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Enhancing Pedestrian Volume Estimation and Developing HCM Pedestrian Methodologies for Safe and Sustainable Communities

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Pedestrian Crossing Delay and LOS

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Appendix D: Revised Model for Predicting Pedestrian Delay at Uncontrolled Crossings

INTRODUCTION

This working paper describes proposed revisions to the pedestrian delay prediction methodology in Chapter 20 of the *Highway Capacity Manual* (HCM) 6th edition. This methodology is used to predict pedestrian delay at two-way stop-controlled (TWSC) intersections and midblock crossings, at which pedestrians cross up to four through lanes on the major street. The revisions are intended to address some discontinuities found in the predicted pedestrian delay when it is examined for a range of traffic volumes.

This paper consists of four sections. The first section provides a review of the pedestrian delay prediction methodology in HCM Chapter 20. The second section describes the development of the proposed revisions to the methodology that are intended to address the aforementioned discontinuities. The third section presents the proposed "motorist yield rates." These rates describe the proportion of motorists that yield to pedestrians at a TWSC intersection or midblock crossing. The last section describes a plan for calibrating and validating the revised methodology using pedestrian delay measurements at uncontrolled crossings collected during Task 6D.

BACKGROUND

This section provides the findings from a review of the pedestrian delay prediction methodology in Chapter 20 of the HCM 6th edition. The findings are categorized in three subsections. The first subsection provides a brief overview of the computational steps that comprise the methodology. The second subsection describes the findings from a sensitivity analysis of the methodology. The third subsection summarizes the motorist yield rates found in the research literature.

HCM Methodology Computational Steps

The methodology for predicting pedestrian delay at TWSC intersections and midblock crossings was first introduced in Chapter 18 of the HCM2000. The methodology considers pedestrian volume to predict the typical number of pedestrians that will cross when the vehicle headway exceeds the minimum (i.e., critical) headway. This predicted pedestrian group size is then used to estimate the minimum headway that the group will need to cross a street. The distribution of vehicle headways is assumed to follow the negative exponential distribution. On this basis, an equation is provided for predicting pedestrian delay (i.e., the delay incurred while waiting for a headway to exceed the group minimum headway; at which time the pedestrians are able to enter the crosswalk and begin the crossing). The HCM2000 indicates that the key analytic elements of this methodology are described in TRB *Special Report 165* (Gerlough and Huber 1975, Section 8.5.2).

For the 2010 HCM, the methodology in Chapter 18 of the HCM2000 was updated to include consideration of motorists that yield the right-of-way to pedestrians desiring to cross the street. The HCM2000 methodology is based on the conservative assumption that no drivers will yield. However, many innovative pedestrian crossing treatments have been found to successfully induce most drivers to yield to pedestrians. To incorporate this behavior, the methodology was updated to include equations to estimate the delay associated with two delay-producing scenarios. The first scenario represents the delay incurred before the first yielding driver. The second scenario represents the delay incurred if no driver yields. The methodology estimates the average delay by using a weighted average of the two scenarios where the weight of the first scenario is the "probability of a driver yielding given that one or more pedestrians are delayed" and the weight of the second term is the "probability of no driver yielding given that one or more pedestrians were delayed." The updated procedure was developed by Parks (2009) for NCHRP Project 03-92. The updated methodology was subsequently reproduced in the HCM 6^{th} edition in 2015.

The computational steps associated with the 2010 HCM methodology are provided in the following list.

- Step 1. Identify two-stage crossings
- Step 2. Determine critical headway
- Step 3. Estimate probability of a delayed crossing
- Step 4. Calculate average delay to wait for adequate gap
- Step 5. Estimate delay reduction due to yielding vehicles
- Step 6. Calculate average pedestrian delay and determine level of service

Steps 3 and 5 were added to the methodology when it was updated for the 2010 HCM.

Step 1: Identify Two-stage Crossings

Step 1 does not include any calculations. Rather, the analyst is guided to decide whether pedestrians cross the entire street in a single stage or, instead use the median as a refuge to complete the crossing in two stages. When pedestrians cross in two stages, pedestrian delay is estimated separately for each stage of the crossing and the two delay values are added to produce the total delay incurred when crossing the street. The calculation sequence for the remaining steps is summarized below to facilitate the subsequent discussion of the proposed changes.

Step 2: Determine Critical Headway

This step describes a procedure for computing the critical headway for group of pedestrians waiting to cross the street. If the pedestrian volume is high, the procedure assumes pedestrians will cross in groups during each crossing opportunity. The procedure begins with the calculation of the critical headway for a single pedestrian using the following equation.

$$t_c = \frac{L}{S_p} + t_s \qquad \text{Equation D1}$$

where

t_c	=	critical headway for a single pedestrian (s),
S_p	=	average pedestrian walking speed (default: 3.5 ft/s) (ft/s),
L	=	crosswalk length (ft), and
t_s	=	pedestrian start-up time and end clearance time (default: 3.0 s) (s).

The average number of pedestrians waiting to cross is computed using the following equation.

$$N_c = \frac{v_p e^{v_p t_c} + v e^{-v t_c}}{(v_p + v) e^{(v_p - v) t_c}} \qquad \text{Equation D2}$$

where

N_c	=	total number of pedestrians in the crossing platoon (p),
v_p	=	pedestrian flow rate (p/s),
v	=	conflicting vehicular flow rate (veh/s) (combined flows for one-stage crossings; separate flows for two-stage crossings), and
t_c	=	single pedestrian critical headway (s).

The pedestrians waiting to cross are assumed to form rows, with the first row in position to cross and subsequent rows lined behind the first row. The number of rows is computed using the following equation.

$$N_p = \text{int}\left[\frac{8.0(N_c - 1)}{W_c}\right] + 1 \qquad \text{Equation D3}$$

where

N_p	=	spatial distribution of pedestrians (p),
N_c	=	total number of pedestrians in the crossing platoon (p),
W_c	=	crosswalk width (ft), and
8.0	=	default clear effective width used by a single pedestrian to avoid interference when passing other pedestrians (ft).

Finally, the group critical headway is computed using the following equation.

$$t_{c,G} = t_c + 2(N_p - 1) \qquad \text{Equation D4}$$

where $t_{c,G}$ is the group critical headway (s) and all other variables are as previously defined.

Step 3: Estimate Probability of a Delayed Crossing

The probability that a given lane cannot be crossed is the same as the probability that the vehicle headway in the subject lane does not exceed the group critical headway. This probability is computed using the following equation.

$$P_b = 1 - e^{\frac{-t_{c,G}\, v}{N_L}} \qquad \text{Equation D5}$$

where

P_b	=	probability of a blocked lane,
N_L	=	number of through lanes crossed,
$t_{c,G}$	=	group critical headway (s), and
v	=	conflicting vehicular flow rate (veh/s) (combined flows for one-stage crossings; separate flows for two-stage crossings).

A crossing can occur when each of the lanes crossed has a vehicle headway in excess of the group critical headway. A delayed crossing occurs when the headway in one or more of the lanes crossed is less than the group critical headway. The probability of a delayed crossing is computed using the following equation.

$$P_d = 1 - (1 - P_b)^{N_L} \qquad \text{Equation D6}$$

where P_d is the probability of a delayed crossing and all other variables are as previously defined.

Step 4: Calculate Average Delay to Wait for Adequate Gap

The average delay per pedestrian to wait for an adequate headway (i.e., a headway longer than the minimum critical headway) is computed using the following equation.

$$d_g = \frac{1}{v}\left(e^{v t_{c,G}} - v t_{c,G} - 1\right) \qquad \text{Equation D7}$$

where

d_g	=	average pedestrian delay (s),
$t_{c,G}$	=	group critical headway (s), and
v	=	conflicting vehicular flow rate (veh/s) (combined flows for one-stage crossings; separate flows for two-stage crossings).

The average delay for any pedestrian who is unable to cross immediately upon reaching the intersection (e.g., any pedestrian experiencing nonzero delay) is computed using the following equation.

$$d_{gd} = \frac{d_g}{P_d} \qquad \text{Equation D8}$$

where d_{gd} is the average delay for pedestrians who incur nonzero delay, and all other variables are as previously defined.

Step 5: Estimate Delay Reduction due to Yielding Vehicles

When a pedestrian arrives at a crossing and finds the vehicle headway is shorter than needed to cross, that pedestrian is delayed until either a headway greater than the critical headway is available, or motor vehicles yield and allow the pedestrian to cross. Equation D7 estimates pedestrian delay when motorists on the major approaches do not yield to pedestrians. When motorist yield rates are significantly higher than zero, pedestrians will experience considerably less delay than that estimated by Equation D7.

Consider a pedestrian waiting for a crossing opportunity at an uncontrolled crossing. Vehicles in each conflicting through lane arrive at an average of h seconds apart. In other words, a potential yielding event occurs every h seconds.

For any given yielding event, each through lane is in one of two states:

- *Clear*—no vehicles are arriving within the critical headway window, or
- *Blocked*—a vehicle is arriving within the critical headway window. The pedestrian may cross only if vehicles in each blocked lane choose to yield.

If vehicles do not yield, the pedestrian must wait an additional h seconds for the next yielding event. On average, this process will be repeated until the wait exceeds the expected delay required for an adequate headway in traffic (d_{gd}), at which point the average pedestrian will receive an adequate headway in traffic and will be able to cross the street without having to depend on yielding motorists.

Average pedestrian delay can be calculated with Equation D9, where the first term in the equation represents the expected delay from crossings occurring when motorists yield, and the second term represents the expected delay from crossings when pedestrians wait for an adequate headway.

$$d_p = \sum_{i=1}^{n} h(i - 0.5)P(Y_i) + \left(P_d - \sum_{i=1}^{n} P(Y_i)\right) d_{gd} \qquad \text{Equation D9}$$

with

$$h = \frac{N_L}{v} \qquad \text{Equation D10}$$

$$n = \text{int}\left(\frac{d_{gd}}{h}\right) \qquad \text{Equation D11}$$

where

d_p	=	average pedestrian delay (s);
i	=	crossing event ($i = 1$ to n);
h	=	average headway for each through lane (s);
$P(Y_i)$	=	probability that motorists yield to pedestrian on crossing event i;
P_d	=	probability of a delayed crossing; and
n	=	average number of vehicle crossing events before an adequate headway is available.

For a one-lane crossing, the probability that motorists yield to the waiting pedestrians is calculated using the following equation.

$$P(Y_i) = P_d M_y \left(1 - M_y\right)^{i-1} \qquad \text{Equation D12}$$

where

M_y	=	motorist yield rate (decimal), and
i	=	crossing event ($i = 1$ to n).

Additional equations are provided in HCM Chapter 20 for computing $P(Y_i)$ for two-, three-, and four-lane crossings.

Sensitivity to Traffic Volume

This section summarizes the findings from an evaluation of the pedestrian delay prediction methodology in Chapter 20 of the 6th edition HCM. The evaluation examines the sensitivity of the predicted delay to traffic volume.

The motivation for this evaluation was the findings reported in Appendix A of the Interim Report as they related to the pedestrian delay methodology (see discussion associated with Figure A5). Notably, these findings indicated that there was a discontinuity in the predicted pedestrian delay when it is examined for a range of traffic volumes. More importantly, the methodology seemed to over-predict delay when the proportion of motorists yielding is high.

The sensitivity analysis findings described in this section are based on the evaluation of pedestrian delay for a four-lane street with a two-way left-turn lane. Pedestrians crossed the street in one stage because there is no median. The following list identifies the input variables and values:

- Crossing width: 52 ft
- Pedestrian walking speed: 3.5 ft/s
- Crosswalk width: 10 ft
- Pedestrian startup time: 3 s
- Pedestrian flow rate: 20 ped/h
- Traffic volume: 100 to 1100 veh/h

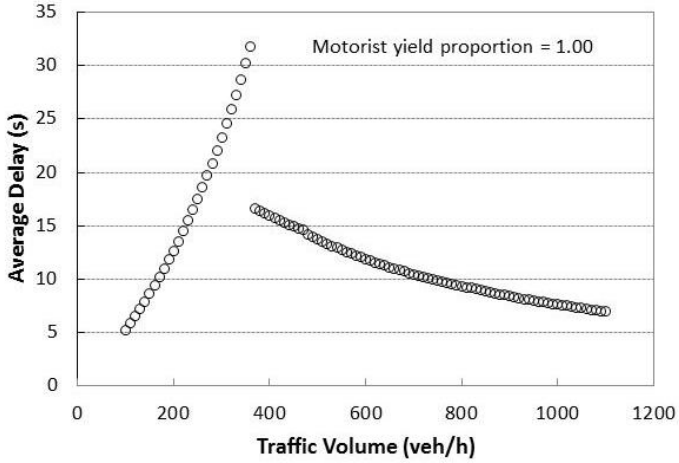
Traffic volume was varied over the range of values indicated in the list above. Pedestrian delay was computed for each volume level. The results are shown in Figure D1. Three figures are shown; each figure shows the relationship between traffic volume and pedestrian delay for a given pedestrian yield rate. Figure D1a corresponds to a motorist yield proportion of 1.0 (i.e., 100% of drivers yield to pedestrians). Figure D1b corresponds to a yield proportion of 0.5 and Figure D1c corresponds to a proportion of 0.0 (i.e., no yielding).

An examination of Figure D1a revealed two issues with the methodology. One issue is the discontinuity in the trend line at a traffic volume of about 370 veh/h. At this volume, the average number of crossing events before an adequate headway (n, as computed with Equation D11 changes from 1 to 2. All volumes less than 370 veh/h coincide with a value of n equal to 1. The trend lines predict 30 s delay for a volume of 360 veh/h and 17 s for a volume of 370 veh/h. This significant decrease in delay is unlikely to occur in reality.

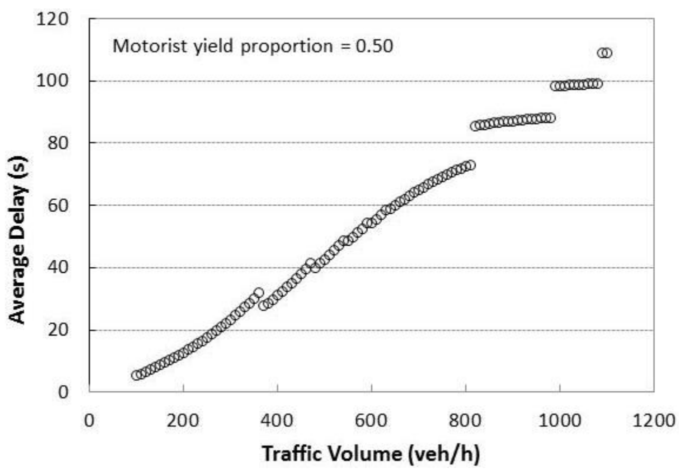
A second issue is the magnitude of delay being predicted in Figure D1a at any volume level. It is logical that delay would be very small (smaller than shown in the figure) for a scenario where all drivers are expected to yield whenever a pedestrian is waiting to cross.

An examination of Figure D1b indicates the same discontinuity at a volume of 370 veh/h. Additional (but smaller) discontinuities occur at 480, 550, 600, 640, 670, and 700 veh/h. These volume levels correspond to conditions where the value of n increases one integer value.

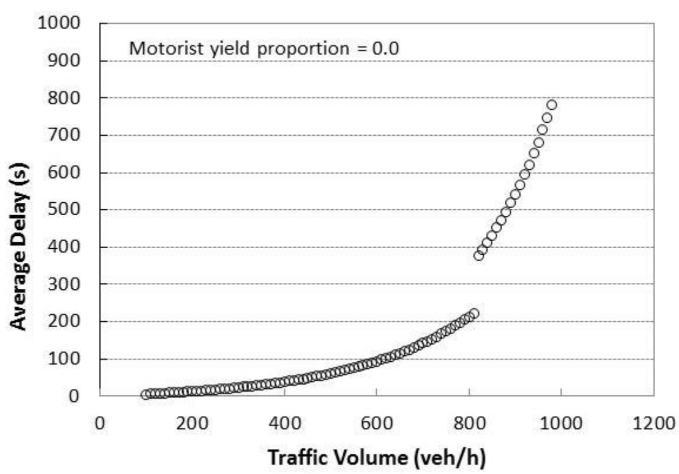
An examination of Figure D1b and Figure D1c indicates additional discontinuities at volume levels of 820, 990, and 1090 veh/h. Unlike the discontinuities discussed in the previous paragraphs, these discontinuities are associated with a significant *increase* in delay. These discontinuities coincide with a change in the spatial distribution of pedestrians (N_p, as computed with Equation D3). For example, the discontinuity at a volume level of 820 veh/h results when N_p changes from 1 to 2. All volumes less than 820 veh/h coincide with a value of N_p equal to 1. The value of N_p increases with an increase in volume.



a. Proportion motorists yielding equal to 1.0.



b. Proportion motorists yielding equal to 0.5.



c. Proportion motorists yielding equal to 0.0.

Figure D1. Influence of vehicular traffic volume on pedestrian delay—existing methodology.

Motorist Yield Rates

This section presents the literature review findings on the effectiveness of pedestrian crossing treatments at uncontrolled crossings. Treatment effectiveness was measured in terms of motorist compliance with legal requirements when approaching a crossing location with one or more pedestrians present (i.e., yielding or stopping as required by the law). Table D1 summarizes the motorist yield rates reported in the literature.

The results in Table D1 are grouped by pedestrian crossing treatment. Each row of the table corresponds to the findings for a study of one treatment in one location. The average motorist yield rate for the locations studied is shown as a percentage in column 5 of the table. A range of motorist yield rates is shown in braces when the study included two or more locations and the observed rates were reported for each location.

For some studies, the researchers reported results for staged and for unstaged crossings. Staged crossings represent crossings where the researchers solicited a volunteer to cross the street for the express purpose of observing motorist yielding behavior. Unstaged crossings represent crossings where a pedestrian from the general population crossed the street without any interaction with, or encouragement from, the researchers. In general, all motorist yield rates in column 5 of the table represent unstaged crossing behaviors unless they are explicitly identified as staged crossing rates.

Staged crossings were used for two reasons. First, they were used to control the variability in pedestrian behavior among regions of the country. The researchers rationalized that pedestrians in one region may be more or less assertive than in the other regions. Second, they ensured that the research team had sufficient sample size at study sites with moderate to low pedestrian traffic volumes (Fitzpatrick et al. 2014).

The following list describes the key findings from a review of the rates shown in Table D1.

The motorist compliance rates for staged pedestrians and unstaged pedestrians were similar in value for most crossing treatments. Only one crossing treatment, *overhead flashing beacon with passive activation*, is associated with a difference of 10 percent or more between the rates for staged and unstaged pedestrians.

Rectangular rapid flashing beacon (RRFB), half signal, and pedestrian hybrid beacon (HAWK) treatments consistently perform well. In fact, the compliance rates for the half signal and HAWK are often above 90 percent. This high level of effectiveness likely stems from the fact that these treatments send a clear message to motorists that they should stop (i.e. with a red signal 'stop') for pedestrians.

Pedestrian crossing flags and overhead or in-street crossing signs were relatively effective in increasing motorist yielding. Their use was associated with approximately 70 and 60 percent compliance, respectively.

Table D1. Summary of motorist yield rates for alternative pedestrian crossing treatments.

Treatment	Study Location	Pedestrian Sample Size	Intersection Sample Size	Motorist Yield Rate (%) {reported range}	Reference
a. Overhead or in-street crosswalk sign	Tucson, AZ	440	3	51.7	Huang et al. (2000)
	Redmond, CA	not available	3	87 {82-91} – Staged; 90 {84-97} – Unstaged	Fitzpatrick et al. (2006)
b. Median refuge island	Portland, OR	not available	3	34 {7-75} – Staged; 29 {7-54} – Unstaged	Fitzpatrick et al. (2006)
	Santa Monica, CA	not available	2		
	College Station, TX	not available	1		
	Berkeley, CA	202	5	{65-92}	Yang et al. (2015)
c. High-visibility signs and markings	Tucson, AZ	not available	2	17 {10-24} – Staged; 20 {4-35} – Unstaged	Fitzpatrick et al. (2006)
	Austin, TX	not available	1		
d. Continental markings [1]	Berkeley, CA	43	1	79	Yang et al. (2015)
e. Rectangular rapid flashing beacon (RRFB)	Billings, MT	157	1	45.2	Al-Kaisy et al. (2018)
	Bozeman, MT	84	1	84.5	Al-Kaisy et al. (2018)
	Bend Parkway, OR	211	3	79.9	Ross et al. (2011)
	Miami, FL	not available	2	{55.2-60.1}	Fitzpatrick et al. (2014)
	Bend, OR	not available	2	83	Fitzpatrick et al. (2014)
	Florida	not available	17	84 {78-95}	Fitzpatrick et al. (2014)
	Illinois	not available	2	65 {62-68}	Fitzpatrick et al. (2014)
	Washington, D.C.	not available	1	80	Fitzpatrick et al. (2014)
f. Pedestal mounted flashing beacon	not available	not available	not available	57 – Unstaged	Nemeth et al. (2014)
g. Overhead flashing beacon with push-button activation	not available	not available	10	52 {13-91}	Turner et al. (2006)
	Towson, MD	not available	1	49 {38-62} – Unstaged	Fitzpatrick et al. (2006)
	Salt Lake City, UT	not available	3	47 {29-73} – Staged; 49 {38-62} – Unstaged	Fitzpatrick et al. (2006)
h. Overhead flashing beacon with passive activation	Los Angeles, CA	not available	25	74 {72-76}	Fitzpatrick et al. (2006)
	Los Angeles, CA	not available	4	31 {25-43} – Staged; 67 {61-73} – Unstaged	Fitzpatrick et al. (2006)

Treatment	Study Location	Pedestrian Sample Size	Intersection Sample Size	Motorist Yield Rate (%) {reported range}	Reference
i. In-road warning lights	Six California cities	not available	6	53 day; 65 night	Fitzpatrick et al. (2006)
	Orlando, FL	not available	1	11	Fitzpatrick et al. (2006)
	Lakeland, FL	not available	1	30	Fitzpatrick et al. (2006)
	Kirkland, WA	not available	2	91 day; 97 night	Fitzpatrick et al. (2014)
j. School crossing guards with RRFB	Garland, TX	not available	1	{78-81} – Staged; {81-98} – Unstaged	Brewer et al. (2012)
k. Pedestrian hybrid beacon (HAWK)	Austin, TX	not available	64	{83-95}	Fitzpatrick et al. (2014)
	Tucson, AZ	not available	5	97 {94-100} – Staged; 99 {98-100} – Unstaged	Fitzpatrick et al. (2006)
l. Half signal	Portland, OR	not available	3	97 {94-100} – Staged; 98 {96-100} – Unstaged	Fitzpatrick et al. (2006)
	Seattle, WA	not available	3		
m. Crosswalk markings (any type)	Gainesville, FL	110	1	70	Zheng et al. (2017)
	Washington, D.C.	99	1	42	Zheng et al. (2017)
	San Francisco, CA	not available	1	60.5	Banerjee et al. (2007)
n. Pedestrian crossing flags	Salt Lake City, UT	not available	3	65 {46-79} – Staged; 74 {72-80} – Unstaged	Fitzpatrick et al. (2006)
	Kirkland, WA	not available	3		

1 – Continental markings consist of a set of parallel white lines that delineate the crosswalk. The lines are perpendicular to the crossing direction. They are 12 to 24 inches wide and set 12 to 24 inches apart.

The measured compliance rates for many crossing treatments varied considerably among the sites. This variability is likely due to regional differences in driver behavior and to site-to-site differences in environmental factors that may influence the driver's decision to yield (e.g., traffic volume, speed limit, number of lanes, roadway width, and lane configuration).

PROPOSED REVISIONS TO METHODOLOGY

This section consists of two subsections. The first subsection describes several proposed revisions to the pedestrian delay methodology in HCM Chapter 20. These revisions address the issues identified in the previous section. The second subsection describes the findings from a sensitivity analysis based on the proposed revisions.

Revised Calculation Steps

This section describes the proposed revisions to the HCM methodology. The revisions are based on theoretic principles and adherence to logical boundary conditions. They are described in each of two subsections. The first subsection describes the group of revisions intended to address the discontinuities associated with the lower volume levels (as noted in the discussion of Figure D1a and Figure D1b). The second subsection describes the group of revisions intended to address the discontinuities associated with the higher volume levels (as noted in the discussion of Figure D1b and Figure D1c). The last subsection describes some additional factors to consider when implementing the methodology.

Revision Group 1 – Changes to Address Lower Volume Discontinuities

The revisions in this group are focused on the calculation of delay in Step 5 of the methodology. Equation D9 and Equation D10 are the subject of these revisions.

Change 1. Set the probability of yielding $P(Y_0)$ when there are no crossing events (i.e., $n = 0$) to equal to 0.0 regardless of how many lanes are crossed. This condition is clearly stated in the HCM for the three- and four-lane crossing situations. However, it is not clearly stated for the one- and two-lane crossing situations.

Change 2. In Equation D9, change the initial value of the two summations from "$i = 1$" to "$i = 0$" such that both summations are inclusive of all values of $P(Y_i)$ from $i = 0$ to n. The revised equation is reproduced as follows:

$$d_p = \sum_{i=0}^{n} h(i-0.5)P(Y_i) + \left(P_d - \sum_{i=0}^{n} P(Y_i)\right) d_{gd} \qquad \text{Equation D13}$$

Change 3. Change Equation D10 to compute the "average headway of those headways less than the group critical headway" $t_{c,G}$. As currently shown, Equation D10 is used to compute the "average headway of all headways in a given lane." However, the first term of Equation D9 quantifies the delay incurred before the first yielding driver arrives *given* that one or more pedestrians are delayed (i.e., waiting to cross all lanes). Therefore, the headways that the pedestrians are assessing during this delay period are always less than the group critical headway. The following equation should be used to compute the appropriate headway h needed by the methodology (Bonneson and McCoy 1993).

$$h = \frac{1/v - \left(t_{c,G} + 1/v\right)\exp\left[-v\, t_{c,G}\right]}{1 - \exp\left[-v\, t_{c,G}\right]} \qquad \text{Equation D14}$$

where

h	=	average headway of all headways less than the group critical gap (s);
$t_{c,G}$	=	group critical headway (s), and
v	=	conflicting vehicular flow rate (veh/s) (combined flows for one-stage crossings; separate flows for two-stage crossings).

When the average headway h is computed using Equation D14, the average number of vehicle crossing events is correctly computed using Equation D11. In fact, Equation D5 to Equation D8 can be combined with Equation D14 in Equation D11 and mathematically reduced to the following simple equation.

$$n = \text{int}\left(\frac{1}{\exp\left[-v\, t_{c,G}\right]}\right) \qquad \text{Equation D15}$$

The result inside the parentheses in Equation D15 is shown by Gerlough and Huber (1975; Equ. 8.49) to equal the "average number of vehicles between the start of gaps." Allowing for the HCM's change to the use of "headway" for what was historically called a "gap," the definition by Gerlough and Huber is the same as that in the HCM for the variable n. This result is further support for the use of Equation D14 to compute the value of h as it is used in the HCM methodology.

Change 4. The use of $M_y = 1.0$ in Equation D12 is problematic when using most calculators or spreadsheets because it requires the calculation of "0^0" which is undefined in these tools. To avoid this error, the value of M_y should be limited to 0.999 or less. This problem is limited to the calculation of $P(Y_i)$ for one-lane crossings; however, the restriction of M_y to 0.999 or less could be extended to all calculations, regardless of the number of lanes crossed, to ensure consistency of results when compared for different numbers of lanes crossed.

Revision Group 2 – Changes to Address Higher Volume Discontinuities

The revisions in this group are focused on the calculation of the spatial distribution of pedestrians N_p in Step 2 of the methodology. Equation D3 is the subject of these revisions. The use of the "integer" function in Equation D3 causes a "jump" in the volume–delay relationship when the quantity computed in the brackets of Equation D3 resolves to a new integer value.

Consider that X pedestrian crossings occur during a specified evaluation period. Each crossing has an integer number of pedestrian rows. Some crossings have a same number of waiting pedestrians so the number of rows is 1; most crossings have 2 rows; a few crossings serve a relatively high number of pedestrians in 3 rows. To determine the group critical headway, the value of N_p used in Equation E4 should equal the average number of rows observed to cross during the evaluation period (i.e., the average of X observations of row size). This average is a real number – it is not an integer.

The following equation predicts the average number of pedestrian rows as a real number, provided that it exceeds 1.0. It should be used to replace the existing Equation D3.

$$N_p = \max\left[\frac{8.0\, N_c}{W_c}, 1.0\right] \qquad \text{Equation D16}$$

where

N_p	=	spatial distribution of pedestrians (pedestrian rows),
W_c	=	crosswalk width (ft), and
8.0	=	default clear effective width used by a single pedestrian to avoid interference when passing other pedestrians (ft).

As a point of clarification, the variable N_p should have units of "pedestrian rows" or "rows" as opposed to "pedestrians" as defined in the HCM.

Additional Implementation Considerations

During the evaluation of the pedestrian delay methodology, a couple of items were noted in the methodology description that should be clarified to avoid implementation issues. This section describes these items, their potential impact on procedure applications, and the need for advisory information in the HCM to mitigate the associated implementation challenges.

One item relates to the conflicting vehicular flow rate v. When this variable is increased, delay increases. However, the logical lower limit of zero delay at zero flow rate cannot be tested because a zero flow rate value produces division-by-zero calculation errors in Equation D7 and Equation D8. To resolve this issue, the variable should have its lower limit set to some small positive value (e.g., 0.0001).

