. (TRAIS)

11. Contract or Grant No.

DTFH61-92-R-00138

12. Sponsoring Agency Name and Address

Office of Safety & Traffic Operations Research & Development
Federal Highway Administration
6300 Georgetown Pike
McLean, Virginia 22101-2296

13. Type of Report and Period Covered

Final Report
April 1995 - February 1998

14. Sponsoring Agency Code

15. Supplementary Notes

Contracting Officer's Technical Representative: Carol Tan Esse (HSR-20)

16. Abstract

The objective of this project is to develop revised operational analysis procedures for transportation facilities with pedestrian and bicyclist users. This document contains both new and revised procedures for analyzing various types of exclusive and mixed-use pedestrian facilities. These procedures are recommended to determine the level of service for pedestrian facilities on the basis of a summary of available U.S. and international literature, as described in the Federal Highway Administration (FHWA) document, "Literature Synthesis for Chapter 13, Pedestrians, of the *Highway Capacity Manual*," by these same authors. These procedures are scheduled for incorporation into a revised U.S. *Highway Capacity Manual* in 2000.

17. Key Words:

pedestrian, level of service, platoon, delay, capacity

18. Distribution Statement

No restrictions. This document is available to the
public through the National Technical Information
Service, Springfield, Virginia 22161.

19. Security Classif. (of this report)	**20. Security Classif. (of this page)**	**21. No. of Pages**	**22. Price**
Unclassified	Unclassified	71	

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1 INTRODUCTION

In the United States, the *Highway Capacity Manual* (*HCM*), published by the Transportation Research Board (TRB), a unit of the National Research Council, provides guidance for the analysis of transportation facilities. Chapter 13 of the 1994 (update to the 1985) *HCM* discusses the operational and planning analysis of pedestrian facilities. The *HCM* pedestrian chapter begins by positing some relationships between pedestrian speed, flow, and density. It continues with analysis procedures for walkways, street corners, and crosswalks. Although offering the traffic engineer the means to analyze the most common pedestrian facilities, some of the procedures rely on incomplete and outdated information. This is unfortunate, because many intersections and walkways in downtown areas, near college campuses, by transit stops, etc., have moderate to heavy pedestrian flows, thus warranting accurate procedures (Figure 1).

The need for new procedures stems from reasons besides outdated methods, however. The heightened importance of "livability" in American communities presents the traffic engineer with the challenge to fully incorporate pedestrians in transportation analysis. The "Pedestrian Preamble" that opens the Florida Walkable Communities Guide provides a unique perspective of the role of the pedestrian in the transportation system: "This community, in providing for trip making, grants pedestrians and motorists of all ages and abilities: rights, privileges, safety, mobility, and access.... *Intersections should not favor either motorist or pedestrian, but give equal service and support to both....*" (*Florida DOT, 1995; emphasis added*).

This report summarizes the pedestrian characteristics-related recommendations from the companion volume, *Literature Review for Chapter 13, Pedestrians, of the Highway Capacity Manual (Rouphail et al., 1998).* It also includes a comprehensive set of recommended service measures of effectiveness, as well as methods for computing selected service measures. Finally, this report provides a summary of recommendations, including a listing of the affected subsections in Chapter 13 of the *HCM*. This summary is provided at the end of this chapter for ease of reference, and also at the conclusion of the report in section 5.

1.1 A Note on Liability

The current *HCM* provides curves for speeds greater than the maximum freeway speed limits at the time of publishing (*TRB, 1994*). Consistent with the *HCM*'s demonstrated intent of reflecting actual conditions rather than legal thresholds, the recommendations contained in both this *Recommended Procedures for Chapter 13, "Pedestrians.*" and in the companion *Literature Synthesis for Chapter 13, "Pedestrians," (Rouphail et al., 1998)* are to help achieve more realistic analytical procedures for the *HCM*. However, nothing in this *Recommended Procedures for Chapter 13, "Pedestrians*," or in the companion *Literature Synthesis for Chapter 13, "Pedestrians,"* or in the *Highway Capacity Manual*, is to be construed as advocating the violation of traffic laws by either pedestrians or drivers. In addition, *Recommended Procedures for Chapter 13, "Pedestrians,*" the companion *Literature Synthesis for Chapter 13, "Pedestrians,"* and the *Highway Capacity Manual* should not be used as a defense for the violation of traffic laws in any of the States.

Recommended Procedures For Chapter 13

FIGURE 1

A wide variety of transportation facilities must effectively serve a wide variety of users

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1.2 Summary of Recommendations for Design and/or Analysis of Pedestrian Facilities

Recommendation	Page(s)	Figure	Table	HCM Ch. 13 Subsections affected	HCM variables and adjustments affected
Body ellipse for standing areas	4	2	-	introductory narrative only	primarily a design recommendation
Body buffer zone for walking	4	-	-	walkways, street corners, crosswalks	walkway LOS E/F threshold changes in Table 13-3
Crosswalk walking speeds	5	-	1	[Ch. 9: Methodology, Input module]	new values replace 4.0 ft/s in equation (eq.) 9-8
				Ch. 13: introduction, crosswalks	new values replace 4.5 ft/s in eq. 13-14
Grade and stairs walking speeds	7	-	-	walkway narrative, crosswalks	speeds decrease by 0.1 m/s in eq. 13-14 with grades
Crossing speeds for platoons	7	-	-	N/A	-- no change --
Pedestrian start-up time	7	-	-	N/A	-- no change --
Capacity thresholds	8	-	-	walkways, street corners, crosswalks	walkway LOS E/F threshold changes in Table 13-3
Temporal flow variation	8	-	-	N/A	-- no change --
LOS (Level of Service) for walkways	11	5	4	walkways	walkway LOS A/B, E/F thresholds change, Table 13-3
LOS for walkways with platoons	12,13	-	6	walkways	new table replaces equation 13-3
LOS for transportation terminals	15	-	8	walkways (new measure)	new table applies to terminals with platoon flow
LOS for stairs	16	-	9	walkways	new table applies only to stairs

				(new measure)	
LOS for crossflows	17	-	10	walkways (new measure)	new table serves as secondary check for walkways
LOS for mixed-use paths	21	-	13	walkways (new measure)	new table applies only to mixed-use paths
Noncompliance time adjustments	26	-	-	street corners, crosswalks	minor, major red times in equations 13-6, 13-7 change;[d] effective red time reduced in computing ped delay
LOS for signalized crossings[a]	29	-	18	street corners (new measure)	new table based on ped delay; space now secondary
Swept-path method for vehicle effects	30	-	-	crosswalks	caution to use only under aggressive driver behavior
LOS for unsignalized crossings[b]	32,33	-	20	street corners (new measure)	new table based on ped delay
LOS for pedestrian networks[c]	35,36	-	22	networks (new section)	new table shows proposals for analysis of ped networks
Ped delay at signalized crossings	45	-	-	street corners (new measure)	method for computing ped delay
Effective crosswalk time-space	48	-	-	crosswalks	equation 13-13 corrected; calculated TS_w will decrease
Crossing time in platoons	49, 60	-	-	crosswalks	new equations replace eq. 13-14 with large platoons
Ped delay at unsignalized crossings	54	-	-	street corners (new measure)	method for computing ped delay

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[a] Offers a comparison with delay-based Level of Service for drivers computed in *HCM* Chapter 9, "Signalized Intersections"

[b] Offers a comparison with delay-based Level of Service for drivers computed in *HCM* Chapter 10, "Unsignalized Intersections"

[c] Offers a comparison with Level of Service for drivers computed in *HCM* Chapter 11, "Urban and Suburban Arterials"

[d] Current *HCM* is ambiguous regarding the definition of minor and major red times (R_{mi}, R_{mj}); therefore, the effect of the proposed noncompliance adjustments will depend on the analyst's interpretation of the *HCM*

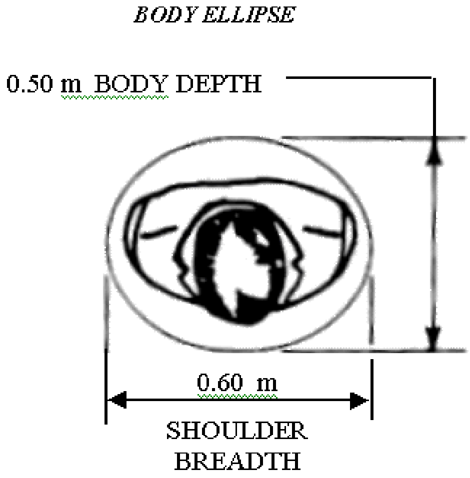
2 SUMMARY OF PEDESTRIAN CHARACTERISTICS

This section summarizes the recommendations regarding pedestrian characteristics as reported in the companion volume, *Literature Synthesis for Chapter 13, Pedestrians, of the Highway Capacity Manual (Rouphail et al., 1998).*

2.1 Pedestrian Space Requirements

Body Ellipses and Buffer Zones

Recommendation. This study recommends for design a simplified body ellipse of 50 cm x 60 cm for standing areas, with a total area of 0.3 m^2, or roughly 108% of the ellipse suggested by Fruin (*1971*). This shape (Figure 2) serves as an approximate metric equivalent to Fruin's ellipse. This study also recommends a body buffer zone of 0.75 m^2 for walking, near the upper end of the buffer zone range provided by Pushkarev and Zupan (*1975a*) and just before "unnatural shuffling" commences.



Recommended Procedures For Chapter 13

FIGURE 2

Recommended pedestrian body ellipse for standing areas

2.2 Pedestrian Walking Speeds

Age

Recommendation. This study recommends a pedestrian crosswalk walking speed value of 1.2 m/sec (3.9 ft/s) for most conditions, consistent with recommendations described in the *Literature Review for Chapter 13, Pedestrians, of the Highway Capacity Manual* from several sources. In areas with large numbers of older pedestrians, this study recommends a crosswalk walking speed value of 1.0 m/s, a nearly 30% decrease from current *HCM* values.

The question may arise, "What constitutes large numbers of older pedestrians?" A suggested answer is, "large numbers of older pedestrians exist when the elderly proportion begins to materially affect the *overall* speed distribution at the facility."

Through a simple analysis of a simulated dataset, it was found that the 15th percentile speed for the overall population will drop to 1.15 m/s (i.e., at least 0.05 m/s below the recommended default value of 1.2 m/s) when the elderly proportion increases to about 20%. Therefore, this study recommends the use of the lower 1.0 m/s value when the percentage of elderly *using the facility in question* exceeds 20%. Table 1 summarizes the recommendations. For demographics information, consider census data at the neighborhood level. Figures 3 and 4 illustrate some typical users who may benefit from the proposed changes.

TABLE 1
Recommended pedestrian crosswalk walking speeds

Facility Population Above Age 65	Suggested Walking Speed[a] for Time-Limited Walkways[b]
(% of all facility users) 0-20 < 20	(m/s)(ft/s) (% decrease from current HCM[c]) 1.2 3.9 14% 1.0 3.3 29%

[a] If necessary, adjust minimum crossing time for platoon flow
[b] Crosswalks and other facilities where available user time is limited
[c] Current HCM uses 1.4 m/s (4.5 ft/s) design crosswalk walking speed

Recommended Procedures For Chapter 13
FIGURE 3
This elderly pedestrian, and others like her, may be helped by the proposed revisions to crosswalk walking speeds

Recommended Procedures For Chapter 13
FIGURE 4
The Proposed revisions to crosswalk walking speeds may also benfit people who are not elderly, such as this pedestrian pushing a stroller

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Grades and Stairs

Recommendation. This study recommends that the HCM include a policy of not correcting for grades less than 10%. Above 10% on upgrades, this study advocates a 0.1 m/s reduction in walking speed as an approximation (roughly the amount found by the Institute of Transportation Engineers in 1976).

Platoons

Recommendation. For most situations where platoons are prevalent, this study does not recommend the use of walking speeds lower than 1.2 m/s (1.0 m/s for large elderly populations). However, in light of the research by Virkler (1997c) described in the Literature Review for Chapter 13, Pedestrians, of the Highway Capacity Manual, this study recommends increasing the minimum signalized intersection crossing time when typical platoons exceed 15 people. This report details several crossing time computational methods later. This study also cautions the analyst to consider impairments to full usage of the crosswalk. These may include: lack of a stop bar, lack of high-visibility crosswalk markings, crosswalks misaligned with the natural flow of the sidewalk, and corner obstructions.

2.3 Pedestrian Start-up Times

Recommendation. For simplicity, this study recommends retaining the *HCM's* value of 3 s, a reasonable mid-range value between the 50th- and 85th-percentile design values (2.5 and 3.75 s, respectively) for older pedestrians suggested by Knoblauch, Pietrucha, and Nitzburg (1996) and described in the companion *Literature Review for Chapter 13, Pedestrians, of the Highway Capacity Manual*.

