Capacity Analysis of Pedestrian and Bicycle Facilities

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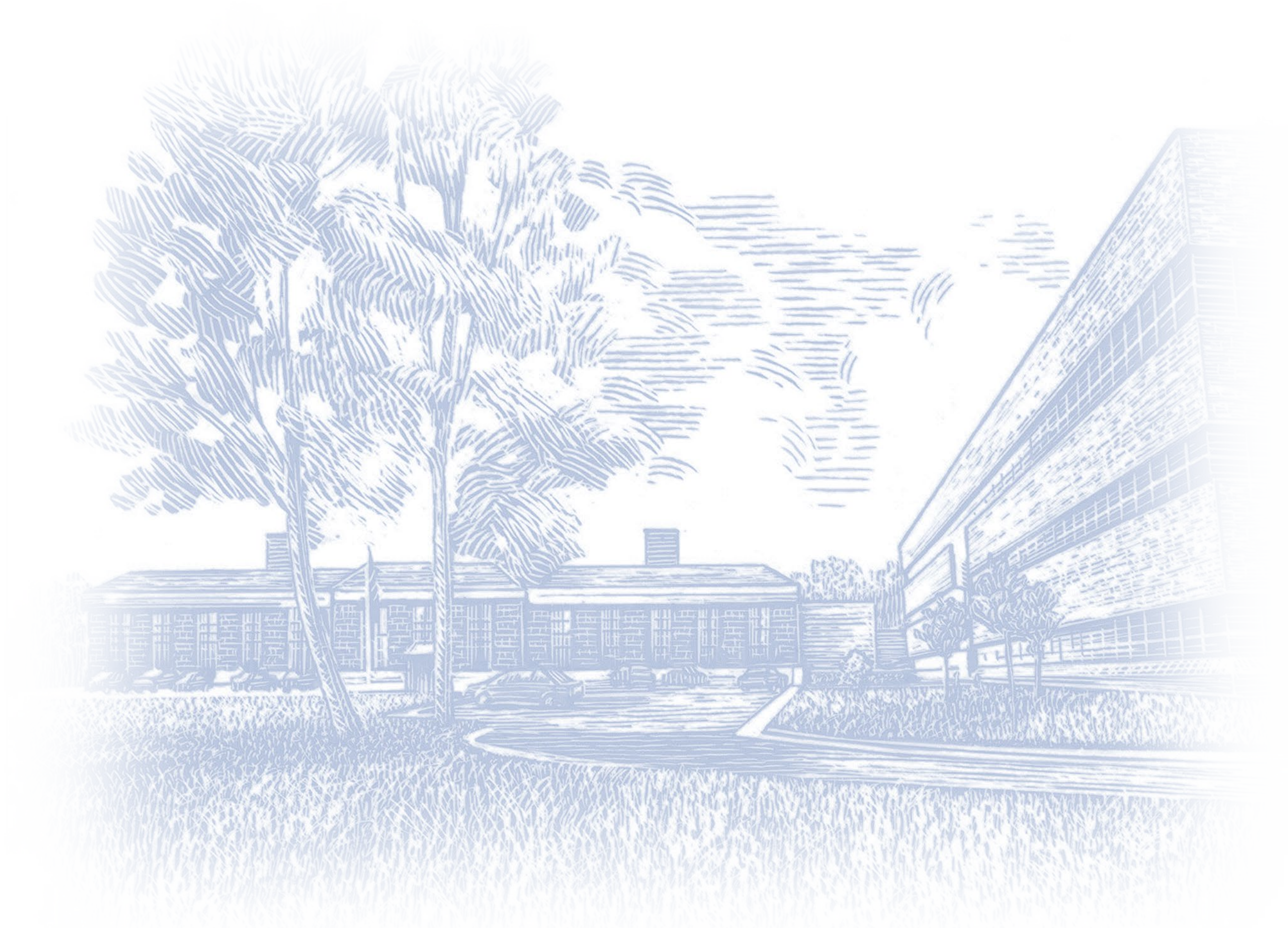

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16. Abstract

The objective of this project is to develop revised operational analysis procedures for transportation facilities with pedestrian and bicyclist users. This document describes the effects of pedestrians and bicyclists on the capacity of signalized intersections. These procedures augment the existing *Highway Capacity Manual* signalized intersection Level of Service procedures for locations with substantial pedestrian and/or bicycle traffic conflicting with vehicular turning movements. This document incorporates the results of a multi-regional data-collection effort that confirms the validity of a conflict zone occupancy approach to analyze pedestrian and bicycle effects on signalized intersection capacity.

In addition to this report, there were two additional reports produced as part of this effort on Capacity Analysis of Pedestrian and Bicycle Facilities. These reports are subtitled as:

1. Recommeded Procedures for the "Pedestrian" Chapter of the Highway Capacity Manual (FHWA-RD-98-107)

2. Recommended Procedures for the "Bicycles" Chapter of the Highway Capacity Manual (FHWA-RD-98-108)

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INTRODUCTION

In the United States, the Highway Capacity Manual (HCM) published by the Transportation Research Board, a unit of the National Research Council, provides guidance for the analysis of transportation facilities. Chapter 9 of the 1994 (update to the 1985) *HCM* discusses the operational and planning analysis of signalized intersections. The methodology contained in the chapter overlooks some aspects of the interaction between pedestrians and turning vehicles. This is unfortunate, because many intersections in downtown areas, near college campuses, by transit stops, etc., have moderate to heavy pedestrian flows that interact with turning vehicles. In addition, as the popularity of bicycling increases, so too does the importance of accurately including the effects of bicycle traffic in the analyses of signalized intersections.

Figure 1 demonstrates that high pedestrian and bicycle flows can severely affect the ability of vehicles to execute their turn. Based on the results of a multi-regional data collection effort conducted by the research team, this paper offers procedures that describe the effect of pedestrians and bicycles on turning vehicles and thus signalized intersection capacity.

Figure 1: Pedestrians and bicycles causing delay to turning vehicles in Eugene, Oregon

In conjunction with the above effort, the research team also conducted an extensive literature review of pedestrian characteristics and facilities. This document summarizes the pedestrian-related recommendations resulting from that literature synthesis that may affect procedures in Chapter 9.