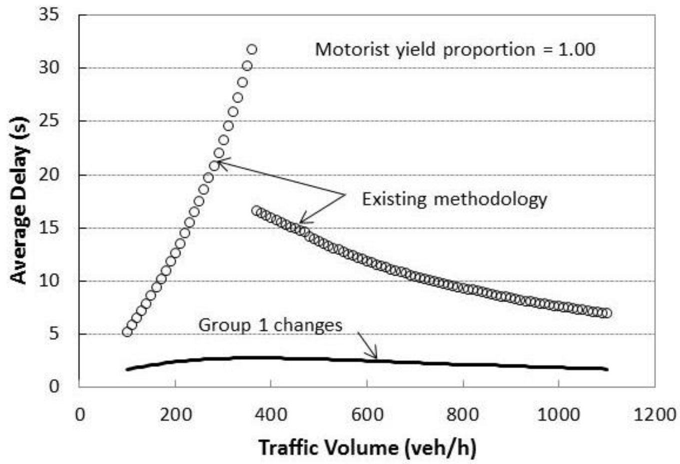
A second item relates to the potential for the variable n to have large values (e.g., $n > 100$). Examination of Equation D15 indicates that n will exceed 148 when the product $v \times t_{c,G}$ exceeds 5. The size of n has implications on the number of terms included in the two summation elements of Equation D9 (and Equation D13). This characteristic should be considered for manual applications of the procedure because it will increase the analysis time requirements for higher volume situations. It should also be considered when automating the procedure. In this regard, related programming statements should be structured to allow for several hundred values in the summation terms and to include a check to ensure that any related matrices do not exceed their range limits.

Sensitivity to Traffic Volume

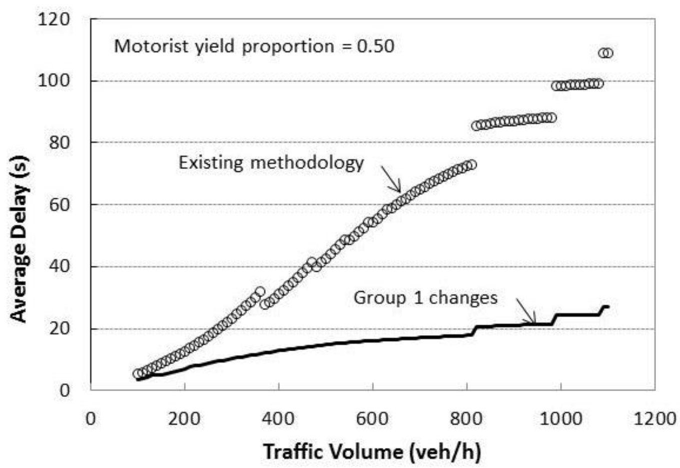
This section summarizes the findings from an evaluation of the revised pedestrian delay prediction methodology. The evaluation examines the sensitivity of the predicted delay to traffic volume. The first subsection examines the influence of the Revision Group 1 changes. The section subsection examines the influence of both Groups 1 and 2 combined. The input variable values used to develop Figure D1 were also used for this analysis to facilitate comparison between the HCM methodology and the revised methodology.

Revision Group 1 Changes

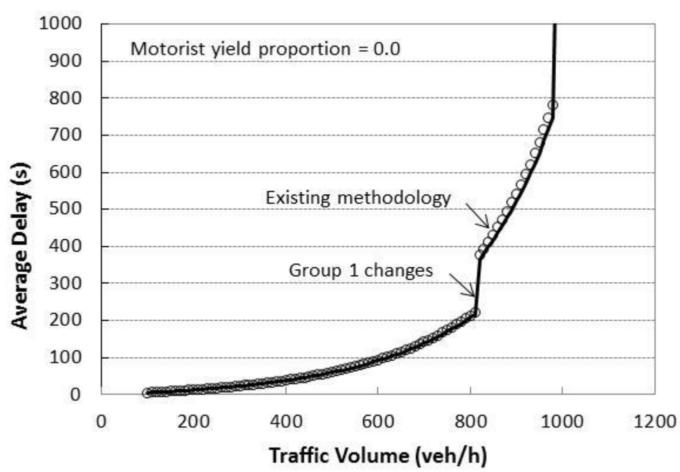
Figure D2 illustrates the relationship between pedestrian delay and traffic volume.



a. Proportion motorists yielding equal to 1.0.



b. Proportion motorists yielding equal to 0.5.



c. Proportion motorists yielding equal to 0.0.

Figure D2. Influence of vehicular traffic volume on pedestrian delay—Group 1 revisions.

The trend lines formed by circles represent the delay predicted by the existing HCM methodology. The solid trend line represents the delay predicted by the HCM methodology with the Group 1 revisions. The revised-methodology trend line indicates a smooth relationship (i.e., no discontinuity) for the range of traffic volumes considered. More importantly, the revised-methodology trend line indicates that the delay is much lower than predicted by the existing HCM methodology. Both trends are consistent with intuition. That is, there should be no discontinuity and there should be negligible delay when all motorists yield to pedestrians.

Revision Group 1 and 2 Changes

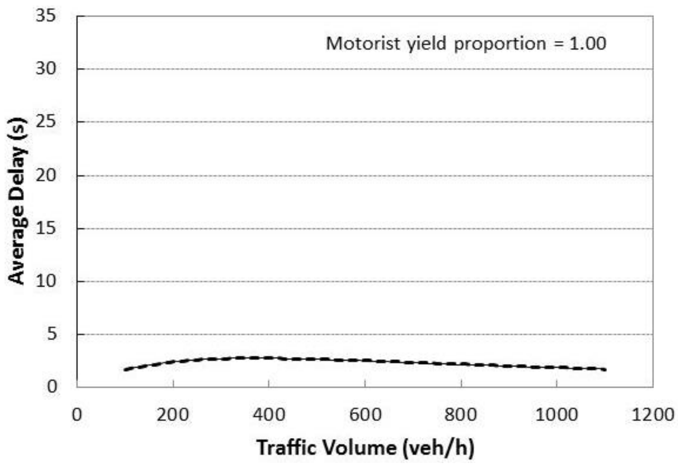
Figure D3 illustrates the relationship between pedestrian delay and traffic volume when both the Group 1 and Group 2 revisions are implemented in the methodology. As before, the solid trend line represents the delay predicted by the HCM methodology with the Group 1 revisions. The dashed trend line represents the delay predicted by HCM methodology with both the Group 1 and 2 revisions. Most notably, the dashed trend line is shown to remove the discontinuities associated with the use of Equation D9 to compute the spatial distribution of pedestrians N_p. The influence of the Group 2 revisions is shown in the figure to be more influential when the motorist yield rate M_y is less than 1.0.

PROPOSED MOTORIST YIELD RATES

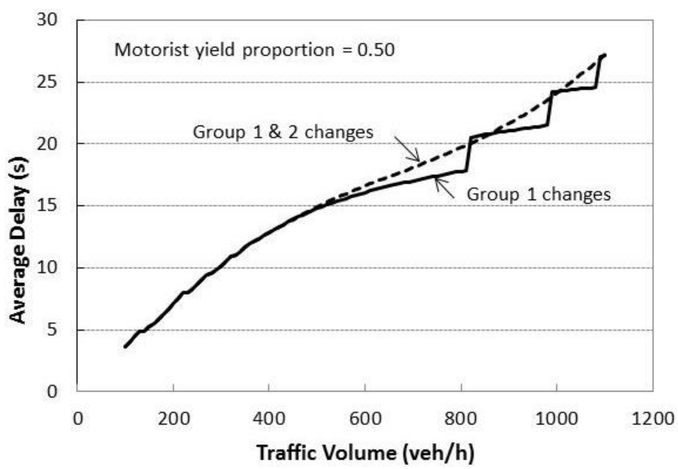
This section presents the proposed motorist yield rates for selected engineering treatments at uncontrolled pedestrian crossings. The literature review findings in Table D1 were used as the basis for determining the proposed rates.

In total, the studies summarized in Table D1 provide compliance information for 14 pedestrian crossing treatments. The studies were included in the table were selected such that some regional representation was provided for each crossing treatment. This goal could not be achieved for three treatments, i.e. *continental markings*, *overhead flashing beacon with passive activation*, and *school crossing guards with RRFB*.

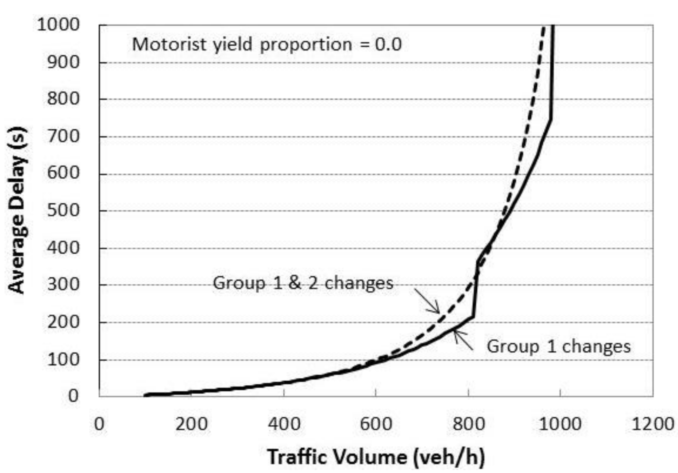
The motorist yield rates reported in Table D1 were checked to confirm that the original researchers used a common method for calculating yield rate. Specifically, these researchers calculated yield rate as the percentage of motorists that yielded or stopped when one or more pedestrians were present.



a. Proportion motorists yielding equal to 1.0.



b. Proportion motorists yielding equal to 0.5.



c. Proportion motorists yielding equal to 0.0.

Figure D3. Influence of vehicular traffic volume on pedestrian delay—Group 1 & 2 revisions.

The proposed motorist yielding rates were calculated as a weighted average of the reported motorist yield rates, where sample size was used as the weight factor. The sample size was represented either by the number of sites or the number of pedestrian crossings. The research team used one sample size unit while calculating the weighted average of motorist yield rates (in terms of number of sites or the number of pedestrian crossings). Those studies that did not provide sample size information (in terms of sites or pedestrians for the specific engineering treatment) were not used in calculating the weighted average of the motorist yield rates. The weighted average was computed using the following equation:

$$\widehat{M_y} = \frac{\sum_{i=1}^{n}(M_{y,i} \times s_i)}{\sum_{i=1}^{n} s_i} \qquad \text{Equation D17}$$

where

$\widehat{M_y}$ = average motorist yield rate (decimal);
$M_{y,i}$ = motorist yield rate for study i (decimal); and
s_i = sample size (in terms of number of sites or pedestrians) for study i.

The proposed rates were based on reported rates for unstaged crossings. They do not include the findings based on staged pedestrian crossings.

The proposed motorist yielding rates are summarized in Table D2 for each of 14 crossing treatments.

Table D2. Proposed motorist yield rates for alternative pedestrian crossing treatments.

Crossing Treatment	Sample Size		Average Yield Rate (%)	Range of Yield Rate (%)
	Sites	Pedestrians		
a. Overhead or in-street crosswalk sign	N/A	293	71	51 - 97
b. Median refuge island	N/A	202	80	65 - 92
c. High-visibility signs and markings	3	N/A	20	4 - 35
d. Continental markings	N/A	43	79	N/A
e. Rectangular rapid flashing beacon	27	N/A	79	45 - 95
f. Pedestal mounted flashing beacon	N/A	N/A	57	N/A
g. Overhead flashing beacon with push-button activation	14	N/A	51	13 - 91
h. Overhead flashing beacon with passive activation	29	N/A	73	61 - 76
i. In-road warning lights	11	N/A	58	53 - 65
j. School crossing guards with RRFB	1	N/A	N/A	81 - 98
k. Pedestrian hybrid beacon (HAWK)	69	N/A	88	83 - 100
l. Half signal	6	N/A	98	96 - 100
m. Crosswalk markings (any type)	N/A	209	56	42 - 70
n. Pedestrian crossing flags	6	N/A	74	72 - 80

Note: N/A = not available.

NEXT STEPS

This section describes a plan for calibrating and validating the revised methodology. These activities will be based on pedestrian delay data collected at uncontrolled crossings during Task 6D. The data collected will include pedestrian volume, motor vehicle volume, motor vehicle speed, pedestrian behavior, motorist compliance, and pedestrian delay.

After the data are reduced, a large portion of the data will be used for initial calibration of the methodology. A small portion will be held out for a subsequent validation activity. In each case, the researchers will compare the measured delay to the delay predicted by the revised methodology. During calibration, the researchers will revise the methodology to minimize any systematic error found in the predicted delay values. The findings from these activities will be documented in a working paper.

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Appendix E: Revised Model for Predicting the Influence of Midsegment Crossing Difficulty on Pedestrian LOS

INTRODUCTION

This working paper describes proposed revisions to the pedestrian level of service (LOS) prediction methodology in Chapter 18 of the 6th edition *Highway Capacity Manual* (HCM). This methodology is used to predict pedestrian LOS for travel along and across an urban street segment. The proposed revisions are intended to address some issues with the methodology that are related to the service provided to pedestrians crossing the street segment. These issues include (1) pedestrian segment LOS is relatively insensitive to the ease (or difficulty) that a pedestrian has when crossing the segment and (2) segment length tends to have negligible effect on the ease (or difficulty) that a pedestrian has when crossing the segment. Both issues are described in more detail in this paper.

This paper consists of two sections. The first section provides a review of several pedestrian LOS prediction methodologies. The second section describes the development of the proposed revisions to the HCM Chapter 18 methodology that are intended to address the aforementioned issues.

BACKGROUND

This section provides the findings from a review of several pedestrian LOS prediction methodologies. The findings are categorized in three subsections. The first subsection provides an overview of two methodologies for evaluating midsegment crossing LOS. The second subsection provides an overview of two methodologies for evaluating pedestrian segment LOS. The third subsection describes the findings from a sensitivity analysis of the segment LOS methodologies.

Midsegment Crossing LOS

This section provides an overview of two methodologies that can be used to evaluate the pedestrian's level of difficulty when crossing a street segment. Each methodology is described in a separate subsection.

National Center for Transit Research (NCTR) Report

Methodology. Chu and Baltes (2001) developed a methodology for predicting the LOS provided to pedestrians crossing an urban street at a midsegment location. They recorded traveler assessments of crossing quality at 33 midsegment study sites in Florida. At each site, travelers were asked to observe traffic and road conditions near a designated midsegment crossing location and to then rate their perceived crossing difficulty on a six-point scale that ranged from A (no difficulty) to F (extreme difficulty). In this assessment, the travelers were asked to consider the risk of being hit by a vehicle, the amount of time to wait for a suitable gap in traffic, presence of a median or other refuge, parked cars, speed, and any other factors that might affect crossing difficulty.

Results of the study showed that crossing difficulty tended to increase with an increase in any of the following: width of painted median, segment length, and vehicle speed. The presence of a pedestrian signal or a marked crosswalk at the crossing location reduced the crossing difficulty. The regression model that they recommended for computing the predicted crossing LOS is shown using the following equation.

$$\begin{aligned} I_{p,mx} = -2.4778 &+ 0.4937\, P_{>65} + 0.0758\, (V_{total}/1000) + 0.0016\, V_{turn} \\ &+ 0.0107\, S_r + 0.0195\, W_x - 0.0661\, W_{m,r} + 0.0712\, W_{m,p} \\ &- 0.2762\, I_{xing} - 0.4930\, I_{p,sig} + 0.0284\, C + 0.0007\, L \end{aligned} \qquad \text{Equation E1}$$

where

$I_{p,mx}$	=	pedestrian LOS score for midsegment crossing (A = 1, B = 2, ..., F = 6),
$P_{>65}$	=	proportion of pedestrians 65 years or more in age,
V_{total}	=	motorized vehicle volume on segment near midsegment crossing (two-way total) (veh/h);
V_{turn}	=	motorized vehicle turn volume near midsegment crossing (two-way total) (veh/h);
S_r	=	midsegment running speed (mi/h);
W_x	=	crossing width (i.e., exclude median width; total for both travel directions) (ft);
$W_{m,r}$	=	width of restricted median (= 0 if restricted median not present) (ft);
$W_{m,p}$	=	width of painted median (= 0 if painted median not present) (ft);
I_{xing}	=	indicator variable for marked crosswalk presence (= 1 if crosswalk present, otherwise 0);
$I_{p,sig}$	=	indicator variable for pedestrian signal presence (= 1 if signal present, otherwise 0);
C	=	average signal cycle length (s); and
L	=	segment length (= distance between adjacent signalized intersections) (ft).

NCHRP Report 616

Methodology. Dowling et al. (2008) also developed a methodology for predicting the LOS provided to pedestrians crossing an urban street at a midsegment location. The researchers made 33 videotape recordings of pedestrian travel along 14 streets in two U.S. cities. The recordings were shown to travelers in four U.S. cities. When viewing a video recording, the travelers were asked to observe traffic and road conditions near the segment and to then rate segment LOS on a six-point scale that ranged from A (best) to F (worst).

Results of the study showed that midsegment crossing difficulty was influenced by two key factors. One factor is the delay incurred by the pedestrian waiting for an acceptable gap in which he or she could cross the street. This delay is defined as "pedestrian waiting delay (d_{pw})" in HCM Chapter 20. The procedure used by Dowling et al. (2008) to compute this delay is similar to that provided in HCM Chapter 20; however, the Dowling et al. procedure does not consider the probability that a motorist will yield to a waiting pedestrian (i.e., it predicts the delay incurred when no motorist yields).

The second factor found by Dowling et al. (2008) to influence crossing difficulty is the additional travel time required by the pedestrian if he or she chooses to divert to the nearest signalized intersection to complete the crossing maneuver. This additional travel time is considered to represent a delay to the crossing pedestrian because it represents the additional time needed to complete the crossing, relative to crossing at the desired midsegment location. The pedestrian diversion delay is computed by the following equation.

$$d_{pd} = \frac{2\,D_c}{S_p} + d_{pc} \qquad \text{Equation E2}$$

with

$$d_{pc} = \frac{\left(C - g_p\right)^2}{2\,C} \qquad \text{Equation E3}$$

where

d_{pd}	=	pedestrian diversion delay (s/p),
D_c	=	distance to nearest signal-controlled crossing (default: L/3) (ft),
S_p	=	average pedestrian walking speed (ft/s),
d_{pc}	=	pedestrian delay incurred in crossing the segment at the nearest signal-controlled crossing (s/p);
g_p	=	average pedestrian service time (s), and all other variables are as previously defined.

The variable g_p represents the time provided for pedestrians to cross the major street each signal cycle. It is an average for all cycles that occur during the evaluation period. Dowling et al. (2008) recommended that this variable's value should equal the green interval duration for the minor street through movement. In contrast, the HCM 6th Edition indicates that the variable's value should equal the Walk interval duration plus 4 seconds. If the subject phase is actuated, the HCM indicates that many agencies use a Walk duration of 7 seconds; however, some agencies use as little as 4 seconds. If the subject phase is pretimed or coordinated, the Walk duration is equal to the minor street through green interval duration less the pedestrian clearance time (= crossing distance divided by average walking speed).

Once the two delay values are computed, each delay is converted to an equivalent LOS score by using the thresholds listed in Table E1. When the computed delay is between the range limits shown, interpolation is used to estimate the corresponding LOS score.

Table E1. Pedestrian LOS and delay thresholds.

Delay Range, s	Equivalent LOS Score Range
0 and ≤10	0 and ≤1.5
>10 and ≤20	>1.5 and ≤2.5
>20 and ≤30	>2.5 and ≤3.5
>30 and ≤40	>3.5 and ≤4.5
>40 and ≤60	>4.5 and ≤5.5
>60	>5.5

Finally, the midsegment crossing LOS score is computed using the following equation.

$$I_{p,mx} = \min[I_{pw}, I_{pd}] \qquad \text{Equation E4}$$

where

$I_{p,mx}$ = pedestrian LOS score for midsegment crossing (A = 1, B = 2, ..., F = 6),
I_{pw} = LOS score for pedestrian waiting delay (based on Table E1), and
I_{pd} = LOS score for pedestrian diversion delay (based on Table E1).

Change in Delay vs. Change in LOS. The first term of Equation E2 represents the travel time from the crossing point to the nearest signalized intersection and then back to the crossing point. The HCM suggests that a reasonable estimate of the distance from the crossing point to the nearest signal is one-third of the segment length. If this estimate is used with a walking speed of 4.0 ft/s, a segment length of 330 ft has a diversion travel time of 55 s (= 2 × 330/[3 × 4]). Given that almost all U.S. streets have a segment length of 330 ft or more, it is almost a certainty that the LOS score for pedestrian diversion delay (as obtained from Table E3) will equal or exceed 4.5 for segments found in U.S. cities. For delays of more than 40 s, the delay and LOS score thresholds shown in Table E3 produce a "20 seconds per LOS level" relationship [= (60 – 40)/(5.5 – 4.5)]. This relationship is used the next subsection to investigate the effect of travel time on LOS.

Segment Length Influence on LOS. The methodology developed by Chu and Baltes (2001) and that developed by Dowling et al. (2008) both include a sensitivity to segment length. The sensitivity of each methodology to segment length can be quantified by taking the first derivative of the respective equations for $I_{p,mx}$ with respect to segment length L. For Equation E1, this derivative equals a constant value of 0.0007.

For Equation E4, this derivative equals the following equation (where $D_c = L/3$). The term in parenthesis in this equation represents the delay-to-LOS relationship derived from Table E1, as discussed in the previous paragraph.

$$\frac{dI_{p,mx}}{dL} = \left(\frac{1}{20}\right)\frac{2}{3\,S_p} \qquad \text{Equation E5}$$

For a typical segment walking speed S_p of 4 ft/s, Equation E5 computes to a constant value of 0.0083.

The two constants (i.e., 0.0007 and 0.0083) differ considerably in magnitude. Of the two values, the 0.0007 value has a strong empirical basis, so it is considered to be the more accurate representation of the degree to which pedestrians consider diversion travel time to influence their perception of service quality. Following this assumption, the first term of Equation E2 should be multiplied by the value 0.084 (= 0.0007/0.0083) to more accurately reflect the influence of segment length on LOS. The following equation represents the revised form of Equation E2. This equation provides the same influence of segment on LOS as does the methodology developed by Chu and Baltes (2001).

$$d_{pd,LOS} = 0.084\,\frac{2\,D_c}{S_p} + d_{pc} \qquad \text{Equation E6}$$

where $d_{pd,LOS}$ is the LOS-based pedestrian-perceived diversion delay (s/p) and all other variables are as previously defined.

Segment LOS

This section provides an overview of two methodologies that can be used to evaluate the pedestrian LOS for a street segment. This LOS reflects consideration of pedestrian service along the segment, at the boundary intersection, and when crossing the street at a midsegment location. Each methodology is described in a separate subsection.

NCHRP Report 616

Dowling et al. (2008) developed a methodology for computing segment LOS based on traveler perception studies in several cities throughout the U.S. The methodology computes pedestrian density and a pedestrian LOS score. Both the density and the LOS score are converted to a LOS letter grade. The LOS for the segment then is reported as the "worst" LOS letter grade of the two grades considered. The discussion in this section describes the methodologic steps for computing the LOS score.

Step 1. Determine Pedestrian Delay at Intersection

This step involves the calculation of two pedestrian delays values. One value is the pedestrian waiting delay d_{pw}. It represents the delay incurred by pedestrians waiting for a gap to cross the segment at a midsegment location. An equation is provided by Dowling et al. for calculating this delay.

The second value is the pedestrian delay incurred in crossing the segment at the nearest signal-controlled crossing d_{pc}. Equation E3 is provided for this calculation.

Step 2. Determine Pedestrian LOS Score for Intersection

The pedestrian LOS score for the boundary intersection $I_{p,int}$ is determined in this step. Dowling et al. provide an equation for computing this score when the boundary intersection is signalized. If the boundary intersection is two-way STOP-controlled (with the subject segment uncontrolled and the cross street STOP-controlled), the score is equal to 0.0.

Step 3. Determine Pedestrian LOS Score for Link

The pedestrian LOS score for walking along the street $I_{p,link}$ is determined in this step. Dowling et al. provide an equation for computing this score.

Step 4. Determine Roadway Crossing Difficulty Factor

The roadway crossing difficulty factor is used to adjust the segment LOS to reflect the ease (or difficulty) of midsegment crossings. It is computed using the following equation.

$$F_{cd} = 1.0 + \frac{I_{p,mx} - \left(0.318\, I_{p,link} + 0.220\, I_{p,int} + 1.606\right)}{7.5} \qquad \text{Equation E7}$$

where

F_{cd} = roadway crossing difficulty factor,
$I_{p,link}$ = pedestrian LOS score for link,
$I_{p,int}$ = pedestrian LOS score for intersection, and
$I_{p,mx}$ = pedestrian LOS score for midsegment crossing.

If the factor obtained from Equation E7 is less than 0.80, the factor is set equal to 0.80. If the factor is greater than 1.20, it is set equal to 1.20. The variable $I_{p,mx}$ is computed using Equation E2 to Equation E4.

Step 5. Determine Pedestrian LOS Score for Segment

The pedestrian LOS score for the segment is determined by using the following equation. The computed score reflects consideration of pedestrian service along the segment, at the boundary intersection, and when crossing the street at a midsegment location.

$$I_{p,seg} = F_{cd}\left(0.318\, I_{p,link} + 0.220\, I_{p,int} + 1.606\right) \qquad \text{Equation E8}$$

where $I_{p,seg}$ is the pedestrian LOS score for the segment and all other variables are as previously defined.

Examination of Equation E8 indicates that the roadway difficulty crossing factor is used as a multiplicative adjustment to both the link and intersection LOS scores. The report by Dowling et al. (2008) does not discuss why intersection LOS should be adjusted by the roadway crossing difficulty when computing the segment LOS score.

Highway Capacity Manual

The methodology developed by Dowling et al. (2008) was largely incorporated in the HCM, with a few modifications. The methodology computes pedestrian density and a pedestrian LOS score. Both density and the LOS score are each converted to a LOS letter grade, where the LOS for the segment is reported as the worst LOS letter grade of the two grades considered. The discussion in this section describes the methodologic steps for computing the LOS score.

The computational steps associated with the HCM methodology are provided in the following list.

- Step 1: Determine Free-Flow Walking Speed
- Step 2: Determine Average Pedestrian Space (i.e., density)
- Step 3: Determine Pedestrian Delay at Intersection
- Step 4: Determine Pedestrian Travel Speed
- Step 5: Determine Pedestrian LOS Score for Intersection
- Step 6: Determine Pedestrian LOS Score for Link
- Step 7: Determine Link LOS
- Step 8: Determine Roadway Crossing Difficulty Factor
- Step 9: Determine Pedestrian LOS Score for Segment
- Step 10: Determine Segment LOS

The HCM guidance and associated calculations are not repeated in total herein. Rather, only the guidance and equations that are the subject of this research are reproduced in this section.

Step 3. Determine Pedestrian Delay at Intersection

This step involves the calculation of three pedestrian delay values. One value is the pedestrian waiting delay d_{pw}. It represents the delay incurred by pedestrians waiting for a gap to cross the segment at a midsegment location. An equation is provided in HCM Chapter 20 for this purpose.

The second value is the pedestrian delay incurred in crossing the segment at the nearest signal-controlled crossing d_{pc}. Equation E3 is provided for this calculation.

The third value is the delay incurred by pedestrians who travel through the boundary intersection along a path that is parallel to the segment centerline d_{pp}. Equation E3 is also used for this calculation; however, the pedestrian service time value is based on the green interval duration for the *major* street through movement.

Step 5. Determine Pedestrian LOS Score for Intersection

The pedestrian LOS score for the boundary intersection $I_{p,int}$ is determined in this step. HCM Chapter 19 provides an equation for computing this score if the boundary intersection is signalized. If the boundary intersection is two-way STOP controlled (with the subject segment uncontrolled and the cross street stop-controlled), the score is equal to 0.0.

Step 6. Determine Pedestrian LOS Score for Link

The pedestrian LOS score for walking along the street $I_{p,link}$ is determined in this step. HCM Chapter 18 provides an equation for computing this score.

Step 8. Determine Roadway Crossing Difficulty Factor

The roadway crossing difficulty factor is used to adjust the segment LOS to reflect the ease (or difficulty) of midsegment crossings. It is a function of crossing delay d_{px} which is based on pedestrian diversion delay d_{pd} and pedestrian waiting delay d_{pw}. Equation E2 is used to compute pedestrian diversion delay. It is used with the following equation to compute the roadway crossing difficulty factor value.

$$F_{cd} = 1.0 + \frac{0.10\, d_{px} - \left(0.318\, I_{p,link} + 0.220\, I_{p,int} + 1.606\right)}{7.5} \qquad \text{Equation E9}$$

where

F_{cd} = roadway crossing difficulty factor,
d_{px} = crossing delay = min(d_{pd}, d_{pw}, 60) (s/p),
d_{pd} = pedestrian diversion delay (s/p),
d_{pw} = pedestrian waiting delay (s/p),
$I_{p,link}$ = pedestrian LOS score for link,
$I_{p,int}$ = pedestrian LOS score for intersection, and
$I_{p,mx}$ = pedestrian LOS score for midsegment crossing.

If the factor obtained from Equation E9 is less than 0.80, the factor is set equal to 0.80. If the factor is greater than 1.20, it is set equal to 1.20. The factor value increases as the midsegment LOS score increases (i.e., as the crossing becomes more difficult).