2.4 Pedestrian Traffic Flow Relationships

Capacity

Recommendation. Given the comfort zone requirements for Americans, it seems that walkway capacity lies between 4,000 and 5,000 pedestrians/h/m. For simplicity, this study recommends an assumed capacity of 75 ped/min/m (4,500 ped/h/m). This study recommends an assumed speed at capacity of 0.75 m/s. In addition, this study recommends the pedestrian buffer zone space of 0.75 m^2/ped for a capacity threshold.

Temporal Variation

Recommendation. This study recommends the use of platoon flow Level of Service (LOS) considerations (discussed later) in lieu of a pedestrian "peak-hour-factor" (PHF) or similar measure. Pedestrian queueing is of comparatively short duration relative to the vehicular queues that a PHF typically describes.

3 SERVICE MEASURES OF EFFECTIVENESS

3.1 Uninterrupted Pedestrian Facilities

Sidewalks and Walkways

The current *HCM* uses pedestrian space as the primary measure of effectiveness (MOE), with mean speed and flow rates as secondary measures (Table 2; *TRB, 1994*). Carrying units of area per pedestrian in the existing *HCM*, the measure offers a simple, intuitive method of service evaluation. The chapter defines capacity as 6 ft^2/ped (about 0.56 m^2/ped).

TABLE 2
Existing *HCM* walkway Level of Service (LOS) criteria

	Space		Flow Rate		Average Speed		v/c ratio
LOS	(m^2/ped)	(ft^2/ped)	(ped/min/m)	(ped/min/ft)	(m/s)	(ft/min)	-
A	≥12	≥130	≤7	≤2	≤1.32	≥260	0.08
B	3.7-12	40-130	23-Jul	7-Feb	1.27-1.32	250-260	0.08-0.28
C	2.2-3.7	24-40	23-33	10-Jul	1.22-1.27	240-250	0.28-0.4
D	1.4-2.2	15-24	33-49	15-Oct	1.14-1.22	225-240	0.4-0.6
E	0.6-1.4	15-Jun	49-82	15-25	0.76-1.14	150-225	0.6-1.0
F	≤0.6	≤6	var.	var.	≤0.76	≤150	var.

SOURCE: TRB, 1994.

Alex Sorton of Northwestern University suggests that the current LOS A space requirement is excessive, and should be reduced from 130 ft^2/ped (12 m^2/ped) to 60 ft^2/ped (5.6 m^2/ped). Indeed, the *Interim Materials on Highway Capacity (TRB, 1980)* recommended an even lower space threshold (3.7 m^2/ped or 40 ft^2/ped) than Sorton's recommendation. This report has stated earlier that capacity probably occurs around 75 peds/min/m, somewhat lower than *HCM* values.

As a point of comparison, Table 3 compares LOS values in the *HCM* with those reported from other researchers. Tanaboriboon and Guyano (*1989*) developed LOS standards for Bangkok, Thailand. Although probably not useful for most areas of the United States, their data in the table highlight the importance of cultural values and physical characteristics on LOS breakpoints. The authors note that one result of the difference between Thai and American LOS standards is that pedestrian facilities in Thailand can accommodate higher flows at a given LOS. Stating that capacity limitations do not normally dominate pedestrian facility concerns, Brilon stated that Germany's revised pedestrian LOS standards will have breakpoints based on density (*1994*). The boundaries for Polus et al.'s work correspond to the three regimes of pedestrian flow reported by those researchers.

TABLE 3
Walkway Level of Service (LOS) thresholds by space (m^2/ped) and flow rate (ped/m/min)

	United States of America			Germany	Israel	Thailand
	HCM	Fruin	Pushkarev-Zupan	Brilon	Polus et al.	Tanaboriboon-Guyano
LOS	(m^2/ped)	(m^2/ped)	(m^2/ped)	(m^2/ped)	(m^2/ped)	(m^2/ped)
			49[a]			
A	12	3.2	Dec-49	10		2.38
B	3.7-12	2.3-3.2	12-Apr	3.3-10		1.60-2.38
C	2.2-3.7	1.4-2.3	4-Feb	2-3.3	1.67 [b]	0.98-1.60
D	1.4-2.2	0.9-1.4	1.5-2	1.4-2	1.33-1.66	0.65-0.98
					0.8-1.33	
E	0.6-1.4	0.5-0.9	1-1.5	0.6-1.4	0.5-0.8	0.37-0.65
F	0.6	0.5	0.2-1	0.6	unknown	0.37
LOS	(ped/min/m)	(ped/min/m)	(ped/min/m)		(ped/min/m)	(ped/min/m)
			1.6[a]			
A	6.6	23	1.6-7.0			28

B	6.6-23	23-33	20-Jul		28-40
C	23-33	33-49	20-33	40 [b]	40-61
D	33-49	49-66	33-46	40-50	61-81
				50-75	
E	49-82	66-82	46-59	75-95	81-101
F	var.	var.	0-82	unknown	101 or var.

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[a] Instead of *HCM* LOS designations "A"-"B"-"C"-"D"-"E"-"F", Pushkarev and Zupan use"Open"-
"Unimpeded"- "Impeded"-"Constrained"- "Crowded"- "Congested"- "Jammed"
[b] Instead of *HCM* LOS designations "A"-"B"-"C"-"D"-"E"-"F", Polus et al. use A-B-C_1-C_2-D

SOURCES: *TRB, 1994; Fruin, 1971; Pushkarev and Zupan, 1975b; Brilon, 1994; Polus et al., 1983; Tanaboriboon and Guyano, 1989.*

Recommendation. This study recommends keeping the current *HCM* walkway LOS B, C, and D thresholds. This study also recommends changing the capacity thresholds to the values mentioned earlier. Table 4 summarizes the recommendations. Figure 5 approximates the revised service levels.

TABLE 4
Recommended HCM walkway Level of Service (LOS) criteria

	Space		Flow Rate		Average Speed		v/c ratio
LOS	(m^2/ped)	(ft^2/ped)	(ped/min/m)	(ped/min/ft)	(m/s)	(ft/min)	
A	≥5.6	≥60	≤16	≤5	≥1.3	≥255	0.21
B	3.7-5.6	40-60	16-23	7-May	1.27-1.30	250-255	0.21-0.31
C	2.2-3.7	24-40	23-33	10-Jul	1.22-1.27	240-250	0.31-0.44
D	1.4-2.2	15-24	33-49	15-Oct	1.14-1.22	225-240	0.44-0.65
E	0.75-1.4	15-Aug	49-75	15-23	0.75-1.14	150-225	0.65-1.0
F	≤0.75	≤8	var.	var.	≤0.75	≤150	var.

Platoons. The companion volume, *Literature Review for Chapter 13, Pedestrians, of the Highway Capacity Manual* noted the effect of platoons on walkway flow. Table 5 summarizes the initial research on platoons. Pushkarev and Zupan (*1975b*) note that earlier research found the ability to pass slow-moving pedestrians to be relatively unrestricted at space modules above 3.3 m^2/ped, difficult between 1.7 and 3.3 m^2/ped, and essentially impossible below 1.7 m^2/ped. Pushkarev and Zupan also compared average flow rates with possible flow in platoons. They found no difference between the flow conditions at any service level, except at that point in "Impeded" flow (approximately LOS B) when platoons begin *(1975b)*.

The *Interim Materials on Highway Capacity* (*TRB, 1980*) contained platoon flow criteria. This work, relying on the "rule of thumb" mentioned earlier, simply rewrote the recommended walkway values up one level for platoons. The current *HCM*, which does not contain a platoon flow service level table, uses different walkway values for average flow rate and space at most service levels than those in the *Interim Materials*. Therefore, one cannot simply apply the values listed in the *Interim Materials* to the current *HCM*. One can develop platoon flow LOS criteria based on a synthesis of the relationship between average and platoon flow described in the companion *Literature Review*, the existing *HCM* walkway standards for midrange LOS values (*TRB, 1994*), and the earlier work of Pushkarev andZupan (*1975b*) for extreme values. For LOS A, this report uses Pushkarev and Zupan's relationship between average and platoon flow (Figure 20 in the *Literature Review*) and defines this breakpoint to be just before the discontinuity, at 1.6 ped/min/m (0.5 ped/min/ft), identical to the "Open" flow of Pushkarev and Zupan. For LOS B through D, this study applies metricized "rule of thumb" to 1994 *HCM* walkway values, by subtracting 13 ped/min/m from walkway flow rates. For LOS E, and thus LOS F, this report uses the highest platoon flow rate found by Pushkarev and Zupan, 59 peds/min/m. The resulting values, shown in Table 6, provide a sound basis for determining the level of service experienced by people who travel in platoons, such as the pedestrians shown in Figure 6.

Recommendation. This study recommends incorporating the walkway platoon criteria in Table 6 into the *HCM*.

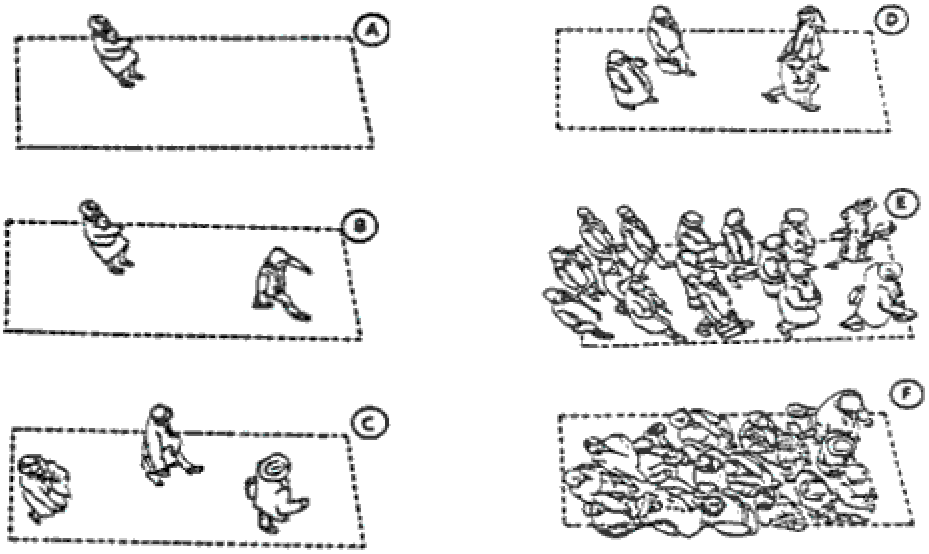

FIGURE 5
Illustration of proposed walkway Level of Service thresholds
SOURCE: TRB, 1994; adapted from FRUIN, 1971.

TABLE 5
Platoon-adjusted walkway Level of Service (LOS) thresholds

	Space				Flow Rate			
	Pushkarev-Zupan		Interim Materials		Pushkarev-Zupan		Interim Materials	
LOS	(m^2/ped)	(ft^2/ped)	(m^2/ped)	(ft^2/ped)	(ped/min/m)	(ped/min/ft)	(ped/min/m)	(ped/min/ft)
A[a]	≥49[b]	≥530	12[c]	130	≥1.6b	≥0.5	6[c]	2
B	6-Apr	40-60	12-Apr	40-130	15-20	4.5-6	20-Jun	6-Feb
C	4-Feb	24-40	4-Feb	24-40	20-33	10-Jun	20-33	10-Jun
D	1.5-2	16-24	1.5-2	16-24	33-46	14-Oct	33-46	14-Oct
E	1-1.5	16-Nov	1-1.5	16-Nov	46-59	14-18	46-59	14-18
F	1	11	0.6-1	11-Jun	59	18	59-82	18-25

[a] Instead of *HCM* LOS designations "A"-"B"-"C"-"D"-"E"-"F", Pushkarev and Zupan use "Open"- "Impeded"-"Constrained"- "Crowded"- "Congested"- "Jammed"
[b] Values given by Pushkarev and Zupan for flow rates and space are within platoons
[c] Values given in the *Interim Materials* for flow rates and space are under average flow conditions

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The LOS shown at each flow rate or pedestrian space level represents the walkway LOS (based on *Interim Materials* service levels) under these average flow rates when platoons arise
SOURCE: *Pushkarev and Zupan, 1975b; TRB, 1980.*

TABLE 6
Recommended HCM platoon-adjusted walkway Level of Service (LOS) criteria

	Space		Flow Rate[a]	
LOS	(m^2/ped)	(ft^2/ped)	(ped/min/m)	(ped/min/ft)
A	49	530	1.6	0.5
B	Aug-49	90-530	1.6-10	0.5-3
C	8-Apr	40-90	20-Oct	6-Mar
D	4-Feb	23-40	20-36	11-Jun
E	2-Jan	23-Nov	36-59	18-Nov
F	1	11	59	18

*Flow rate in the table represent average flow rates over a 5-6 min period. The LOS shown is the
walkway LOS under these average flow rates when platoons arise

Transportation terminals provide a special case of platoon flow. Davis and Braaksma (*1987*) analyzed the pedestrian flow within an airport corridor by a "floating pedestrian" method, in which the surveyor measures traffic parameters from within the pedestrian stream. Table 7 shows the LOS standards developed by the authors for platoon flow in transportation terminals. By implication, the use of the term "transportation terminal" refers to both an airport and to those other locations with tendencies for the platooning behavior common in airport walkways. Note that, although maximum speed and space occur at the highest LOS (A+ in the table), the maximum flow occurs at the boundary between LOS D and E. Also of note, the extremely high flows in these facilities warrant much less restrictive service criteria. To facilitate incorporation into the *HCM*, one can eliminate or consolidate one of their seven service levels (Table 8). This report consolidates Davis and Braaksma's LOS A and B into LOS B and redesignates LOS A+ as LOS A. In effect, this expands the transportation terminal LOS B to a range roughly coincident with platoon-adjusted walkway criteria LOS E. In addition, LOS E reflects the capacity thresholds suggested earlier.