BACKGROUND

Limited information exists on the effects of pedestrians and bicycles at signalized intersections. Chapter 9 of the *HCM* provides an adjustment for pedestrians conflicting with right turns, and suggests applying this factor for left turns from one-way streets. The *HCM* makes no provision for dealing with the effect of pedestrians on left turns in other situations. While this may be acceptable with large opposing volumes (Figure 2), it certainly underestimates the effect of pedestrians on left turns when opposing traffic volumes are low (Figure 3). The *HCM* suggests in Chapter 14 that, to adjust for bicycles, one may consider one bicycle as one pedestrian. The result is an incomplete, theoretically unconnected framework for pedestrian-bicycle adjustments.

Figure 2: Opposing traffic screens pedestrians from the view of left-turning drivers at this intersection in Chicago, Illinois

To give a sense of the differences between the HCM and other adjustment factors worldwide, values of the right-turn saturation flow adjustment factor from various sources were compared (Figure 4). The South African model shown technically covers left turns, but vehicles keep to the left in that country. Each value represents the additional adjustment to right-turning flow due to pedestrians (i.e., beyond the saturation flow adjustment due to turn radius). Of all the methods represented, only the Swedish model and one of the Polish models flatten out with higher pedestrian volumes. The remaining models are roughly parallel above 600 pedestrians/h, with the exception of the HCM, which falls at a steeper rate. The range of adjustments was quite striking: The difference between Zegeer's method and Canada's model fro Edmonton excees 0.5 across all pedestrian volumes. While pedestrian or driver behavior may explain some of this variance, a difference of 50 percent seems rather high

Figure 3: Pedestrians affect left turns when there is no opposing traffic at the same Chicago, Illinois intersection

The range of values represented in the literature, the lack of an intuitive lessening of additional pedestrian impact at higher pedestrian volumes in the HCM procedure, and the large variation between the HCM and competing methods together call for a reexamination of the effect of pedestrians on turning vehicles. These reasons are in addition to the lack of an adjustment of left-turning saturation flow due to pedestrians. These concerns highlight a need for a congruent, theoretically sound framework for all pedestrian adjustments. In addition, the complete absence of a bicycle adjustment factor is obviously problematic, given the increasing bicycle volumes in the United States.

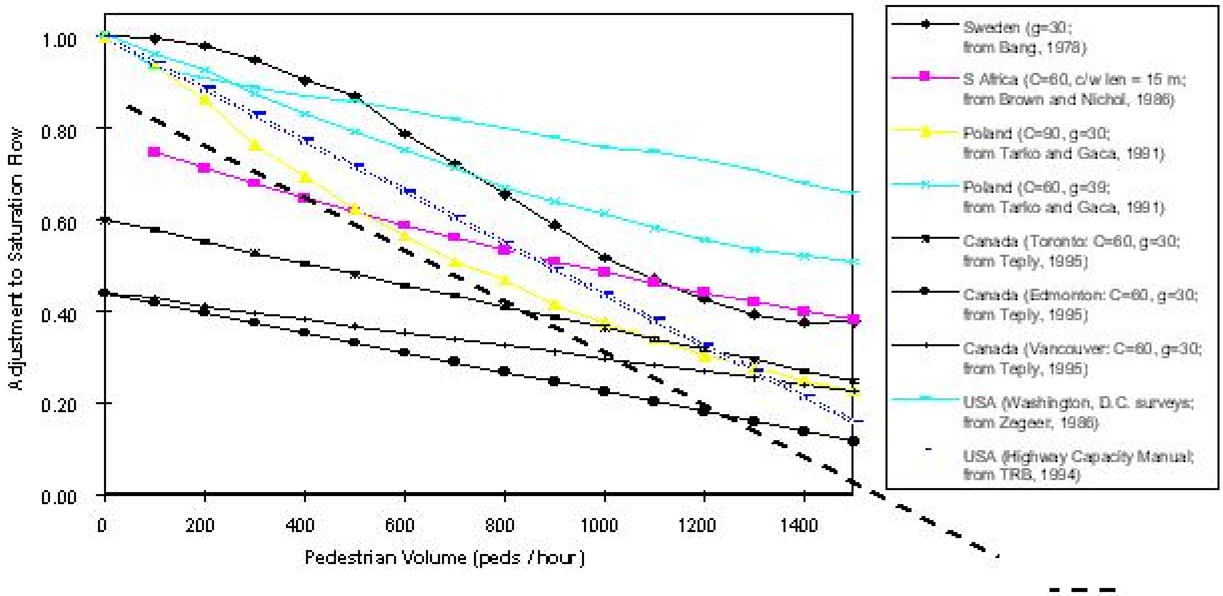

Figure 4: Comparison of various right-turn saturation flow adjustment factors due to pedestrians.

RESEARCH METHODOLOGY

After pertinent literature was reviewed, empirical data to describe the effect of pedestrians and bicycles on turning vehicles were collected. After conversations with professional and personal contacts from various areas, a few cities were identified for further study. For pedestrian analysis, Atlanta, Georgia; Chicago, Illinois; Eugene and Portland, Oregon; and Washington, D.C., were visited. For bicycle analysis, Davis, California; Eugene, Oregon; and Gainesville, Florida, were visited. The Atlanta, Chicago, and Washington, D.C., areas were visited in July 1995; the Davis, Eugene, and Portland areas were visited in March 1996; and Gainesville was visited in April 1996. A total of nine intersections were used for pedestrian data collection. Table 1 provides a summary of pertinent intersection parameters for the pedestrian data collection sites. In addition, a total of six intersections were used for bicycle data collection.

To quantify the impact of pedestrians on turning vehicles, study locations that isolated this effect from other factors that influence capacity were desired. Specifically, intersections with a significant volume of both pedestrians and turning vehicles, but with limited opposing traffic (for left turns from two-way streets) and permitted phasing were highly sought after. Central Business Districts (CBDs) provided the most likely sources of potential study locations with the preceding characteristics. Fortunately, intersections meeting these criteria were available throughout the United States.

Wigan (1995) terms a pedestrian to be someone who is walking, usually in public places, and particularly on or adjacent to public rights of way for vehicles. This study generally followed this definition, in that walkers, runners, and people who use wheelchairs were counted as pedestrians. In addition, an individual pushing a baby in a stroller was counted as two pedestrians. Either a single or tandem bicycle was counted as one bicycle for the purposes of the study. While the preceding definitions are certainly open to discussion, they were selected as being reasonable, and allowed the study to proceed.