Step 9. Determine Pedestrian LOS Score for Segment

The pedestrian LOS score for the segment is determined by using the following equation. The computed score reflects consideration of pedestrian service along the segment, at the boundary intersection, and when crossing the street at a midsegment location.

$$I_{p,seg} = 0.75 \left[\frac{\left(F_{cd}\, I_{p,link} + 1\right)^3 L/S_p + \left(I_{p,int} + 1\right)^3 d_{pp}}{L/S_p + d_{pp}} \right]^{1/3} + 0.125 \qquad \text{Equation E10}$$

where $I_{p,seg}$ is the pedestrian LOS score for the segment and all other variables are as previously defined.

The form of Equation E10 is based on research conducted by Petritsch and Scorsone (2014). In practical applications of the NCHRP Project 616 methodology, they found that Equation E8 understated the impact of a poor link LOS on segment LOS. They argued that the link and intersection LOS scores should be computed as a weighted average of their respective "exposure times." For links, the exposure time was computed as the link travel time and for intersections, the exposure time was computed as the delay incurred by pedestrians who travel through the boundary intersection along a path that is parallel to the segment centerline d_{pp}. With this type of weighted-average-approach, Petritsch and Scorsone rationalized that the computed segment LOS would be more representative of link LOS and more likely to yield a segment LOS score that properly reflected the impact of a poor link LOS.

Both of the LOS scores used in Equation E10 are increased by the value of 1.0 (and cubed) before the weighted average is computed. The multiplier 0.75 in this equation is believed to offset some of the "increase by 1.0" but not all. Petritsch and Scorsone (2014) do not discuss why the "increase by 1.0" is needed in the equation.

Petritsch and Scorsone (2014) also rationalized that the roadway crossing difficulty factor F_{cd} should be applied only to the link LOS score. In Equation E8, this factor is used to adjust both the link and intersection LOS scores. When developing Equation E10, Petritsch and Scorsone used the factor to adjust only the link score.

Sensitivity Analysis

This section summarizes the findings from an evaluation of the pedestrian segment LOS prediction methodology in NCHRP Report 616 and in Chapter 18 of the HCM 6th edition. The evaluation examines the sensitivity of the predicted segment LOS score to changes in link LOS score, roadway crossing difficulty, and segment length.

Sensitivity to Link and Intersection LOS Scores

The motivation for this evaluation was the findings reported in the previous section. Notably, it was found that the change to Equation E10 (from Equation E8) was needed to improve the sensitivity of segment LOS score to link LOS score, especially for links with a poor LOS score. This analysis investigates the degree to which this improvement was achieved.

The sensitivity analysis findings described in this section are based on the evaluation of pedestrian segment LOS score for a street segment. The following list identifies the input variables and values:

- Pedestrian LOS score for intersection, $I_{p,int}$: 1, 2, 3, 4, 5, 6
- Pedestrian LOS score for link, $I_{p,link}$: equal to $I_{p,int}$
- Walking speed, S_p: 4 ft/s

- Segment length, L: 330 ft
- Pedestrian delay incurred in walking parallel to the segment, d_{pp}: equal to 0.1 × L/S_p
- Roadway difficulty crossing factor, F_{cd}: 1.0

The intersection LOS score (which equals the link score) was varied over the range of 1 to 6. Equation E8 and Equation E10 were used to compute the segment LOS score. The results are shown in Figure E1. The solid trend line shows the predicted segment LOS score using Equation E8. The dashed line shows the predicted segment LOS score using Equation E10. The slope of the dashed line is shown to be steeper than that of the solid line indicating that Equation E10 provides greater sensitivity to the intersection and link LOS scores, as intended by Petritsch and Scorsone (2014).

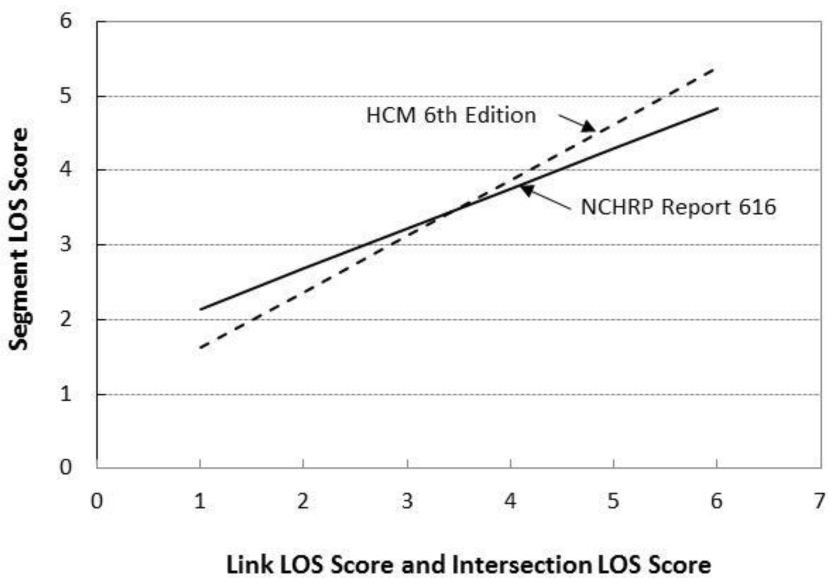

Figure E1. Influence of intersection and link LOS score on segment LOS – existing methodology.

For the conditions stated in the bullet list above (i.e., the link LOS score equals the intersection LOS score), the expectation should be that the predicted segment LOS score would equal that of the intersection and link. For example, if the intersection LOS score is 1.0, the link LOS score is 1, and the roadway crossing difficulty factor is 1.0, the expectation is that the segment LOS score should also equal 1.0. It is difficult to imagine a situation where any value other than 1.0 could be rationalized for the stated conditions. However, as shown in Figure E1, neither equation predicts a segment LOS value of 1.0.

Similarly, when the intersection LOS score is 6.0, the link LOS score is 6, and the roadway crossing difficulty factor is 1.0, the expectation is that the segment LOS score should also equal 6.0. However, as shown in Figure E1, neither equation predicts a segment LOS value of 6.0.

Specific values of walking speed, segment length, and pedestrian delay are cited in the bullet list at the start of this section. These variables are used only in Equation E10 (i.e., HCM 6th Edition). However, the trends in Figure E1 for the HCM equation are insensitive to the values selected for these variables because the link and intersection LOS scores are the same.

Sensitivity to Roadway Crossing Difficulty

The motivation for this evaluation was the findings reported in the previous section regarding the application of the roadway crossing difficulty factor. Notably, it was found that this factor was applied to only the link LOS score in Equation E10. In contrast, the factor was applied to both the link LOS score and the intersection LOS score in Equation E8.

The sensitivity analysis findings described in this section are based on the evaluation of pedestrian segment LOS score for a street segment. The following list identifies the input variables and values:

- Pedestrian LOS score for intersection, $I_{p,int}$: 1, 2, 3, 4, 5, 6
- Pedestrian LOS score for link, $I_{p,link}$: equal to $I_{p,int}$
- Walking speed, S_p: 4 ft/s
- Segment length, L: 330 ft
- Pedestrian delay incurred in walking parallel to the segment, d_{pp}: equal to 0.1 × L/S_p
- Roadway difficulty crossing factor, F_{cd}: 0.8, 1.2

The intersection LOS score (which equaled the link score) was varied over the range of 1 to 6. The roadway crossing difficulty factor was assigned values of 0.8 and 1.2. Equation E8 and Equation E10 were used to compute the segment LOS score. The results are shown in Figure E2. The solid trend line shows the predicted segment LOS score using Equation E8. The dashed line shows the predicted segment LOS score using Equation E10. One pair of trend lines correspond to a roadway crossing difficulty factor of 0.8 and one pair correspond to a factor of 1.2.

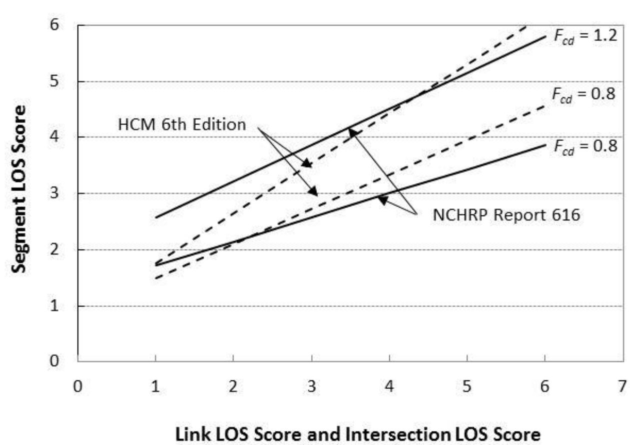

Figure E2. Influence of roadway crossing difficulty on segment LOS – existing methodology.

The two solid trend lines in Figure E2 indicate that the segment LOS score ranges from 1.7 to 2.6 (a difference of 0.9) when the link and intersection LOS scores are 1.0. When the link and intersection scores are 6.0, this range increases to 1.9. In contrast, the two dashed trend lines have a range of 0.3 and 1.6 for link/intersection LOS scores of 1.0 and 6.0, respectively.

The aforementioned ranges describe the maximum possible effect of roadway crossing difficulty on segment LOS. The ranges associated with the original research by Dowling et al. (2008) (i.e., NCHRP Report 616) suggest that crossing difficulty can have a relatively large effect on segment LOS. However, the rationally based changes by Petritsch and Scorsone (2014) have indirectly reduced the range and associated impact potential of crossing difficulty on segment LOS.

Sensitivity to Segment Length

This section summarizes the findings from an evaluation of segment LOS score as influenced by segment length. Segment length is a variable in Equation E10 so it has a direct influence on the segment LOS score for the HCM methodology. Segment length is also used in Equation E2 to compute the pedestrian diversion delay. This delay is then used in the NCHRP Report 616 methodology and the HCM methodology to compute the roadway crossing difficulty factor. This factor is then used in Equation E8 and Equation E10 to compute the segment LOS score for each of the two methodologies.

The sensitivity analysis findings described in this section are based on the evaluation of pedestrian segment LOS score for a street segment. The following list identifies the input variables and values:

- Pedestrian LOS score for intersection, $I_{p,int}$: 3
- Pedestrian LOS score for link, $I_{p,link}$: 3
- Pedestrian waiting delay, d_{pw}: 50 s/p
- Walking speed, S_p: 4 ft/s
- Segment length, L: 330, 660, 990, 1320 ft
- Pedestrian delay incurred in walking parallel to the segment, d_{pp}: 6 s/p
- Pedestrian delay incurred in crossing the segment at the nearest signal, d_{pc}: 23 s/p

Using Equation E2, the variables in the preceding list result in pedestrian diversion delays d_{pd} of 78, 133, 188, and 243 s/p for segment lengths of 330, 660, 990, and 1320 ft; respectively. These delays exceed the pedestrian waiting delay of 50 s/p so pedestrians are assumed to prefer to cross the street without diverting. As a result, diversion delay (and segment length) does not influence the computed roadway crossing difficulty factor value. This finding is contrary to that of Chu and Baltes (2001) who found that crossing difficulty is influenced by segment length.

The segment length was varied over the range of values shown in the previous list. The two aforementioned methodologies were used to compute the segment LOS score. The results are shown in Figure E3. The solid trend line shows the predicted segment LOS score using the NCHRP Report 616 methodology. The dashed line shows the predicted segment LOS score using the HCM methodology.

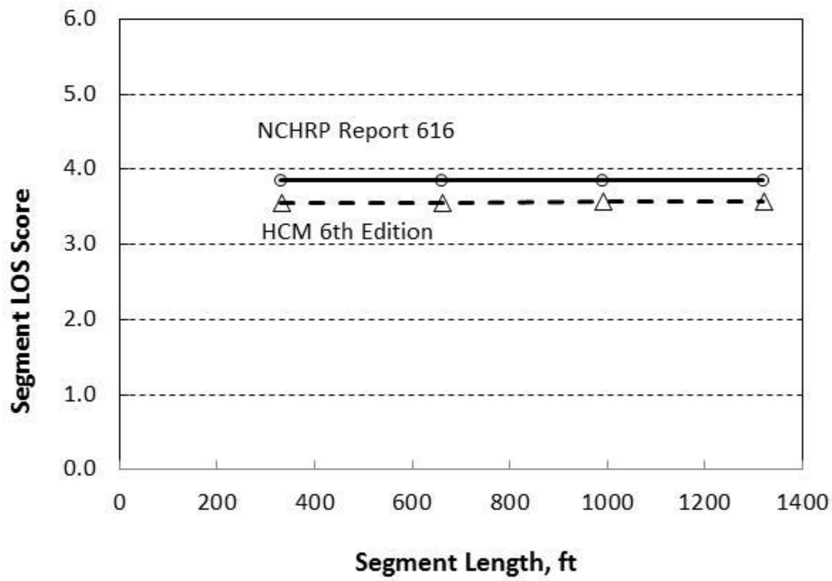

Figure E3. Influence of segment length on segment LOS – existing methodology.

The trend lines in Figure E3 indicate that segment length has negligible influence on the segment LOS score. This finding holds for link LOS scores in the range of 1 to 6 and for intersection LOS scores in the range of 1 to 6. It also holds for any value of pedestrian waiting delay.

PROPOSED REVISIONS TO HCM METHODOLOGY

This section consists of two subsections. The first subsection describes several proposed revisions to the pedestrian LOS methodology in HCM Chapter 18. These revisions address the issues identified in the previous section. The second subsection describes the findings from a sensitivity analysis based on the proposed revisions.

Revised Calculation Steps

This section describes the proposed revisions to the HCM methodology. The revisions are based on empirical evidence and adherence to logical boundary conditions. The focus of the revisions is the 10-step HCM methodology described in a previous section titled, *Highway Capacity Manual*. The following discussion is presented using the 10-step sequence; however, only those steps that have a recommended change are presented. Those steps that are not presented in the following discussion are unchanged.

Step 8. Determine Pedestrian LOS Score for Midsegment Crossing

This step replaces existing Step 8 - Determine Roadway Crossing Difficulty Factor. This step is used to compute the LOS score for the midsegment crossing. The pedestrian-perceived delay incurred due to diversion is calculated using the following equation.

$$d_{pd,LOS} = 0.084\,\frac{2\,D_c}{S_p} + d_{pc} \qquad \text{Equation E11}$$

where

$d_{pd,LOS}$	=	LOS-based pedestrian-perceived diversion delay (s/p),
D_c	=	distance to nearest signal-controlled crossing (default: L/3) (ft),
S_p	=	average pedestrian walking speed (ft/s), and
d_{pc}	=	pedestrian delay incurred in crossing the segment at the nearest signal-controlled crossing (s/p).

The LOS-based pedestrian-perceived diversion delay and the pedestrian waiting delay are each converted to an equivalent LOS score by using the thresholds listed in Table E1. Specifically, $d_{pd,LOS}$ is used with Table E1 to determine the LOS score for diversion delay I_{pd}. Similarly, d_{pw} is used with Table E1 to determine the LOS score for waiting delay I_{pw}. When either delay value is between the range limits shown in the table, interpolation is used to estimate the corresponding LOS score.

Finally, the midsegment crossing LOS score is computed using the following equation.

$$I_{p,mx} = \min\left[I_{pw}, I_{pd}\right] \qquad \text{Equation E12}$$

where

$I_{p,mx}$	=	pedestrian LOS score for midsegment crossing (A = 1, B = 2, ..., F = 6),
I_{pw}	=	LOS score for pedestrian waiting delay (based on Table E1), and
I_{pd}	=	LOS score for pedestrian diversion delay (based on Table E1).

Step 9. Determine Pedestrian LOS Score for Segment

The pedestrian LOS score for the segment is determined by using the following equation. The computed score reflects consideration of pedestrian service along the segment, at the boundary intersection, and when crossing the street at a midsegment.

$$I_{p,seg} = \left[\frac{\left(I_{p,link}\,[1 - p_{mx}] + I_{p,mx}\,p_{mx}\right)^3 L/S_p + \left(I_{p,int}\right)^3 d_{pp}}{L/S_p + d_{pp}}\right]^{1/3} \qquad \text{Equation E13}$$

where $I_{p,seg}$ is the pedestrian LOS score for the segment, p_{mx} is the proportion of pedestrian demand that desires to cross at a midsegment location (default: 0.35), and all other variables are as previously defined.

The segment LOS score is a weighted average of three separate LOS scores. As a result, it is likely to be less sensitive to a change in any one of the three separate LOS scores. In other words, the segment LOS score can mask important factors that are influencing link, intersection, or midsegment crossing LOS in isolation. For this reason, the HCM recommends that the analyst separately consider the link and intersection LOS scores individually to ensure that all factors influencing system performance are fully considered. This recommendation should be extended to the analyst's consideration of the midsegment crossing LOS score.

Sensitivity Analysis

This section summarizes the findings from an evaluation of the revised pedestrian segment LOS prediction methodology. The evaluation examines the sensitivity of the predicted segment LOS score to changes in link LOS score, roadway crossing difficulty, and segment length. The input variable values used to develop Figure E1 to Figure E3 were also used for this analysis to facilitate comparison between the HCM methodology and the revised methodology.

Sensitivity to Link and Intersection LOS Scores

Figure E4 illustrates the relationship between the link/intersection LOS score and segment LOS score. The solid trend line and the dashed trend line were previously shown in Figure E1. The "dot-dash" trend line reflects the predicted segment LOS using the proposed Equation E13. For this analysis, the midsegment LOS score was also assumed to equal the link and intersection LOS scores. Unlike the other two trend lines, the dot-dash trend line has the desirable characteristic of predicting a segment LOS score that equals the link/intersection LOS scores when the link and intersection scores are equal.

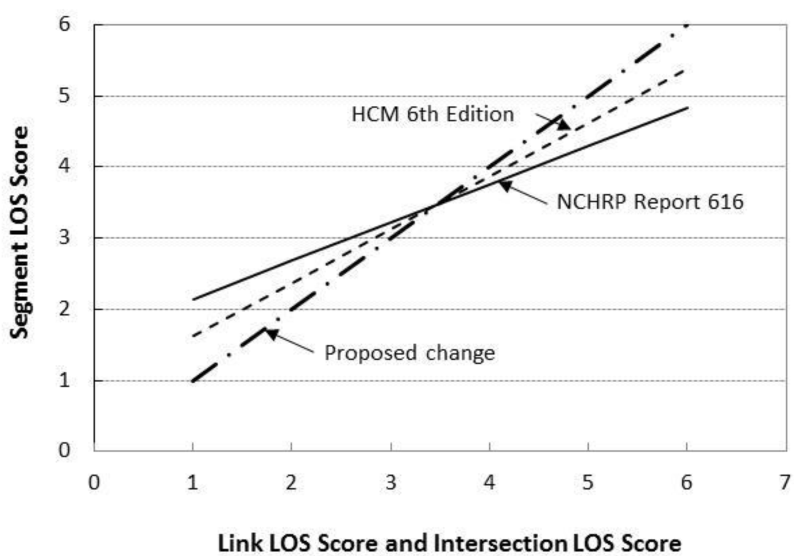

Figure E4. Influence of intersection and link LOS score on segment LOS – proposed changes.

Sensitivity to Roadway Crossing Difficulty

Figure E5 illustrates the relationship between the link/intersection LOS score and segment LOS score for various levels of roadway crossing difficulty. The solid trend line and the dashed trend line were previously shown in Figure E2. The two "dot-dash" trend lines reflect the predicted segment LOS using the proposed Equation E13. One trend line corresponds to a midsegment LOS score $I_{p,mx}$ of 1.0. The other trend line corresponds to a midsegment LOS score of 6.0. For this analysis, the proportion of pedestrian demand that desires to cross at a midsegment location p_{mx} was set to 0.35.

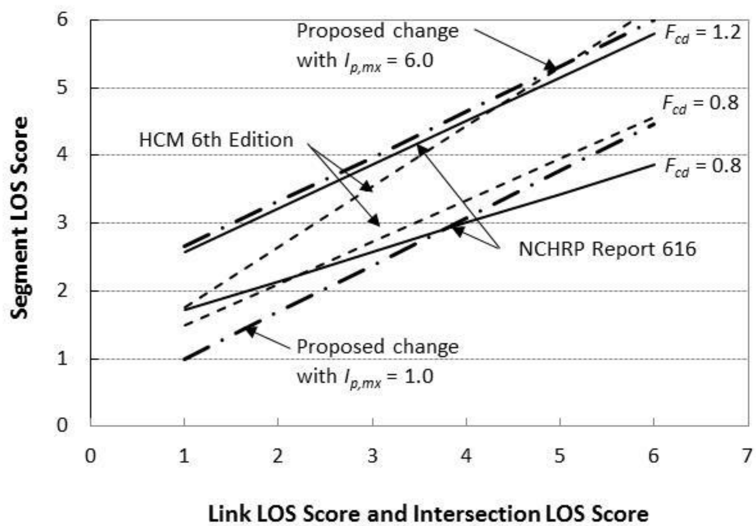

Figure E5. Influence of roadway crossing difficulty on segment LOS – proposed changes.

The two dot-dash trend lines in Figure E5 (corresponding to the proposed changes) indicate that the segment LOS score ranges from 1 to 2.7 (a difference of 1.7) when the link and intersection LOS scores are 1.0. When the link and intersection scores are 6.0, this range is 1.5. The dot-dash trend line for the midsegment LOS score of 6.0 is almost identical to that for NCHRP Report 616 when the crossing difficulty factor is 1.2.

The proposed change provides a wider range of segment LOS scores than the HCM methodology for link/intersection LOS scores smaller than about 5.0. The additional range width at link/intersection LOS scores less than 5.0 are created by the dot-dash trend line associated with a midsegment LOS score of 1.0. As discussed in the previous section, this trend line passes through the point where the link/intersection LOS score, the midsegment LOS score, and the segment LOS score all equal 1.0, which is a logical boundary condition.

Sensitivity to Segment Length

Figure E6 illustrates the relationship between the segment LOS score and segment length for various levels of link/intersection LOS score. The solid trend line and the dashed trend lines in Figure E6b were previously shown in Figure E3. The "dot-dash" trend line reflects the predicted segment LOS using the proposed changes to the HCM methodology. For the given input variable values (i.e., the variables identified in the discussion of Figure E3), the midsegment LOS score ranges from 3.2 to 4.6. The lower and upper limits of this range correspond to segment lengths of 330 and 1320 feet, respectively.

The trend lines in Figure E6 for the HCM and for the NCHRP Report 616 methodologies are horizontal which indicates that their predicted segment LOS score is not sensitive to segment length. In contrast, the dot-dash trend line representing the proposed changes does indicate a logical increase in the segment LOS score with increasing segment length.

In general, the proposed changes provide a predicted segment LOS score that is between (or near) that predicted by the HCM and NCHRP Report 616 methodologies. In Figure E6b, the proposed changes yield a predicted segment LOS of 3.1 for the 330-ft segment length. Even though this value is outside the range shown for the HCM and NCHRP Report 616 methodologies, the value of 3.1 is logical given that the link and intersection LOS scores are 3.0 and the midsegment LOS score is 3.2.

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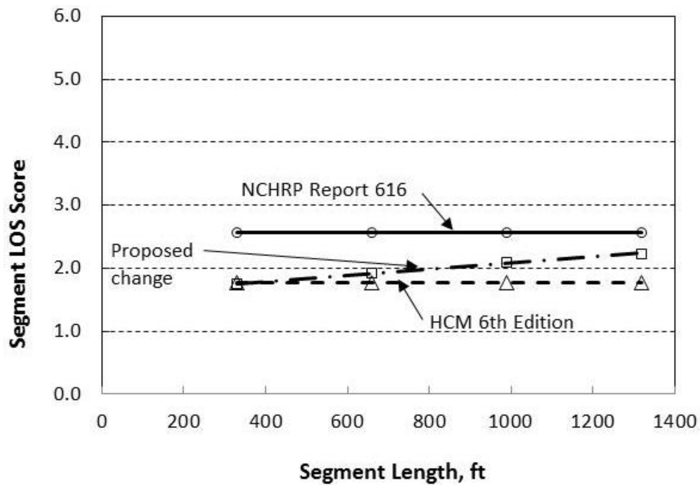
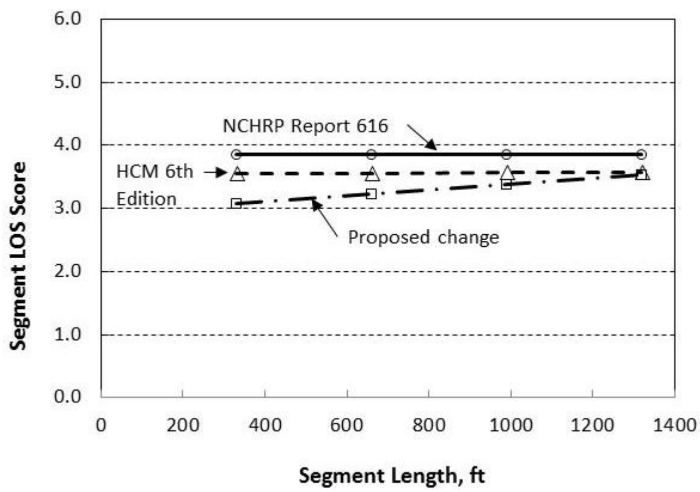
Dowling, R., D. Reinke, A. Flannery, P. Ryus, M. Vandehey, T. Petritsch, B. Landis, and J. Bonneson. (2008). *NCHRP Final Report 616: Multimodal Level of Service Analysis for Urban Streets*. National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C.

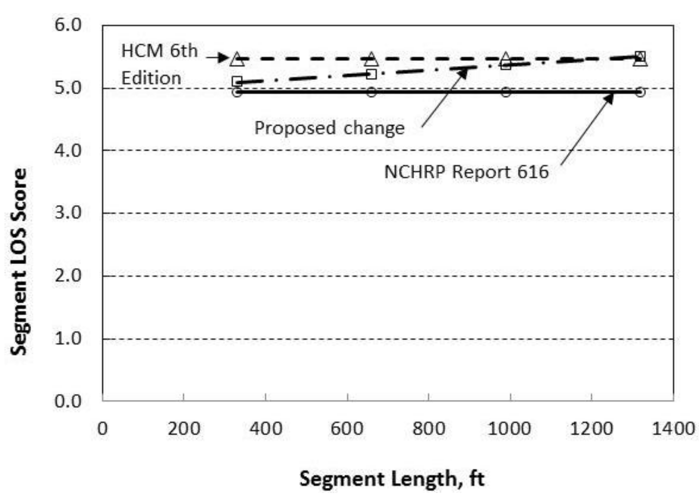
Petritsch, T., and T. Scorsone. (2014). *Potential Modification of the HCM Pedestrian Level of Service Model for Arterial Roadways. Final Report*. Sprinkle Consulting, Florida.



a. ***Link LOS Score and Intersection LOS Score equal to 1.0.***



b. Link LOS Score and Intersection LOS Score equal to 3.0.



c. Link LOS Score and Intersection LOS Score equal to 6.0.

Figure E6. Influence of segment length on segment LOS – proposed changes.

Appendix C: Model for Predicting the Pedestrian Delay at Signalized Intersections

INTRODUCTION

This paper describes the development of a methodology for predicting the delay to pedestrians that cross a street at a signalized intersection. Historically, this delay has been computed based on the assumptions that (1) pedestrian arrivals to the crossing location are random and (2) the signal operation is such that pedestrians can cross the intersection leg (corner-to-corner) during one signal phase. However, recent research has demonstrated that that the assumed random arrival process is not appropriate when computing the delay to pedestrians that cross the leg during two “stages” (or phases). During a two-stage crossing, the pedestrian crosses to the median during one phase and then crosses to the far corner during a second phase. Most of the pedestrians arrive to the median in a group (as opposed to randomly) and with a predictable wait before the signal indicates they can complete their crossing. Two-stage crossings are sometimes used when the leg being crossed is relatively wide and there is a median of adequate width to provide a refuge area for pedestrians. This signal phasing technique is used to improve traffic operations for the intersecting street.

Also, recent research has found that the assumed random arrival process is not appropriate for those pedestrians completing a “diagonal” crossing (i.e., they cross first one intersection leg, turn about 90 degrees, and then cross the adjacent leg to arrive at the corner that is diagonally opposite the corner on which the crossing started). Most of these pedestrians arrive to the crosswalk for the second leg in a group (as opposed to randomly) and with a predictable wait before the signal indicates they can complete their crossing. Procedures that recognize this arrival process provide more accurate estimates of pedestrian delay than simple procedures that assume random arrivals to every corner.

This paper consists of two sections. The first section provides a brief summary of the literature regarding the prediction of pedestrian crossing delay at signalized intersections. The second section describes a methodology for predicting pedestrian crossing delay at signalized intersections. The methodology describes one delay-prediction procedure for each of the following crossing cases: single-stage crossing, two-stage crossing, and diagonal crossing.

BACKGROUND

This section provides a brief summary of the findings from a literature review regarding the prediction of pedestrian crossing delay. The focus of this review is on pedestrian delay at a signalized intersection where arrivals to a given crosswalk of interest may be influenced by the intersection phase sequence and timing. This focus includes crossings that require the pedestrian to complete the crossing in two phases. It also includes street crossings where some of the pedestrians in the subject crosswalk are completing the first or second part of a diagonal crossing.