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FIGURE 6

Pedestrians who know each other travel in platoons

Recommendation. This study recommends incorporating the transportation terminal criteria adapted from Davis and Braaksma in Table 8 into the *HCM*.

TABLE 7

Level of Service (LOS) thresholds for platoon flow in transportation terminals[a]

LOS	Space (m^2/ped)	Flow Rate (ped/min/m)	Speed (m/s)
A+	≥2.3	≤37	≥1.4
A	1.7-2.3	37-46	1.3-1.4
B	1.3-1.7	46-57	1.2-1.3
C	1.0-1.3	57-68	1.1-1.2
D	0.8-1.0	68-75	1.0-1.1
E	0.7-0.8	57-75	0.7-1.0
F	≤0.7	≤57	≤0.7

[a] Airports or other facilities where platoon flow is prevalent along pedestrian walkways

SOURCE: *Davis and Braaksma, 1987*.

TABLE 8
Recommended HCM pedestrian Level of Service (LOS) criteria for platoon flow in transportations[a]

LOS	Space (m^2/ped)	Flow Rate (ped/min/m)	Speed (m/s)
A+	≥2.3	≤37	≥1.4
A	1.7-2.3	37-46	1.3-1.4
B	1.3-1.7	46-57	1.2-1.3
C	1.0-1.3	57-68	1.1-1.2
D	0.8-1.0	68-75	1.0-1.1
E	0.7-0.8	57-75	0.7-1.0
F	≤0.7	≤57	≤0.7

aAirports or other facilities where platoon flow is prevalent along pedestrian walkways

Stairs. To allow for the determination of pedestrian arterial ("network" in this review) LOS, Virkler utilized a 20-year-old proposed ITE stairways standard (*ITE, 1976*), which provided space and flow values at various stairway LOS. Virkler states that he modified this standard somewhat "to ensure that the basic equation of traffic flow is satisfied," although this review of his research could discern no difference between his values and the space and flow values given in the ITE stairways standard.

Table 9 shows the recommended *HCM* pedestrian LOS criteria. The values reflect ITE's flow values, Fruin's (*1971*) original breakpoints for stairway level of service, and Virkler's values for speed and volume-capacity ratio. Note that the LOS E values of 49 and 56 ped/min/m for Virkler and Fruin, respectively, are noticeably less than the 62-73 ped/min/m capacity ranges found in the Hong Kong and London transit systems listed earlier by Lam et al. (*1995*).

Recommendation. In so far as Virkler's paper corrects earlier research by ensuring congruence with pedestrian traffic flow theory, his work remains the best available for American users. This study recommends this material (Table 9) for the *HCM*, pending further research on capacity limits.

TABLE 9
Recommended *HCM* pedestrian Level of Service (LOS) criteria for stairs

	Space	Flow Rate	Avg. Horiz. Speed		v/c ratio
LOS	(m2/ped)	(ped/min/m)	(m/min)	(m/s)	
A	1.9	16	32	0.53	0.33
B	1.6-1.9	16-20	32	0.53	0.33-0.41
C	1.1-1.6	20-26	29-32	0.48	0.41-0.53
D	0.7-1.1	26-36	25-29	0.42	0.53-0.73
E	0.5-0.7	36-49	24-25	0.4	0.73-1.00
F	< 0.5	var.	< 24	< 0.40	var.

Crossflows. A crossflow is a pedestrian flow that is roughly perpendicular to and crosses another pedestrian stream. In general, one refers to the smaller of the two flows as the crossflow. Khisty (*1982*) notes that pedestrian crossflows occur in hallways and corridors and are "ubiquitous." Table 10 notes his suggestions for acceptable criteria regarding corridor crossflows. These values correspond roughly with the bottom half of *HCM* walkway LOS E; by terming them minimums and maximums, he implies that his values establish LOS boundaries for crossflows.

Recommendation. This study recommends the incorporation into the *HCM* of Khisty's crossflow standards listed in Table 10 below as an interim measure pending further research.

TABLE 10
Recommended capacity thresholds for crossflows

LOS	Speed (m/s)	Flowb (ped/min/m)	Density (ped/m^2)	Space (m^2/ped)
E[a]	1	75	0.8	1.25

[a] Khisty terms these threshold values "minimums" and "maximums"; by implication, this is

LOS E.

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[b] *Total of the major and minor flow*

SOURCE: *Khristy, 1982*.

Off-street paths

Exclusive pedestrian trails. Virkler and Balasubramanian (*1997*), in their discussion of flow characteristics on shared user trails, imply that the current *HCM's* LOS walkway guidelines apply for exclusive pedestrian trails.

Shared pedestrian-bicycle paths. Virkler and Balasubramanian (*1997*) describe a 1995 study by Hein Botma of shared pedestrian-bicycle facilities in The Netherlands. This study develops LOS guidelines for both pedestrians and bicyclists on the basis of the frequency of passing (same direction) and meeting (opposite direction) other users on the trail. Botma characterizes these two occurrences as "events," with an overtaking equal to one event and a meeting equivalent to one-half of an event. Under this framework, LOS F refers to "very bad quality of traffic operation," not congestion (*Botma, 1995*). More specifically, it refers to a situation where an average user experiences "hindrance" more than 1.0 times in a 1-km trail segment. Virkler and Balasubramanian note that, for one-way paths, pedestrians seldom overtake other pedestrians, and thus the LOS afforded a pedestrian on a shared path depends on the frequency with which an average pedestrian would be overtaken by bicyclists. In Botma's discussion of his own work (*1995*), he poses the question of whether it is justified to neglect hindrance due to pedestrian interactions. As the authors of this report have observed moderate pedestrian-pedestrian hindrances on various mixed-use trails, it is likely that Botma's assumption of negligible pedestrian interactions is not entirely correct.

Botma's expression describing the total number of overtakings of pedestrians by bicyclists, $N_{f/s}$, is:

$$N_{f/s} = X\ T\ Q_f\ Q_s\ (1/U_s - 1/U_f)$$

where:

X = length of site, m;
T = time period considered, s;
Q_f = flow of faster group in subject direction, bicyclists/s;
Q_s = flow of slower group in subject direction, pedestrians/s;
U_f = mean speed of faster group, m/s (for bicyclists); and
U_s = mean speed of slower group, m/s (for pedestrians).

Using an average pedestrian speed of 1.25 m/s and an average bicyclist speed of 5 m/s, Botma developed a LOS table for pedestrians on one-way, two-lane shared-use paths. Table 11, which converts "frequency" of events into period between events to eliminate fractions, provides Botma's LOS thresholds.

TABLE 11

Level of Service (LOS) thresholds for one-way, two-lane, mixed-use paths

LOS	Period Between Events (s/event)	Service Volume (bicycles/h)
A	> 150	< 33
B	75-150	33 - 64
C	35 - 75	65 - 136
D	20 - 35	137 - 240
E	15 - 20	240 - 320
F	< 15	> 320

SOURCE: Adapted from *Botma, 1995.*

For two-way trails, Botma states that pedestrians still seldom overtake other pedestrians, and thus the LOS afforded a pedestrian on a shared path depends on the frequency with which an average pedestrian experiences meetings of and overtakings by bicyclists. Using the speed assumptions listed above for one-way paths, Botma established a table for pedestrians traveling on two-lane, two-way, shared-use paths. Table 12 , again substituting period for frequency, shows Botma's service levels.

As an aside, if one applied either of the tables to an exclusive pedestrian trail, one would always have a service level of A, regardless of pedestrian volume, since the tables depend entirely on bicycle volume. Therefore, Virkler and Balasubramanian's implication to use existing walkway standards certainly seems more reasonable than the use of Botma's method for an exclusive pedestrian facility.

TABLE 12

Level of Service (LOS) thresholds for two-way, two-lane, mixed-use paths

LOS	Period Between Events (s/event)	Service Volume (bicycles/h)
A	> 95	< 29
B	60 - 95	29 - 44
C	35 - 60	45 - 75
D	25 - 35	76 - 105
E	20 - 25	106 - 131
F	< 20	> 131

SOURCE: Adapted from *Botma, 1995.*

Virkler and Balasubramanian (*1997*) studied flow characteristics on two-way, shared-use trails in both Columbia, Missouri, and Brisbane, Australia. They found bicycling speeds of 5.95 m/s and 5.76 m/s in Missouri and Australia, respectively, both of which were somewhat higher than the 5 m/s speed used by Botma. However, Botma uses 5 m/s for simplicity; field studies of trails in The Netherlands show slightly higher average speeds of 5.28 m/s (*Botma, 1995*). Also, they found that the standard deviations of bicycling speeds, 2.1 m/s for Missouri and 1.33 m/s for Australia, were much higher than the 0.83 m/s average speed reported by Botma. Finally, they observed average "hiking" (presumably walking) speeds of 1.59 and 1.56 m/s in Missouri and Australia, respectively. Upon comparison between predicted (by Botma's tables) and observed values, Virkler and Balasubramanian found that their results generally supported the framework espoused by Botma for bicyclists overtaking pedestrians.

Although not mentioned by Virkler and Balasubramanian (*1997*), if one rounds the Missouri average speed measurements to the nearest 0.5 m/s (i.e., rounding bicycling speeds from 5.95 m/s to 6 m/s and walking speeds from 1.59 m/s to 1.5 m/s), then the resulting table of values for both one- and two-way trails will be *identical* to that by Botma. Therefore, in so far as Botma's assumptions are correct, one can directly apply Botma's pedestrian LOS tables listed above to at least one American mixed-use trail.

Recommendation. In light of the validation of Botma's method on an American mixed-use path by Virkler and Balasubramanian (*1997*), this study recommends the incorporation of the Botma mixed-use path criteria in the *HCM*. Table 13 summarizes the recommended LOS thresholds for these paths, identical to Botma's values.

TABLE 13
Recommended *HCM* pedestrian Level of Service (LOS) criteria for two-lane, mixed-use paths

	One-Way Paths		Two-Way Paths	
LOS	Period[a] (s/event)	Service Volume (bicycles/h)	Period[a] (s/event)	Service Volume (bicycles/h)
A	> 150	< 33	> 95	< 29
B	75-150	33 - 64	60 - 95	29 - 44
C	35 - 75	65 - 136	35 - 60	45 - 75
D	20 - 35	137 - 240	25 - 35	76 - 105
E	15 - 20	240 - 320	20 - 25	106 - 131
F	< 15	> 320	< 20	> 131

[a] Period between events; where an event is either a bicycle meeting or passing a pedestrian.

3.2 Interrupted Pedestrian Facilities

Signalized Crossings

Overview of Noncompliance. The pedestrian literature contains several articles dealing with pedestrian disobedience of traffic signals. In addition, anecdotal evidence suggests that assuming legal behavior will not sufficiently resemble reality for analysis purposes. Therefore, before considering a delay-based service measure of effectiveness in detail, one should examine the effects of pedestrian noncompliance. Figures 7 and 8 are illustrative of the problem.

Middleton (*1981*), bemoaning the levels of pedestrian accidents in Australia and the United States, notes the presence of what he terms an "over-supply of pedestrian facilities at signalized intersections." He notes that safety-motivated pedestrian control signals at signalized intersections may actually reduce safety by encouraging noncompliance to avoid the "largely unnecessary delay imposed" on pedestrians. Indeed, the author observed disobedience rates as high as 70 percent in Queensland, Australia. Stating that the "very existence of this widespread lawbreaking in the community should be sufficient evidence that the system needs attention," he reiterates an earlier suggestion by F.R. Fulsher to change the legal meaning of the DON'T WALK signal to "Yield to Vehicles." In so far as the resulting change in pedestrian signals from regulation to guidance may discourage avoidance of pedestrian signals, he hypothesizes that safety improvements may result.