To simplify the analysis of the complex interaction between turning vehicles and pedestrians and/or bicycles, this study focused on the area where intersection users must compete for space, termed a conflict zone (Figure 5). After two unsuccessful attempts with alternative analysis methods, a modeling approach based on the occupancy of a conflict zone was selected. The problem was considered from the perspective of the turning driver. Under permitted phasing, she is searching for a usable gap in the nonmotorized traffic stream (Figure 6). In other words, she asks Can I make this turn? or, in regard to the pedestrians and other users in the crosswalk area, Is there a space open now for me to execute my turn? This space is the aforementioned conflict zone. In general, however, she does not ask, Is the entire crosswalk free of pedestrians? any more than a turning driver looking for a gap in an opposing vehicle stream expects the entire road ahead to be empty. In addition, from the perspective of the turning driver, it only matters if a conflict zone is occupied, not which users happen to occupy the conflict zone.

In general, a pedestrian cannot occupy a conflict zone at the same time as a vehicle, except under low speeds and at least one aggressive user. If the zone remains vacant long enough, one or more vehicles can execute a turn. Of course, factors such as lost time, opposing traffic, and unpredictability in user behavior ensure that vehicles will not use all of the vacant time, even with sufficient turning demand. Under this framework, the primary goal changes to finding the relationship between occupancy of a conflict zone and the adjustment to saturation flow.

A four-phase methodology based on conflict zone occupancy was developed to determine the effect of pedestrians and bicycles on lane groups containing turning vehicles. The first phase examines the relationship between pedestrian volume and the resulting occupancy of the conflict zone. The second phase, which applies only with opposing vehicular traffic (left turn from two-way street) or concurrent bicycle traffic (right turn from one-way street), determines the amount of that occupancy that actually affects the saturation flow of turning vehicles. A theoretical model was used for the left-turn case, while the results from a parallel research effort (Allen, 1996) were employed for the right-turn case. Therefore, no data collection was performed related to phase two.

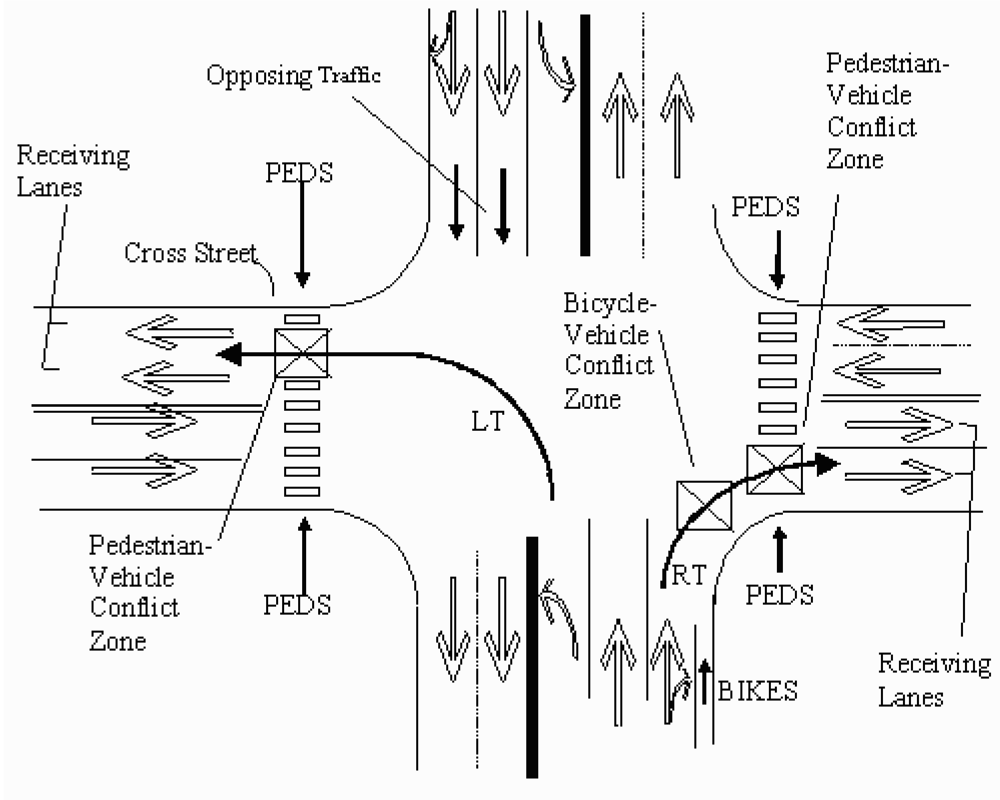

Figure 5: Sample conflict zone location

The third phase considers the actual relationship between conflict zone occupancy and turning vehicle saturation flow rate. Quantification of this phase-three relationship required intersections at which permitted turns departing from a queue interact only with pedestrians or other non-motorized traffic, such as bicycles. Although desired, no locations in which left turns from a two-way street encountered this situation could be found. Therefore, sites at which queued, turning traffic from a one-way street interacted with nonmotorized users (e.g., pedestrians, bicyclists, skateboarders, etc.) were employed.

The fourth and final phase applies this adjustment to a lane group, taking into account both the proportion of turning vehicles in the group and the proportion of turning vehicles using the protected phase. This phase merely involved an algebraic manipulation of formulas, so no data collection was performed for this last phase.

Figure 6: Queued turning vehicles waiting for a gap in a pedestrian stream in Portland, Oregon

A total of 612 signal cycles were observed where bicycles crossed without substantial vehicular interference across 6 sites for the development of a bicycle volume-conflict zone occupancy model. A total of 935 cycles where pedestrians crossed without substantial vehicular interference across 8 sites were observed for the development of the pedestrian volume-conflict zone occupancy model. In addition, a total of 266 queues of 5 or more vehicles across 8 sites were observed for development of the model relating conflict zone occupancy to saturation flow. Spreadsheets were used to assist the development of the pedestrian volume-conflict zone occupancy model. Using a series of macros, the spreadsheet took the recorded conflict zone and signal status event information and computed parameters such as average occupancy per green phase. It also used the event information to develop a time profile of occupancy over the green phase. In addition, spreadsheets were also used to assist the development of the model relating conflict zone occupancy to saturation flow. Using a series of macros, the spreadsheet took the recorded conflict zone and discharging vehicle event information and computed parameters such as average occupancy per queue. Milazzo II (1996) provides more detailed information on the analysis of the field data.