Pedestrian Delay for One Leg Crossed during One Phase

This section examines the delay prediction equation offered in Chapter 19 of the 6th edition Highway Capacity Manual (HCM) for computing the delay to pedestrians that cross a specified intersection leg during one phase (referred to hereafter as a "one-stage crossing"). This equation is based on the following three assumptions: (1) pedestrian arrivals to the crossing location (i.e., street corner) are random, (2) the signal operation is such that pedestrians can cross the entire width of the intersection leg (corner-to-corner) during one signal phase, and (3) random arrivals over an large number of signal cycles can be modeled deterministically using a uniform arrival rate. The HCM provides the following equation for computing this delay.

Equation 1

$$d_p = \frac{\left(C - g_{\text{Walk},\, i}\right)^2}{2\, C}$$

where

d_p = pedestrian delay (s/p),

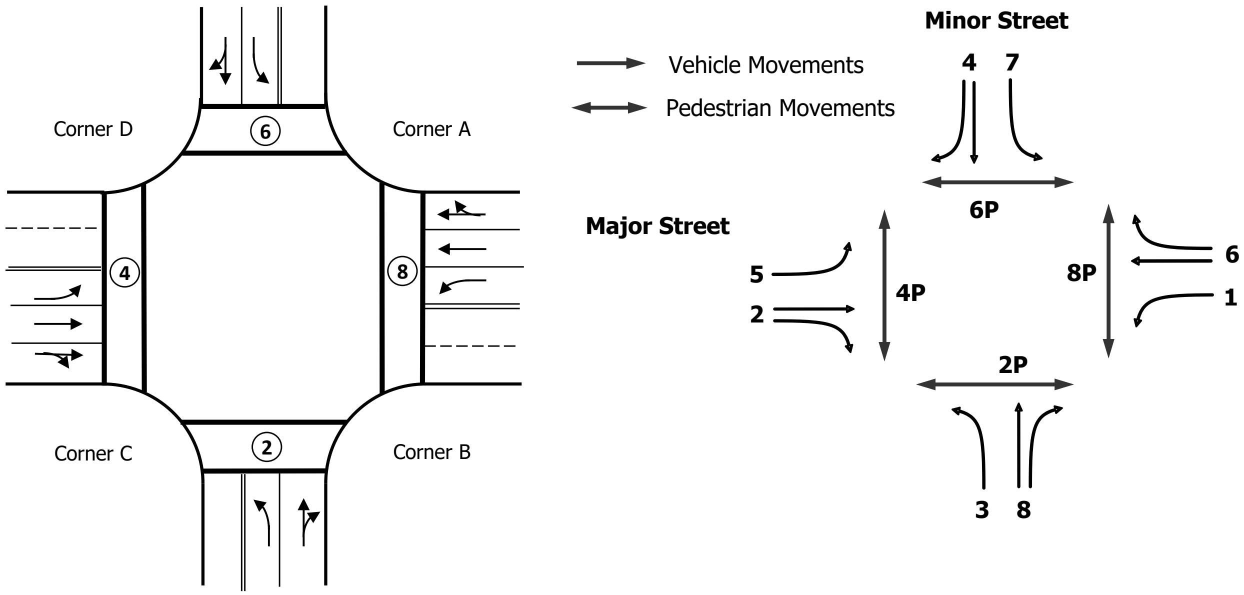
C = cycle length (s), and

$g_{\text{Walk},i}$ = effective walk time for phase i serving the subject pedestrian movement (s).

Equation 1 does not account for the possibility that some arrivals may come from the intersecting crosswalk as part of a diagonal crossing.

The effective walk time is determined by following the guidance in the HCM on pages 19-78 and 19-36 (it is also repeated in the section titled Pedestrian Delay Prediction Methodology). This time effectively represents the time available to serve pedestrians with regard to their initiating the process of crossing the street.

Figure 1a indicates the number assigned to each crosswalk. Figure 1b indicates the number assigned to each intersection traffic movement. The numbers shown in Figure 1b are established to be coincident with the signal phase that serves the corresponding traffic movement. Notably, the pedestrian movement and the adjacent through vehicle movement share the same number because they are served during the same phase. For example, vehicle movement 2 is a through movement on the left side of the intersection. This movement is served by signal phase 2. Pedestrian movement 2P crosses in crosswalk number 2. This pedestrian movement is also served by signal phase 2.



a. Crosswalk numbering scheme. *b. Traffic movement numbering scheme.*

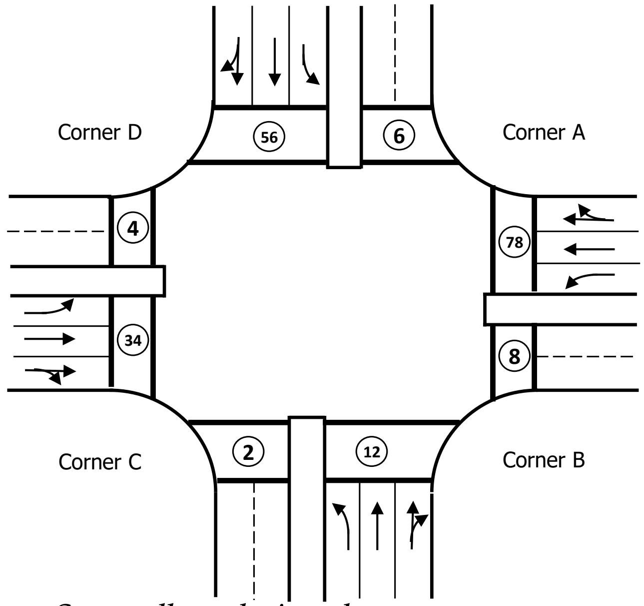
Figure 1. Intersection traffic movement and crosswalk numbering scheme.

Based on the preceding explanation of traffic movement numbers and signal phases, the delay to pedestrian movement 2P is based on the cycle length *C* and the effective walk time for phase 2 $g_{Walk,2}$. This delay is computed using Equation 1. The delay value describes the delay to pedestrians crossing in either direction in crosswalk 2 (i.e., from corner C to corner B, and from corner B to corner C).

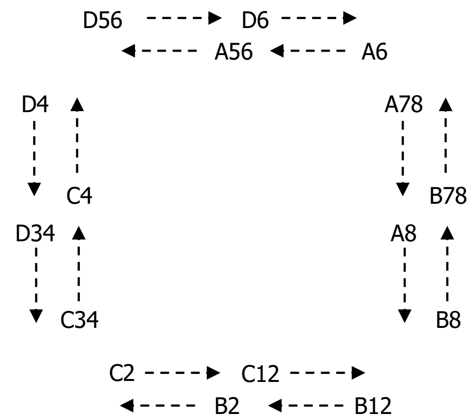
Pedestrian Delay for One Leg Crossed during Two Phases

This section describes a procedure developed by Wang and Tian (2010) for estimating the delay to pedestrians that cross a specified intersection leg in two phases (referred to hereafter as a "two-stage crossing"). The signal operation is such that pedestrians need two phases to complete the crossing (waiting on the median before crossing the second half of the street). In the next few paragraphs, a crosswalk and movement numbering scheme is described to facilitate the discussion of this crossing maneuver. Then, the procedure developed by Wang and Tian is described.

Figure 2a illustrates an intersection where each leg has a median that is sufficiently wide as to justify consideration of a two-stage crossing. This figure also indicates the number assigned to each section of crosswalk. For those crosswalk sections that have a single-digit number, the number shown matches that of the pedestrian movement (as shown in Figure 1b), the adjacent through vehicle movement, and the signal phase providing pedestrian service.



a. Crosswalk numbering scheme.



b. Pedestrian movement numbering scheme.

Figure 2. Pedestrian movement and crosswalk numbering scheme for two-stage crossing.

For those crosswalk sections that have a two-digit number, the even numbered digit matches that of the pedestrian movement, the adjacent through vehicle movement, and one of the two signal phases providing pedestrian service. The odd numbered digit identifies a second signal phase that can be used to provide pedestrian service for this crosswalk section.

The crosswalk numbering in Figure 2a identifies the most logical signal phases to serve the associated crosswalk sections. However, each two-digit crosswalk section can be served during other signal phases (other than those indicated by the numbers shown in Figure 2a) provided that the phase settings are such that conflicting vehicular movements will not time concurrently.

The two-stage crossing can require one or two signal cycles to complete, depending on the phase sequence and the pedestrian direction of travel. In the case where the odd phase leads the even phase (i.e., leading left-turn phasing), the clockwise crossing direction (e.g., corner A to B, B to C, C to D) can be served by sequential phases during one cycle and the counterclockwise direction is served in two cycles. In the case where the odd phase lags the even phase (i.e., lagging left-turn phasing), the counterclockwise crossing direction can be served during one cycle and the clockwise direction is served in two cycles.

Figure 2b indicates the letter-number label assigned to each pedestrian movement. Each label is unique to a specific crosswalk section and travel direction. The letter in each label indicates the corner from which the crossing began. The number in each label indicates the crosswalk section number, as discussed previously for Figure 2a. For example, pedestrian movement C2 corresponds to the first stage of a two-stage crossing from corner C to B. It is used to describe the pedestrians departing corner C and traveling to the median in crosswalk section 2 (which is served by signal phase 2). Pedestrian movement C12 corresponds to the second stage of a two-stage crossing from corner C to B. It is used to describe pedestrians departing the median and traveling to corner B in crosswalk section 12.

Based on the preceding explanation of movement numbers and signal phases, the two travel directions associated with a given crosswalk will receive service at different times during one or both of the crossing stages. Therefore, at a given crosswalk with two-stage crossing, the delay to one travel direction is unlikely to equal the delay to the other travel direction.

Wang and Tian (2010) developed a procedure for estimating the delay to pedestrians that undertake a two-stage crossing. This procedure is based on the following two assumptions: (1) pedestrian arrivals to the first crossing location (i.e., street corner) are random and (2) the signal operation is such that pedestrians will need two phases to complete the crossing (waiting on the median before crossing the second half of the street). The researchers rationalized that arrivals to the corner may be random, but arrivals to the median (where the second stage of the crossing begins) are predictable based on the signal timing and phasing.

The delay prediction procedure developed by Wang and Tian (2010) suggests that pedestrian delay for a two-stage crossing can be computed using the following equation.

Equation 2

$$d_p = \left[d_{1,DW1} P_{DW1} + d_{1,W1}(1 - P_{DW,1})\right]_1 + \left[d_{2,DW1} P_{DW,1} + d_{2,W1}(1 - P_{DW,1})\right]_2$$

where

d_p = pedestrian delay (s/p);

$d_{1,DW1}$ = delay at corner for stage 1, given arrival is during a Don't Walk indication at corner (s/p);

$d_{1,W1}$ = delay at corner for stage 1, given arrival is during the Walk indication at corner (s/p);

$d_{2,DW1}$ = delay on median for stage 2, given arrival is during a Don't Walk indication at corner (s/p);

$d_{2,W1}$ = delay on median for stage 2, given arrival is during the Walk indication at corner (s/p); and

P_{DW1} = proportion of arrivals during a Don't Walk indication at corner (s/p).

The delay computed using Equation 2 is specific to the signal phase sequence. As a result, the procedure is applied separately to each crosswalk travel direction of interest. For example, it is applied once to estimate the delay to pedestrians crossing on crosswalk 2 from corner C to corner B. It is applied a second time to estimate the delay for pedestrians crossing from corner B to corner C.

The "proportion of arrivals during a Don't Walk indication at the corner" P_{DW1} is computed using the following equation.

Equation 3

$$P_{DW1} = \frac{(C - g_{\text{Walk},\,i})}{C}$$

where

C = cycle length (s); and

$g_{\text{Walk},i}$ = effective walk time for phase i serving the subject pedestrian movement (s).

The first term in brackets in Equation 2 represents the delay incurred at the corner before the first crosswalk section is crossed (to the median). It consists of two delay components: the delay at the corner to those pedestrians that arrived at the corner during a Don't Walk indication (flashing or solid) $d_{1,DW1}$ and the delay at the corner to those pedestrians that arrived at the corner during the Walk indication $d_{1,W1}$. The first component is computed as $d_{1,DW1} = (C - g_{Walk,i})/2$ and the second component is $d_{1,W1} = 0.0$ (i.e., no delay). When these two components are multiplied by their corresponding proportions (as shown in Equation 2), the delay incurred at the corner reduces to Equation 1.

The second term in brackets represents the delay incurred on the median before the second crosswalk section is crossed (to the far corner). It consists of two delay components: the delay on the median to those pedestrians that arrived at the corner during a Don't Walk indication (flashing or solid) $d_{2,DW1}$ and the delay on the median to those pedestrians that arrived at the corner during the Walk indication $d_{2,W1}$. The value of each delay component is based on the pedestrian travel time for the first crosswalk section and the time between the start of the Walk indication on the corner and the start of the Walk indication on the median.

Wang and Tian (2010) provide a series of equations that are used to compute each of the two components of delay on the median. The equations used to compute $d_{2,DW1}$ consider the start time of the Walk interval at the corner and the start time of the Walk interval on the median. At the start of the Walk interval at the corner, the waiting pedestrians cross to the median as a group where they wait for the start of the second Walk indication. The delay $d_{2,DW1}$ is computed as the difference between the two Walk start times less the time required to cross the first crosswalk section (from corner to median).

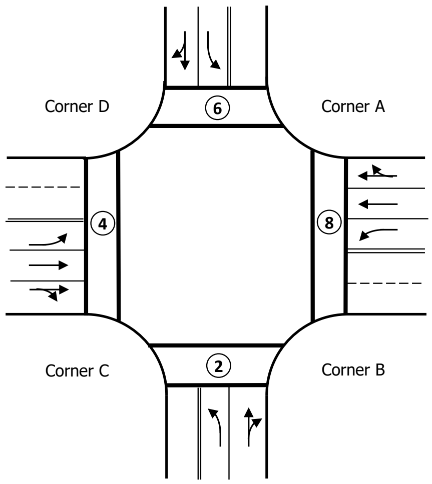
The equations used to compute $d_{2,W1}$ are more complicated and numerous. Their focus is those pedestrians that arrive during the Walk indication. These pedestrians cross to the median (without delay at the corner) and wait on the median until the start time of the next Walk interval. The equations provided for computing this delay consider six different scenarios. Each scenario considers a different relationship between the start time of the two Walk intervals, and their respective durations.

Wang and Tian (2010) used a microscopic simulation model to validate their proposed procedure. The developed 50 simulation scenarios had a range of cycle length, Walk interval durations, and phase sequences. Each scenario was simulated for one hour with five replications. The predicted delays from the simulation model were compared with those from the proposed procedure using linear regression analysis. The analysis results showed that the procedure was able to explain 99.9% of the variability in the delay data from the simulation model (i.e., $R^2 = 0.999$).

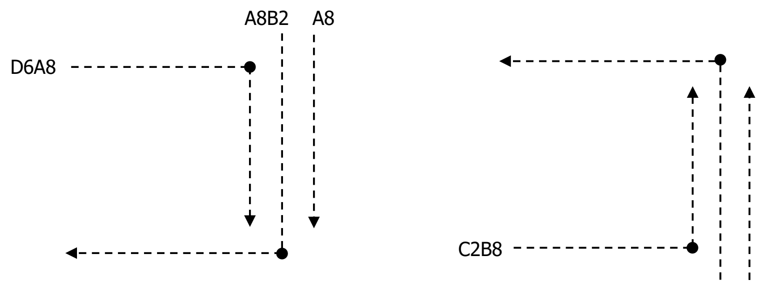
Pedestrian Delay for Two Legs Crossed during Two Phases

This section describes a procedure developed by Zhao and Liu (2017) for estimating the delay to pedestrians that cross two intersection legs during two phases of one cycle (referred to hereafter as a "diagonal crossing"). For this crossing maneuver, the pedestrians cross first one leg and then the adjacent leg to arrive at the corner that is diagonally opposite of the corner on which they started. The signal operation is such that pedestrians need two phases of the signal cycle to complete the crossing (waiting on the intermediate corner before crossing the second leg). In the next few paragraphs, a crosswalk and movement numbering scheme is described to facilitate the discussion of this crossing maneuver. Then, the procedure developed by Zhao and Liu is described.

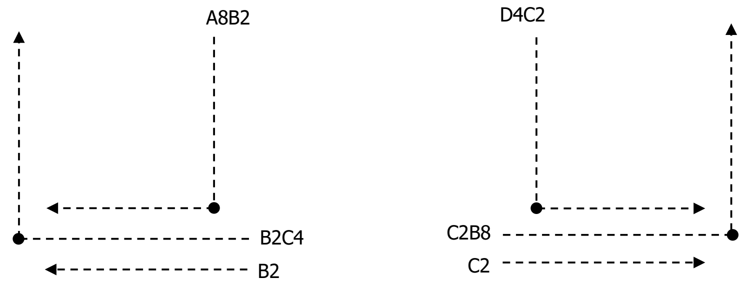
Figure 3a shows the number assigned to each crosswalk for the case where the crosswalk is crossed in one phase. The crosswalk numbers shown are the same as in Figure 1a. Figure 3b to Figure 3e indicate the letter-number label assigned to each pedestrian movement associated with crosswalk numbers 8, 2, 4, and 6, respectively. Each figure indicates that a crosswalk has two directions of travel and each direction of travel is associated with three pedestrian movements.



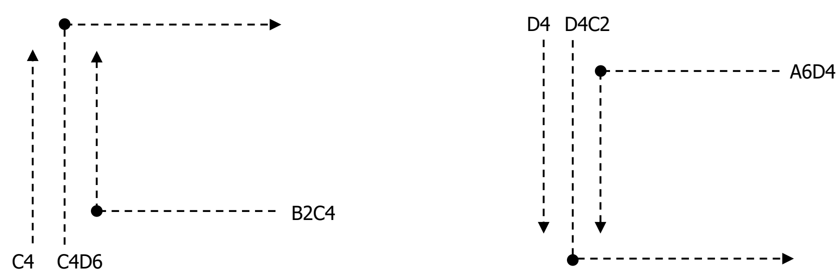
a. Crosswalk numbering scheme.



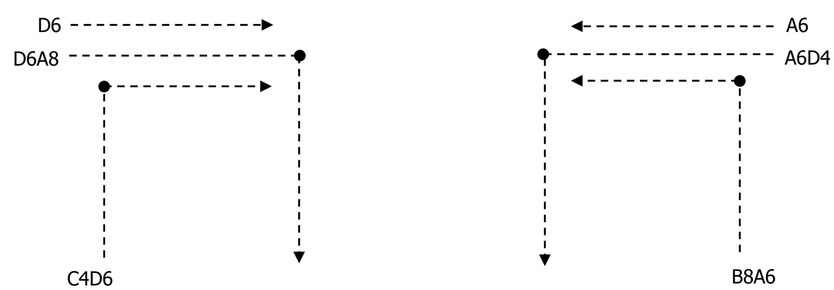
b. Pedestrian movement numbering for crosswalk 8.



c. Pedestrian movement numbering for crosswalk 2.



d. Pedestrian movement numbering for crosswalk 4.



e. Pedestrian movement numbering for crosswalk 6.

Figure 3. Pedestrian movement and crosswalk numbering scheme with diagonal movements.

The first letter and first number in each pedestrian movement label are interpreted together. The first letter in each label indicates the corner at which the pedestrian began the crossing maneuver. The first number indicates the crosswalk (and phase) that serves the crossing. Similarly, if the crossing is a diagonal movement, the second letter and second number are interpreted together. The second letter indicates the second corner reached during the crossing maneuver. The second number indicates the crosswalk (and phase) that serves the second leg of the diagonal crossing.

The movement numbering scheme can be illustrated by example. Consider crosswalk 2 and pedestrians crossing from corner C to B. As shown in Figure 3c, the following pedestrian movements are of interest: D4C2, C2B8, and C2. Movement D4C2 represents the pedestrians that are completing a diagonal crossing from corner D to corner B. These pedestrians cross initially from corner D to C in crosswalk 4 and are served during the Walk interval of phase 4. When they arrive at corner C, they continue the second part of their crossing in crosswalk 2 and are served during the Walk interval of phase 2. The delay that they incur on corner C at the start of the second leg is relevant to the subject crosswalk (i.e., crosswalk 2).

Movement C2B8 represents the pedestrians that are completing a diagonal crossing from corner C to corner A. These pedestrians cross initially from corner C to B in crosswalk 2 and are served during the Walk interval of phase 2. When they arrive at corner B, they continue the second leg of their crossing in crosswalk 8 and are served during the Walk interval of phase 8. The delay that they incur on corner C at the start of the first leg is relevant to the subject crosswalk (i.e., crosswalk 2).

Movement C2 represents the pedestrians that are crossing from corner C to corner B and are not arriving from (or destined for) any other intersection corner. The pedestrians cross in crosswalk 2 and are served during the Walk interval of phase 2. The delay that they incur at corner C is relevant to the subject crosswalk (i.e., crosswalk 2).

Based on the preceding explanation of movement numbers and signal phases, each of the two travel directions associated with a given crosswalk can be associated with three pedestrian movements. The delay incurred by each movement is different because they have different arrival patterns and times to the subject crosswalk. Therefore, at given crosswalk with a significant proportion of pedestrians crossing diagonally, the delay to one travel direction is unlikely to equal the delay to the other travel direction.

Zhao and Liu (2017) developed a procedure for estimating the delay to pedestrians completing a diagonal crossing. This procedure is based on the following two assumptions: (1) pedestrian arrivals to the first crossing location (i.e., street corner) are random, and (2) they will begin their crossing during the first available Walk interval (regardless of whether it is to cross the minor street leg or the major street leg). Assumption 2 reflects the pedestrian's desire to minimize their total diagonal crossing delay. The researchers rationalized that arrivals to the first corner may be random, but arrivals to the second corner are predictable based on the signal timing and phasing.

The delay prediction procedure produced by Zhao and Liu indicates that pedestrian delay for a diagonal crossing can be computed by modeling the two crossings as a system where entry to the system begins with the start of the Walk on the first corner and exit from the system begins with the start of the Walk on the second corner. Prior to entry to the system, the pedestrian waits for the first Walk indication. After the first Walk indication, the pedestrian crosses to the second corner and then waits for the second Walk indication. The pedestrian delay is computed as the sum of these waiting times minus the travel time between the first and second corners.

Zhao and Liu (2017) used field measurements at two signalized intersections to validate their proposed procedure. They collected four hours of data for each of three consecutive days at each intersection. A total of 13,619 pedestrians were counted during the study period. Average pedestrian delay was computed for each of the 12 hours at each intersection. A comparison of the predicted and observed delay values indicated an overall error (i.e., difference between the predicted and observed delays) of −0.1 s/p. A statistical test indicated that this difference was not significantly different from 0.0.

PEDESTRIAN DELAY PREDICTION METHODOLOGY

This section describes a methodology for computing the delay to pedestrians crossing an intersection leg at a signalized intersection. The methodology recognizes that pedestrian delay can be influenced by the phase sequence, signal operation, and pedestrian travel paths at the subject crossing location. The methodology addresses the following cases:

- Pedestrians cross one leg of the intersection during one signal phase (i.e., one-stage crossing)
- Pedestrians cross one leg of the intersection during two signal phases (i.e., a two-stage crossing)
- Pedestrians cross two legs of the intersection during two signal phases (i.e., a diagonal crossing)

One procedure has been developed to address each of the cases identified in the previous list. The procedure for predicting delay for one-stage crossings is described in Chapter 19 of the 6th edition HCM. The procedures for predicting delay for two-stage crossings and for diagonal crossings are described in this section.

Two-Stage Crossing Procedure

This section describes the procedure for computing the delay to pedestrians that cross a specified intersection leg in two phases. This procedure is used to estimate the delay to a given direction of travel in a specified crosswalk. The procedure is separately applied to evaluate the other direction of travel in the specified crosswalk or to evaluate other crosswalk locations. The procedure is based on that developed by Wang and Tian (2010).

This procedure is based on the following two assumptions: (1) pedestrian arrivals to the first crossing location (i.e., street corner) are random and (2) the signal operation is such that pedestrians will need two phases to complete the crossing (waiting on the median before crossing the second half of the street). With regard to Assumption 1, this procedure does not account for the delay associated with diagonal crossings (i.e., all pedestrians are assumed arrive randomly to the first corner).

Procedure

The procedure described in this section is based on the vehicle movement numbering scheme shown in Figure 1a. These vehicle movement numbers correspond to the signal phase that serves the movement (i.e., vehicle movement 2 is served by signal phase 2), which follows the traditional eight-phase dual-ring structure. The procedure is also based on the crosswalk numbering scheme shown in Figure 2a and the pedestrian movement scheme shown in Figure 2b.

With a two-stage crossing, the signal operation accommodates pedestrians crossing an intersection leg by providing pedestrian service during two signal phases. During the first phase, the pedestrians cross from the first corner to the median. During the second phase, they cross from the median to the next corner. The first phase to occur is denoted by the letter "X" and the second phase to occur is denoted by the letter "Y."

The crossing direction of interest and the phase sequence are considered to determine which phase is "Phase X" and which phase is "Phase Y". The two phase numbers of interest are identified in in Figure 2a by the two-digit crosswalk number associated with the crosswalk of interest. For example, if the crosswalk between corner C and corner B is of interest, phases 1 and 2 are used to define Phase X and Phase Y. The crossing direction and phase sequence are considered in the following manner:

- If the crossing direction is clockwise (i.e., from corner B to corner C) and phase 1 leads phase 2 in the phase sequence, then Phase X is phase 1 and Phase Y is phase 2.
- If the crossing direction is clockwise (i.e., from corner B to corner C) and phase 1 lags phase 2 in the phase sequence and, then Phase X is phase 2 and Phase Y is phase 2.
- If the crossing direction is counterclockwise (i.e., from corner C to corner B), then Phase X is phase 2 and Phase Y is phase 1 regardless of whether phase 1 leads or lags phase 2.

Required Data

The data needed for the procedure are identified in the following list:

- Cycle length, s
- Phase sequence (list of phases in order of occurrence)
- Phase duration (sum of the duration of the green, yellow change, and red clearance intervals) for all phases, s
- Walk interval duration for Phase X and Phase Y, s
- Distance crossed during Phase X (i.e., distance from first corner to far side of median), ft

- Yellow change interval duration for Phase X and Phase Y (needed only if rest-in-walk is enabled or no pedestrian signal head provided), s
- Red clearance interval duration for Phase X and Phase Y (needed only if rest-in-walk is enabled or no pedestrian signal head provided), s
- Pedestrian clear duration for Phase X and Phase Y (needed only if phase is actuated and rest-in-walk is enabled), s

If the signal control is fully actuated, then an average value is used for the cycle length and the green interval durations. If the signal control is semiactuated, then an average value is used for the green interval duration of the actuated phases.

Step 1. Determine the Effective Walk Time

During this step, the analyst determines the effective walk time for Phase X and for Phase Y. The following guidance is provided to estimate the effective walk time for a given phase. This guidance is derived from the 6th edition HCM.

If the subject phase is either (a) actuated with pedestrian signal head and rest-in-walk is not enabled or (b) pretimed with a pedestrian signal head, then the following equation is used to compute the effective walk time.

Equation 4

$$g_{Walk,i} = \mathrm{Walk}_i + 4.0$$

where

$g_{\mathrm{Walk},i}$ = effective walk time for phase *i* serving the subject pedestrian movement (s), and

Walk_i = Walk interval duration for phase *i* (s).

If the phase providing service to the pedestrians is actuated with a pedestrian signal head and rest-in-walk enabled, then the following equation is used to compute the effective walk time.

Equation 5

$$g_{Walk,i} = D_{p,i} - Y_i - R_{c,i} - PC_i + 4.0$$

where

$D_{p,i}$ = duration of phase *i* (s),

Y_i = yellow change interval duration for phase *i* (s),

$R_{c,i}$ = red clearance interval duration for phase *i* (s), and

PC_i = pedestrian clear duration for phase *i* (s).

For all other situations (i.e., there is no pedestrian signal head) the following equation is used to compute the effective walk time.

Equation 6

$$g_{Walk,i} = D_{p,i} - Y_i - R_{c,i}$$

For those crosswalk sections associated with two phases (i.e., the section has a two-digit number), time to cross the section is provided to pedestrians during one or both phases. If they are served during both phases, then an overlap is used. When using Equation 5 or Equation 6 for a crosswalk section served by two phases (i.e., when overlap is used), the duration of phase i $D_{p,i}$ used in either equation must equal the sum of the duration of both phases that are parent to the overlap. The yellow change, red clearance, and pedestrian clear values are equal to those for the parent phase that occurs last in the overlap pair. For example, when using Equation 5 to compute the effective walk time for crosswalk section 12, the variable $D_{p,i}$ in this equation must equal the sum of the durations for phases 1 and 2 (i.e., $D_{p,12} = D_{p,1} + D_{p,2}$).

Step 2. Determine Crossing Time during First Phase

The time required to cross from the first corner to the median is determined in this step. This time is computed using the following equation.

Equation 7

$$t_X = \frac{L_X}{S_p}$$

where

t_X = time for pedestrians to cross during Phase X (s),

L_X = distance from the first corner to the far side of the median (measured along the path of the pedestrian crossing) (ft), and

S_p = average pedestrian crossing speed (ft/s).

The 6th edition HCM recommends the use of 4.0 ft/s for the pedestrian walking speed S_p when less than 20 percent of the pedestrians are elderly (i.e., 65 years of age or older). If the percentage of elderly pedestrians exceeds 20 percent, then a walking speed of 3.3 ft/s should be used.

Step 3. Determine the Start of the Walk Intervals

During this step, the relative time in the cycle that the subject Walk intervals start is determined. Specifically, this is the start time for the Walk intervals associated with Phase X and Phase Y. To establish the relative start time for a given Walk interval T_{Walk}, one phase in the sequence will be established as time "0" (i.e., the start of the cycle). The start time of all subsequent phases will established using the cumulative duration of preceding phases.