The *Literature Review for Chapter 13, Pedestrians, of the Highway Capacity Manual* included a study by Rouphail (*1984*) noting the preference of pedestrians for midblock crossings. However, when a pedestrian crossing is displaced from the intersection, the increase in travel path for many users walking along the cross-street may tend to breed signal noncompliance in some situations, as people tend to use the intersection crosswalks regardless of signal indication (*Pretty et al., 1994*).

Hunt and Griffiths (*1991*) note that pedestrians experience very little delay at zebra crossings, since they always have the right-of-way. However, they note that pedestrians who are unable or unwilling to accept gaps in traffic during the DON'T WALK period at the signalized pelican (pedestrian light controlled) midblock crossings in Britain incur substantial delay. They suggest that pedestrians crossing illegally at signalized intersections could be less safe than those crossing at random points along a roadway since drivers approaching a green signal will not expect to have to yield to a pedestrian.

Griffiths et al. (*1984a*) observed during their field studies that significant numbers of pedestrians are prepared to begin crossing during either flashing or steady DON'T WALK pedestrian indications. They noted that noncompliant behavior occurred almost exclusively when two-way conflicting vehicle flows were below 1,500/h.

Gordon and Robertson (*1988*) noted that driver noncompliance with traffic signals is a serious problem as well, particularly at low-volume intersections. They recommend a combination of higher enforcement levels, stiffer violation penalties, education of the public, and the removal of unnecessary informational or regulatory control devices adjacent to intersection approaches.

Knoblauch, Pietrucha, and Nitzburg (*1996*) noted that, of the pedestrians they observed during their field study of intersections in eastern cities, those who crossed against the signal (i.e., noncompliant pedestrians) tended to walk faster than those who crossed legally.

A study of Hong Kong pedestrians noted that pedestrians walk faster during the red phase at signals, confirming the ubiquity of noncompliant pedestrians (*Lam et al., 1995*). The authors report an average noncompliant pedestrian crosswalk speed of 1.5 m/s in Hong Kong crosswalks, much higher than the 1.27 m/s level observed at those facilities during the WALK indication.

Virkler (*1997a*) noted that, based on his observations of intersections in Brisbane, Australia, pedestrians typically treat about 69 percent of the flashing DON'T WALK signal as an effective WALK. He discerns two groups of noncompliant pedestrians:

"jumpers," who start crossing before the WALK indication begins, and "runners," who begin crossing after the flashing DON'T WALK signal commences. Between the two groups, he observed that the runners saved over 7 times as much delay per person as jumpers, so he focused on the behavior of the former group.

North Carolina State University (NCSU) also noticed similar noncompliant behavior at several sites during its field study of American intersections. NCSU calculated that pedestrians typically treated the first 5 s of flashing DON'T WALK as a de facto WALK signal indication. Indeed, the NCSU data-collection team observed some crossings during both flashing DON'T WALK (which typically coincides with the latter part of the vehicular green) and the vehicular clearance interval. Milazzo II (*1996*) adjusted his volume-occupancy data collection framework to allow for pedestrian occupancy of the crosswalk at any time during the pedestrian clearance interval.

Recommended Procedures For Chapter 13

FIGURE 7

Noncompliant pedestrian behavior is common at this Chicago, Illinois intersection due to low conflicting vehicle volumes

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Viney and Pretty (*1982)* examined pedestrian and vehicle interactions at Brisbane, Australia, intersections. They observed an average WALK "extension time" (i.e., de facto WALK) of 1.95 s with a standard deviation of 2.7 s. They used 2 s as an allowance for disobedient pedestrians.

It is important to note that changes in signal timing can affect noncompliance. For example, the slight increase in green time and cycle length that may occur under the assumption of reduced walking speeds will increase pedestrian delay and probably increase pedestrian noncompliance. Of course, the presence of excessive cycle lengths and/or unnecessary phases also causes pedestrian delay and noncompliance. Some jurisdictions use "early release" signal timing, where pedestrians receive the WALK before the concurrent vehicles receive the green, in an effort to reduce pedestrian delay. Regardless of the phasing scheme chosen, most facility users are local pedestrians who will learn the signal timing and try to reduce their own delay.

Recommended Procedures For Chapter 13

FIGURE 8

Noncompliant behavior is not limited to pedestrians at the same Chicago, Illinois intersection

In summary, any delay measure to pedestrians should include some mechanism for considering noncompliance. Table 14 summarizes the findings of the last three research groups mentioned; coincidentally, two of the three groups examined downtown Brisbane, Australia. All of this empirical research seems to indicate that pedestrians, recognizing the margin of safety built into the pedestrian clearance interval, treat the initial part as an effective walk time.

TABLE 14

Selected de facto WALK extension times

	Location	De Facto WALK Interval,[a] s
Viney and Pretty	Brisbane, Australia	WALK + 2
NC State	United States[b]	WALK + 5
Virkler	Brisbane, Australia	WALK + 8[c] or WALK + 69% of flashing DON'T WALK

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[a] Observed or calculated total effective WALK interval as used by pedestrians

[b] Washington, D.C.; Portland, Oregon; Atlanta; and Chicago

[c] Virkler only reports the percentage of flashing DON'T WALK (clearance) time; 8 s is approximately 69% of the 11.1-s mean clearance time for Virkler's study

SOURCES: *Viney and Pretty, 1982; Virkler, 1997a*.

Recommendation. Based on the middle range of values from the above research on noncompliance, this study suggests the following adjustments to pedestrian signalized crossing timing for simplicity:

$WALK_e = WALK + 5$

Flashing DON'T $WALK_e$ = Flashing DON'T WALK - 5

where:

WALK = nominal WALK time, s;
$WALK_e$ = effective WALK time, s;
Flashing DON'T WALK = nominal flashing DON'T WALK time, s; and
Flashing DON'T $WALK_e$ = effective flashing DON'T WALK time, s.

The analyst should be aware, however, that intersections with high conflicting traffic and/or large street widths have excellent compliance, primarily because pedestrians have no choice but to wait.

Delay. Currently, no LOS standard based on pedestrian delay at signalized intersections exists in the *HCM*. However, the *HCM* does incorporate vehicular delay at these facilities into its LOS criteria for vehicles at signalized intersections (Table 15). The Australian signalized intersection software package SIDRA considers pedestrian delay (*Akçelik, 1989*) as a performance measure.

The following paragraphs, which give the results of several delay studies, provide a useful frame of reference for establishing a suitable pedestrian delay criteria at signalized crossings.

TABLE 15
Existing *HCM* signalized intersection Level of Service (LOS) criteria

LOS	Stopped Delay per Vehicle (s)
A	< 5
B	15-May
C	15-25
D	25-40
E	40-60
F	60

SOURCE: TRB, 1994.

Noland (*1996*) states that any street crossing, regardless of the control device used, will result in some delay to pedestrians due to caution before entering the crosswalk. He also argues that, since average delay to pedestrians is frequently ignored at signals, total "costs to society" may rise due to unfavorable timing patterns. He notes that, if pedestrian green phases remain constant while cycle lengths increase, average delay to pedestrians can increase quite rapidly.

Griffiths et al. (*1984a*) examined pedestrian delay at both signalized and unsignalized crossings in Great Britain. Table 16 shows the results.

TABLE 16
Pedestrian and vehicle delay at midblock crossings in Great Britain

	Unsignalized	Signalized	
	Zebra	Fixed-time Pelican	Vehicle-actuated Pelican
	(s)	(s)	(s)
Pedestrian Delay	1.4	10.1	9.8
Vehicle Delay	5.2	4.2	3.9

SOURCE: *Griffiths et al., 1984a.*

The authors note that Great Britain began installing unsignalized pedestrian crossings in 1935, with signalized pelican installations commencing in 1969. The latter device was introduced to provide the "flexibility of a Zebra" with the "positive command to drivers to stop." Along these lines, Dunn and Pretty *(1984*) state that, provided that pelicans are a legal device in the jurisdiction, one should always install a pelican crossing over a standard pedestrian signalized crossing, because they provide reduced vehicular delay with no detriment to pedestrian delay.

At a field survey of fixed-time signalized crossings in Great Britain, Griffiths et al. (*1984a*) found significant increases in pedestrian delay for increases in vehicular delay over a wide (400-1,400 veh/h) range. They did not observe any additional effect on pedestrian delay at signalized crossings with vehicle actuation over these volume levels.

MacLean and Howie (*1980*) examined the performance of pedestrian crossings in Victoria, Australia. They found that mean pedestrian delay was 17 s at signalized crossings.

Table 17, based on anecdotal evidence and empirical observation, provides some maximum delay thresholds recommended by various researchers for signalized intersections. Dixon (*1996*) terms the choice of 40 s for Gainesville, Florida, a compromise value. Kaiser (*1994*) notes the increase in pedestrian impatience and risk-taking behavior beyond 30 s of delay; Dunn and Pretty (*1984*) also mention that pedestrians become increasingly impatient when delayed beyond 30 s. Hunt and Griffiths (*1991*), noting that risk-taking behavior increases with pedestrian delays of 30 s or more, state that the vehicle precedence time should not exceed 40 s at a pelican crossing in Great Britain. Of course, with sufficiently high conflicting vehicle volume, pedestrians can face delays above 60 s (*Dunn and Pretty, 1984*). Under these conditions, pedestrian compliance increases, because sufficient gaps do not exist in the vehicle stream for pedestrians to utilize.

TABLE 17
Selected thresholds for maximum pedestrian delay at signalized intersections

	Location	Maximum Recommended Pedestrian Delay[a] (s)
Brilon	Germany	60
Dixon	Gainesville, Florida	40
Dunn and Pretty	Australia	30
Hunt and Griffiths	Great Britain	30
Kaiser	United States	30

[a]Values typically based on observation of pedestrian impatience and noncompliance

SOURCES: *Brilon, 1994; Dixon 1996; Dunn and Pretty; 1984; Hunt and Griffiths, 1991; Kaiser 1994.*

Recommendation. This study recommends the incorporation of pedestrian delay as a measure of effectiveness for signalized intersections. This study recommends the establishment of the delay thresholds shown in Table 18, based on both the anecdotal evidence of pedestrian tolerance of delay tabulated above and congruence with similar values for vehicles in Chapter 9, Signalized Intersections, of the current HCM. As mentioned above, the current HCM contains no procedures for midblock crossings. The signalized type resembles an intersection crossing in that the signal incorporates a time element with a limited, predictable duration for pedestrians to legally complete their crossing. Therefore, this study recommends the above intersection crossing criteria for signalized midblock crossings.

TABLE 18
Recommended HCM pedestrian Level of Service (LOS) criteria for signalized crossing delay

LOS	Average Delay Per Pedestrian (s)	Likelihood of Pedestrian Noncompliance
A	< 10	Low
B	20-Oct	
C	20-30	Moderate
D	30-40	
E	40-60	High
F	60	Very High

Space. As was the case with walkways, the current *HCM* uses pedestrian walkway space criteria as the primary MOE for street corners. However, in this case, the methodology centers on a validated "time-space" framework developed by Fruin and Benz (*1984*). It provides average space values of 5 ft^2/ped in a queue and average time values of 3 to 5 s for moving through the corner.

The existing *HCM* also offers a crude method of describing the effect of turning vehicles on pedestrians at intersections, by assuming a swept-path for a vehicle and decrementing the crosswalk time-space available to pedestrians. Indeed, despite the legal precedence of pedestrians over vehicles in the crosswalk, Virkler (*1997c*) found that vehicles occasionally occupy a portion of the crosswalk during the pedestrian phase.

Unsignalized Crossings.

Delay. The current *HCM* does not have a method for analyzing unsignalized crossing facilities. However, the *HCM* unsignalized intersection chapter does provide a mechanism for computing vehicular delay at these locations. Table 19 provides delay thresholds for vehicles at (two- or all-way) stop-controlled intersections, the most common unsignalized intersection types in the United States.

TABLE 19

Existing *HCM* unsignalized intersection Level of Service (LOS) criteria

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	Average Total Delay
LOS	(s/vehicle)
A	< 5
B	10-May
C	20-Oct
D	20-30
E	30-45
F	45

SOURCE: TRB, 1994.

As in the signalized intersection case, it is useful to examine existing research on pedestrian delay at unsignalized crossings to gain a feel for actual delay levels at these facilities. Dunn and Pretty (*1984*) examined pedestrian and vehicle delay at Australian and New Zealand midblock crossings. They neglected pedestrian delay at unsignalized (zebra) crossings, however, effectively terming it negligible. They therefore focused solely on vehicle delay for the unsignalized case.