TABLE 1 Data collection site characteristics

Site Number	Methodology Phase(s)	Approach Street Type	Receiving Street Type	Approach Lanes Configuration (incl. de facto turn lanes)	Receiving Lanes Configuration	N# of Turning Lanes	N# of Opposing Lanes	N# of Receiving Lanes	Receiving Width (ft)	Crosswalk Length (ft)	Distance to Conflict	Heavy vehicles?	Aprx. Approach % Grade	Adjacent Parking?	Adjacent Bus Stops?	Central Business District (CBD)?	Approx. Turn Radius, ft	Intersection Angle	Marked Crosswalk?	Approach Street Turning Signal Type	Pedestrian Signal?	Green Time (g), s	Cycle Length (C), s	g/C
1	1	2-way	1-way	LT-T	(P)-3T	1	2	3	32	40	20	Y	~0	N	N	CBD	40	90°	Y	Prot-Perm	Y	17	70	0.2
2	1,3	1-way	2-way	L-LT-R	3T	2	-	3	35	78	28	Y	~0	N	N	CBD	25	90°	Y	Protected	Y	25.	105	0.24
3	1,3	2-way	1-way	LT-T-(P)	2T	1	1	2	28	36	28	Y	~0	N	N	N	50	90°	Y	Per	Y	36.	75	0.48
4	3	1-way	1-way	(P)-LR-(bic)-(P)	(P)-T-(bic)-(bus)	1	-	1	11	33	21	Y	+1	Y	N	CBD	50	90°	N	(no signal)	N	60.	60	1.00
5	1,3	1-way	1-way	(P)-LT-2T-(P)	(P)-2T-(P)	2	-	2	20	36	22	N	~0	Y	N	CBD	30	90°	Y	Protected	Y	24.	56	0.43
6	1,3	1-way	1-way	L-(bus)	(P)-2T-(P)	1	-	2	20	36	22	N	-3	N	Y	CBD	30	90°	Y	Protected	Y	24.	56	0.43
7	1,3	1-way	2-way	L-4T-R	2T-R	1	-	2	24	80	30	Y	~0	N	N	CBD	30	90°	Y	Protected	Y	25.	70	0.36
8	1,3	1-way	1-way	L-LT-2T	5T-(P)	2	-	5	47	56	46	Y	~0	N	N	CBD	25	90°	Y	Protected	Y	27.	80	0.34
9	1,3	1-way	1-way	L-LT-3T-(P)	2T-(P)	2	-	2	22	32	26	Y	~0	N	N	CBD	25	90°	Y	Protected	Y	39.	80	0.49

PROPOSED REVISIONS TO HCM CHAPTER 9 PROCEDURES

4.1 Overview of Recommended Procedure for Determining fLpb and fpb

This section summarizes the recommended procedure for calculating the value of an adjustment factor that describes the effect of pedestrians and bicycles on lane group saturation flow. For left turns, the adjustment is termed f_{Lpb}; for right turns, the adjustment is termed f_{Rpb}. The procedure consists of four basic parts that correspond to the four phases of the data reduction methodology described earlier. They are:

Part 1: Determine average pedestrian occupancy, OCC_{pedg}, during the entire pedestrian green;

Part 2: Find relevant conflict zone occupancy, OCC_r , by adjusting OCC_{pedg}as needed for opposing traffic (left turns) or conflicting bicycles (right turns);

Part 3: Compute permitted phase saturation flow adjustment just for turning vehicles due to pedestrian and bicycle interference, A_{pbT}; and

Part 4: Determine saturation flow adjustment factor for the lane group f_{Lpb} for left turns and f_{Rpb}t. for right turns.

Table 2 contains two groups of parameters that comprise all of the input requirements needed to determine f_{Lpb} and f_{Rpb}. The first group lists several qualitative intersection parameters, while a second group contains quantitative parameters needed to complete the procedure. Within each group, the table lists the parameters in the order the procedure first needs them. While one will need between 9 and 13 input parameters, depending on the situation, the proposed procedure does not require any additional field data collection. In other words, the procedure requires no (zero) new input parameters beyond those needed for the current HCM. The following paragraphs provide an overview of each of the four parts. To aid the user, Figure 7 provides a flowchart, which serves as a visual outline to the procedure. In addition, Table 3 provides a list of symbols used in the computation of f_{Lpb} and f_{Rpb}.

TABLE 2 Input Requirements for Determination of f Rpb and f Lpb

Qualitative Parameter

Turn direction (left or right)
Street type (one-way or two-way)
Turn lane type (exclusive, shared, or single)
Signal phasing type (protected, permitted, or protected-permitted)

Quantitative Parameter (also consult *Figure 2*)	Symbol
Cycle Length (s)	C
Extent of Opposing Vehicle Queue (s) [a]	g_q
Opposing Flow Rate After Queue Clears (veh/h) [a]	v_o
Effective Number of Turning Lanes	N_{turn}
Effective Number of Departure Lanes	N_{dep}
Proportion of Left- or Right-turns in Lane Group [b]	P_{LT} ; P_{RT}
Proportion of Left- or Right-turns using Protected Phase [c]	P_{LTA} ; P_{RTA}
Pedestrian Volume (peds/h or peds/h ped-green) [d]	V_{ped} or V_{pedg}
Bicycle Volume (bikes/h or bikes/h green) [e]	V_{bike} or V_{bikeg}
Effective Green (for vehicles or bicycles, s)[f]	g
Ped Green Time (Walk + Flashing Don't Walk), s[g]	g_p