With the relative phase start times established in this manner, the relative time for the start of a phase's Walk interval can be established by summing the preceding phase durations. In general, a Walk interval's relative start time is equal to its parent phase's relative start time. However, if a leading pedestrian interval is used, then the Walk interval's relative start time equals the phase relative start time minus the leading interval duration. Similarly, if a lagging pedestrian interval is used, then the Walk interval's relative start time equals the phase relative start time plus the lagging interval duration.

To illustrate the guidance provided for this step, consider an analysis of the pedestrian crossing from corner B to corner C in Figure 2a, where the intersection has the phase sequence shown in Figure 4. Based on the numbering scheme shown in Figure 2a, this crossing is served by phases 1 and 2. Based on Figure 4, phase 1 occurs first for the subject crossing direction (i.e., X = 1) and phase 2 occurs second (i.e., Y = 2). The start time of Phase X is "0." The start time of Phase Y is equal to the duration of phase 1 D_{p1}. Although not needed for this illustration, the start time for phase 3 is shown in Figure 4 to equal the sum of the phase 1 duration and phase 2 duration.

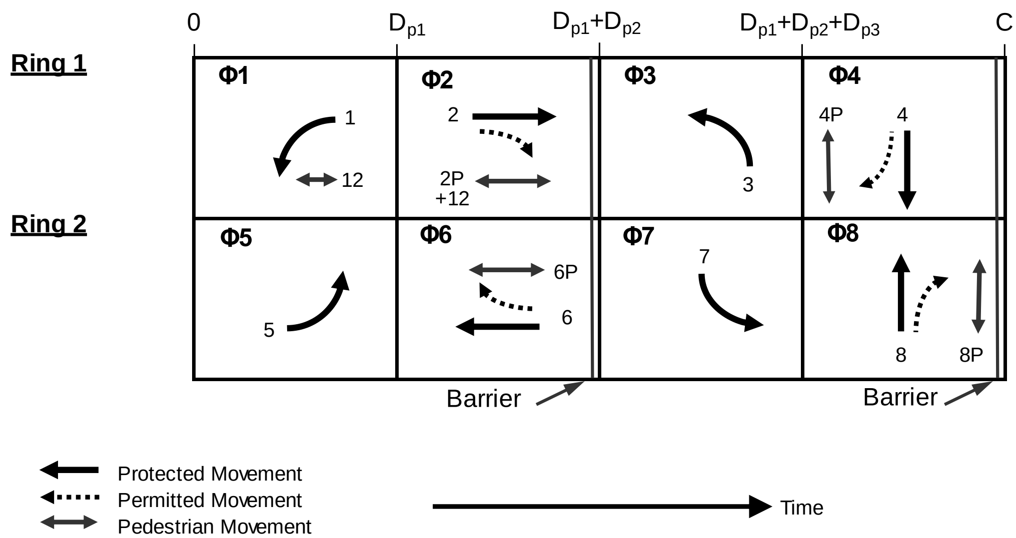


Figure 4. Example phase sequence for two-stage crossing shown using dual-ring structure.

Both Walk intervals start with their parent phase for this illustration, so the relative start time of the Walk interval for Phase X $T_{Walk,X}$ is "0" and that for Phase Y $T_{Walk,Y}$ is equal to D_{p1}. Other values will likely be obtained for other phase sequences.

Continuing the illustration, consider an analysis of the pedestrian crossing from corner C to corner B in Figure 2a, where the intersection has the phase sequence shown in Figure 4. Based on the numbering scheme shown in Figure 2a, this crossing is served by phases 1 and 2. Based on Figure 4, phase 2 occurs first for the subject crossing direction (i.e., X = 2) and phase 1 occurs second (i.e., Y = 1). The start time of Phase X is equal to D_{p1}. The start time of Phase Y is equal to "0."

Step 4. Compute Delay for First Stage Crossing

During this step, the delay for the first stage crossing is that incurred by pedestrians waiting at the first corner. This delay is computed using the following equation.

Equation 8

$$d_{p,1} = \frac{\left(C - g_{\text{Walk},X}\right)^2}{2\,C}$$

where

$d_{p,1}$ = pedestrian delay at corner for stage 1 (s/p),

C = cycle length (s), and

$g_{\text{Walk},X}$ = effective walk time for Phase X serving the subject pedestrian movement (s).

Step 5. Compute Delay for Second Stage Crossing Given Arrival is during Don't Walk

During this step, the second stage crossing delay is computed for one portion of the pedestrian stream. This particular delay is that incurred by pedestrians waiting *on the median* that arrived at the first corner during a Don't Walk indication (flashing or solid). The other portion of the second stage crossing delay is computed in the next step.

A. Compute the Time between Walk Intervals

The time between the Walk interval for Phases X and Y is computed using the following equation.

Equation 9

$$t_{YX} = \text{Modulo}\left(T_{\text{Walk},Y} - T_{\text{Walk},X}, C\right)$$

where

t_{YX} = time between start of Walk intervals (s),

$T_{\text{Walk},X}$ = relative start time of the Walk interval for Phase X (s),

$T_{\text{Walk},Y}$ = relative start time of the Walk interval for Phase Y (s), and

C = cycle length (s).

The modulo function in Equation 9 ensures that the value for t_{YX} is a non-negative number that is less than the cycle length. When used, the equation in the parentheses is computed and the resulting value is compared to the range 0 to C. If this value is outside the range, the value is changed by adding (or subtracting) one cycle length and then range satisfaction reassessed. The value is changed by adding or subtracting additional cycle length increments until it is within the range 0 to C.

B. Compute the Delay Given Arrival is during Don't Walk

The delay is that incurred by pedestrians waiting *on the median* that arrived at the first corner during a Don't Walk indication is computed using the following equation.

Equation 10

$$d_{2,DW1} = \begin{cases} t & \text{if } t < C - g_{\text{Walk},Y} \\ 0 & \text{if } t \geq C - g_{\text{Walk},Y} \end{cases}$$

with

Equation 11

$$t = \text{Modulo}(t_{YX} - t_X, C)$$

where

$d_{2,DW1}$ = delay on median for stage 2, given arrival is during a Don't Walk indication at corner (s/p);

t = waiting time on median when pedestrians reach median during a Don't Walk indication (s);

$g_{\text{Walk},Y}$ = effective walk time for Phase Y serving the subject pedestrian movement (s);

t_X = time for pedestrians to cross during Phase X (s); and

all other variables are as previously defined.

Step 6. Compute Delay for Second Stage Crossing Given Arrival is during Walk

During this step, the second-stage crossing delay is computed for the second portion of the pedestrian stream. This particular delay is that incurred by pedestrians waiting *on the median* that arrived at the first corner during the Walk indication.

There are two sets of equations that can be used to compute the second-stage crossing delay. The correct set of equations is determined by comparing the value of t with the effective walk time for Phase X. These two sets of equations are described in the following paragraphs.

When $t < g_{\text{Walk},X}$ compute the second-stage crossing delay using the following equation.

Equation 12

$$d_{2,W1} = \begin{cases} \dfrac{0.5(a+t)^2 + a\left(C - g_{\text{Walk},X}\right)}{g_{\text{Walk},X}} & \text{If } \left(t + g_{\text{Walk},Y}\right) < g_{\text{Walk},X} \\ \dfrac{0.5\,t^2}{g_{\text{Walk},X}} & \text{If } g_{\text{Walk},X} \leq \left(t + g_{\text{Walk},Y}\right) \leq C \\ \dfrac{0.5\left(C - g_{\text{Walk},Y}\right)^2}{g_{\text{Walk},X}} & \text{If } \left(t + g_{\text{Walk},Y}\right) > C \end{cases}$$

with

Equation 13

$$a = g_{\text{Walk},X} - g_{\text{Walk},Y} - t$$

where

$d_{2,W1}$ = delay on median for stage 2, given arrival is during the Walk indication at corner (s/p);

t = waiting time on median when pedestrians reach median during a Don't Walk indication (s);

a = undefined intermediate variable; and

all other variables are as previously defined.

When $t \geq g_{\text{Walk},X}$ compute the second-stage crossing delay using the following equation.

Equation 14

$$d_{2,W1} = \begin{cases} t - 0.5\, g_{\text{Walk},X} & \text{If } \left(t + g_{\text{Walk},Y}\right) < C \\ \dfrac{0.5\, b^2 + b\left(t - g_{\text{Walk},X}\right)}{g_{\text{Walk},X}} & \text{If } C \leq \left(t + g_{\text{Walk},Y}\right) \leq \left(C + g_{\text{Walk},X}\right) \\ 0 & \text{If } \left(t + g_{\text{Walk},Y}\right) > \left(C + g_{\text{Walk},X}\right) \end{cases}$$

with

Equation 15

$$b = g_{\text{Walk},X} - g_{\text{Walk},Y} - t + C$$

where

$d_{2,W1}$ = delay on median for stage 2, given arrival is during the Walk indication at corner (s/p);

b = undefined intermediate variable; and

all other variables are as previously defined.

Step 7. Compute Delay for Second Stage Crossing

The pedestrian delay for a two-stage crossing is computed using the following equation.

Equation 16

$$d_p = d_{p,1} + \left[d_{2,DW1}P_{DW,1} + d_{2,W1}(1 - P_{DW,1})\right]_2$$

with

Equation 17

$$P_{DW1} = \frac{\left(C - g_{\text{Walk},X}\right)}{C}$$

where

d_p = pedestrian delay (s/p);

$d_{p,1}$ = pedestrian delay at corner for stage 1 (s/p);

$d_{2,DW1}$ = delay on median for stage 2, given arrival is during a Don’t Walk indication at corner (s/p);

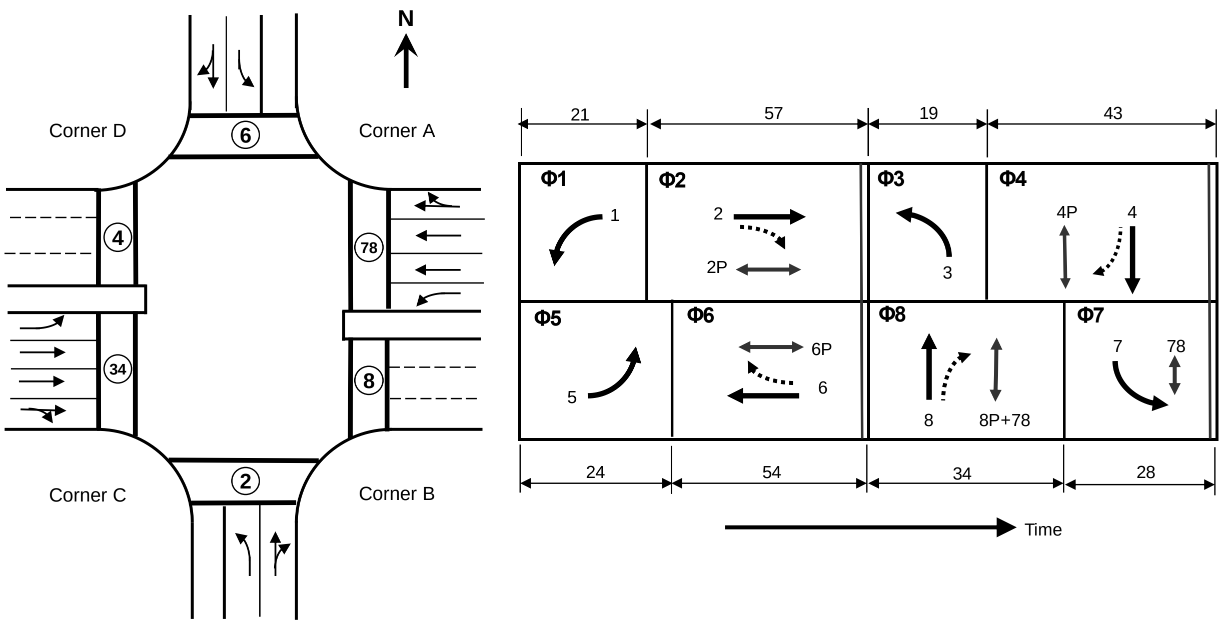
$d_{2,W1}$ = delay on median for stage 2, given arrival is during the Walk indication at corner (s/p); and

P_{DW1} = proportion of arrivals during a Don’t Walk indication at corner (s/p).

Example Application

The Intersection

The pedestrian crosswalk of interest is on the east leg of an intersection. This intersection is shown in Figure 5a where north is toward the top of the figure. The pedestrian movement of interest travels north, from corner B to corner A. A two-stage crossing is provided for this leg of the intersection. Signal heads are provided for all pedestrian movements.



a. Intersection Geometry. ***b. Signal phase sequence.***

Figure 5. Example intersection to illustrate the two-stage crossing procedure.

The east-west street is the major street. The major street traffic signals provide coordination for the through movements using a 140-second cycle length. The minor movements are actuated. Rest-in-walk is not used for any phases. The duration of each phase is shown in Figure 5b. The Walk intervals are set at 5.0 seconds and they start at the same time as the associated phase (i.e., they do not lead or lag the phase). The distance crossed for crosswalk section 8 is 40 feet. The median on the major street (at the location of pedestrian storage) is 16 feet wide.

The Question

The analyst desires to estimate the delay to the northbound pedestrian movement on the east leg of the intersection.

Computational Steps

The solution follows the steps of the Two-Stage Crossing Procedure. The first stage of the crossing occurs in crosswalk section 8. It is served by phase 8 so Phase X is phase 8 (i.e., X = 8). The second stage of the crossing occurs in crosswalk section 78. It is served by phases 7 and 8. Phase 7 is shown to occur next (after 8) so Phase Y is phase 7 (i.e., Y = 7).

Step 1. Determine the Effective Walk Time

The subject phases are actuated and rest-in-walk is not enabled so the effective walk time is determined by Equation 4. This equation indicates that the effective walk time for Phase X and Phase Y is 9 seconds (= 5 + 4).

Step 2. Determine Crossing Time during First Phase

The local pedestrian population is about 30 percent elderly so an average pedestrian crossing speed of 3.3 ft/s is used for the analysis. Equation 7 is used to compute a travel time t_X of 17.0 seconds for Phase X. This value describes the time for pedestrians to travel the 56-ft distance (= 40 + 16) from corner B to the far side of the median.

Step 3. Determine the Start of the Walk Intervals

The relative start time of the Walk intervals for Phase X and Phase Y are determined by inspection of Figure 5b. For Phase X (i.e., phase 8), the relative start time $T_{\text{Walk},X}$ is 78 seconds (= 21 + 57). For Phase Y (i.e., phase 7), the relative start time $T_{\text{Walk},Y}$ is 112 seconds (= 21 + 57 + 34).

Step 4. Compute Delay for First Stage Crossing

The delay for the first stage crossing is computed using Equation 8 with an effective walk time of 9 s (from Step 1) and a cycle length of 140 seconds. The computed delay value $d_{p,1}$ is 61.3 seconds.

Step 5. Compute Delay for Second Stage Crossing Given Arrival is during Don't Walk

The time between the Walk interval for Phases X and Y t_{YX} is computed using Equation 9. The computed value is 34 seconds (= 112 – 78).

The waiting time on the median t (for those pedestrians that reach the median during a Don't Walk indication) is computed using Equation 11. The computed value of t is 17 seconds (= 34 – 17).

The delay is that incurred by pedestrians waiting *on the median* that arrived at the first corner during a Don't Walk indication $d_{2,DW1}$ is computed using Equation 10. Because the value of t is less than "$C – g_{\text{Walk},Y}$" (i.e., 17 < 140 – 9), the delay $d_{2,DW1}$ is equal to 17.0 s/p.

Step 6. Compute Delay for Second Stage Crossing Given Arrival is during Walk

Because t is greater than $g_{\text{Walk},X}$ (i.e., 17 > 9), Equation 14 is used to compute the delay on the median for stage 2 $d_{2,W1}$. Given that "$t + g_{\text{Walk},Y}$" is less than C, the first part of this equation is used to compute the desired delay value. Using this equation, the delay $d_{2,W1}$ is computed as 12.5 s/p (= 17 – 0.5×9).

Step 7. Compute Delay for Second Stage Crossing

The proportion of arrivals during the Don't Walk indication at the corner P_{DW1} is computed using Equation 17. The computed value is 0.936. This value, along with the delay values computed in Steps 4, 5, and 6, is used in Equation 16 to compute a pedestrian delay d_p of 78 s/p.

Diagonal Crossing Procedure

This section describes the procedure for estimating the delay to pedestrians that cross two intersection legs during two phases of one cycle to complete a diagonal crossing. The delay when crossing the first crosswalk is computed and the delay for crossing both crosswalks as a system is computed. The delay when crossing the second crosswalk is computed by subtracting the first crosswalk delay from the system delay. The procedure is based on that developed by Zhao and Liu (2017).

A diagonal crossing at the typical four-leg intersection has two possible travel paths depending on whether the major street leg is crossed first or second. These two paths are referred to herein as the "clockwise path" and the "counterclockwise path." The procedure described herein is used to estimate the delay to a given path of travel when crossing from one corner to the diagonally opposite corner using two crosswalks. The procedure is separately applied to evaluate the other travel path between the two diagonal corners or to evaluate diagonal crossings for other corner combinations.

The procedure is based on the following two assumptions: (1) pedestrian arrivals to the first crossing location (i.e., street corner) are random, and (2) they will begin their crossing during the first available Walk interval (regardless of whether it is to cross the minor street leg or the major street leg). Assumption 2 reflects the pedestrian's desire to minimize their total diagonal crossing delay. This procedure does not address a two-stage crossing of the minor street leg or the major street leg.

Procedure

The procedure described in this section is based on the vehicle movement numbering scheme shown in Figure 1a. These vehicle movement numbers correspond to the signal phase that serves the movement (i.e., vehicle movement 2 is served by signal phase 2), which follows the traditional eight-phase dual-ring structure. The procedure is also based on the crosswalk numbering scheme shown in Figure 3a and the pedestrian movement schemes shown in Figure 3b to Figure 3e.

With a diagonal crossing, the signal operation accommodates pedestrians crossing to the diagonally opposite corner by providing pedestrian service during two signal phases. During the first phase, the pedestrians cross from the first corner to the second corner. During the second phase, they cross from the second corner to the last corner.

The delay incurred during a diagonal crossing is dependent on the direction the pedestrian travels around the intersection (i.e., clockwise or counterclockwise). As a result, the direction of interest must be specified when using the procedure. The first phase to occur in the subject travel direction is denoted by the letter "X." The second phase to occur in the subject direction of travel is denoted by the letter "Y." Had the pedestrian decided to cross in the other direction around the intersection, two different signal phases would provide pedestrian service. The first phase to serve travel in the other direction is denoted by the letter "Z" (i.e., Phase Z is the first phase to serve the pedestrian starting the diagonal crossing in a direction *opposite* to the direction of interest).

To illustrate the aforementioned rules, consider the intersection shown in Figure 3a. An analyst desires to compute the delay to a pedestrian traveling in a clockwise path from corner B to D. Based on this information, the first phase to serve the pedestrian crossing in the subject travel direction (i.e., from corner B to corner C) is phase 2 so Phase X is phase 2 (i.e., X = 2). The second phase to serve pedestrians in the subject travel direction (i.e., from corner C to corner D) is phase 4 so Phase Y is phase 4 (i.e., Y = 4). If the pedestrian were to travel in the other direction, phase 8 would be the first phase to provide service (i.e., from corner B to corner A) so Phase Z is phase 8 (i.e., Z = 8).

Required Data

The data needed for the procedure are identified in the following list:

- Cycle length, s
- Phase sequence (list of phases in order of occurrence)
- Phase duration (sum of the duration of the green, yellow change, and red clearance intervals) for all phases, s
- Walk interval duration for Phase X and Phase Z, s
- Distance crossed during Phase X (i.e., distance from first corner to second corner), ft
- Yellow change interval duration for Phase X and Phase Z (needed only if rest-in-walk is enabled or no pedestrian signal head provided), s
- Red clearance interval duration for Phase X and Phase Z (needed only if rest-in-walk is enabled or no pedestrian signal head provided), s
- Pedestrian clear duration for Phase X and Phase Z (only needed if phase is actuated and rest-in-walk is enabled), s

If the signal control is fully actuated, then an average value is used for the cycle length and the green interval durations. If the signal control is semi actuated, then an average value is used for the green interval duration of the actuated phases.

Step 1. Determine the Effective Walk Time

During this step, the analyst determines the effective walk time for Phase X and for Phase Z. The following guidance is provided to estimate the effective walk time for a given phase. This guidance is derived from the 6th edition HCM.

If the subject phase is either (a) actuated with pedestrian signal head and rest-in-walk is not enabled or (b) pretimed with a pedestrian signal head, then the following equation is used to compute the effective walk time.

Equation 18

$$g_{Walk,i} = \text{Walk}_i + 4.0$$

where

$g_{\text{Walk},i}$ = effective walk time for phase *i* serving the subject pedestrian movement (s), and

Walk_i = Walk interval duration for phase *i* (s).

If the phase providing service to the pedestrians is actuated with a pedestrian signal head and rest-in-walk enabled, then the following equation is used to compute the effective walk time.

Equation 19

$$g_{Walk,i} = D_{p,i} - Y_i - R_{c,i} - PC_i + 4.0$$

where

$D_{p,i}$ = duration of phase *i* (s),

Y_i = yellow change interval duration for phase *i* (s),

$R_{c,i}$ = red clearance interval duration for phase *i* (s), and

PC_i = pedestrian clear duration for phase *i* (s).

For all other situations (i.e., there is no pedestrian signal head) the following equation is used to compute the effective walk time.

Equation 20

$$g_{Walk,i} = D_{p,i} - Y_i - R_{c,i}$$

Step 2. Determine Crossing Time during First Phase

The time required to cross from the first corner to the second corner is determined in this step. This time is computed using the following equation.

Equation 21

$$t_X = \frac{L_X}{S_p}$$

where

t_X = time for pedestrians to cross during Phase X (s),

L_X = distance from the first corner to the second corner (measured along the path of the pedestrian crossing) (ft), and

S_p = average pedestrian crossing speed (ft/s).

The 6th edition HCM recommends the use of 4.0 ft/s for the pedestrian walking speed S_p when less than 20 percent of the pedestrians are elderly (i.e., 65 years of age or older). If the percentage of elderly pedestrians exceeds 20 percent, then a walking speed of 3.3 ft/s should be used.

Step 3. Determine the Start of the Walk Intervals

During this step, the relative time in the cycle that the subject Walk intervals start is determined. Specifically, this is the start time for the Walk intervals associated with Phase X, Phase Y, and Phase Z. To establish the relative start time for a given Walk interval T_{Walk}, one phase in the sequence will be established as time "0" (i.e., the start of the cycle). The start time of all subsequent phases will be established using the cumulative duration of preceding phases.

With the relative phase start times established in this manner, the relative time for the start of a phase's Walk interval can be established by summing the preceding phase durations. In general, a Walk interval's relative start time is equal to its parent phase's relative start time. However, if a leading pedestrian interval is used, then the Walk interval's relative start time equals the phase relative start time minus the leading interval duration. Similarly, if a lagging pedestrian interval is used, then the Walk interval's relative start time equals the phase relative start time plus the lagging interval duration.

To illustrate the guidance provided for this step, consider an analysis of the clockwise diagonal crossing from corner B to corner D in Figure 3a, where the intersection has the phase sequence shown in

Figure *6*. Based on the numbering scheme shown in Figure 3a, the subject travel direction is served first by phase 2 and then phase 4. Had a counterclockwise crossing been taken, the diagonal crossing would be served first by phase 8.

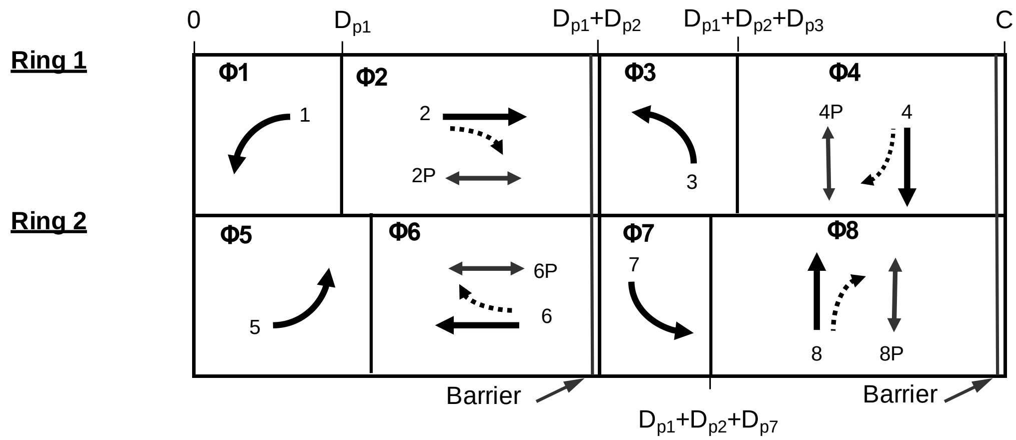


Figure 6. Example phase sequence for diagonal crossing shown using dual-ring structure.

Based on

Figure *6*, phase 2 occurs first for the subject travel direction (i.e., X = 2) and phase 4 occurs second for the subject direction of travel (i.e., Y = 4). Phase 8 occurs first for the other travel direction (i.e., Z = 8). The start time of Phase X is equal to the duration of phase 1 D_{p1} (since phase 2 starts when phase 1 ends for the sequence shown in

Figure *6*). The start time of Phase Y is equal to the duration of phases 1, 2, and 3 (= $D_{p1} + D_{p2} + D_{p3}$) (since phase 4 starts when phase 3 ends for the sequence shown in

Figure *6*). Similarly, the start time of Phase Z is equal to the duration of phases 1, 2, and 7 (= $D_{p1} + D_{p2} + D_{p7}$). Note that the dual-ring structure shown in

Figure *6* has a barrier at the end of phases 2 and 6 which requires the duration of phase 1 plus phase 2 to equal the duration of phase 5 plus phase 6.

Both Walk intervals start with their parent phase for this illustration, so the relative start time of the Walk interval for Phase X $T_{Walk,X}$ is D_{p1}, Phase Y $T_{Walk,Y}$ is $D_{p1} + D_{p2} + D_{p3}$ and that for Phase Z $T_{Walk,Z}$ is $D_{p1} + D_{p2} + D_{p7}$. Other values will likely be obtained for other phase sequences.

Step 4. Compute Delay for First Stage Crossing

During this step, the delay for the first stage crossing in the subject travel direction is computed. This delay is incurred by pedestrians that have been waiting at the first corner since the end of the effective walk time for the other travel direction.

A. Compute the End of Effective Walk Time

The end of the effective walk time for Phase X is computed using the following equation.

Equation 22

$$T_X = \text{Modulo}\left(T_{\text{Walk},X} + g_{\text{Walk},X}, C\right)$$

where

T_X = relative end time of the effective walk period for Phase X (s),

$T_{\text{Walk},X}$ = relative start time of the Walk interval for Phase X (s),

C = cycle length (s), and

$g_{\text{Walk},X}$ = effective walk time for Phase X serving the subject pedestrian movement (s).

The end of the effective walk time for Phase Z is computed using the following equation.

Equation 23

$$T_Z = \text{Modulo}\left(T_{\text{Walk},Z} + g_{\text{Walk},Z}, C\right)$$

where

T_Z = relative end time of the effective walk period for Phase Z (s),

$T_{\text{Walk},Z}$ = relative start time of the Walk interval for Phase Z (s),

C = cycle length (s), and

$g_{\text{Walk},Z}$ = effective walk time for Phase Z serving the subject pedestrian movement (s).

B. Compute the Delay for the First Stage Crossing

The delay for the first stage crossing is computed using the following equation.

Equation 24

$$d_{p,1} = \frac{\left(t_{XZ} - g_{\text{Walk},X}\right)^2}{2\, t_{XZ}}$$

with

Equation 25

$$t_{XZ} = \text{Modulo}(T_X - T_Z, C)$$

where

$d_{p,1}$ = pedestrian delay at corner for stage 1 (s/p),

t_{XZ} = time between end of effective walk time for Phase Z and start of effective walk time for Phase X (s), and

all other variables are as previously defined.

Step 5. Compute Delay for Entire Diagonal Crossing

The delay for the entire diagonal crossing in the subject travel direction is computed in this step. This delay represents the sum of the delay incurred on the first corner and that incurred on the second corner. The delay for just the second stage crossing is computed in the next step.

The diagonal crossing delay is computed using the following equation.

Equation 26

$$d_p = t_d - t_X$$

with

Equation 27

$$t_d = \begin{cases} T_{\text{Walk},Y} - \dfrac{T_X + T_Z}{2} & \text{If } T_{\text{Walk},Y} \geq T_X \geq T_Z \\ T_{\text{Walk},Y} - \dfrac{T_X + T_Z - C}{2} & \text{If } T_X < T_Z \\ T_{\text{Walk},Y} - \dfrac{T_X + T_Z}{2} + C & \text{If } T_X \geq T_Z \geq T_{\text{Walk},Y} \end{cases}$$

where

d_p = pedestrian delay (s/p),

t_d = time between arrival to first corner and departure from second corner (s),

t_X = time for pedestrians to cross during Phase X (s),

$T_{Walk,Y}$ = relative start time of the Walk interval for Phase Y (s), and

all other variables are as previously defined.