MacLean and Howie (*1980*) examined the performance of pedestrian crossings in the Australian state of Victoria. They found that mean pedestrian delay was 1.7 s at unsignalized midblock crossings in Victoria, dramatically (and somewhat surprisingly) less than the 17-s mean delay at signalized midblock crossings. Mean pedestrian delay at zebra crossings was 2.3 s in metro Melbourne but negligible in rural areas.

At low to moderate vehicle volumes, Griffiths et al. (*1984a*) found little pedestrian mean delay at unsignalized crossings. They also noted that average pedestrian delay decreases as pedestrian flow increases because more pedestrians can take advantage of "an established pedestrian precedence."

Song, Dunn, and Black (*1993*) examined the interaction of pedestrians and vehicles for pedestrians crossing at least 10 m away from a designated crossing. The authors collected pedestrian gap acceptance characteristics at several streets in Sydney, Australia. They divide pedestrian crossing tactics into four categories: "double-gap," "risk-taking," "two-stage," and "walk'n-look," each of which serves to minimize crossing time while still providing a degree of safety. Their approach assumes that each crossing tactic, rather than each person, has critical gaps for the near lane, far lane, and combined traffic streams associated with it. A corollary is that different demographic groups will typically use a particular crossing tactic; for example, disabled and elderly pedestrians, and mothers with children, will often use the cautious "double-gap" tactic.

The "double-gap" tactic involves identifying a gap of size *a* in the near stream and *2a* in the far stream, in order to ensure successful crossing of the entire street in one continuous motion. The "risk-taking" tactic involves selecting individual gaps of *a* in each of the lane-by-lane traffic streams. A "two-stage" crossing involves the use of a median as a refuge. The "walk'n-look" tactic involves walking parallel to the street in the direction of desired travel until a suitable gap arrives, then crossing using one of the previous three tactics. Users of this tactic can essentially eliminate crossing delay under low to moderate conflicting vehicle volumes; in addition, the authors note that by minimizing interaction with vehicles, little accident risk exists for users of this tactic (*Song et al., 1993*).

Palamarthy et al. (*1994*) describe available crossing tactics to pedestrians at signalized intersections analogous to those described by Song et al. (*1993*), except that a lane-by-lane crossing substitutes for the "walk'n-look" at these locations. Palamarthy et al. found that pedestrians are more likely to look for an overall gap rather than separate gaps in individual traffic streams. The authors found mean critical gaps of 3.33 s for the near traffic stream under all crossing tactics, 7.14 s for the far stream under a double-gap crossing, 3.58 s for the far stream under a risk-taking crossing, and 3.81 s for the far stream under a two-stage crossing.

TABLE 20

Recommended *HCM* pedestrian Level of Service (LOS) criteria
for unsignalized crossing delay

Average Delay Per Pedestrian[a] Likelihood of Risk-Taking Behavior
LOS (s) by Pedestrians[b]

LOS	Average Delay Per Pedestriana (s)	Likelihood of Risk-Taking Behavior by Pedestrians[b]
A	< 5	Low
B	10-May	
C	20-Oct	Moderate
D	20-30	
E	30-45	High

F	≥45	Very High

[a] Delay includes waiting on one side to begin crossing and/or waiting in the median to complete the crossing

[b] Likelihood of acceptance of short gaps

Finally, the *HCM* contains no provision for a space-based measure of effectiveness for unsignalized crossings. In this case, the periodic element found at a signalized intersection is not as pronounced, and the delay to pedestrians predominates.

Other Waiting Areas

Space. The current *HCM* uses pedestrian space as the primary MOE. Based on average pedestrian space, personal comfort, and degree of internal mobility, capacity here is 2 ft^2/pedestrian (0.19 m^2/ ped). The values of space for queueing or waiting areas at each level of service shown in Table 21 vary from 10 to 50 percent of the space required for circulation on walkways.

TABLE 21
Existing *HCM* queueing area Level of Service (LOS) criteria

	Space		Interperson Spacing	
LOS	(m2/ped)	(ft2/ped)	(m)	(ft)
A	≥1.21	≥13	1.2	≥ 4
B	0.93-1.21	13-Oct	0.9-1.2	3.5-4
C	0.65-0.93	10-Jul	0.7-0.9	3-3.5
D	0.27-0.65	7-Mar	0.3-0.7	3-Feb
E	0.19-0.27	3-Feb	< 0.3	< 2
F	< 0.19	≤ 2	negligible	negligible

SOURCE: *TRB, 1994; from Fruin, 1971.*

3.3 Pedestrian Networks

The German *Highway Capacity Manual* recommends a maximum pedestrian delay of 90 s total for a series of signals (*Brilon, 1994*).

Virkler (*1996*) notes that the *HCM's* arterial analysis chapter (11) uses overall average travel speed as the measure of effectiveness in determining LOS. He recommends use of average travel speed for pedestrian arterials (routes) as well. Table 22 compares his recommended travel speed values with appropriate speed values from the *HCM's* vehicular arterial analysis chapter. Virkler's values represent an adaptation of pedestrian walkway and signalized intersection vehicular delay LOS standards. For a given LOS, the pedestrian arterial values represent an average travel speed, assuming the average walkway speed at that LOS with a delay over a 100-m length equal to that signalized intersection LOS. Examination of the above criteria reveals that one would have to maintain normal walking speeds throughout the entire arterial (i.e., essentially no stopping at signals or other nodes) in order to achieve the upper levels of service.

TABLE 22

Comparison of existing *HCM* vehicle arterial Level of Service (LOS) criteria with pedestrian arterial threshold proposals by both Virkler and North Carolina State University

							Pedestrian arterial threshold proposals				
	Cl. I *Vehicle Arterials*			*Cl. III Vehicle Arterials*			Virkler				NCSU
LOS	(m/s)	(mi/h)	(%FFSa)	(m/s)	(mi/h)	(%FFSb)	(m/min)	(m/s)	(mi/h)	(%FFSc)	(ratiod)
A	16	35	88	11	25	93	80	1.33	3	95	90
B	13	28	70	8.5	19	70	70	1.17	2.6	84	70-90
C	9.8	22	55	5.8	13	48	60	1	2.2	71	50-70
D	7.6	17	42	4	9	33	50	0.83	1.9	59	40-50
E	5.8	13	33	3.1	7	26	35	0.58	1.3	41	30-40
F	< 5.8	< 13	< 33	< 3.1	< 7	< 26	< 35	< 0.58	< 1.3	< 41	30

[a] Percent of 18 m/s (40 mi/h) free-flow speed for Class I vehicle arterials that favor mobility

[b] Percent of 12 m/s (27 mi/h) free-flow speed for Class III vehicle arterials that favor access

[c] Percent of 1.4 m/s (3.1 mi/h or 84 m/min) free-flow speed for pedestrian walkways

[d] Ratio of calculated minimum travel time to actual travel time, multiplied by 100 for easier
comparison with "percent of free-flow speed" used for vehicle arterial thresholds

SOURCES: *TRB, 1994; Virkler, 1996.*

One alternative method could be to determine the minimum travel time at a given LOS, compare this with the actual travel time (i.e., incorporating any delay), and define a pedestrian network LOS based on this ratio. The following equation shows this:

Minimum Travel Time . Calculated Minimum Travel Time
Time Ratio = =
Delay + Minimum Travel Time Actual Observed Travel Time
where:

$0 <$ Time Ratio 1

With this expression, a trip with no delay will have a time ratio of 1.0, while a trip taking four times as long as the minimum will have a time ratio of 0.25. In addition, this formulation allows for calibration of minimum times at a local site. However, Virkler's proposal offers the convenience of a fixed-speed criterion for each service level.

4 METHODS FOR COMPUTING MEASURES OF EFFECTIVENESS

Note: All values for walking speeds are those used by the original researcher, rather than those recommended in this report, unless otherwise noted.

4.1 Uninterrupted Facilities

Sidewalks and Walkways

The existing *HCM* contains detailed analysis procedures for these facilities (*TRB, 1994*). Although this report recommends new LOS thresholds, the basic procedures for the facilities will not change.

Off-street paths

Exclusive pedestrian trails. As stated earlier, the existing *HCM* procedures for walkway analysis apply here. Although this study recommends new service level thresholds, the basic procedure for these facilities will not change.

Shared pedestrian-bicycle paths. For these facilities, Botma's procedure, described earlier, is the only viable alternative in the literature. The procedure consists of measuring bicycle volume and then assigning a pedestrian LOS based on this volume.

4.2 Interrupted Pedestrian Facilities

Signalized Crossings

The existing *HCM* contains detailed analysis procedures for these facilities (*TRB, 1994*). Chapter 13 notes that one can analyze a crosswalk as a time-space zone, similar to a street corner. According to the *HCM*, the demand for space equals the product of pedestrian crossing flow and average crossing time. The chapter notes that a surge condition exists when the two opposing platoons meet. One determines the primary measure of effectiveness, space per pedestrian, using this time-space methodology. No delay measures exist, as stated earlier.

Delay: Pretty's Method. Pretty (*1979*) analyzed the delays to pedestrians at signalized intersections using relatively simple models. For pedestrians crossing one street at an intersection, he developed the following formula for pedestrian delay, based on uniform arrival rates and equal pedestrian phases:

$$d_1 = \frac{P}{2C}(C - w)^2$$

where:

d_1 = total delay to pedestrians crossing one street, ped-h/h;
P = pedestrian volume crossing one street, peds/h;
C = cycle length, s; and
w = WALK time, s.

For pedestrians crossing two streets at an intersection, he offers the following formula, which assumes that one-half the cycle length separates the two WALK periods:

$$d_2 = P_d\,(0.75C - w)^2$$

where:
d_2 = total delay to pedestrians crossing two streets successively, ped-h/h;
P_d = pedestrian volume crossing two streets, ped/h.

For an all-pedestrian phase, sometimes referred to as a "barn dance" or "Barnes dance," the total pedestrian delay is of the same form as that for a single crossing:

$$d_{1\&2} = \frac{P + P_d}{2C} (C - w)^2$$

where:
$d_{1\&2}$ = total delay to pedestrians crossing two streets diagonally, ped-h/h.

Delay: Dunn and Pretty's Method. Dunn and Pretty (*1984*) determined the following formulas for pedestrian delay at signalized pedestrian (Pelican) crossings:

$d = \frac{(g + 10)^2}{2\,(g + 15)}$ for a narrow roadway (about 7.5 m or two lanes)

$d = \frac{(g + 15)^2}{2\,(g + 20)}$ for a wider roadway (about 15 m or four lanes)

where:
d = average delay per pedestrians, s; and
g = vehicular green signal.

The parenthetical expressions in the denominator represent the cycle length for the above expressions, which assume pedestrian signal compliance.

Delay: Griffiths et al.'s Method. Griffiths et al. (*1984a*) conducted field surveys of delay at midblock pedestrian crossings in Great Britain. Figure 9 shows the results of the authors' field study. The top graph represents zebra crossings. The middle graph represents fixed-time pelican crossings. The lower graph represents vehicle-actuated pelican crossings.

As mentioned earlier, Griffiths et al. (*1984c*) performed extensive simulation analyses on a 10-m-wide pelican crossing. The authors found an increase in pedestrian delay with increases in vehicle flow, because the former group enjoys reduced opportunities to cross in gaps in traffic under higher vehicle flow conditions. The authors found a moderate increase in pedestrian delay with increases in pedestrian flow. Under vehicular actuation, the authors found that an increase in vehicular green from 20 to 40 s (in response to higher vehicle flows) resulted in rapid increases in pedestrian delay above two-way flows of 1,000 veh/h but no change in pedestrian delay below these levels.

Figures 10 and 11 graphically depict the results of their simulation analyses on pelican crossings. Figure 10 refers to a fixed-time pelican crossing with a vehicle precedence period (f_{max}) of 20 s. Figure 11 shows a vehicle-actuated pelican crossing, with the solid lines representing f_{max} = 20 s and the dashed line representing f_{max} = 40 s. The latter figure shows the effect of increasing pedestrian flow on pedestrian delay at higher vehicle flows.

This report has also mentioned that Griffiths et al. (*1985*) developed mathematical expressions for delay at fixed-time signal crossings. The appendix describes these formulas.