[a] necessary only for left turns from a two-way street; see 1994 HCM, page 9-20
[b] necessary only for right turns from a single lane approach or for a shared turning lane
[c] necessary only if protected plus permitted phasing
[d] ignore those pedestrians who cross against the green (i.e., noncompliant pedestrians)
[e] necessary only for right turns impeded by bicycles
[f] ultimately needed in all cases to compute lane group capacity; however, only necessary at this point in the procedure for right turns impeded by bicycles
[g] if no pedestrian signal, use g as a proxy for g_p ; if numerous pedestrians crossing the street after the conclusion of the flashing DON'T WALK conflict with turning vehicles, extend the effective pedestrian green time accordingly

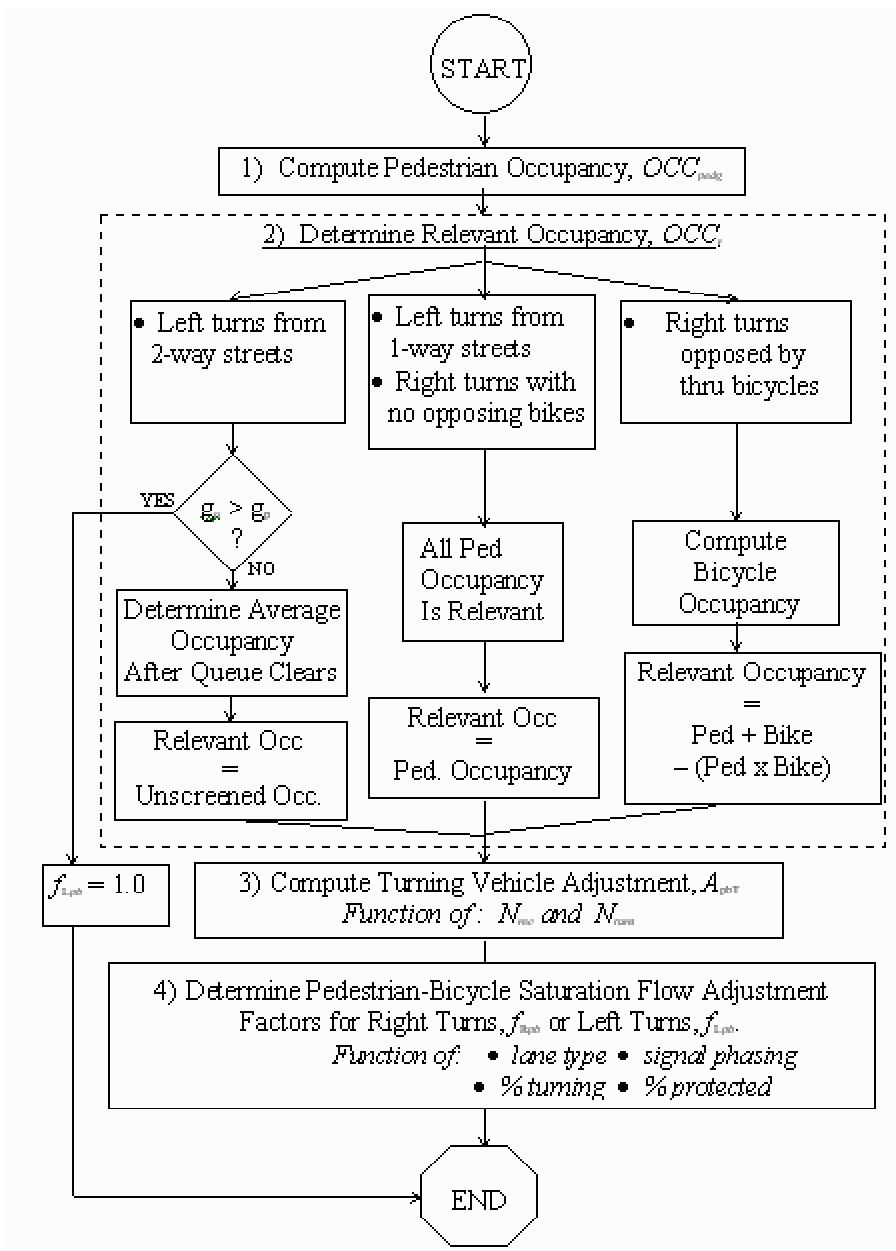

Figure 7: Outline of computational precedure for f_{Rpb} and f_{Lpb}

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TABLE 3 List of symbols used in determination of fRpb and fLpb

Cycle Length (s)	C
Pedestrian Volume (pedestrians/h)	V_{ped}
Pedestrian Flow Rate (pedestrians/h of green)	V_{pedg}
Pedestrian Green Time (Walk + Flashing Don't Walk), s	g_p
Average Pedestrian Occupancy During the Effective Pedestrian Green Time	OCC_{pedg}
Bicycle Volume (bicycles per h)	V_{bike}
Effective Green (for vehicles or bicycles/s)	g
Bicycle Flow Rate (bicycles/h of green)	V_{bikeg}
Average Bicycle Occupancy During the Effective Green Time	OCC_{bikeg}
Extent of Opposing Vehicle Queue (s)	g_q
Opposing Flow Rate After Queue Clears (vehicles/h)	v_o
Average Pedestrian Occupancy After the Opposing Queue Clears	OCC_{pedu}
Relevant Conflict Zone Occupancy From the Driver's Perspective	OCC_r
Effective Number of Turning Lanes	N_{turn}
Effective Number of Receiving Lanes	N_{rec}
Permitted Phase Pedestrian-Bicycle Adjustment for Turning Vehicles	A_{pbT}
Proportion of Left or Right turns in Lane Group	P_{LT} ; P_{RT}
Proportion of Left or Right turns Using Protected Phase	P_{LTA} ; P_{RTA}
Pedestrian-Bicycle Adjustment Factor for Right Turns	f_{Rpb}
Pedestrian Adjustment Factor for Left Turns	f_{Lpb}

The first part of the procedure determines the average occupancy of the conflict zone over the entire pedestrian green phase, OCC_{pedg} . Practitioners can utilize existing counts by converting them to an hourly flow rate using the equations listed. Alternatively, if one counted pedestrians for an entire hour of pedestrian green time for a movement, the user could then enter the resulting count as the pedestrian volume/h green (V_{pedg}) without conversion. If possible, data collectors should only count those pedestrians who conflict with turning vehicles.