Step 6. Compute Delay for Second Stage Crossing

During this step, the delay for the second stage crossing in the subject travel direction is computed. This delay is incurred by pedestrians waiting at the second corner. It is computed using the following equation.

Equation 28

$$d_{p,2} = d_p - d_{p,1}$$

where

$d_{p,2}$ = pedestrian delay at corner for stage 2 (s/p),

d_p = pedestrian delay (s/p), and

$d_{p,1}$ = pedestrian delay at corner for stage 1 (s/p).

Closing Comments

The procedure described in this section can be used to estimate the delay for a diagonal crossing maneuver for a specified travel path (i.e., clockwise or counterclockwise) between two diagonal corners. The procedure can also be used to evaluate the delay associated with a given crosswalk. As shown in Figure 3b to Figure 3e, there are six pedestrian movements associated with each crosswalk. That is, each crosswalk has two directions of travel and each direction of travel is associated with three pedestrian movements.

Consider crosswalk 2 and pedestrians crossing from corner C to B. As shown in Figure 3c, the following pedestrian movements are of interest: D4C2, C2B8, and C2. Movement D4C2 represents the pedestrians that are completing a counterclockwise diagonal crossing from corner D to corner B. Their delay in crosswalk 2 can be estimated as the second-stage crossing delay of the diagonal crossing procedure (i.e., Equation 28).

Movement C2B8 represents the pedestrians that are completing a counterclockwise diagonal crossing from corner C to corner A. Their delay can be estimated as the first-stage crossing delay of the diagonal crossing procedure (i.e., Equation 24).

Finally, movement C2 represents the pedestrians that are crossing from corner C to corner B and are not destined for any other intersection corner. Their delay can be estimated using the procedure described in the 6th edition HSM (i.e., Equation 1).

If the volume of each of these three movements is known, they can be used to compute a volume-weighted average delay for the subject travel direction of the crosswalk.

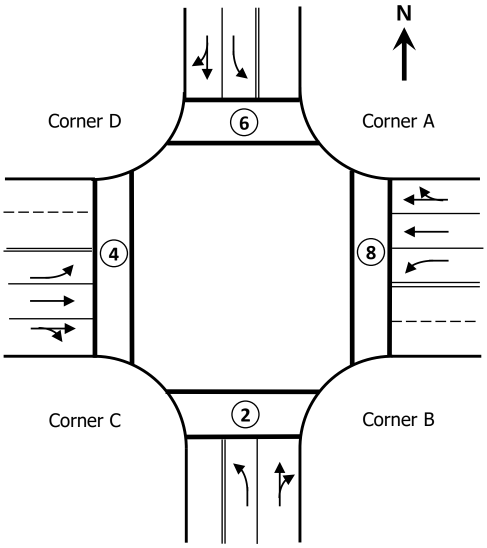
The process outlined in the preceding paragraphs can be repeated to evaluate the three pedestrian movements for the opposing travel direction of the subject crosswalk. A volume-weighted average delay for this travel direction can also be computed if the pedestrian volume is known for each of the three pedestrian movements.

Finally, if both travel directions of a given crosswalk have been evaluated to produce a delay for each of the six pedestrian movements and the volume of these six movements are known, then a volume-weighted average delay can be computed for the crosswalk.

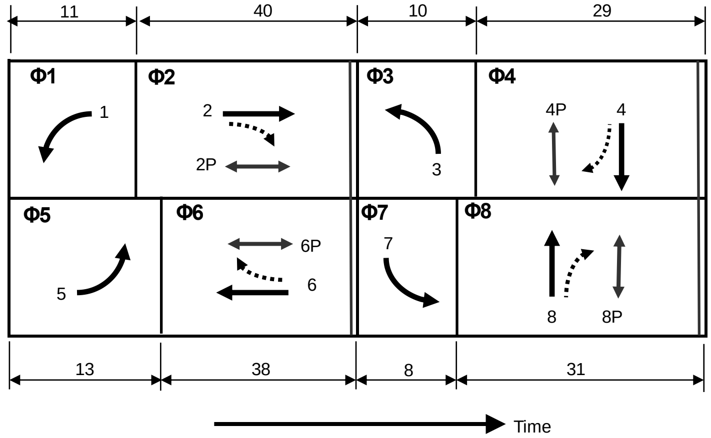
Example Application

The Intersection

The pedestrian crosswalks of interest are on the south and west legs of an intersection. This intersection is shown in Figure 7a where north is toward the top of the figure. The pedestrian movement of interest travels clockwise from corner B to corner C and then to corner D. Signal heads are provided for all pedestrian movements.



a. Intersection Geometry.



b. Signal phase sequence.

Figure 7. Example intersection to illustrate the diagonal crossing procedure.

The east-west street is the major street. The major street traffic signals provide coordination for the through movements using a 90-second cycle length. The minor movements are actuated. Rest-in-walk is not used for any phases. The duration of each phase is shown in Figure 7b. The Walk intervals are set at 5.0 seconds and they start at the same time as the associated phase (i.e., they do not lead or lag the phase). The distance crossed for crosswalk 2 is 38 feet.

The Question

The analyst desires to estimate the delay to pedestrians traveling from corner B to corner D by crossing the south leg and then the west leg.

Computational Steps

The solution follows the steps of the Diagonal Crossing Procedure. The first stage of the crossing occurs in crosswalk 2. It is served by phase 2 so Phase X is phase 2 (i.e., X = 2). The second stage of the crossing occurs in crosswalk 4. It is served by phase 4 so Phase Y is phase 4 (i.e., Y = 4). Finally, if the pedestrian decided to cross in the other direction around the intersection (i.e., counterclockwise), the first phase to serve this travel direction is phase 8 so Phase Z is phase 8 (i.e., Z = 8).

Step 1. Determine the Effective Walk Time

The subject phases are actuated and rest-in-walk is not enabled so the effective walk time is determined by Equation 18. This equation indicates that the effective walk time for Phase X and Phase Z is 9 seconds (= 5 + 4).

Step 2. Determine Crossing Time during First Phase

The local pedestrian population is about 30 percent elderly so an average pedestrian crossing speed of 3.3 ft/s is used for the analysis. Equation 21is used to compute a travel time t_X of 12.0 seconds for Phase X. This value describes the time for pedestrians to travel the 38-ft distance from corner B to corner C.

Step 3. Determine the Start of the Walk Intervals

The relative start time of the Walk intervals for Phase X, Phase Y, and Phase Z are determined by inspection of Figure 7b. For Phase X (i.e., phase 2), the relative start time $T_{Walk,X}$ is 11 seconds. For Phase Y (i.e., phase 4), the relative start time $T_{Walk,Y}$ is 61 seconds (= 11 + 40 + 10). For Phase Z (i.e., phase 8), the relative start time $T_{Walk,Z}$ is 59 seconds (= 11 + 40 + 8).

Step 4. Compute Delay for First Stage Crossing

The end of the effective walk time for Phase X T_X is computed using Equation 22. The computed value of T_X is 20 seconds (= 11 + 9). Similarly, the end of the effective walk time for Phase Z T_Z is computed using Equation 23. The computed value of T_Z is 68 seconds (= 59 + 9).

The time between the end of effective walk time for Phase Z and the start of effective walk time for Phase X t_{XZ} is computed using Equation 25. The computed value of t_{XZ} is 42 seconds (= 20 – 68 + 90).

Finally, the delay for the first stage crossing is computed using Equation 24. The computed delay value $d_{p,1}$ is 13.0 s/p.

Step 5. Compute Delay for Entire Diagonal Crossing

The relative end time of the effective walk period for Phase X T_X is less than that for Phase Z T_Z (i.e., 20 < 68) so the second part of Equation 27 is used to compute the desired time interval t_d. Using this equation, the value of t_d is computed as 62.0 seconds (= 61 – [20 + 68 – 90]/2).

Finally, the diagonal crossing delay is computed using Equation 26. Using this equation, the delay d_p is computed as 50.0 s/p (= 62.0 – 12.0).

Step 6. Compute Delay for Second Stage Crossing

The delay for the second stage crossing $d_{p,2}$ is computed using Equation 28. Using this equation, the delay $d_{p,2}$ is computed as 37.0 s/p (= 50.0 – 13.0).

REFERENCES

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Zhao, J., and Y. Liu. (2017). "Modeling Pedestrian Delays at Signalized Intersections as a Function of Crossing Directions and Moving Paths." *Transportation Research Record No. 2615*. Transportation Research Board, Washington, D.C., pp. 95–104.

Appendix B: Validation of Pedestrian Delay Method for Uncontrolled Crossings

INTRODUCTION

This working paper describes the findings and recommendations from a validation analysis of the revised model for predicting pedestrian delay at uncontrolled crossings. The original form of the model is described in Chapter 20 of the *Highway Capacity Manual* (HCM) 6th edition. Chapter 20 of the HCM describes a methodology for using the model to predict pedestrian delay at two-way stop-controlled (TWSC) intersections and midblock crossings. The revisions address some discontinuities that are present in the delay predicted by the original model. These discontinuities are evident when the delay is examined for a range of traffic volumes. The development of the revised model is documented in Working Paper 1, "Revised Model for Predicting Pedestrian Delay at Uncontrolled Crossings."

The validation analysis is based on the comparison of measured and predicted pedestrian delay. Delay was measured at 20 sites. The revised HCM model was used to predict the delay for each site. Initially, the researchers intended to use a portion of the data to calibrate the revised model and the remaining portion to validate the calibrated model. However, the pedestrian sample size and the range of measured delays were both relatively small such that they would not likely support statistically valid conclusions if the database was partitioned into both calibration and validation datasets.

Given the aforementioned data limitations, an alternative approach was undertaken to make best use of the available data. With this approach, the field data would be used to assess the fit of the predicted delay to the measured delay. If the findings suggested that an empirical adjustment to the model was needed to eliminate prediction bias, then the data would be used to compute the adjustment factor. On the other hand, if the findings suggested that an empirical adjustment was not needed, then the results would be documented as the findings from a validation analysis. In fact, this latter path was found to be the case, and the remaining sections of this paper describe the findings from the validation analysis.

This paper consists of four sections. The first section provides an overview of the data collection procedures and a summary of the collected data. The second section briefly describes the validation process. The third section documents the findings from the validation analysis. The last section describes the conclusions reached as a result of this analysis.

DATABASE DEVELOPMENT

This section provides an overview of the database and data collection procedures as well as a summary of the collected data. Each observation in the database represents traffic conditions and traveler behavior just prior to (and after) the arrival of one or more pedestrians to a specific crossing location. To clarify this definition, consider a crosswalk oriented in an east-west direction. If one eastbound pedestrian arrives to the back-of-curb at the start of the crosswalk, then this pedestrian's behavior (and associated traffic conditions and driver behavior) are recorded as one observation in the database. Similarly, if two westbound pedestrians arrive to the back-of-curb at the start of the crosswalk, then their collective experience is recorded as one observation in the database.

Observations were collected for two two-hour study periods at each of 22 crossing locations (i.e., sites). Each site had an undivided cross section or a two-way left-turn lane. The start and end times associated with each two-hour period were selected to bracket a time period of high pedestrian demand at each site.

Two sites included a right-turn lane to be crossed by pedestrians. The HCM methodology is based on the evaluation of traffic lanes in which the vehicles are moving at relatively constant speed and the volume is somewhat evenly distributed. Vehicles in a turn lane are decelerating and typically have a volume that is notably smaller than that of the adjacent through lanes. Given that right-turn lanes are not explicitly recognized in the HCM methodology, it was decided to exclude the two sites with right-turn lanes from the validation database.

DATA COLLECTION PROCEDURES

This section describes the data that were collected and reduced to produce the variables identified in the following list.

- Motorized vehicle volume
- Motorist yield rate
- Pedestrian delay

For each observation in the database, motorized vehicles on the street to be crossed were counted for the 60-second period that ends with the associated pedestrian's arrival. In other words, each observation includes the number of vehicles that crossed the crosswalk for the 60-second period just prior to the pedestrian's arrival. For each two-hour study period, these one-minute counts were averaged across all observations and then the average was multiplied by 60 minutes per hour to obtain an equivalent hourly flow rate.

The motorist yield rate was determined by observing the response of the "first driver able to stop" following the pedestrian's arrival to the crossing location. Any driver within the stopping sight distance of the crosswalk was excluded from this consideration because this driver was believed to be unable to safely stop in advance of the crosswalk. The action of the first driver able to stop while the pedestrian waited was recorded as "yielded" or "did not yield." If the pedestrian was able to begin the crossing as soon as they arrived (i.e., the gap between vehicles was sufficiently long that the pedestrian could safely cross without any delay), then "no interaction" was recorded. Thus, a "status indicator" (i.e., yielded, did not yield, or no interaction) was recorded for each lane intersecting the crosswalk.

To compute the motorist yield rate for a given site and study period, two numbers were computed by summing the status indicator value across all observations. The first number was computed as the number of lanes in which the first driver yielded. The second number was computed as the number of lanes in which a first driver was present (i.e., the response was either "yield" or "did not yield"). The motorist yield rate (in decimal) for the study period was computed by dividing the first number by the second number.

Pedestrian delay is defined in the HCM as the time the pedestrian waits to start the crossing. One delay value was recorded for each observation. This value was computed as the difference between the time the pedestrian arrived to the crossing location and the time the pedestrian stepped off the curb to start the crossing. For each two-hour study period, the delay values were averaged across all observations to obtain an estimate of the average pedestrian delay.

DATABASE SUMMARY

This section provides a summary of the data collected at each site during each study period. The first subsection describes the study site location and geometry. The second subsection provides a summary of the key traffic characteristics and performance measures measured at each site.

Study Sites

The characteristics of the 20 study sites represented in the validation database are shown in Table B-1. Eleven sites are located in Portland, Oregon and the remaining sites are located in Chapel Hill, North Carolina. The street on which the subject crosswalk is located is described in the last three columns of the table. The speed limit in the set of sites ranges from 20 to 35 miles per hour. The annual average daily traffic (AADT) volume ranges from 3,600 to 41,000 vehicles per day.

Table B-1. Study site characteristics

Site No.	Location (City, State)	Site Name	Description of Street Being Crossed		
			Street Name	Speed Limit (mi/h)	AADT (veh/day)
1	Portland, OR	SE 80th Ave. & SE Stark St.	SE Stark St.	20	10,600
2	Chapel Hill, NC	S Columbia St. (by Merritt's)	S Columbia St.	35	14,000
3	Chapel Hill, NC	Estes Dr. & Wilson Park Trail	Estes Dr.	35	13,900
4	Chapel Hill, NC	Willow Dr. & S Mall Entrance	Willow Dr.	25	9,000
5	Chapel Hill, NC	W Franklin St. & N. Roberson St.	W Franklin St.	25	15,000
6	Portland, OR	NE Glisan St. & NE 80th Ave.	NE Glisan St.	30	16,400
7	Portland, OR	SE Hawthorne Blvd. & SE 46th Ave.	SE Hawthorne Blvd.	20	14,500
8	Portland, OR	NE MLK Blvd. & NE Sumner St.	NE MLK Blvd.	30	29,700
9	Portland, OR	NE 33rd Ave. & NE Emerson St.	NE 33rd Ave.	30	15,000
10	Portland, OR	NE 33rd Ave. & NE Shaver St.	NE 33rd Ave.	30	15,000
11	Portland, OR	NE MLK Blvd. & NE Graham St.	NE MLK Blvd.	30	29,700
12	Portland, OR	NE 26th Ave. & E. Burnside St.	E. Burnside St.	30	17,400
13	Chapel Hill, NC	Pittsboro St. & Dauer Dr.	Pittsboro St.	25	8,300
14	Chapel Hill, NC	Pittsboro St. & Vance St.	Pittsboro St.	25	8,500
15	Chapel Hill, NC	Seawell School Rd. & High School Rd.	Seawell School Rd.	35	3,600
16	Chapel Hill, NC	Willow Dr. (at Willow Terrace Apts.)	Willow Dr.	25	7,900
17	Portland, OR	NE Sandy Blvd. & NE 17th Ave.	NE Sandy Blvd.	30	25,100
18	Portland, OR	SE Powell Blvd. & SE 36th Ave.	SE Powell Blvd.	35	41,000
19	Chapel Hill, NC	South Rd. & Stadium Dr.	South Rd.	25	7,400
20	Portland, OR	SW 37th Ave. & SW Vermont St.	SW Vermont St.	35	9,400

The streets on which the subject crosswalk is located were selected to collectively offer a range of geometric features. These features are listed in Table B-2. The sites are shown to have either an undivided or a two-way-left-turn lane cross section. Candidate sites having a divided cross section were not included in this validation analysis because the median could function as a refuge for some pedestrians (and not for others). Those pedestrians that used the median as a refuge would effectively be crossing two one-way streets (one at a time). Those pedestrians that did not stop on the median would effectively be crossing a two-way street. Each of these two scenarios would have different delay implications and would require a distinctly different application of the HCM methodology. To avoid this complication (and associated uncertainty to the predicted delays), the validation analysis focused on streets where the crossing maneuver should always be completed in one stage.

The possible influence of right-turn lanes was previously discussed as a complicating factor in the validation analysis. For this reason, the two sites with a right-turn lane were excluded from the database. A similar concern is present for sites with a left-turn lane. However, sites with left-turn lanes were kept in the database given their prevalence at unsignalized crossing locations and, thus, the need to conduct a validation analysis for these locations. The presence of left-turn lanes was recorded (as shown in column 6 of Table B-2) to facilitate the evaluation of this influence on pedestrian delay.

Table B-2. Geometric features of the street being crossed

Site No.	Street Name	Travel Directions Supported	Cross Section Type	Number of Through Lanes	Number of Left-Turn Lanes	Pedestrian Crossing Distance (ft)
1	SE Stark St.	One way	Undivided	2	0	43
2	S Columbia St.	Two way	Undivided	2	1	44
3	Estes Dr.	Two way	Undivided	2	0	32
4	Willow Dr.	Two way	TWLTL	2	1	35
5	W Franklin St.	Two way	Undivided	4	0	60
6	NE Glisan St.	Two way	TWLTL	2	1	50
7	SE Hawthorne Blvd.	Two way	TWLTL	2	1	53
8	NE MLK Blvd.	Two way	Undivided	4	0	56
9	NE 33rd Ave.	Two way	Undivided	2	0	24
10	NE 33rd Ave.	Two way	Undivided	2	0	37
11	NE MLK Blvd.	Two way	Undivided	4	0	45
12	E. Burnside St.	Two way	TWLTL	3	1	55
13	Pittsboro St.	One way	Undivided	2	0	30
14	Pittsboro St.	One way	Undivided	2	0	30
15	Seawell School Rd.	Two way	Undivided	2	1	50
16	Willow Dr.	Two way	Undivided	2	0	35
17	NE Sandy Blvd.	Two way	Undivided	4	0	58
18	SE Powell Blvd.	Two way	TWLTL	4	1	60
19	South Rd.	Two way	Undivided	2	1	40
20	SW Vermont St.	Two way	Undivided	2	0	40

Summary Statistics

The traffic data collected for each site and study period are summarized in Table B-3. At each site, data were collected during a weekday and a weekend day. The weekday study period was typically from 4:00 to 6:00 pm. The weekend day study period was typically from 12:00 to 2:00 pm. Vehicle volume during the study periods ranged from 120 to 2,693 vehicles per hour. The low pedestrian volume at some sites limited the number of observations of the "first driver able to stop" and pedestrian delay.

Motorist yield rates are shown in the last column of Table B-3. In general, one rate was computed for each combination of site and study period. The rates are shown to range from 0.333 to 1.000. To ensure reasonable statistical validity in the computed motorist yield rates at a given site, the observations for any study period for which there were fewer than 9 observations was combined with the observations for the other study period at the same site. In this situation, the pooled data were used to compute one motorist yield rate for the site.

The measured pedestrian volumes, pedestrian crossing times, and pedestrian delays are shown in Table B-4. The pedestrian volumes range from 1 to 128 pedestrians per hour. The pedestrian crossing times range from 4.8 to 14.9 seconds. The delays range from 0.2 to 15.8 seconds per pedestrian.

Table B-3. Traffic characteristics at the subject crossing – motorized vehicles

Site No.	Street Name	Day Type	Study Period	Vehicle Volume (veh/h)	Motorist Yield Data: Motorist Observations	Motorist Yield Data: Motorist Yield Rate (decimal)
1	SE Stark St.	Weekday	4:00-6:00 pm	785	32	0.625
		Weekend	12:00-2:00 pm	747	69	0.986
2	S Columbia St.	Weekday	11:50-1:50 pm	1159	22	1.000
		Weekend	12:00-2:00 pm	969	153	0.333
3	Estes Dr.	Weekday	4:00-6:00 pm	1120	7	0.750
		Weekend	12:00-2:00 pm	990	5	
4	Willow Dr.	Weekday	4:00-6:00 pm	676	12	0.471
		Weekend	12:00-2:00 pm	630	5	
5	W Franklin St.	Weekday	4:00-6:00 pm	862	23	0.913
		Weekend	12:00-2:00 pm	791	56	0.839
6	NE Glisan St.	Weekday	4:00-6:00 pm	1449	13	0.947
		Weekend	12:00-2:00 pm	1493	6	
7	SE Hawthorne Blvd.	Weekday	4:00-6:00 pm	1033	24	0.500
		Weekend	12:00-2:00 pm	919	41	0390
8	NE MLK Blvd.	Weekday	4:00-6:00 pm	1960	121	0.785
		Weekend	12:00-2:00 pm	1842	68	0.750
9	NE 33rd Ave.	Weekday	4:00-6:00 pm	1197	181	0.989
		Weekend	12:00-2:00 pm	892	68	0.926
10	NE 33rd Ave.	Weekday	4:00-6:00 pm	1296	5	0.556
		Weekend	12:00-2:00 pm	1065	4	
11	NE MLK Blvd.	Weekday	4:00-6:00 pm	2220	20	0.700
		Weekend	12:30-2:30 pm	1727	16	0.500
12	E. Burnside St.	Weekday	4:00-6:00 pm	2052	24	0.833
		Weekend	12:00-2:00 pm	1133	16	0.813
13	Pittsboro St.	Weekday	4:00-6:00 pm	655	7	0.571
		Weekend	12:00-2:00 pm	390	0	
14	Pittsboro St.	Weekday	4:00-6:00 pm	651	114	0.974
		Weekend	12:00-2:00 pm	556	9	0.556
15	Seawell School Rd.	Weekday	4:00-6:00 pm	620	14	0.867
		Weekend	12:00-2:00 pm	120	1	
16	Willow Dr.	Weekday	4:00-6:00 pm	508	8	0.889
		Weekend	12:00-2:00 pm	420	1	
17	NE Sandy Blvd.	Weekday	4:00-6:00 pm	2120	7	0.550
		Weekend	12:00-2:00 pm	940	13	
18	SE Powell Blvd.	Weekday	4:00-6:00 pm	2693	36	0.972
		Weekend	12:00-2:00 pm	2415	42	0.952
19	South Rd.	Weekday	4:00-6:00 pm	800	4	0.667
		Weekend	6:50-8:50 pm	700	2	
20	SW Vermont St.	Weekday	4:00-6:00 pm	885	2	0.500
		Weekend	4:00-6:00 pm	375	5	0.600

Table B-4. Traffic characteristics at the subject crossing – pedestrians

Site No.	Street Name	Day Type	Pedestrian Volume (ped/h)	Pedestrian Crossing time (s)	Pedestrian Delay (s/p)
1	SE Stark St.	Weekday	25.5	8.9	2.6
		Weekend	64.5	10.3	1.1
2	S Columbia St.	Weekday	71.0	10.1	12.4
		Weekend	128.0	10.1	9.7
3	Estes Dr.	Weekday	3.0	5.7	6.8
		Weekend	3.0	5.0	3.0
4	Willow Dr.	Weekday	9.5	8.6	1.9
		Weekend	3.0	8.2	0.3
5	W Franklin St.	Weekday	19.5	12.6	5.1
		Weekend	53.0	12.8	6.0
6	NE Glisan St.	Weekday	4.0	11.8	2.6
		Weekend	4.5	12.9	3.1
7	SE Hawthorne Blvd.	Weekday	14.5	13.8	2.4
		Weekend	33.0	14.9	2.7
8	NE MLK Blvd.	Weekday	29.5	11.5	3.3
		Weekend	18.0	11.3	4.0
9	NE 33rd Ave.	Weekday	87.5	5.4	1.9
		Weekend	54.0	4.8	1.8
10	NE 33rd Ave.	Weekday	3.5	7.9	4.9
		Weekend	2.0	6.2	4.8
11	NE MLK Blvd.	Weekday	5.5	10.2	4.8
		Weekend	6.0	8.8	5.3
12	E. Burnside St.	Weekday	20.0	10.1	10.3
		Weekend	10.0	10.6	2.9
13	Pittsboro St.	Weekday	12.0	6.5	6.4
		Weekend	3.0	6.3	0.2
14	Pittsboro St.	Weekday	90.5	6.3	2.9
		Weekend	7.5	6.3	1.8
15	Seawell School Rd.	Weekday	9.5	9.7	3.5
		Weekend	1.5	8.1	1.8
16	Willow Dr.	Weekday	11.5	8.1	1.6
		Weekend	1.0	6.7	4.4
17	NE Sandy Blvd.	Weekday	3.0	12.2	9.9
		Weekend	10.0	11.2	15.8
18	SE Powell Blvd.	Weekday	8.5	10.4	3.2
		Weekend	13.0	12.9	3.6
19	South Rd.	Weekday	1.5	9.5	5.4
		Weekend	2.5	9.8	13.3
20	SW Vermont St.	Weekday	2.0	8.4	2.2
		Weekend	13.5	10.7	3.8

VALIDATION PROCESS

The model validation process consisted of a series of steps that facilitated a comparison of delay estimates from the revised HCM model with the measured delay at the study sites. As a first step of the process, the overall average walking speed was estimated. This speed was computed by dividing the measured pedestrian crossing distance by the measured average crossing time. It was then used in Step 2 of the HCM methodology to estimate the critical headway for a single pedestrian t_c.

The second step of the validation process entailed using the aforementioned critical headway in the remaining steps of the HCM methodology to compute the predicted average pedestrian delay. The measured vehicle and pedestrian volumes were used as input values to the HCM methodology to further tailor the calculation of the predicted delay to each site and study period combination.

The third step of the validation process entailed using graphical presentations and statistical measures to assess the fit of the predicted delay estimates to the measured delay estimates. It was during this step that a determination was made regarding the need for an empirical adjustment to the model to remove any observed bias in the predicted delay. Fortunately, no bias was found and the empirical adjustment was not needed. The findings from this step are discussed in the next section.

FINDINGS

This section documents the findings from the validation analysis. It consists of two subsections. The first subsection describes the findings from the evaluation of average walking speed. The second subsection describes the findings from the validation of the revised model for predicting pedestrian delay.

Crosswalk Walking Speed

The measured crossing time was divided into the measured crossing distance to compute the average crosswalk walking speed for each of the site and study period combinations. The average walking speed was computed as 4.7 ft/s with a range of 3.6 to 6.5 ft/s across the 40 combinations. An exploratory analysis investigated the possible influence of state (i.e., Oregon vs North Carolina), pedestrian volume, vehicle volume, and crossing distance on walking speed. None of these variables were found to have statistically significant influence on speed. However, it was noted that speed tended to decrease with an increase in pedestrian volume. This influence of pedestrian volume is consistent with the pedestrian walking speed prediction equation cited in HCM Chapter 18.

The average walking speed of 4.7 ft/s that was computed from the data is slightly larger than the sidewalk free-flow walking speed of 4.4 ft/s that is recommended in HCM Chapter 18. The pedestrians observed at the study sites typically crossed alone or as a group of two. Thus, in general, they are considered to have been walking in a free-flow condition during the study period. The fact that the observed average crosswalk walking speed of 4.7 ft/s is larger than the sidewalk walking speed of 4.4 ft/s suggests that pedestrians in the crosswalk desire to minimize their "time exposure" to conflicting vehicles by walking quickly. It should be noted that HCM Chapter 20 (which documents the delay prediction methodology discussed in this paper) recommends a default pedestrian crossing speed of 3.5 ft/s. All of the study sites had an average walking speed in excess of 3.5 ft/s.

The average walking speed of 4.7 ft/s was divided into the crossing distance to compute the predicted crossing time. This predicted crossing time was then examined graphically over the range of crossing times found at the study sites. A comparison of the predicted and measured crossing times is shown in Figure B-1. The predicted crossing time is shown in the figure to provide an unbiased estimate of the measured crossing time over the range of 5 to 13 seconds crossing time. The R^2 value of 0.75 indicates that the predicted crossing time explains about 75 percent of the variation in the measured crossing times.

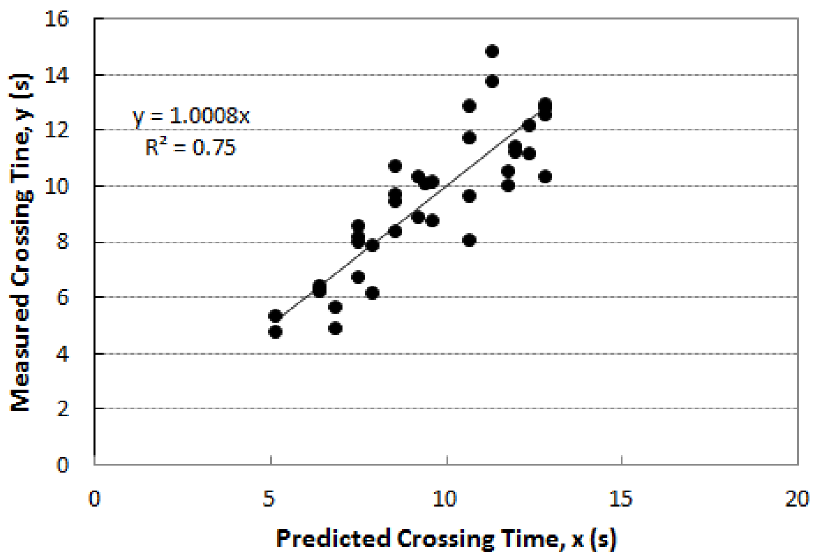

Figure B-1. Comparison of predicted and measured crossing time.