Delay: Roddin's Method. Roddin (*1981*) offers the following equation for average delay (D) to pedestrians at signalized intersections:

$$D = \frac{F\,(R - A)^2}{[\,2 \times (G - R - A)\,]}$$

where:

F = fraction of pedestrians who wait when they arrive at a red, amber, or flashing DON'T WALK signal; i.e., compliant pedestrians;

R = duration of red or DON'T WALK signal;

A = duration of amber or flashing DON'T WALK signal; and

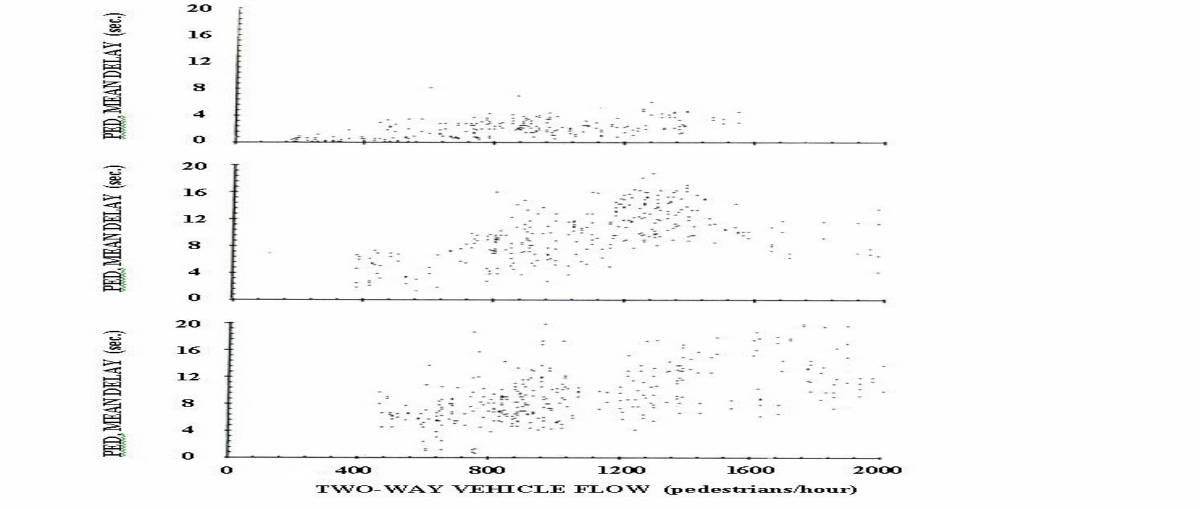
G = duration of green or WALK signal.

Roddin assumes random pedestrian crossings during WALK and random vehicle arrivals throughout the cycles.

Recommended Procedures For Chapter 13

FIGURE 9

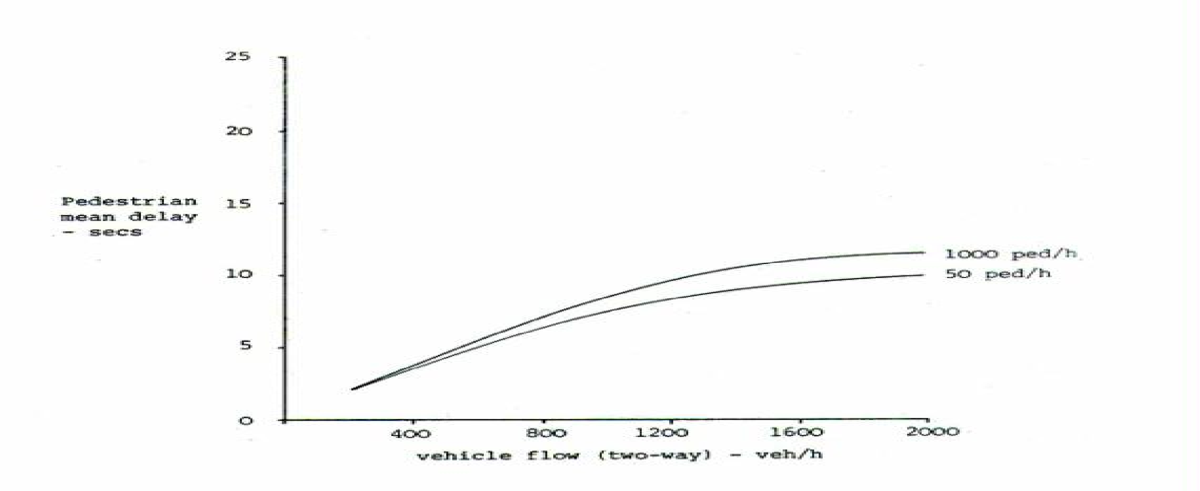
Field Measurements of pedestrian delay at midblock crossings in Great Britain



Recommended Procedures For Chapter 13

FIGURE 10

Simulation results of pedestrian dealy at fixed-time Pelican crossings in Great Britain

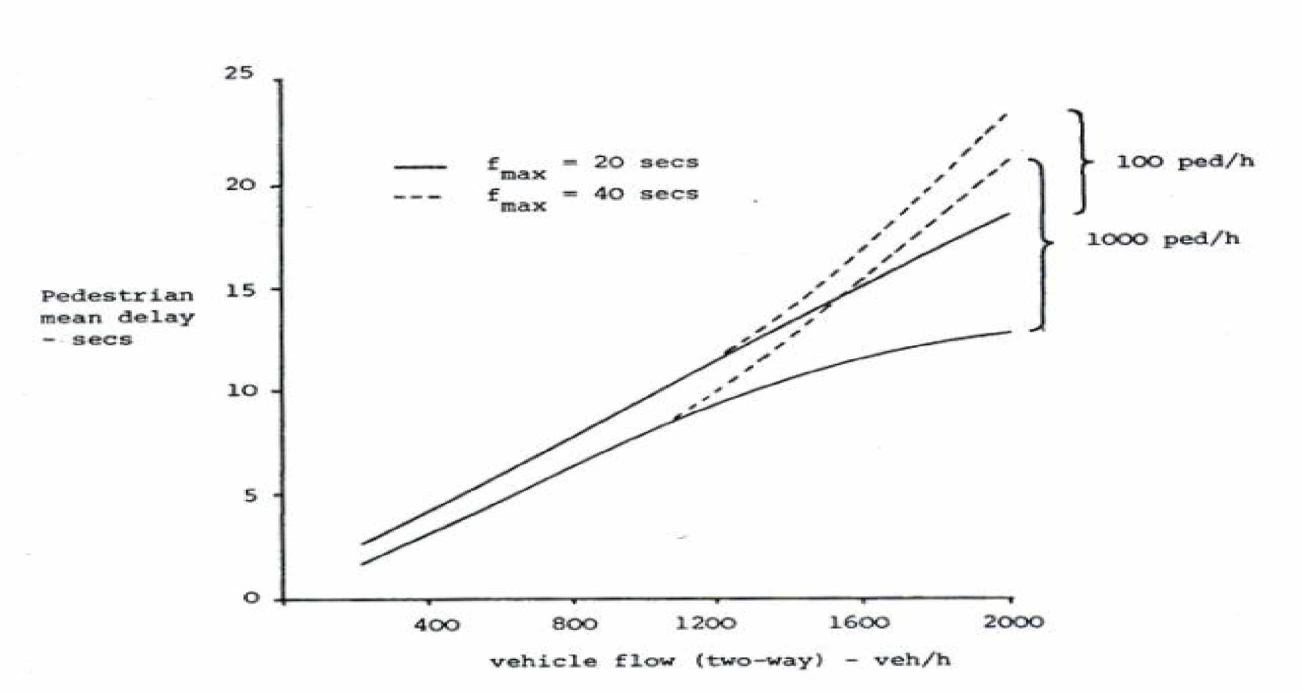


Delay: Virkler's Method. Virkler clearly states that "pedestrians can save significant amounts of delay by using more than just the WALK interval to enter the intersection." He develops a new model of pedestrian delay that reflects the benefits of noncompliance on pedestrian delay:

$$D = \frac{[C - (G + 0.69A)]^2}{2C}$$

where:
D = average delay per pedestrian, s;
C = cycle length, s;
G = duration of WALK signal; and
A = duration of flashing DON'T WALK signal.

Virkler applied this equation to actual measured delay at 18 Brisbane, Australia, crosswalks and found that the equation predicted delay about 1 percent higher than observed values



Recommended Procedures For Chapter 13
FIGURE 11
Simulation results of pedestrian delay at vehicle-actuated Pelican crossings in Great Britain

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Delay: NCSU's Method. Gerlough and Huber (*1975*) discuss several intersection delay and queueing models for vehicles. They derive a fluid (or continuum) delay model for a pretimed signal, and then note that this formulation is identical to the first term of the famous Webster analytical model for computing delay. One can write this portion of the model as:

$$d = \frac{C\,(1-\lambda)^2}{2\,(1-\_\lambda\,x)}$$

where:
d = delay, s;
C = cycle length, s;
λ_=_proportion of cycle that is effectively green = g / C;
g = effective green time, s;
x = q C / (g s);
q = arrival rate on approach, ped/h; and
s = saturation flow rate on approach per/hour green.
Noting that λ_=_g / C and $\lambda x = q / s$, and using the identity that red time (r) = C - g. one has:

$$d = \frac{r^2}{2\,C\,\{1-(q/s)\}}$$

The NCSU research team observed flow rates up to 5,000 ped/h ped-green at some locations. Inserting this value for the maximum pedestrian saturation flow rate, one has:

$$d = \frac{r^2}{2\ C\ \{1 - (q\ /\ 5000\ \text{ped/h})\}}$$

However, the NCSU team observed no capacity constraints, even with pedestrian flow rates of 5,000 ped/h. Therefore, rather than substitute this value for a maximum saturation flow rate, one could alternatively assume that the maximum saturation flow rate(s) approaches infinity for pedestrians. In this case, the term in brackets {1 - q/s} will tend to unity as s approaches infinity, and the following simple formula remains:

$d = r^2 / 2C$

This last expression is identical to that found in the Australian Road Research Board Report 123 for pedestrian delay *(Akçelik, 1989).*

Space. The *HCM* contains a detailed analysis procedure for determining the space measure of effectiveness for pedestrians for signalized crossings. Although the general time-space framework appears sound, several researchers have noted problems associated with particular aspects of the procedure. These areas include street corner waiting areas, corner circulation times, start-up times, and minimum crossing times.

Space: Fruin, Ketcham, and Hecht's Method. Fruin, Ketcham, and Hecht (*1988*) recommend several changes to the *HCM* method based on time-lapse photographic observations of Manhattan Borough, New York City, street corners and crosswalks. First, they advocate the use of 7 ft^2/person (about 0.65 m^2/person) for standing area on a street corner, rather than the *HCM* value of 5 ft^2/person (0.46 m^2/person). They also recommend a change in corner circulation time from a constant of 4 s to the following formula based on corner dimensions:

$T_o = 0.12\ (W_a + W_b) + 1.4$

where:

T_o = circulation time (s); and

W_a, W_b = intersecting sidewalk widths (ft).

Metricized, the equation becomes:

$T_o = 0.37\ (W_a + W_b) + 1.4$

where:

W_a, W_b = intersecting sidewalk widths (m)

Space: Virkler's et al. Methods. Virkler, Elayadath, and Geethakrishnan (*1995*) note that the signalized intersection chapter of the *HCM*, among other references, contains a basic crossing time (T) equation of the following general form:

$T = D + L / u$

where:

D = initial startup delay, s

L = walking distance, m or ft; and

u = walking speed, m/s or ft/s.

Virkler and Guell (*1984*) provide a method for determining intersection crossing time (T) that incorporates platoon size:

$T = t + (L/V) + H\ (N/W)$

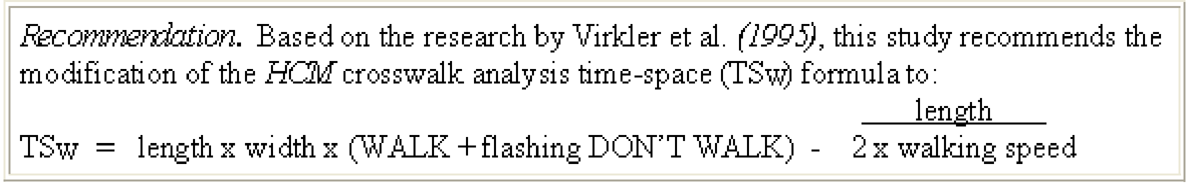
where:

T = crossing time;

t = pedestrian startup time = 3 s (from *TRB, 1980*);

L = length of crosswalk, ft or m;
V = walking speed = 4.5 ft/s or 1.5 m/s;
H = time headway between persons = 6.7 s / (ped/ft) or 2 .0 s / (ped/m). A later article (*Virkler et al., 1995*) uses a higher value for H of 2.61 s/(ped/m);
N = number of pedestrians crossing during an interval; and
W = crosswalk width, ft or m.

Virkler, Elayadath, and Geethakrishnan (*1995*) note that the Virkler and Guell equation does not address the problem of opposing platoons meeting in a crosswalk. In addition, these authors state that the current *HCM* time-space methodology suffers from two flaws dealing with the available time-space and walking time. Concerning the former, Virkler et al. (*1996*) believe that the *HCM* methodology overestimates the available time-space by about 20 percent, because legally crossing pedestrians cannot reach the space in the center of the crosswalk at the beginning of the phase and must have cleared this space by the end of the phase. Regarding the latter, Virkler et al. note that the time-space product ignores the fact that pedestrians must have sufficient time to physically traverse the entire length of the crosswalk. They imply that one should subtract the quotient of the crosswalk length and twice the assumed walking speed from the crosswalk time-space product for accuracy.