The second part determines the relevant occupancy of the conflict zone from the perspective of the turning driver, OCC_r. Follow the appropriate group of steps depending on the potential for interference by either opposing vehicles (left turns) or bicycles (right turns), if any. Of course, even an Aunopposed@ left turn can still experience a substantial reduction in turning capacity (Figure 8). In addition, based on field observations at California, Oregon, and Florida, if bicycle traffic weaves with right-turning traffic in advance of the stop-bar, the interaction between bicycles and right-turning vehicles is completely independent of the interaction with pedestrians, and one should ignore the bicycle volume when analyzing the signalized intersection. In other words, while weaving between bicycles and right turns may take place some distance upstream

Figure 8: Pedestrians causing substantail delay to an "unopposed" left turn in Portland, Oregon

from the intersection, the interaction between pedestrians and right turns will occur at the intersection itself.

The third part determines the adjustment to turning vehicle saturation flow during the permitted phase due to pedestrian or bicycle interference, A_{pbt}. Use the effective (i.e., A as actually used @ number of turning lanes (N_{turn}) and receiving lanes (N_{rec}), which may or may not match those suggested by traffic control devices. For example, vehicles may consistently turn from an outer lane illegally, or double-parked vehicles may block a turn or receiving lane.

The fourth part determines the actual saturation flow adjustment factor, f_{Rpb} or f_{Lpb}. This factor represents the adjustment to saturation flow for a lane group containing turning vehicles subject to pedestrian and/or bicycle interference. One can A grossly estimate @ the proportion of right turns using the protected phase (P_{RTA}) as the proportion of the green phase that is protected, as suggested in the HCM on page 9-18 (TRB, 1994). Also, one can A grossly estimate @ the proportion of left turns using the protected phase (P_{LTA}) as equal to (1- permitted phase f_{LT}) / 0.95.

4.2 Details of Recommended Procedure for Determining f_{Lpb} and f_{Rpb}

The following paragraphs contain the detailed procedure for computing the pedestrian-bicycle adjustment factor for right turns, f_{Rpb}, or left turns, f_{Lpb}. As an additional aid, Figures 9 and 10 provide supplemental worksheets containing this information in tabular form.

1) Calculate pedestrian conflict zone occupancy, *OCCpedg*.
First, get the pedestrian flow rate, V*pedg* from the conflicting pedestrian hourly volume, V*ped*:

V*pedg* = V*ped* * (C/g*p*) (V*pedg* < 5000)

Then, compute the average pedestrian occupancy during the effective pedestiran green time. Refer to Table 4 for the average occupancy, *OCCpedg*, or use one of the following equations:

- ***For pedestrian flow rates up to 1000 pedestrians/h green:***

  OCCpedg = *Vpedg* / 2000 (*Vpedg* < 1000; *OCCpedg* < 0.5)

- ***For pedestrian flow rates between 1000 and 5000 pedestrians/h green:***

  OCCpedg = 0.4 + *Vpedg* / 10,000 (1000 < *Vpedg* < 5000; 0.5 < *OCCpedg* < 0.9)

2) Determine the relevant conflict zone occupancy from the driver's perspective, *OCCr*.

- ***For a right turn with no bicycle interference or a left turn from a one-way street:***

  The relevant occupancy is exactly the pedestrian occupancy computed above,
  and: *OCCr* = *OCCpedg*

- ***For a right turn with bicycle interference:***

  First convert bicycle hourly volume, Vbike, to bicycles/h green, Vbikeg: Vbikeg = V*bike* * (C/g) (Vbikeg < 1900)

  Next, determine the relevant, combined occupancy of the adjacent pedestrian and bicycle conflict zones. Table 5 provides this relevant occupancy, *OCC r*, directlry from Vbikeg . Alternatively,

determine the occupancy of the bicycle conflict zone by itself, *OCCbikeg*:
OCC*bikeg* = 0.02 + V*bikeg* / 2700 (V*bikeg* < 1900; OCC*bikeg* < 0.72) and then compute the relevant, combined occupancy, OCC*r*, by: OCC*r* = OCC*pedg* + OCC*bikeg* – (OCC*pedg* * OCC*bikeg*)

- ***For a left turn from a two-way street:***

  First check if opposing traffic screens the conflict zone for the entire effective green time: If g*q* > g*p* Then *fLpb* = 1.0 ; end procedure.

  If the opposing queue does not consume the entire pedestrian green, determine the pedestrian occupancy after the opposing queue clears, OCC*pedu*. Use Table 6, or: OCC*pedu* = OCC*pedg* * (1 - 0.5 (g*q* /g*p*))

  The relevant conflict zone occupancy after the queue clears is the occupancy that is not screened by additional opposing vehicles. To determine this relevant occupancy, OCC*r*, multiply the total occupancy after the queue clears, OCC*pedu*, by the probability that opposing vehicles do not screen the conflict zone. Use Table 7 or: OCCr = OCC*pedu* * $e^{-(5/3600)Vo}$

3) Calculate the permitted phase pedestrian-bicycle adjustment for turning vehicles, A*pbT*.

- ***If the number of receiving lanes equals the number of turning lanes (i.e., Nrec < = Nturn):***

  Vehicles cannot maneuver around pedestrians or bicycles, and the adjustment is logically the proportion of time the conflict zone is unoccupied from the turning driver's perspective. Use Table 8, or: A*pbT* = 1 - OCC*r*

- ***If the number of receiving lanes exceeds the number of turning lanes (i.e., Nrec > Nturn):***

  Vehicles may have opportunities to maneuver around pedestrians or bicycles, and the effect of pedesestrians and bicycles on turning traffic is reduced. Use Table 8, or: A*pbT* = 1 – 0.6 * OCC*r*

4) Compute the pedestrian-bicycle adjustment factor for right turns, f*Rpb*, or left turns, f*Lpb*.

- ***For right turns, the pedestrian-bicycle adjustment factor, fRpb, is:***

  f*Rpb* = 1.0 – PRT (1 – A*pb*T)(1- PRTA)
  See Table 9 for simplified equations for each of six cases for f*Rpb*.

- ***For left turns, the pedestrian adjustment factor, fLpb, is:***

  fLpb = 1.0 - PLT(1 - A*pb*T) (1 - PLTA)
  See Table 10 for simplified equations for each of six cases for fLpb.