Pedestrian Delay

The revised model (described in Working Paper 1) was used to calculate the average pedestrian delay for each of the site and study period combinations. As part of this calculation, the walking speed of 4.7 ft/s was used to calculate the "critical headway for a single pedestrian" t_c for each site. This calculation used the following equation.

$$t_c = \frac{L}{S_p} + t_s \qquad \textbf{Equation B-1}$$

where

t_c = critical headway for a single pedestrian (s),

S_p = average pedestrian walking speed (ft/s),

L = crosswalk length (ft), and

t_s = pedestrian start-up time and end clearance time (default: 3.0 s) (s).

The measured pedestrian volume and the measured vehicle volume were used to compute average pedestrian group size and group critical headway. The measured vehicle volume was also used to compute the probability of a delayed crossing and the average delay when waiting for an adequate gap to cross. The measured motorist yield rate was used to compute the probability that motorists would yield to pedestrians waiting to cross the traffic lanes at each site. This rate and the other intermediate results were then used to compute the average pedestrian delay.

The predicted and measured pedestrian delay values were assessed using graphical presentations and statistical measures. An exploratory analysis investigated the prediction "error" (= measured delay – predicted delay) and the squared error. The intent of the investigation was to understand the conditions that might be associated with relatively large errors. The analysis revealed that the "pedestrian start-up time and end clearance time" variable t_s in Equation B-1 had a significant effect on the magnitude of the error. Further investigation revealed that reducing the value of this variable from the default value of 3.0 s to 0.0 s greatly reduced the overall square error. This trend suggests that pedestrians at the study sites tend to be anticipating the arrival of an adequate gap (i.e., they do not require any start-up time) and start immediately upon its arrival. It also suggests that they are not requiring any end clearance time. However, it is more likely that (1) they do not need as much end clearance time as suggested by the 3.0 s value and (2) the vehicle defining the end of the adequate gap is often not traveling in the last lane crossed by the pedestrian (hence, crossing safety is assured spatially by lane separation rather than temporally by a second or two of clearance time). For these reasons, the value of t_s was retained as 0.0 s for the presentation of validation results.

The exploratory analysis also revealed that the presence of a left-turn lane had an influence on the squared error value. As a result, the sites were grouped into two sets. One set included all sites that do not have a left-turn lane in the path of the crosswalk. The other set included all sites that have a left-turn lane in the path of the crosswalk. A comparison of the predicted and measured average delays in the first and second sets is shown in Figure B-2 and Figure B-3, respectively.

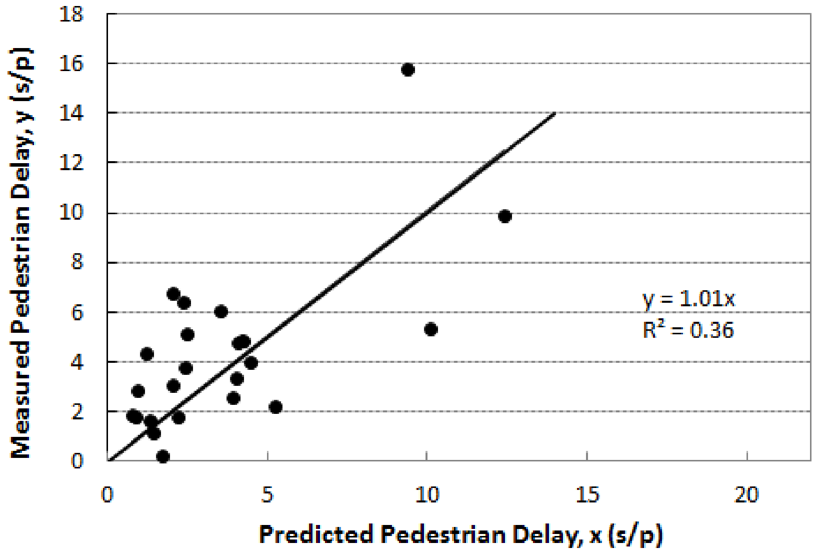

Figure B-2. Comparison of predicted and measured delay – crossings without a left-turn lane

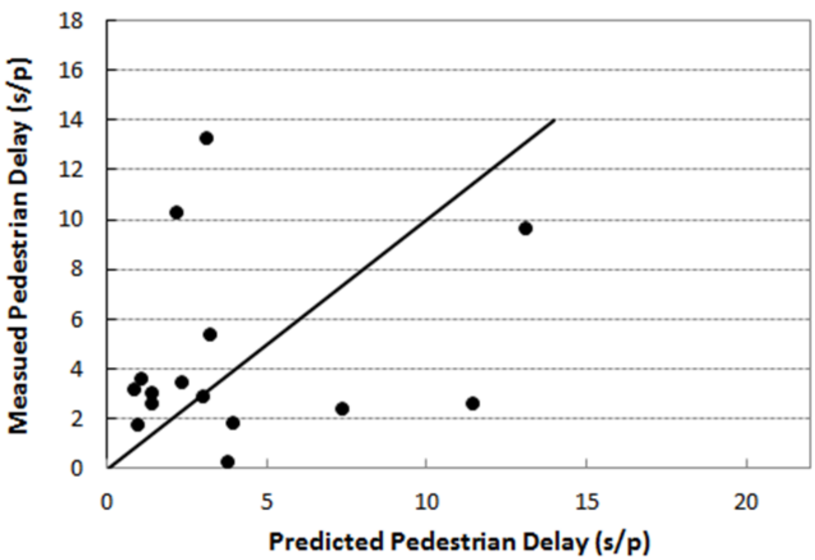

Figure B-3. Comparison of predicted and measured delay – crossings with a left-turn lane

Two factors should be noted as relates to the variation in the data shown in Figure B-2 and Figure B-3. First, field-measured delays have highly variable values. As a result, a relatively large number of delay observations must be measured at a given site to produce a stable estimate of the site's expected average delay. The relatively light pedestrian volumes at most study sites resulted in there being a relatively small sample of delay observations at these sites. As a result, the uncertainty in the delay data is relatively high.

Second, statistics that describe overall model fit (e.g., R^2) can provide a more reliable indication of goodness-of-fit when there is a wide range in the independent variable (i.e., predicted delay). As shown in the figures, the predicted delays are in a relatively narrow range of 1 to 13 s/p. Delays in excess of 13 s/p would be found at sites where the volume is high and the motorist yield rate is low. However, the higher-volume sites in this study typically have a high yield rate because they have a special treatment applied at the crossing location to encourage motorist yielding to pedestrians. As a result, the range in the predicted delay at the set of sites studied is relatively small and limited to pedestrian delays associated with levels of service A, B, or C.

The data in Figure B-2 show that the revised model can provide an unbiased prediction of the delay for crossings that do not include a left-turn lane. The R^2 of 0.36 suggests that the predictive model explains about 36 percent of the variability in the measured delay data. If the value of t_s is changed to 3.0, several sites have an exceptionally large predicted delay (and associated error) such that the R^2 is effectively zero.

If the revisions described in Working Paper 1 (presented in the quarterly progress report for the first quarter of 2019) are not applied (i.e., the HCM methodology is used without revision), the predicted delay overestimates the measured delay by a factor of about 3.7 (i.e., measured delay = 0.27 × predicted delay) and the R^2 is reduced to 0.31. If the revisions are not applied and the value of t_s is changed to 3.0, several sites have an exceptionally large predicted delay (and associated error) such that the R^2 is effectively zero.

The data in Figure B-3 show weak correlation between the predicted and measured delay for crossings that include a left-turn lane. In fact, the R^2 is negligibly small. The data appear to be located around the diagonal line (i.e., the line where predicted values equal measured values) which suggests that there is no bias in the prediction—just a large degree of uncertainty.

As noted previously for right-turn lanes, the presence of a left-turn lane is not explicitly recognized in the HCM methodology. This methodology is based on the evaluation of traffic lanes in which the vehicles are moving at relatively constant speed and the volume is somewhat evenly distributed. Vehicles in a turn lane are decelerating and typically have a volume that is notably smaller than that of the adjacent through lanes.

The data in Figure B-3 indicate that the predicted pedestrian delay is much larger than the measured delay at some sites. Yet, at other sites, the opposite trend is found. The presence of a left-turn lane could increase pedestrian delay at a site if the left-turning vehicle is stopped at the crosswalk waiting for a gap in opposing vehicle traffic and the waiting pedestrians doubt that the left-turn driver will yield to them should they cross in front of the vehicle (so they do not start their crossing). On the other hand, the presence of a left-turn lane could decrease pedestrian delay if the unoccupied left-turn lane is used as a pedestrian refuge area (such that the crossing can be completed in two stages).

CONCLUSIONS AND RECOMMENDATIONS

Based on the findings documented in the previous section, the following conclusions are offered:

- At sites that do *not* have a left-turn lane, the revised model can reliably predict the average pedestrian delay. The data collected confirm this conclusion for delays less than 15 s/p. The theoretic basis of the delay model formulation provides reasonable confidence that this predictive reliability extends to delay values that exceed 15 s/p.
- At sites that have a left-turn lane, the revised model can provide an unbiased prediction of the average pedestrian delay. However, the uncertainty associated with the predicted value will be large because the true left-turn delay will depend on the left-turn volume, left-turn capacity, and whether the left-turn lane is used by pedestrians as a refuge so they can complete the crossing in two stages. The predicted delay for these sites should be used carefully and it should be confirmed by field observation whenever possible.
- The reliability of the predicted delay is highly dependent on the values used for the crosswalk walking speed S_p and the "pedestrian start-up time and end clearance time" t_s. Local values should be established for these two variables whenever possible. This research has shown that values of 4.7 ft/s and 0.0 s for S_p and t_s, respectively, provided the most reliable delay estimates for the study sites. The HCM default values 3.5 ft/s and 3.0 s for S_p and t_s, are likely to provide conservatively high delay estimates (which may be appropriate for some design applications).

It is recommended that additional research be undertaken to extend the revised HCM model so that it can be used to obtain reliable estimates of the predicted average pedestrian delay at sites where the crosswalk crosses a left-turn lane, a right-turn lane, or both. For the "left-turn lane present" case, this research should consider the effect of the following factors on pedestrian delay: left-turn volume, left-turn capacity, and whether the left-turn lane is used by pedestrians as a refuge so they can complete the crossing in two stages.

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TECHNICAL MEMORANDUM

PBOT Bicycle Signal Support, Task 4: Person Delay

Proposed Person Delay Methodology

Date:	May 20, 2015	Project #:18031.4
To:	Peter Koonce	
From:	Paul Ryus	
cc:	Jesse Boudart & Joe Bessman, KAI	

INTRODUCTION

The objective of Task 4 is to develop a methodology for estimating the impact of traffic signal timing changes on overall person delay, considering all of the multimodal users of an intersection (i.e., autos, trucks, pedestrians, bicyclists, and transit passengers). *Highway Capacity Manual* (HCM) methods for estimating delay for pedestrians and bicycles do not address the full range of signal timing options available to the city. This task will develop the necessary models for estimating vehicular delay by mode, and will develop a spreadsheet that will import data from Synchro, perform vehicular delay calculations for each travel mode, and estimate total person-delay given user-supplied average vehicle occupancies.

This technical memo describes the proposed delay-calculation methods by mode, summarizes the data needed to be (1) obtained from Synchro output and (2) provided by the user, and offers comments on the sensitivity of the methods to various inputs.

AUTO MODE DELAY CALCULATION

The following steps are followed to calculate auto person-delay:

1. Calculations are performed by turning movement. The letter i is used in this memorandum to indicate a particular turning movement and to differentiate movement-specific values from intersection-wide or global values. A given intersection will have n different turning movements.

2. Motorized vehicle volume V_i (veh/h), the peak hour factor PHF_i (decimal), the control delay d_i (s), and the heavy vehicle percentage $HV\%_i$ (unitless) are available directly from Synchro output for each movement.

3. The user supplies an average vehicle occupancy for autos AVO_{auto} (p/auto).

4. The auto flow rate during the peak 15 minutes for movement *i* (in automobiles) is: $v_{auto,i} = (V_i/PHF_i) \times [\,(100 - HV\%_i)/100] \times T$, where *T* is the analysis period length in hours (=0.25 h).

5. The total auto person delay in the peak 15 minutes, in person-seconds, is: $TPD_{auto} = AVO_{auto} \times \sum_{i=1}^{n} v_{auto,i} d_i$

6. The average auto person delay, in seconds, is: $PD_{auto} = TPD_{auto}/(AVO_{auto} \times \sum_{i=1}^{n} v_{auto,i})$

If transit signal priority (TSP) is in use at the intersection, Synchro's output control delay may need to be modified to reflect signal timing changes when priority is granted. This modification is discussed in the transit mode section.

TRUCK MODE

Trucks and buses are addressed together as different types of "heavy vehicles" in the HCM, but are addressed separately here because of the widely different vehicle occupancies for the two modes and the potential for transit signal priority for buses. The following steps are followed to calculate truck person-delay:

1. Motorized vehicle volume V_i (veh/h), the peak hour factor PHF_i (decimal), control delay d_i (s), and the heavy vehicle percentage $HV\%_i$ (unitless) are available directly from Synchro output for each movement.

2. The user supplies an average vehicle occupancy for trucks AVO_{truck} (p/truck), and the number of buses (or other transit vehicles) per hour by turning movement $V_{bus,i}$ (bus/h).

3. The heavy vehicle volume for movement *i* is: $V_{HV,i} = V \times [\,(100 - HV\%_i)/100]$.

4. The truck volume for movement *i* is: $V_{truck,i} = V_{HV,i} - V_{bus,i}$.

5. The truck flow rate during the peak 15 minutes for movement *i* is: $v_{truck,i} = V_{truck,i}/PHF_i \times T$ where *T* is the analysis period length (=0.25 h).

6. The total truck person delay in the peak 15 minutes, in person-seconds, is: $TPD_{truck} = AVO_{truck} \times \sum_{i=1}^{n} v_{truck,i} d_i$

7. The average truck person delay, in seconds, is: $PD_{truck} = TPD_{truck}/(\sum_{i=1}^{n} v_{truck,i} \times AVO_{truck})$

If transit signal priority (TSP) is in use at this intersection, Synchro's output control delay may need to be modified to reflect signal timing changes when priority is granted. This modification is discussed in the transit mode section.

BICYCLE MODE

There are two scenarios for the bicycle mode. In the first scenario, bicycles share a lane with automobiles and have no opportunity to pass automobiles on the right to move past stopped cars. In this scenario, average delay per bicycle is equal to average delay per auto. The person-delay calculation is also the same as for autos, except that an average bicycle occupancy AVO_{bike} (in persons per bicycle, reflecting tandem bicycles, bike trailers, etc.) is substituted for AVO_{auto}.

In the second scenario, a bicycle lane or shoulder is provided that allows bicycles to move separately from the parallel auto traffic. The HCM provides Equation 18-79 for estimating bicycle delay for a bicycle lane. This equation assumes that the traffic signal is the only source of bicycle delay. It allows the bicycle lane to be timed differently from parallel traffic (i.e., a bicycle signal), although the general guidance is to use the same effective green time as for automobiles. The equation assumes that the bicycle lane operates under capacity.

The HCM equation does not account for bicycle progression between traffic signals, which may be better or worse than the progression provided for automobiles. It also does not account for bicycle lane blockage effects (e.g., stopped buses in the bicycle lane) or bicycle lane treatments such as bicycle boxes, both of which may influence bicyclist delay. Therefore, to meet PBOT's needs, the HCM bicycle delay calculation is recreated using additional bicycle-specific inputs. As with the basic HCM delay equation, it is assumed that the bicycle facility operates under capacity for bicycles, both during the peak 15 minutes and in any given cycle. The following steps are involved:

1. Bicycle volumes by movement $V_{bike,i}$ (bicycles/h), the effective green by movement g_i (s), and the cycle length C (s), are available directly from Synchro output. The bicycle saturation flow rate $s_{0,bike}$ is assumed to be 2,000 bicycles per lane per hour of green, per the HCM.

2. An adjusted bicycle saturation flow rate $s_{bike,i}$ is calculated for each movement. Buses that stop in the bicycle lane, parking-related activities, deliveries, etc. may hinder bicyclists using the bicycle lane and reduce the bicycle lane capacity. We are not aware of research that quantifies these effects, and the effect may be site-specific, depending on bicyclists' ability and desire to use the adjacent travel lane to avoid such conflicts. Therefore, the spreadsheet will provide the ability for the user to input an *optional* bicycle saturation flow adjustment factor $f_{bike,i}$ (decimal) by movement to account for these effects. In the absence of other data, the default value for this factor will be 1.0, producing a saturation flow rate consistent with the current HCM method. Then:

$$s_{bike,i} = s_{0,bike} f_{bike,i}$$

3. The user would provide the bicycle arrival type by movement, reflecting the quality of the signal progression provided for bicyclists. These values would be converted by the spreadsheet into a bicycle platoon ratio by movement $R_{p,bike,i}$ on the basis of HCM Exhibit 18-8. The proportion of bicycles arriving on green $P_{bike,i}$ is then:

$$P_{bike,i} = R_{p,bike,i}\left(\frac{g_{bike,i}}{C}\right)$$

In most cases, the bicycle effective green $g_{bike,i}$ will be the same as the auto effective green g_i available from the Synchro output, but if a bicycle signal is provided, $g_{bike,i}$ would need to be supplied by the user.

4. The bicycle flow rate during the peak 15 minutes for movement *i* is: $v_{bike,i} = (V_{bike,i}/PHF_i) \times T$, where *T* is the analysis period length (=0.25 h). $PHF_{bike,i}$ is the bicycle-specific peak hour factor for movement *i*, and should be input by the user if available. If not available, the auto PHF by movement would be used from the Synchro output.

5. The base capacity of the bicycle movement, in bicycles/h, is the product of the adjusted bicycle saturation flow rate $s_{bike,i}$, and the $g_{bike,i}/C$ ratio. The HCM assumes the bicycles ride single-file in the bike lane; however, when bicycle boxes or wide bicycle lanes are provided, or when bicyclists line up side-by-side in the first row or two of bicyclists at the stop bar, bicycle lane capacity would increase because more bicyclists at a time can enter the intersection. Therefore, the bicycle lane capacity is assumed to be the base bicycle capacity plus the extra number of bicyclists per cycle N_{xb} above 1 per row observed during periods of peak bicycle volumes. N_{xb} would be a user input; if not provided (i.e., N_{xb} = 0), the calculated capacity would be the same as currently provided in the HCM. For the peak 15 minutes, the bicycle capacity is:

$$c_{bike,i} = \left[s_{bike,i}\left(\frac{g_{bike,i}}{C}\right) + N_{xb}\left(\frac{3{,}600}{C}\right)\right] \times T$$

6. The volume-to-capacity ratio for the bicycle movement $X_{bike,i}$ during the peak 15 minutes is then:

$$X_{bike,i} = \frac{v_{bike,i}}{c_{bike,i}}$$

7. Given the assumption of under-capacity bicycle operations during the peak 15 minutes, initial queue delay is zero. Given the assumption that no bicycle cycle failures occur, incremental delay is also zero. Therefore bicycle delay d_{bike} is assumed to be equal to the uniform delay $d_{1,bike}$, calculated according to the HCM:

$$d_{1,bike,i} = PF_{bike,i}\ \frac{0.5\ C\left(1 - g_{bike,i}/C\right)^2}{1 - \left[X_i \times g_{bike,i}/C\right]}$$

where

$$PF_{bike,i} = \frac{1 - P_{bike,i}}{1 - g_{bike,i}/C} \times \frac{1 - y_i}{1 - X_{bike,i} \times\ P_{bike,i}} \times \left[1 + y_i\frac{1 - P_{bike,i}\left(\ C/g_{bike,i}\right)}{1 - g_{bike,i}/C}\right]$$

and

$$y_i = X_{bike,i}\left(g_{bike,i}/C\right)$$

8. The total bicycle person delay during the peak 15 minutes, in person-seconds, is: $TPD_{bike} = AVO_{bike} \times \sum_{i=1}^{n} v_{bike,i} d_i$

9. The average bicycle person delay, in seconds, is: $PD_{bike} = TPD_{bike} / (\sum_{i=1}^{n} v_{bike,i} \times AVO_{bike})$

PEDESTRIAN MODE

There are three scenarios for the pedestrian mode: (1) pre-timed or coordinated semi-actuated signal operation with no permissive period provided for the pedestrian phase, (2) coordinated signal operation with a permissive period provided for the pedestrian phase, and (3) free signal operation. Different scenarios may apply to different crosswalks. It is assumed for ease of presentation that scenario #2 only applies to the crosswalks parallel to the minor-street movements; if this is not the case, the equations for scenario #2 can be applied to crosswalks parallel to the major-street movements by treating the major street as the minor street and vice versa.

Pre-Timed and Coordinated Semi-Actuated Without Permissive Period

In this scenario, pedestrian delay for a given movement (crosswalk) *i* is given directly by the HCM:

$$d_{ped,i} = \frac{(C - g_{Walk,i})^2}{2\,C}$$

where the cycle length *C* can be obtained from Synchro output and the effective pedestrian green time $g_{Walk,i}$ is provided by the user, following the guidance in the HCM (see page 18-62, plus guidance on the length of the pedestrian Walk interval under coordinated operation starting on page 18-19).

Coordinated Actuated With Permissive Period

In this scenario, if a minor street call is received during the permissive period *PP* while the major street phase is active, the major street phase is terminated and the call is served following the major street pedestrian clear interval (or the yellow change and red clearance intervals if there is no pedestrian phase associated with the major street or rest in walk is not enabled for the major street). In this situation, the pedestrian delay is equal to the length of the major street pedestrian clear interval (or the yellow change and red clearance interval if the conditions stated above are met). If the minor street pedestrian call occurs outside the permissive period while the major street phase is active, the pedestrian phase is not served until the next cycle.

An added complication is that a pedestrian call for the crosswalk or a call for the corresponding minor-street vehicular phase (if present) may have already occurred prior to the arrival of a given pedestrian, in which case the major street phase would have already terminated by the time the pedestrian arrived. If this were to happen every cycle (i.e., due to high side-street volumes and/or high crosswalk volumes), the signal would act like a pre-timed signal for the crosswalk, and the delay would be the same as in the pre-timed scenario.

The pedestrian delay is therefore a function of (1) the probability P_{PC} that a prior call has been placed that would have activated the pedestrian phase at the start of the cycle, and (2) the length of the permissive period, if no prior call was placed. Calculating the overall delay requires looking at two consecutive cycles and calculating (1) the probability of a call being placed in the prior cycle that would have activated the pedestrian phase at the start of the current cycle and, if no call was placed, (2) the respective probabilities of a call being received during the pedestrian clear interval, the permissive period, and after the permissive period.

Pedestrians and minor street vehicles are assumed to arrive randomly and their arrivals can be represented by a Poisson distribution. The probability that at least one minor street call is received during two consecutive cycles P_{2PC} is given by:

$$P_{2PC} = 1 - e^{-(2C)q}$$

where C is the cycle length in seconds and q is the arrival rate of minor-street vehicles and pedestrians (in vehicles+persons per second) that can trigger a call that would terminate the major street phase, equal to the hourly vehicle and pedestrian volume divided by 3,600 seconds per hour.

The probability P_{PC} of receiving one or more prior calls during the cycle duration C is given by:

$$P_{PC} = 1 - e^{-Cq}$$

As two consecutive cycles are being evaluated, the individual probabilities of a call happening during a specific period within the two cycles need to be normalized by the probability of receiving at least one call during two consecutive cycles. This is done to accurately reflect event probabilities during low-volume conditions where successive calls may occur more than two cycles apart. The probability $P_{PC|2}$ of receiving one or more calls during the cycle duration C, given that one or more calls are received during two consecutive cycles, is:

$$P_{PC|2} = \frac{P_{PC}}{P_{2PC}}$$

The probability $P_{PCI|2}$ of receiving at least one call during the pedestrian clearance interval, given that one or more calls are received during two consecutive cycles is the normalized probability that at least one call is received during the prior cycle duration plus the pedestrian clearance interval, minus the normalized probability that at least one call is received during the prior cycle:

$$P_{PCI|2} = \frac{1 - e^{-(C + PCI_{mj})q}}{P_{2PC}} - P_{PC|2}$$

The probability $P_{PP\text{-}PCI|2}$ of receiving at least one call during the permissive period, given that one or more calls are received during two consecutive cycles is the normalized probability that at least one call is received during the prior cycle plus the greater of the pedestrian clearance interval or the permissive period, minus the normalized probability that at least one call is received during the prior cycle or pedestrian clearance interval:

$$P_{PP-PCI|2} = \frac{1 - e^{-(C + \max[PP, PCI_{mj}])q}}{P_{2PC}} - \frac{1 - e^{-(C + PCI_{mj})q}}{P_{2PC}}$$

Finally, the probability $P_{C\text{-}PP|2}$ of receiving at least one call following the current cycle's permissive period, given that one or more calls are received during two consecutive cycles is 1 minus the normalized probability that at least one call is received during the prior cycle or by the end of the permissive period or pedestrian clearance interval (whichever is greater) in the current cycle:

$$P_{C-PP|2} = 1 - \frac{1 - e^{-(C + \max[PP, PCI_{mj}])q}}{P_{2PC}}$$

The average pedestrian delay for a minor-street crosswalk $d_{ped,mi}$ is then the probability-weighted average of (1) the average delay when a prior call has been placed, (2) the delay with no prior call and a call occurs during the pedestrian clear interval, (3) the delay with no prior call and a call occurs during the time period after the pedestrian clear interval but before the permissive period ends, and (4) the average delay with no prior call and a call occurs outside the permissive period:

$$d_{ped,mi} = P_{PC|2}\, d_{PC,mi} + P_{PCI|2}\, d_{PCI,mi} + P_{PP-PCI|2}\, d_{PP-PCI,mi} + P_{C-PP|2}\, d_{C-PP,mi}$$

where the average delays associated with each case are:

$$d_{PC,mi} = \frac{\left(C - g_{Walk,mi}\right)^2}{2\,C}$$

$$d_{PCI,mi} = \left(\frac{PCI_{mj}}{C}\right)\left(\frac{PCI_{mj}}{2} + YAR_{mj}\right) + \frac{\left(C - PCI_{mj} - g_{Walk,mi}\right)^2}{2\,C}$$

$$d_{PP-PCI,mi} = \left(\frac{\max[PP, PCI_{mj}] - PCI_{mj}}{C}\right) YAR_{mj} + \frac{\left(C - \max[PP, PCI_{mj}] - g_{Walk,mi}\right)^2}{2\,C}$$

$$d_{C-PP,mi} = \frac{\left(C - \max[PP, PCI_{mj}] - g_{Walk,mi}\right)^2}{2\,C}$$

where

PCI_{mj} = pedestrian clear interval for the major street phase (s);

$D_{c,mi}$ = pedestrian crossing distance across the minor steet (ft);

v_p = pedestrian walking speed (ft/s);

$g_{walk,mi}$ = Walk interval duration for the minor street phase (s); and

YAR_{mj} = sum of yellow change and red clearance intervals (s).

This method assumes that the sum of the permissive period, the major street minimum green, and the major and minor street pedestrian clearance intervals (or yellow change and red clearance interval, as appropriate) is less than or equal to the cycle length.

Free Operation

In this scenario, the cycle length is variable, as phases terminate once their demand has been served or the maximum phase length has been reached. The existing HCM signalized intersection method accommodates this scenario and calculates an average cycle length *C* on the basis of the vehicular and pedestrian demand on each approach. This cycle length (obtained from Synchro output) is then used with the pre-timed/semi-actuated coordinated pedestrian delay equation given above to calculate average pedestrian delay for a crosswalk.

Average Pedestrian Delay

1. Pedestrian volume $V_{ped,i}$ is available directly from Synchro output for each crosswalk.

2. The total pedestrian delay during the peak 15 minutes, in person-seconds, is: $TPD_{ped} = \sum_{i=1}^{n} V_{ped,i} d_{ped,i} \times T$, where *T* is the analysis period length (=0.25 h).

3. The average pedestrian delay, in seconds, is: $PD_{ped} = TPD_{ped} / \sum_{i=1}^{n} V_{ped,i}$

TRANSIT MODE

Vehicles in this category include various sizes of public transit buses, school buses, tour buses, streetcars, and light rail vehicles. Larger paratransit vehicles would also qualify, if they would be classified as a heavy vehicle for HCM purposes. For convenience, all types of transit vehicles are referred to as "buses" in the following discussion.

Bus Delay without TSP

The following steps are followed to calculate bus person-delay when TSP is not provided at the intersection:

1. Motorized vehicle control delay by turning movement d_i is available directly from Synchro output. Given that the number of buses per hour is relatively low (e.g., 4 per hour with 15-minute headways), no adjustment to peak-15-minute bus flows is made.