Recommendation. Based on the research by Virkler et al. *(1995)*, this study recommends the modification of the *HCM* crosswalk analysis time-space (TSw) formula to:

$$\text{TSw} = \text{length} \times \text{width} \times (\text{WALK} + \text{flashing DON'T WALK}) - \frac{\text{length}}{2 \times \text{walking speed}}$$

Those authors advocate the use of an approach based on shockwave theory when crossing pedestrian platoons are large, perhaps seven pedestrians per platoon (very roughly, 300 per hour*)*. The shockwave assumptions include: opposing platoons occupy the full walkway width until they meet and one-half of the walkway width upon meeting, pedestrian speeds fall upon meeting and remain low after platoon separation, and pedestrian density increases at platoon meeting. The Appendix contains the expression for required effective green time from Virkler et al. This model implies that, for a 60-s cycle length and a 30-s effective green time, 1,000 ped/h in the major direction would result in inadequate crossing time for crosswalk lengths greater than about 16 m despite an average LOS of B and a surge LOS of C. In addition, 250 ped/h in the major direction would have inadequate time for crosswalk lengths above 27 m, even with a surge LOS of A.

More recently, Virkler conducted a study in the Brisbane, Australia, area to determine appropriate crossing time parameters for two-way and scramble (all-pedestrian phase) crosswalk flow (Virkler, 1997c). Virkler notes that, for both types of facilities, the width of crosswalk actually used by pedestrians increases with increasing crosswalk volume. As mentioned earlier, Virkler also states that vehicles often use a portion of the crosswalk during the pedestrian phase. He therefore cautions that engineers should treat measured crosswalk widths merely as the width "intended for pedestrian use" rather than as an exact measurement of the width pedestrians will actually use. As an aside, Pretty argued against the use of exclusive pedestrian phases because of the considerable increase in pedestrian delay (*Pretty et al., 1994*).

As mentioned in the *Literature Review for Chapter 13, Pedestrians, of the Highway Capacity Manual*, Virkler (*1997c*) found that speeds at the rear of the platoons are not independent of concurrent or opposing platoon sizes. He found that, with large platoon sizes, the typical 7-s WALK interval is insufficient to allow all pedestrians to enter the crosswalk. For platoons of about 15 people or more, he states that the engineers should extend the minimum crossing time on a typical 3-m-wide crosswalk by 0.27 s/ped headway plus 1.71 s. The Appendix contains these calculations.

Unsignalized Crossings

The existing *HCM* contains no procedures for analyzing these facilities.

Delay: Roddin's Method. Roddin (*1981*) describes a method by another researcher for calculating moderate (less than 18 s) mean pedestrian delay (D) at unsignalized intersections:

$D = 6.7 \times 10^{-4} (Q - 0.3)$

where:

Q = total hourly vehicle flow, both directions, if less than 1,600/h.

Delay: Virkler's Method. Virkler (*1996*) describes a similar equation for calculating delay from other research, based on queueing theory. Assuming random vehicle arrivals and normal crossing speeds, the expression is:

$D = 6.7 \times 10^{-6} Q^2 + 0.3$

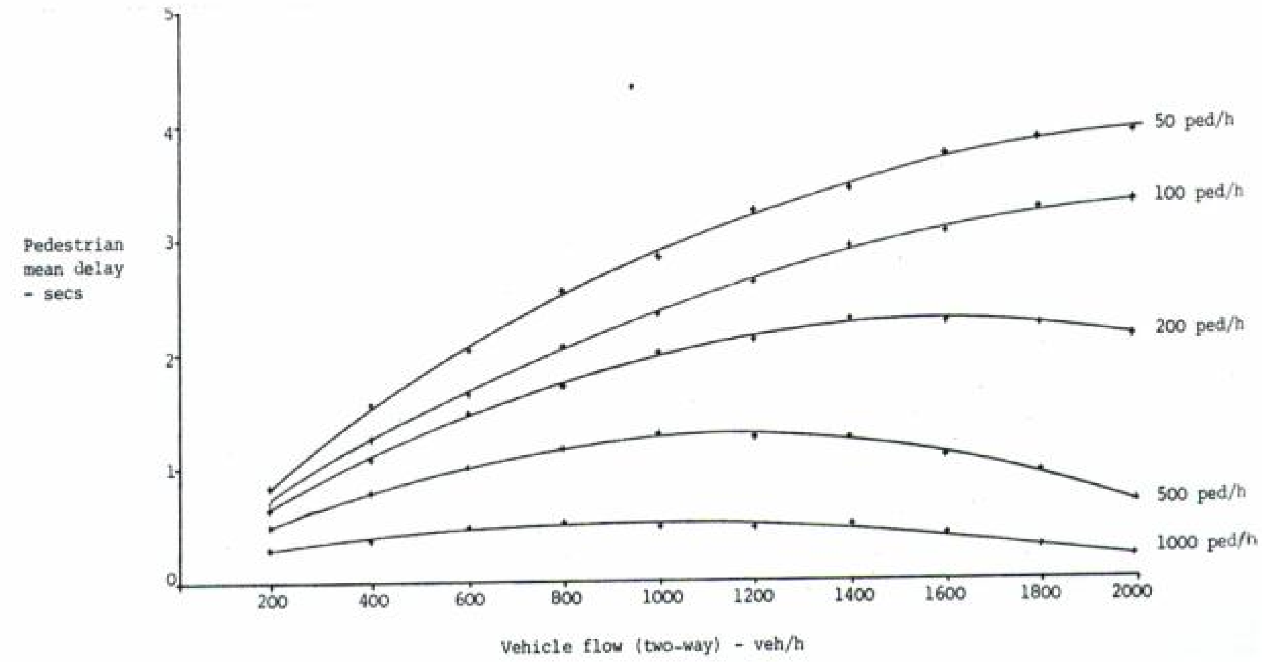
where:

D = delay, s; and

Q = total hourly vehicle flow, both directions.

Delay: Griffiths' et al. Method. As described earlier, Griffiths et al. (*1984b*) performed extensive simulation analysis on zebra crossings. They found that pedestrian delay depends heavily on both pedestrian and vehicle flows; however, they noted that the effect of increasing vehicle flow occurs primarily at low pedestrian volumes. In fact, as vehicle volumes continue to increase, pedestrian delay actually decreases, because most vehicles begin from a stopped (queued) position and pedestrians can establish precedence easier.

Figure 12 depicts the authors' field results.



Recommended Procedures For Chapter 13

FIGURE 12

Simulation results of pedestrian delay at Zebra crossings in Great Britain

This report has also mentioned that these same authors developed mathematical delay models. The Appendix contains the expression developed by Griffiths et al. for pedestrian delay at a zebra crossing.

Smith's et al. Method. Smith et al. (*1987*) refer to an earlier study that demonstrated the effect of crossing width and conflicting vehicle volume on pedestrian delay (Figure 13).

Palamarthy's et al. Method. Palamarthy et al. (*1994*) present the following model for mean pedestrian delay for all pedestrians employing one of the crossing tactics mentioned earlier in the discussion of unsignalized service measures of effectiveness:

$$d_i = \frac{e^{q(\alpha_n + \alpha_f)} - q(\alpha_n + \alpha_f) - 1}{q}$$

where:

d_i = mean delay to pedestrians using tactic *i*, s per pedestrian;

q = vehicular flow in one direction, vehicles/s;

"$_n$ = critical gap in near-lane traffic stream, s; and

"$_f$ = critical gap in far-lane traffic stream, s.

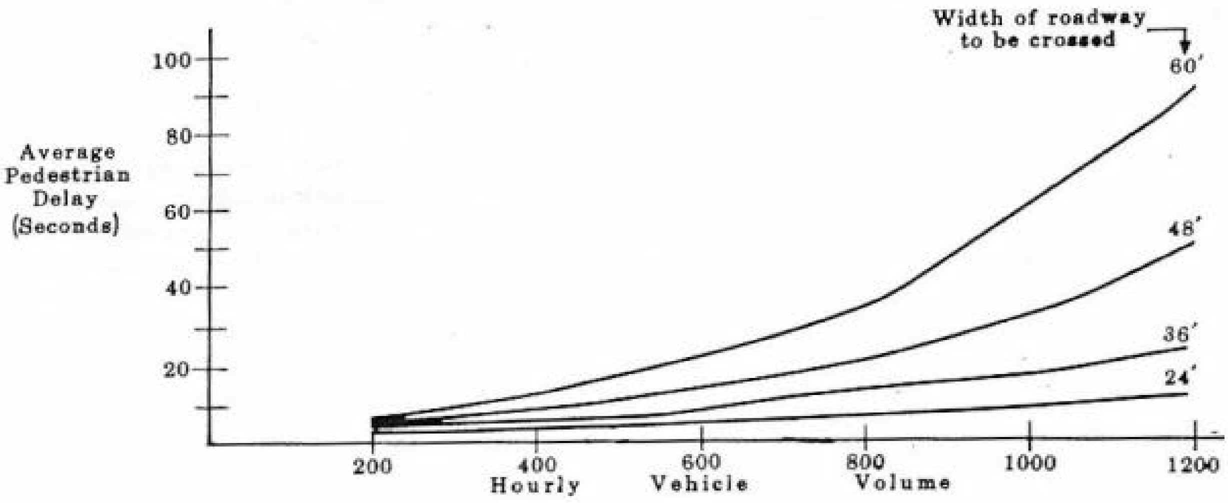
It follows that the mean delay across all tactics is:

$$d = \Sigma\, \phi_i d_i$$

where:

d = mean delay to all crossing pedestrians, s/pedestrian; and

ϕ_i = proportion of pedestrians using tactic i.



Recommended Procedures For Chapter 13
FIGURE 13
Effect of crossing width and conflicting vehicle volume on pedestrian delay

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NCSU's Method. The NCSU research team has developed a formulation for computing pedestrian delay at unsignalized intersections based on gap acceptance by platoons. Since "delays are relatively insensitive to the form of the distribution of the arriving traffic" (*Gerlough and Huber, 1975*), the research team assumed random arrivals for both pedestrians and vehicles. In addition, the procedure described in the following paragraphs assumes that start-up times, headways, walking speeds, and minimum pedestrian body ellipses retain constant values.

The ITE Manual of Traffic Engineering Studies (*Robertson et al., 1994*) contains a general equation describing the minimum safe gap (G) in traffic:

$G = (W/S) + (N-1) H + R$

where:

W = crossing distance or width of roadway, ft or m;
S = walking speed, ft/s or m/s;
N = predominant number of rows (group size);
H = time headway between rows, s; and
R = pedestrian start-up time, s.

Gerlough and Huber (*1975*) note that, for a group of pedestrians, the pedestrian and vehicle volume together determine the size of the platoon:

$$E(n_c) = \frac{pe^{p\tau} + qe^{-q\tau}}{(p+q)\,e^{(p-q)\tau}}$$

where:

E(nc) = size of typical pedestrian crossing platoon, ped;
p = pedestrian flow rate, ped/h;
q = vehicular flow rate, veh/h;
τ_G = pedestrian group critical gap, s.

One can make an estimate of a critical gap, , for a single pedestrian by substituting N = 1 into the ITE equation above and simplifying:

$\tau = G = (W/S) + R$

Then, one substitutes this value for critical gap, τ, into the Gerlough and Huber expression above to determine the number of pedestrians in a typical crossing platoon. To determine the spatial distribution of pedestrians, the research team developed a simple geometric expression incorporating the crosswalk width and the pedestrian body buffer zone:

$$N = \frac{E(n_c) * \text{comfortable body buffer zone}}{\text{crosswalk width}}$$

crosswalk width

As stated earlier, the research team recommends a value of 0.75 m^2 for a design body buffer zone.

Given the critical gap for a single pedestrian computed previously, the ITE equation simplifies to:

G = + (N-1) H

The ITE Manual suggests 2 s as a typical value of headway, H. To avoid confusion, this report will refer to the pedestrian group critical gap (G in the previous equation) as $_G$.

The final issue concerns the average delay to all pedestrians, whether waiting or not. Again, Gerlough and Huber (*1975*) provide guidance:

$$E(t) = \frac{1}{qe^{-q\tau_G}}\;T - \tau_G$$

where:

E(t) = average delay to all pedestrians, s;
T = 1/q = mean vehicle headway, 1/s; and
τ_G = pedestrian group critical gap, s.