Supplemental Worksheet For Pedestrian-Bicycle Effects on Permissive Right Turns (f_{Rpb})

Parameter	Lane Group with Right Turns (add thru or left arrows if nec.) / Parameter Source or Equation	EB	WB	NB	SB
V_{ped}	Conflicting Peds/hr. (RT)[1]				
C	Cycle Length, sec[1]				
g_p	Effective Pedestrian Green Time, sec[1, 2]				
V_{pedg}	$= V_{ped} * (C/g_p)$				
OCC_{pedg}	$= V_{pedg} / 2000$ $(V_{pedg} \le 1000)$ $= 0.4 + V_{pedg} / 10{,}000$ $(1000 < V_{pedg} \le 5000)$ –OR– USE TABLE 4				
V_{bike}	Conflicting Bikes / hr.[1, 3]				
g	Effective Green Time, sec[1]				
V_{bicg}	$= V_{bike} * (C/g)$				
OCC_{bicg}	$OCC_{bicg} = 0.02 + V_{bicg} / 2700$ –OR– GO TO TABLE 5, NEXT STEP				
OCC_r	$OCC_r = OCC_{pedg} + OCC_{bicg} - (OCC_{pedg} * OCC_{bicg})$ –OR– USE TABLE 5				
N_{rec}	Number of cross-street lanes receiving turns[1]				
N_{turn}	Number of turning lanes[1]				
A_{pbT}	$= 1 - OCC_r$ $(N_{rec} = N_{turn})$ $= 1 - 0.6 * OCC_r$ $(N_{rec} > N_{turn})$ –OR– USE TABLE 8				
P_{RT}	Proportion Of RT[4]				
P_{RTA}	Proportion of Right Turns using Prot. Phase[5]				
f_{Rpb}	$= 1.0 - P_{RT}(1 - A_{pbT})(1 - P_{RTA})$ –OR– USE TABLE 9				

[1] see Input Module Worksheet for this parameter

[2] if intersection signal timing given, use P_t (use G + Y if no pedestrian signals). If signal timing must be estimated, use (Green Time - Lost Time per Phase) from Signal Operations Worksheet.

[3] if $V_{bike} = 0$ then $V_{bicg} = 0$, $OCC_{bicg} = 0$ and $OCC_r = OCC_{pedg}$

[4] see Volume Adjustment Worksheet for this parameter

[5] ideally determined from field data; alternatively, assume equal to proportion of turning phase that is protected

Figure 9: Supplemental worksheet for pedestrian-bicycle effects on permissive right turns

SUPPLEMENTAL WORKSHEET FOR PEDESTRIAN EFFECTS ON PERMISSIVE LEFT TURNS (f_{Lpb})

Parameter	LANE GROUP WITH LEFT TURNS (ADD THRU OR RIGHT ARROWS IF NEC.)				
	Parameter Source or Equation	**EB**	**WB**	**NB**	**SB**
V_{ped}	Conflicting Peds/hr. (RT)[1]				
C	Cycle Length, sec[1]				
g_p	Effective Pedestrian Green Time, sec[1, 2]				
V_{pedg}	$= V_{ped} * (C/g_p)$				
OCC_{pedg}	$= V_{pedg} / 2000$ $(V_{pedg} \leq 1000)$ $= 0.4 + V_{pedg} / 10{,}000$ $(1000 < V_{pedg} \leq 5000)$ –OR– USE TABLE 4				
g_q	Effective green blocked by oppos. queue, sec[3, 4]				
g_q / g_p	Effective pedestrian green consumed by queue; IF $g_q / g_p \geq 1$ THEN $f_{Lpb} = 1.0$				
OCC_{pedu}	$= OCC_{pedg} * (1 - 0.5\,(g_q / g_p))$ –OR– USE TABLE 6				
V_o	Opposing vehicle volume, veh. / hr.[3]				
OCC_r	$= OCC_{pedu} * e^{-(5/3600)Vo}$ –OR– USE TABLE 7				
N_{rec}	Number of cross-street lanes receiving turns[1]				
N_{turn}	Number of turning lanes[1]				
A_{pbT}	$= 1 - OCC_r$ $(N_{rec} = N_{turn})$ $= 1 - 0.6 * OCC_r$ $(N_{rec} > N_{turn})$ –OR– USE TABLE 8				
P_{LT}	Proportion Of LT[5]				
P_{LTA}	Proportion of Left Turns using Prot. Phase[6]				
f_{Lpb}	$= 1.0 - P_{LT}(1 - A_{pbT})(1 - P_{LTA})$ –OR– USE TABLE 10				

[1]see Input Module Worksheet for this parameter
[2]if intersection signal timing given, use P_i (use G + Y if no pedestrian signals). If signal timing must be estimated, use (Green Time - Lost Time per Phase) from Signal Operations Worksheet.
[3]see Supplemental Worksheet for Left-turns (Figure 9-17 or 9-18) for this parameter
[4]if unopposed left turn, then $g_q = 0$, $v_o = 0$, and $OCC_r = OCC_{pedu} = OCC_{pedg}$
[5]see Volume Adjustment Worksheet for this parameter
[6]ideally determined from field data; alternatively, assume equal to: (1-permitted phase f_{LT}) / 0.95

Figure 10: Supplemental worksheet for pedestrian effects on permissive left turns

TABLE 4 Intermediate Pedestrian-Bicycle Parameters: Pedestrian Conflict Zone Occupancy (OCC_{pedg})

V_{pedg}[a]	OCC_{pedg}[b]	V_{pedg}	OCC_{pedg}	V_{pedg}	OCC_{pedg}	V_{pedg}	OCC_{pedg}
0	0.00	500	0.25	1000	0.50	3500	0.75
100	0.05	600	0.30	1500	0.55	4000	0.80
200	0.10	700	0.35	2000	0.60	4500	0.85
300	0.15	800	0.40	2500	0.65	≥ 5000	0.90
400	0.20	900	0.45	3000	0.70		

[a] pedestrian volume/h of pedestrian green time
[b] average conflict zone occupancy by pedestrians during pedestrian effective green time

TABLE 5 Intermediate Pedestrian-Bicycle Parameters: Relevant Conflict Zone Occupancy *(OCC_r)* For Right Turns or Unopposed Left Turns