2. The user supplies an average bus vehicle occupancy AVO_{bus} and the number of buses in the peak hour by turning movement $V_{bus,i}$.

3. The total bus person delay in the peak 15 minutes, in person-seconds, is: $TPD_{bus} = AVO_{bus} \times \sum_{i=1}^{n} V_{bus,i} d_i \times T$, where *T* is the analysis period length (=0.25 h).

4. The average bus person delay, in seconds, is: $PD_{bus} = TPD_{bus} / \sum_{i=1}^{n} (V_{bus,i} \times AVO_{bus})$

Bus Delay with TSP

When TSP is provided at an intersection, Synchro's control delay will need to be adjusted to reflect the delay savings provided to the buses granted priority. The following additional information will be needed from Synchro: the traffic signal cycle length *C* and the effective green by movement g_i. The user will need to supply, by movement, the number of buses per hour $V_{bus,i}$, the average number of cycles per hour that an advance green is provided $N_{ag,i}$, the average number of cycles per hour that green extension is provided $N_{ge,i}$, and the priority interval length for advance green t_{ag} in seconds.

The following steps are followed to calculate bus person-delay when TSP is provided at the intersection:

1. Motorized vehicle control delay by turning movement d_i is available directly from Synchro output. If the movement's maximum green time can be reduced as a result of TSP granted to buses on the cross-street, follow the steps for cross-street auto delay described below to adjust the control delay.

2. Average bus delay when TSP is not granted is equal to d_i.

3. Average bus delay when advance green is provided is equal to ($d_i - t_{ag}$).

4. Bus delay when green extension is provided is 0.

5. The weighted average bus delay for movement *i* is the weighted average of the delay, based on the number of cycles without TSP, with advance green, and with green extension:

$$d_{bus,i} = \frac{\left(\left[\frac{3{,}600}{C}\right] - N_{ag} - N_{ge}\right) d_i + N_{ag}\left(d_i - t_{ag}\right)}{\left(\frac{3{,}600}{C}\right)}$$

6. The total bus person delay in the peak 15 minutes, in person-seconds, is: $TPD_{bus} = AVO_{bus} \times \sum_{i=1}^{n} V_{bus,i} d_{bus,i} \times T$, where *T* is the analysis period length (=0.25 h).

7. The average bus person delay, in seconds, is: $PD_{bus} = TPD_{bus} / \sum_{i=1}^{n} V_{bus,i}$

Although it is possible that when TSP is granted in one direction, a bus traveling in the opposite direction (if present) could also benefit, no adjustment is made for this potential benefit. The method also assumes that only one bus per cycle benefits from TSP. At the same time, the method assumes that a bus granted priority can always take advantage of priority, which may not be the case, so these effects will tend to offset each other.

Auto Delay with TSP

Although TCRP Project A-39 found that TSP can provide a small reduction in average delay (e.g., 2–3 seconds) to vehicles on the same intersection approach as a bus granted priority, when the approach's volume-to-capacity (v/c) ratio was close to 1.0, it also found minimal (e.g., 1 second or less) delay reductions when the v/c ratio was 0.8 or less. Therefore, the method makes no reduction in auto delay for movements where TSP is provided.

On the other hand, cross-street delay does increase when TSP is provided. TCRP Project A-39 developed cross-street delay adjustment factors f_{TSP} for different combinations of the movement's v/c ratio, *g/C* ratio, cycle length, and the priority interval length (see Appendix A, developed by Skabardonis). These factors are used to adjust the HCM (Synchro) control delay for the effects of TSP as follows:

$$d_{i,adj} = d_i[1 + \frac{C}{(3{,}600/V_{bus,i})}\left(f_{TSP,i} - 1\right)]$$

where C / (3,600/$V_{bus,i}$) represents the probability that a bus will arrive in a given cycle during the peak hour.

AVERAGE INTERSECTION PERSON DELAY

The total intersection person delay, in person-seconds, during the peak 15 minutes, is:

$$TPD = TPD_{auto} + TPD_{truck} + TPD_{bike} + TPD_{ped} + TPD_{bus}$$

The average intersection person delay, in seconds, is:

$$APD = \frac{TPD}{([V_i - V_{truck} - V_{transit}]AVO_{auto}) + V_{truck}AVO_{truck} + V_{bike}AVO_{bike} + V_{ped} + V_{bus}AVO_{bus}}$$

DATA REQUIREMENTS

The following data are obtained from Synchro:

- Input motorized vehicle, bicycle, and pedestrian volumes by movement
- Input peak hour factor and heavy vehicle percentage by movement
- Input signal timing parameters by movement (e.g., minimum green, pedestrian clearance)
- Output effective green time, average cycle length, and volume-to-capacity ratio by movement

The user inputs the following data into the person-delay calculation spreadsheet:

- Average vehicle occupancy by mode

- Bicycle arrival type
- Optionally, the average number of extra bicyclists, above one per row, lined up at the stop bar at the start of green.
- Effective bicycle green time by movement, if a bicycle signal is present
- Effective pedestrian green by movement
- Signal operation (pre-timed, coordinated without permissive period, coordinated with permissive period, free)
- If coordinated operation, the combined vehicular and pedestrian volume of the minor-street approach(es).
- Transit vehicle volumes by movement
- TSP in use (yes/no)
- If TSP is in use, then by movement: average number of cycles per hour with advance green, average number of cycles per hour with green extension, and the length of the advance green interval.

COMMENTS

- The person delay estimate will be very sensitive to the accuracy of the user-supplied AVOs. AVO values may vary by time of day (e.g., peak vs. off-peak).
- Bicycle delay is highly sensitive to the value selected for the bicycle progression factor. Bicycle delay is only sensitive to the number of extra bicycles lined up per cycle (i.e., changes the delay result by more than 10%) when the bicycle v/c ratio is high (e.g., ≥0.70) and several extra bicycles (e.g., 4 or more) are lined up.
- The reduction in average pedestrian delay associated with a permissive period is greatest when pedestrian (and any minor street vehicular traffic) volumes are low. However, low volumes will also result in only a minor change to overall intersection person-delay. The delay benefit is also reduced when the major street pedestrian clearance interval has to occur during part of the permissive period (e.g., when rest-in-walk is used).

APPENDIX A

Minor-Street Control Delay Factors with TSP

HCM Delay Adjustment Factors for v/c =0.60

CYCLE	g/C=0.35		g/C=0.40		g/C=0.45		g/C=0.50	
LENGTH	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec
70	1.36	*3.25*	1.35	*2.36*	1.34	*2.08*	1.34	*1.81*
80	1.27	*2.05*	1.28	*1.85*	1.29	*1.75*	1.30	*1.74*
90	1.24	*1.74*	1.24	*1.63*	1.25	*1.60*	1.26	*1.60*
100	1.21	*1.56*	1.21	*1.51*	0.99	*1.50*	1.23	*1.52*
110	1.18	*1.46*	1.18	*1.43*	1.19	*1.43*	1.21	*1.45*
120	1.16	*1.39*	1.17	*1.38*	1.17	*1.38*	1.19	*1.40*

HCM Delay Adjustment Factors for v/c =0.70

CYCLE	g/C=0.35		g/C=0.40		g/C=0.45		g/C=0.50	
LENGTH	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec
70	1.54	*5.57*	1.46	*4.10*	1.43	*3.24*	1.43	*2.73*
80	1.40	*3.48*	1.36	*2.74*	1.35	*2.25*	1.35	*2.09*
90	1.32	*2.61*	1.29	*2.10*	1.29	*1.91*	1.29	*1.81*
100	1.26	*2.00*	1.25	*1.78*	1.25	*1.67*	1.25	*1.64*
110	1.22	*1.75*	1.21	*1.60*	1.22	*1.56*	1.23	*1.54*
120	1.19	*1.57*	1.19	*1.49*	1.19	*1.46*	1.20	*1.47*

HCM Delay Adjustment Factors for v/c =0.80

CYCLE	g/C=0.35		g/C=0.40		g/C=0.45		g/C=0.50	
LENGTH	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec
70	2.18	7.78	1.84	6.03	1.78	5.53	1.67	4.74
80	1.76	4.23	1.61	4.37	1.55	3.84	1.50	3.39
90	1.55	3.96	1.46	3.28	1.42	2.93	1.40	2.62
100	1.42	3.08	1.37	2.61	1.35	2.37	1.33	2.18
110	1.36	2.58	1.30	2.19	1.29	2.01	1.29	1.90
120	1.29	2.16	1.26	1.92	1.25	1.81	1.25	1.72

HCM Delay Adjustment Factors for v/c =0.90

CYCLE	g/C=0.35		g/C=0.40		g/C=0.45		g/C=0.50	
LENGTH	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec	e = 5 sec	e=10 sec
70	**3.07**	**8.60**	**2.77**	**7.33**	**2.61**	**6.73**	**2.43**	**6.18**
80	**2.49**	**6.23**	**2.28**	**5.52**	**2.14**	**5.05**	**2.04**	**4.73**
90	**2.13**	**4.95**	**1.97**	**4.37**	**1.87**	**4.05**	**1.80**	**3.79**
100	**1.88**	**3.98**	**1.73**	**3.55**	**1.69**	**3.33**	**1.64**	**3.15**
110	**1.69**	**3.37**	**1.59**	**3.01**	**1.57**	**2.88**	**1.52**	**1.78**
120	**1.39**	**2.53**	**1.51**	**2.66**	**1.47**	**2.49**	**1.44**	**2.38**

Notes: v/c = volume-to-capacity ratio, g/C = green time–to–cycle length ratio, e = TSP interval length.

Source: TCRP A-39 draft final report, Appendix C.

B

Spreadsheet Computational Engine Instructions

Introduction

This appendix provides instructions for using the two Microsoft Excel spreadsheets that implement the pedestrian crossing delay and level of service (LOS) methods described in Appendix A. The most recent versions of the spreadsheets are kept online in *Highway Capacity Manual* (*HCM*) Volume 4 (hcmvolume4.org) at Home > Applications Guides > Planning & Preliminary Applications Guide to the HCM > PPEAG Computational Engines. A free, one-time registration is required to access *HCM* Volume 4.

General questions on the use of the spreadsheets should be posted in the *HCM* Volume 4 Discussion Forum. Reports of potential errors in the spreadsheet or underlying methods should be sent using the error-reporting link in the site's Errata & Updates section. Comments and questions should be specific and refer to specific spreadsheet cells. Note that the spreadsheets are non-commercial software and are maintained on a volunteer basis, so it may take some time before receiving a reply.

No warranty is made by the developers, their employer, the Transportation Research Board, or the National Academies of Sciences, Engineering, and Medicine as to the accuracy, completeness, or reliability of this software and its associated equations and documentation, nor is any responsibility assumed for incorrect results or damages resulting from the use of this software. The software does not perform any checks to identify illogical user input.

Green-shaded cells in the spreadsheets indicate where user input is required; a lighter shade of green is used for optional input. Depending on user selections (e.g., pedestrian timing type), the shading of certain cells may appear or disappear, depending on the inputs required for that particular selection. All other cells are calculated. The formulas used for these calculations are stored in the cells; no macros are used.

Uncontrolled Crossing Pedestrian Delay and LOS

This spreadsheet calculates pedestrian delay and LOS for two uncontrolled crossings, or two scenarios for a single crossing. It contains three sheets: Overview, LOS, and Delay. The Overview sheet contains, among other things, a brief summary of these instructions and the spreadsheet's version history. The other two sections are described in the following sections.

LEVEL OF SERVICE

Figure B-1 shows a screenshot of the LOS sheet. Columns B and C contain user inputs, followed by the calculation results for each intermediate variable used in calculating LOS. The yielding and delay portion of the calculations are described in the Pedestrian Delay Estimation: Uncontrolled Crossings section of Appendix A, while the satisfaction probability calculations are described in the Pedestrian Satisfaction Estimation: Uncontrolled Crossings section of Appendix A. The right side of the sheet contains lookup tables used by some calculations.

Figure B-1. Uncontrolled Crossing Pedestrian LOS Screen.

	A	B	C	D	E	F	G	H	I
1	Scenario	**Existing**	**Mitigated**				**Yielding Rate**		
2	Crossing type	Marked	Median island		**Crossing Type**	**Worse**	**Average**	**NCHRP 17-87**	**Custom**
3	AADT	8,000	8,000		Unmarked	0.00	0.24	0.21	0.24
4	*K*-factor	0.08	0.08		Marked	0.20	0.34	0.56	0.34
5	Peak-hour vehicular flow rate (veh/h) (optional)				Median island	0.50	0.60	0.80	0.60
6	Initial crossing width (ft)	46	20		RRFB	0.70	0.79	0.79	0.79
7	Total crossing width (lanes)	4	4		Island + RRFB	0.80	0.85	0.93	0.85
8	Ped speed (ft/s)	4.0	4.0						
9	Ped start-up and end clearance time (s)	1.0	1.0		**Variable**	**Coefficient**	**Existing**	**Mitigated**	
10	Yielding behavior	Worse	Worse						
12	Critical headway (s)	12.5	6.0		RRFB	1.9572	0	0	
13	Vehicular flow rate (veh/s)	0.178	0.089		Marked	0.9843	1	1	
14	Group critical headway (s)	12.5	6.0		Median Island	1.5496	0	1	
15	Yielding rate	20%	50%		Intercept	0.9951	1	1	
16	First-stage width (lanes)	4	2		No yield	-0.6065	1	1	
17	*P* (blocked lane)	42.62%	23.41%		Slowed	-1.2994	1	1	
18	*P* (delayed crossing)	89.16%	41.34%						
19	*P* (yield)	8.02%	19.30%						
20	*P* (slowed)	82.01%	33.36%						
21									
22	Log odds (no delay)	1.63	3.18						
23	Odds (no delay)	5.10	24.01						
24	Satisfied probability (no delay)	83.6%	96.0%						
25	**Dissatisfied probability (no delay)**	**16.4%**	**4.0%**						
26	Log odds (slowed)	-0.28	1.27						
27	Odds (slowed)	0.76	3.57						
28	Satisfied probability (delay)	43.1%	78.1%						
29	**Dissatisfied probability (delay)**	**56.9%**	**21.9%**						
30	**Dissatisfied Probability (weighted)**	**49.6%**	**10.0%**						
31	**LOS**	**LOS E**	**LOS B**						

The following user inputs are available:

- **Scenario.** These are labels to indicate the crossing or scenario being analyzed.
- **Crossing type.** These cells contain pull-down menus with the following options: unmarked crossing (Unmarked), marked crossing with median island (Median Island), marked crossing with rectangular rapid-flashing beacon (RRFB), marked crossing with a median island and RRFB (Island + RRFB), and all other types of marked crossings (Marked).
- **AADT.** The average annual daily traffic of the roadway being crossed.
- ***K*-factor.** The proportion of AADT occurring during the peak hour, entered as a decimal.
- **Peak-hour vehicular flow rate.** Optionally, the peak-hour flow rate of the street being crossed can be entered. If not provided, it will be calculated as the AADT multiplied by the *K* factor.
- **Initial crossing width.** The curb-to-curb distance, in feet, of the first stage of the crossing (from the curb to the median island if an island is present and the full crossing length otherwise).
- **Total crossing width.** The total number of through travel lanes crossed. If a median island is present, sum the lanes crossed on either side of the island.
- **Pedestrian speed.** The pedestrian speed, in feet per second, to be used in the analysis.
- **Ped start-up and end clearance time.** Buffer time, in seconds, added to the critical headway. It represents extra time that pedestrians allow to begin their crossing after the last vehicle has passed

the crosswalk at the start of the critical headway, and to end their crossing before the first vehicle arrives at the crosswalk at the end of the critical headway.

- **Yielding behavior.** These cells contain pull-down menus with four options for motorist yielding behavior: Average (national average yielding rates, as shown in Table 3-2), NCHRP 17-87 (average yielding rates from the data collection used to create this method, generally better than the national average), Worse (worse yielding rates than the national average, including no yielding at unmarked crosswalks), and Custom. If Custom is selected, the user should enter the yielding rate for each crossing type as decimals in the light-green cells in column I.

By default, the spreadsheet neglects pedestrian platooning (i.e., pedestrians crossing in multiple rows) when calculating LOS, so that the group critical headway equals the critical headway. This setting can be changed on the Delay sheet if desired. When the crossing includes a median island, the spreadsheet assumes that the traffic volume is divided equally between the two directions and that an equal number of through travel lanes are crossed on either side of the island.

Cells B12 through C31 display the calculation results for each variable used to calculate LOS. The LOS result is based on the estimated percentage of pedestrians who would be dissatisfied with their crossing experience.

DELAY

The user should fill in all the user inputs on the LOS sheet prior to using the Delay sheet. Figure B-2 shows a screenshot of the Delay sheet. Cells F2 through G4 contain additional user inputs related to pedestrian platooning:

- **Pedestrian platooning?** These cells contain drop-down menus with two choices: Yes and No. If No is selected, no further user input is needed and the calculation will proceed assuming no platooning. If Yes is selected, two additional user inputs will be highlighted.
- **Crosswalk width.** The crosswalk width, in feet (only used for platooning).
- **Directional pedestrian flow rate.** The number of pedestrians per hour crossing in one direction of the crosswalk (only used for platooning).

The value of n (the average number of potential yielding events before an adequate gap becomes available) is capped at 500. If n exceeds 500, delay will be underestimated, key results will be shown in red, and an error message will be displayed in cell D519. By default, results for only the first 10 potential yielding events are displayed, the results for yielding events 11–500 can be displayed by unhiding rows 27–516. It is possible to manually modify the spreadsheet to accommodate more yielding events by inserting additional rows after row 516 and copying the preceding rows. However, the delay result with 500 yielding events will normally be high enough to indicate an undesirable level of delay.

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Figure B-2. Uncontrolled Crossing Pedestrian Delay Screen.

	A	B	C	D	E	F	G
1		Existing	Mitigated			Existing	Mitigated
2	Critical headway (s)	12.5	6.0		Pedestrian platooning?	No	Yes
3	Vehicular flow rate (veh/h)	640	320		Crosswalk width (ft)	10	10
4	Vehicular flow rate (veh/s)	0.178	0.089		Directional pedestrian flow rate (ped/h)	1	1
5	Spatial distribution of peds (rows)	1.0	1.0		Directional pedestrian flow rate (ped/s)		0.0003
6	Group critical headway, t_{gc} (s)	12.5	6.0		Total peds in crossing platoon (ped)		1.0
7	Yielding rate	20%	50%		Spatial distribution of peds (rows)	1.0	1.0
8	First-stage width (lanes)	4	2				
9	*P*(blocked lane)	42.62%	23.41%				
10	*P*(delayed crossing)	89.16%	41.34%				
11	Average gap delay (s)	33.8	1.9				
12	Average gap delay with nonzero delay (s)	37.9	4.7				
13	Average headway of headways < t_{gc} (s)	4.1	2.7				
14	Average # of potential yielding events before adequate gap available, *n*	9	1				
15	Probability of yielding on yielding event #				Delay increment for yielding event # (s)		
16	0	0.0%	0.0%		0	0.000	0.000
17	1	8.0%	19.3%		1	0.165	0.264
18	2	7.3%			2	0.450	0.000
19	3	6.6%			3	0.682	0.000
20	4	6.0%			4	0.869	0.000
21	5	5.5%			5	1.017	0.000
22	6	5.0%			6	1.131	0.000
23	7	4.6%			7	1.216	0.000
24	8	4.1%			8	1.277	0.000
25	9	3.8%			9	1.317	0.000
26	10				10	0.000	0.000
517	Average delay, 1st crossing stage (s)	22.6	1.3				
518	Average delay, 2nd crossing stage (s)		1.3				
519	**Average pedestrian delay (s)**	**22.6**	**2.6**				

Signalized Crossing Pedestrian Delay

This spreadsheet calculates pedestrian delay and LOS for the following types of signalized pedestrian crossings:

- **One leg, one stage** for up to four legs of an intersection;
- **One leg, two stages** for both directions of a single intersection leg; and
- **Two legs, two stages** for crossing in one direction between one corner and a diagonally opposite corner.

The spreadsheet contains one self-contained sheet for each of these crossing types, plus an Overview sheet providing, among other things, a brief summary of these instructions and the spreadsheet's version history. Chapter 19 of the *HCM* defines traffic signal timing settings in more detail.

ONE LEG, ONE STAGE

Figure B-3 shows a screenshot of the One Leg One Stage sheet. Rows 1 through 10 contain user inputs, followed by the effective Walk time calculations in row 11 and the delay results in row 12. The calculations used by the sheet are described in the Pedestrian Delay Estimation: Signalized Crossings section of Appendix A.

Figure B-3. Signalized Crossing (One Leg, One Stage) Pedestrian Delay Screen.

	A	B	C	D	E
1	Intersection	Main/Elm			
2	Pedestrian crossing location	North	West	South	East
3	Pedestrian timing type	Pre-timed with ped head	Actuated with ped head and rest-in-walk	Pre-timed with ped head	Actuated with ped head and rest-in-walk
5	Cycle length (s)	60			
6	Walk interval duration (s)	4.0	4.0	4.0	4.0
7	Duration of phase serving ped movement (s)		25.0		25.0
8	Yellow change interval (s)		3.0		3.0
9	Red clearance interval (s)		2.0		2.0
10	Pedestrian clear setting (s)		8.0		8.0
11	Effective walk time (s)	8.0	16.0	8.0	16.0
12	**Average pedestrian delay (s/p)**	**22.5**	**16.1**	**22.5**	**16.1**

The following user inputs are available:

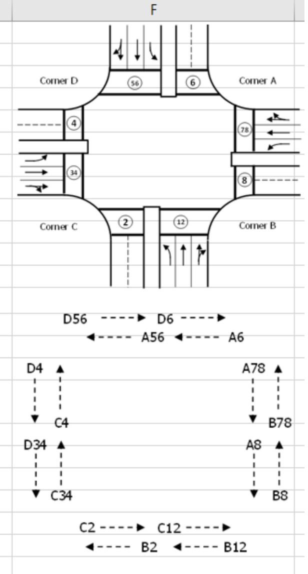
- **Intersection.** A label indicating the intersection being analyzed.
- **Pedestrian crossing location.** Labels indicating the specific crossing or leg being analyzed.
- **Pedestrian timing type.** These cells contain pull-down menus with the following options for each crossing: Pre-timed with ped head, Actuated with ped head, Actuated with ped head and rest-in-walk, and No ped head. The selected timing type will determine which additional user inputs are available in rows 6–10, as well as affect the calculation of effective walk time.
- **Cycle length.** The traffic signal cycle length (or average length, if the signal is actuated), in seconds.
- **Walk interval duration.** The length of time the Walk indication is displayed for each crossing.
- **Duration of phase serving ped movements.** The (average) time, in seconds, of the phase serving the crossing (only used for "rest-in-walk" and "no ped head" timing types).
- **Yellow change interval.** The duration of the yellow change interval, in seconds, for the phase serving the crossing (only used for "rest-in-walk" and "no ped head" timing types).
- **Red clearance interval.** The duration of the red clearance interval, in seconds, for the phase serving the crossing (only used for "rest-in-walk" and "no ped head" timing types).
- **Pedestrian clear setting.** The duration of the pedestrian clear interval (when flashing DON'T WALK is displayed), in seconds, for the phase serving the crossing (only used for "rest-in-walk" timing type).

ONE LEG, TWO STAGES

Figure B-4 shows a screenshot of the One Leg Two Stages sheet. Cells B1 through C13 contain user inputs, followed by intermediate variable calculation results in rows 14–25 and the delay results in row 26. The calculations used by the sheet are described in the Pedestrian Delay Estimation: Signalized Crossings section of Appendix A.

Figure B-4. Signalized Crossing (One Leg, Two Stages) Pedestrian Delay Screen.

	A	B	C
1	Intersection	**Main/Elm**	
2	Pedestrian timing type	Actuated with ped head	
4	Cycle length (s)	140	
5	Pedestrian walking speed (ft/s)	3.3	
6	Pedestrian crossing direction	From Corner A to B	From Corner B to A
7	Distance corner to far side of median (ft)	68	56
8	Relative start time of ped phase (s)	112	78
9	Walk interval duration (s)	5.0	5.0
10	Duration of ped phase, corner to median (s)		
11	Yellow change interval (s)		
12	Red clearance interval (s)		
13	Pedestrian clear setting (s)		
14	Effective walk time, first stage, $g_{Walk,X}$ (s)	9.0	9.0
15	Average pedestrian delay, first stage (s/p)	61.3	61.3
16	Crossing time, first stage (s)	20.6	17.0
17	Time between walk intervals (s)	106.0	34.0
18	Waiting time on median when peds reach median during 2nd-stage Don't Walk (s)	85.4	17.0
19	Delay when median arrival is during Don't Walk, *t* (s/p)	85.4	17.0
21	Intermediate variable *a*		
22	Delay when median arrival is during Walk (s/p)		
23	Intermediate variable *b*	54.6	123.0
24	Delay when median arrival is during Walk (s/p)	80.9	12.5
25	Proportion of arrivals during Don't Walk	0.96	0.96
26	**Average pedestrian delay (s/p)**	**146.5**	**78.2**



The user inputs are generally the same as described above for a one-leg, one-stage crossing, with the following exceptions:

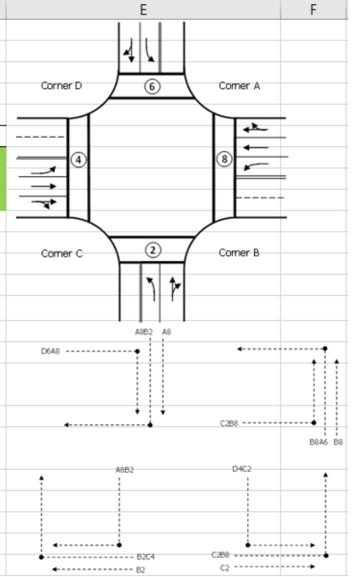
- **Pedestrian timing type.** Only three options are provided: Pre-timed with ped head, Actuated with ped head, and Actuated with ped head and rest-in-walk. Inputs in rows 10–13 are only used with the last timing type.
- **Pedestrian walking speed.** The pedestrian speed, in feet per second, to be used for the analysis.
- **Pedestrian crossing type.** Labels indicating which crosswalk direction is being analyzed. If desired, these labels can refer to the corner names shown in the diagram to the right.
- **Distance corner to far side of median.** The distance along the middle of the crosswalk, in feet, from the near curb to the far edge of the median.
- **Relative start time of ped phase.** The time, in seconds, when the pedestrian phase for the first crossing stage in the direction of interest begins relative to the start of the cycle (time 0).

TWO LEGS, TWO STAGES

Figure B-5 shows a screenshot of the Two Legs Two Stages sheet. Cells B1 through D14 contain user inputs, followed by intermediate variable calculation results in rows 15–20 and 22, and the delay result in row 21. The calculations used by the sheet are described in the Pedestrian Delay Estimation: Signalized Crossings section of Appendix A.

Figure B-5. Signalized Crossing (Two Legs, Two Stages) Pedestrian Delay Screen.

	A	B	C	D
1	Intersection	**Main/Elm**		
2	Cycle length (s)	90		
3	Pedestrian walking speed (ft/s)	3.3		
4	Pedestrian crossing direction	Corner B to C to D		
5	Length of first crosswalk (ft)	38		
6		*Phase X*	*Phase Y*	*Phase Z*
7	Pedestrian timing type	Pre-timed with ped head		Pre-timed with ped head
9	Relative start time of ped phase (s)	11	61	59
10	Walk interval duration (s)	5.0		5.0
11	Duration of ped phase, corner to median (s)			
12	Yellow change interval (s)			
13	Red clearance interval (s)			
14	Pedestrian clear setting (s)			
15	Effective walk time, first stage, $g_{Walk,X}$ (s)	9.0		9.0
16	Crossing time, first corner to second corner (s)	11.5		
17	Relative end of effective walk time (s)	20.0		68.0
18	Time between end of effective walk for Phase Z and Phase X (s)	42.0		
19	Average pedestrian delay, first stage (s/p)	13.0		
20	Time between arrival at first corner and departure to second corner (s)	62.0		
21	**Average pedestrian delay, diagonal crossing (s/p)**	**50.5**		
22	Average pedestrian delay, second stage (s/p)	37.5		
23				
24				
25				



The method defines three pedestrian phases for which user inputs are required:

- **Phase X.** The first crossing in the user-defined analysis direction.
- **Phase Y.** The second crossing in the user-defined analysis direction.
- **Phase Z.** The other option for the first crossing from the starting corner.

For example, if the analysis direction is from Corner B to C to D, as indicated in the diagram in Figure B-5, Phase X would be the crossing from B to C, Phase Y would be the crossing from C to D, and Phase Z would be the crossing from B to A.

The user inputs on this sheet are generally the same as described above for a one-leg, one-stage crossing, with the following exceptions:

- **Pedestrian timing type.** Only three options are provided: Pre-timed with ped head, Actuated with ped head, and Actuated with ped head and rest-in-walk. Inputs in rows 11–14 are only used with the last timing type.
- **Pedestrian walking speed.** The pedestrian speed, in feet per second, to be used for the analysis.
- **Pedestrian crossing direction.** A label indicating which crossing direction is being analyzed, which also helps indicate which crossings are used by Phases X, Y, and Z.
- **Length of first crosswalk.** The curb-to-curb distance along the middle of the crosswalk, in feet, for the first crossing in the analysis direction.
- **Relative start time of ped phase.** The time, in seconds, when each pedestrian phase begins relative to the start of the cycle (time 0).