Other Waiting Areas

Space. The existing *HCM* does not contain detailed analysis procedures for waiting areas, because the methodology is extremely simple. One simply computes the available waiting area and determines the actual or expected number of pedestrians during the critical time period, and then determine the LOS from the average space per pedestrian. Fortunately, queueing areas sufficiently resemble street corners such that one can apply those procedures if needed.

4.3 Pedestrian Networks

Travel Time: Roddin's Method. Roddin (*1981*) mentions one quantitative factor, travel time, in the evaluation of pedestrian transportation. His narrative implies that the following equation applies to pedestrian networks:

Total travel time = Number of ped x (Route length / Walking speed + Signal Delay)

where route length is:
estimated from plans,
generally < 3000 ft (915 m),
generally < 1.4 x straight-line distance, ideally < 1.2 x straight-line distance,
weighted by proportion of ped using alternate routes if available
and:
signal delay is as computed by the method presented earlier.

Travel Time: Virkler's Method. Virkler (*1997b*) provides an extensive method of calculating travel time along a pedestrian network. Incorporating both link and note components, his methodology determines the total walking plus queueing time along the extended pedestrian facility. For congruence with vehicle arterial measures of effectiveness, the method determines the average travel speed along the route as a final step.

Virkler notes that platooning due to an upstream signal can either increase or decrease pedestrian delay at a downstream signal, depending on the offset and the green time at the upstream signal (*1997d*). He argues that one can use field measurements of arrival patterns at signals to modify random arrival-based delay results. Table 24 shows his recommended default delay adjustment factors (DFs) to achieve positive pedestrian platooning.

Examination of the table demonstrates that DF between 0.45 and 0.64 lie within the likely range at all listed green time/cycle length ratios. In addition, the table demonstrates that one will achieve better (lower) delay adjustment factors at higher green ratios (g/C). He notes that the best offsets for pedestrian progression do not necessarily occur when one achieves the highest arrival rate during the green; rather, one must consider the green time itself. Virkler found that, as green times increase, the best offsets are shorter, in order to maximize the benefits of pedestrian platooning.

TABLE 23
Default values of Delay Adjustment Factors (DF) for positive pedestrian platooning

g/C	Default DF	Likely Range of DF Values
0.1	0.65	0.45-0.80
0.2	0.57	0.38-0.77
0.3	0.5	0.30-0.74
0.4	0.42	0.23-0.72
0.5	0.35	0.16-0.68
0.6	0.27	0.12-0.64

SOURCE: *Virkler, 1997d.*

5 SUMMARY OF RECOMMENDATIONS FOR DESIGN AND/OR ANALYSIS OF PEDESTRIAN FACILITIES

Recommendation	Page(s)	Figure	Table	HCM Ch. 13 Subsections affected	HCM variables and adjustments affected

Body ellipse for standing areas	4	2	-	introductory narrative only	primarily a design recommendation
Body buffer zone for walking	4	-	-	walkways, street corners, crosswalks	walkway LOS E/F threshold changes in Table 13-3
Crosswalk walking speeds	5	-	1	[Ch. 9: Methodology, Input module]	new values replace 4.0 ft/s in equation (eq.) 9-8
				Ch. 13: introduction, crosswalks	new values replace 4.5 ft/s in eq. 13-14
Grade and stairs walking speeds	7	-	-	walkway narrative, crosswalks	speeds decrease by 0.1 m/s in eq. 13-14 with grades
Crossing speeds for platoons	7	-	-	N/A	1 no change 1
Pedestrian start-up time	7	-	-	N/A	1 no change 1
Capacity thresholds	8	-	-	walkways, street corners, crosswalks	walkway LOS E/F threshold changes in Table 13-3
Temporal flow variation	8	-	-	N/A	1 no change 1
LOS (Level of Service) for walkways	11	5	4	walkways	walkway LOS A/B, E/F thresholds change, Table 13-3
LOS for walkways with platoons	12,13	-	6	walkways	new table replaces equation 13-3
LOS for transportation terminals	15	-	8	walkways (new measure)	new table applies to terminals with platoon flow
LOS for stairs	16	-	9	walkways (new measure)	new table applies only to stairs
LOS for crossflows	17	-	10	walkways (new measure)	new table serves as secondary check for walkways
LOS for mixed-use paths	21	-	13	walkways (new measure)	new table applies only to mixed-use paths
Noncompliance time adjustments	26	-	-	street corners, crosswalks	minor, major red times in equations 13-6, 13-7 change;d effective red time

					reduced in computing ped delay
LOS for signalized crossingsa	29	-	18	street corners (new measure)	new table based on ped delay; space now secondary
Swept-path method for vehicle effects 30	-	-	crosswalks	caution to use only under aggressive driver behavior	
LOS for unsignalized crossingsb	32,33	-	20	street corners (new measure)	new table based on ped delay
LOS for pedestrian networksc	35,36	-	22	networks (new section)	new table shows proposals for analysis of ped networks
Ped delay at signalized crossings	45	-	-	street corners (new measure)	method for computing ped delay
Effective crosswalk time-space	48	-	-	crosswalks	equation 13-13 corrected; calculated TSw will decrease
Crossing time in platoons	49, 60	-	-	crosswalks	new equations replace eq. 13-14 with large platoons
Ped delay at unsignalized crossings	54	-	-	street corners (new measure)	method for computing ped delay

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[a] Offers a comparison with delay-based Level of Service for drivers computed in *HCM* Chapter 9, "Signalized Intersections"
[b] Offers a comparison with delay-based Level of Service for drivers computed in *HCM* Chapter 10, "Unsignalized Intersections"
[c] Offers a comparison with Level of Service for drivers computed in *HCM* Chapter 11, "Urban and Suburban Arterials"
[d] Current *HCM* is ambiguous regarding the definition of minor and major red times (R_{mi}, R_{mj}); therefore, the effect of the proposed noncompliance adjustments will depend on the analyst's interpretation of the *HCM*

6 APPENDIX: ADDITIONAL FORMULAS FOR COMPUTING RECOMMENDED MEASURES OF EFFECTIVENESS

Interrupted Pedestrian Facilities

Signalized Crossings

Delay: Griffiths et al.'s Method. Griffiths et al. (*1985*) derived the following expression for pedestrian delays with two-way vehicle volumes below 1,500 vehicles/h:

$$d_p = \left(\frac{60}{11} - \frac{4V}{1100}\right) + \left(\frac{V}{1100} - \frac{4}{11}\right)\left(\frac{d_T}{\mu y_2}\right)$$

For vehicle volumes at or above 1,500/h (with pedestrian noncompliance less likely at these high vehicle volumes), they found that the following formula best fit their simulation results:

$$d_p = \frac{d_T}{\mu y_2}$$

where:_

d_p = mean overall delay to pedestrians, s;

V = vehicle mean two-way arrival rate, veh/h;

μ = pedestrian mean arrival rate, ped/s;

$d_T = \mu_{FDW} d\{a + b + e + f + d/2\} + \mu_R(e + f)\{a + b + (e + f)/2\} + \mu_R(a + b)^2/2 + (a + b)e^{-\{\mu_{FDW} d + \mu_R (e+f)\}}$

_

$y_2 = a + b + c + k + (1/\_\mu_R)_e{}^{-\{\mu FDWd + \mu R(e+f)\}}$

μ_{FDW} = pedestrian flow rate during flashing DON'T WALK, ped/s;

μ_R = pedestrian flow rate during steady DON'T WALK, ped/s;

a = vehicular yellow time, s;

b = all red period, s;

c = WALK time, s;

d = flashing DON'T WALK time during vehicle red indication, s;

e = flashing DON'T WALK time during vehicle "yield to peds" indication, s;

f = vehicle green time, s;

k = pedestrian effective red time = d + e + f

Under vehicle actuation, they found the following best matched simulation results:

$$d_p = \frac{d_T}{\mu y_1}$$

where all variables and parameters are as before, except:_

$$d_T = \mu k(a + b + T + k/2) - \mu k T e^{-(\lambda x)} + \mu T(a + b + T/2)(1 - e^{-(\lambda x)}) + (a + b + T)\, e^{-(\mu\_k)} - Te_{(-\mu\_k)}e^{-(\lambda x)} + \mu(a + b)^2/2;$$

$$y_1 = a + b + c + k + e^{-(\mu k)}/\mu + T\{1 - e^{-(\lambda x)}\} = \text{mean cycle length, s;}$$

$$T = x + \{e^{\lambda x} + -\lambda x - 1\}/\lambda\_;$$

$k = d + e + f_{min}$; and

f_{min} = minimum vehicular green, s.

Space: Virkler et al.'s Method. Virkler, Elayadath, and Geethakrishnan (*1995*) offer the following expression for required effective green time (G_{req}):

$G_{req} = t_0 + t_1 + t_2$

where:

$t_0 = R\,[\,\omega_{AB} / (\omega_{BC} - \omega_{AB})] =$ time between start of movement of front and rear of queue

$t_1 = L_q + L/2 - [u_D\,(L_q + u_C \times t_0) / (u_C + u_D)] =$ time for last pedestrian to travel $L_q + L$

$t_2 = \{(L/2) + [u_D\,(L_q + u_C \times t_0) / (u_C + u_D)]\} / u_D$

and where:
R = effective red time, s;
$\omega_{AB} = -\,q_A / (k_B - k_A)$;
$\omega_{BC} = -\,q_C / (k_B - k_C)$;
q_A = flow rate of peds approaching the queue, ped/min;
q_C = flow rate of peds leaving the queue, ped/min;
k_B = density of arriving pedestrians, ped/m^2;
k_A = density of platooned pedestrians, ped/m^2;
L_q = maximum depth of the standing queue (waiting to cross), m;
L = walking distance, m;
u_C = pedestrian walking speed before meeting opposing platoon, m/s; and
u_D = pedestrian walking speed after meeting opposing platoon, m/s.

Regarding space-based methods at signalized intersections, Virkler assumes 1.2 m/s platoon flow speeds in the following calculation, which reflects this:

WALK interval = 3.2 s + (0.19 s/ped) * N_1

where:

N_1 = number of people in the primary movement who arrive before the WALK indication and exit the curb during the WALK indication.

For larger effective crosswalk widths, he offers the following modification:

WALK interval = 3.2 s + (0.57 s/ped/m) * (platoon size/W)

where:

W = effective crosswalk width, m.

Virkler then offers the following method of determining sufficient *total crossing time* (WALK plus flashing DON'T WALK), which accounts for the effects of dispersion of platoons larger than 15 persons, for crosswalks with effective widths up to about 3 m:

$$\text{WALK + flashing DON'T WALK interval} = 3.2\text{ s} + \frac{L}{1.2\text{ m/s}} + 0.27\text{ s/ped} * N_1$$

where:

L = crosswalk length, m.

and for larger effective crosswalk widths, he offers the following modification:

$$\text{WALK + flashing DON'T WALK interval} = 3.2\text{ s} + \frac{L}{1.2\text{ m/s}} + 0.81\text{ s/ped} * \frac{N_1}{W}$$

Recommendation.
This report recommends the above methods of determining *sufficient total crossing time*(WALK plus flashing DON'T WALK) proposed by Virkler into the *HCM*.

Unsignalized Crossings

Delay: Griffiths et al.'s Method. Griffiths et al. (*1985*) established the following expression for pedestrian delay at a zebra crossing:

$d_p = \lambda\_(7\lambda + 6)\ e^{(-\mu\_\propto/2G)}$

where:

d_p = average delay to pedestrians, s;

λ = vehicle mean (two-way) arrival rate, veh/s;

μ = pedestrian mean arrival rate, peds/s;

$\propto$ = mean pedestrian crossing time, s; and

G = mean pedestrian group size, ped.

The exponential portion of the expression reflects the authors' observation that pedestrian groups experience no delay when their arrival at the curbside occurs before a preceding pedestrian group has reached about halfway across the road. **7**

7 ACKNOWLEDGMENTS

The authors would like to thank several graduate students at North Carolina State University who were instrumental to the successful completion of this report. Conredge Lewis helped with field observations in Chicago and Washington. Aemal Khattak offered input into the development of recommended walking speed values for elderly pedestrians. Craig Sheffler gave additional information regarding shared-use paths. Tahsina Ahmed assisted with the development of pedestrian delay models. Brian Eads provided invaluable administrative support. Michael Surasky and Steven Click offered assistance regarding the appearance of the report.

We would also like to thank members of the sponsoring agencies for this report. David Harkey and Charles Zegeer of the University of North Carolina Highway Safety Research Center and Carol Tan Esse of the Federal Highway Administration provided the necessary support and guidance for the project. We would also like to thank our reviewers who gave excellent feedback on a wide variety of issues.

The authors would like to thank Dr. Alex Sorton of Northwestern University and Dr. Mark Virkler of the University of Missouri at Columbia for providing timely assistance and information throughout this project. Alex Sorton and Dan Burden also provided the research team with excellent photographs for inclusion in the document.

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