	Bicycle Volume/h of green, V_{bikeg}											
OCC_{pedg}[a]	0	100	200	300	400	500	750	1000	1250	1500	1750	>1900
0.00	0.00	0.06	0.09	0.13	0.17	0.21	0.30	0.39	0.48	0.58	0.67	0.72
0.05	0.05	0.10	0.14	0.17	0.21	0.24	0.33	0.42	0.51	0.60	0.68	0.74
0.10	0.10	0.15	0.18	0.22	0.25	0.28	0.37	0.45	0.53	0.51	0.70	0.75
0.15	0.15	0.20	0.23	0.26	0.29	0.32	0.40	0.48	0.56	0.64	0.72	0.77
0.20	0.20	0.25	0.28	0.30	0.33	0.36	0.44	0.51	0.59	0.66	0.73	0.78
0.25	0.25	0.29	0.32	0.35	0.38	0.40	0.47	0.54	0.61	0.68	0.75	0.79
0.30	0.30	0.34	0.37	0.39	0.42	0.44	0.51	0.57	0.64	0.70	0.77	0.81
0.35	0.35	0.39	0.41	0.44	0.46	0.48	0.54	0.60	0.66	0.72	0.78	0.82
0.40	0.40	0.43	0.46	0.48	0.50	0.52	0.58	0.63	0.69	0.75	0.80	0.83
0.45	0.45	0.48	0.50	0.52	0.54	0.56	0.61	0.66	0.72	0.77	0.82	0.85
0.50	0.50	0.53	0.55	0.57	0.58	0.60	0.65	0.70	0.74	0.79	0.83	0.86
0.55	0.55	0.58	0.59	0.61	0.63	0.64	0.68	0.73	0.77	0.81	0.85	0.88
0.60	0.60	0.62	0.64	0.65	0.67	0.68	0.72	0.76	0.79	0.83	0.87	0.89
0.65	0.65	0.67	0.68	0.70	0.71	0.72	0.75	0.79	0.82	0.85	0.88	0.90
0.70	0.70	0.72	0.73	0.74	0.75	0.76	0.79	0.82	0.84	0.87	0.90	0.92
0.75	0.75	0.76	0.77	0.78	0.79	0.80	0.82	0.85	0.87	0.89	0.92	0.93
0.80	0.80	0.81	0.82	0.83	0.83	0.84	0.86	0.88	0.90	0.92	0.93	0.94
0.85	0.85	0.86	0.86	0.87	0.88	0.88	0.89	0.91	0.92	0.94	0.95	0.96
0.90	0.90	0.91	0.91	0.91	0.92	0.92	0.93	0.94	0.95	0.96	0.97	0.97

[a]averge conflict zone occupancy by pedestrians during pedestrian effective green time

TABLE 6 Intermediate Pedestrian-Bicycle Parameters: Conflict Zone Occupancy After Opposing Queue Clears *(OCC_{pedu})* for Opposed Left Turns

Ratio of Opposing Queue Time to Effect. Ped. Green, g_q/g_p											
OCC_{pedg}[a]	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	<1.0[b]
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03
0.10	0.10	0.10	0.09	0.09	0.08	0.08	0.07	0.07	0.06	0.06	0.05
0.15	0.15	0.14	0.14	0.13	0.12	0.11	0.11	0.10	0.09	0.08	0.08
0.20	0.20	0.19	0.18	0.17	0.16	0.15	0.14	0.13	0.12	0.11	0.10
0.25	0.25	0.24	0.23	0.21	0.20	0.19	0.18	0.16	0.15	0.14	0.13
0.30	0.30	0.29	0.27	0.26	0.24	0.23	0.21	0.20	0.18	0.17	0.15
0.35	0.35	0.33	0.32	0.30	0.28	0.26	0.25	0.23	0.21	0.19	0.18
0.40	0.40	0.38	0.36	0.34	0.32	0.30	0.28	0.26	0.24	0.22	0.20
0.45	0.45	0.43	0.41	0.38	0.36	0.34	0.32	0.29	0.27	0.25	0.23
0.50	0.50	0.48	0.45	0.43	0.40	0.38	0.35	0.33	0.30	0.28	0.25
0.55	0.55	0.52	0.50	0.47	0.44	0.41	0.39	0.36	0.33	0.30	0.28
0.60	0.60	0.57	0.54	0.51	0.48	0.45	0.42	0.39	0.36	0.33	0.30
0.65	0.65	0.62	0.59	0.55	0.52	0.49	0.46	0.42	0.39	0.36	0.33
0.70	0.70	0.67	0.63	0.60	0.56	0.53	0.49	0.46	0.42	0.39	0.35
0.75	0.75	0.71	0.68	0.64	0.60	0.56	0.53	0.49	0.45	0.41	0.38
0.80	0.80	0.76	0.72	0.68	0.64	0.60	0.56	0.52	0.48	0.44	0.40
0.85	0.85	0.81	0.77	0.72	0.68	0.64	0.60	0.55	0.51	0.47	0.43
0.90	0.90	0.86	0.81	0.77	0.72	0.68	0.63	0.59	0.54	0.50	0.45

[a] average conflict zone occupancy by pedestrians during effective ped. green
[b] if $g_q/g_p \geq 1.0$ then OCC_{pedu}= 0.00 and f_{Lpb}= 1.0

TABLE 7 Intermediate Pedestrian-Bicycle Parameters: Relevant Conflict Zone Occupancy *(OCC_r)*After Opposing Queue Clears For Opposed Left Turns

Conflict Zone Occupancy After Queue, OCC_{pedu}

v_o[a]	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90
0	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90
100	0.00	0.09	0.17	0.26	0.35	0.44	0.52	0.61	0.70	0.78
200	0.00	0.08	0.15	0.23	0.30	0.38	0.45	0.53	0.61	0.68
300	0.00	0.07	0.13	0.20	0.26	0.33	0.40	0.46	0.53	0.59
400	0.00	0.06	0.11	0.17	0.23	0.29	0.34	0.40	0.46	0.52
500	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45
600	0.00	0.04	0.09	0.13	0.17	0.22	0.26	0.30	0.35	0.39
700	0.00	0.03	0.08	0.11	0.15	0.19	0.23	0.26	0.30	0.34
800	0.00	0.03	0.07	0.10	0.13	0.16	0.20	0.23	0.26	0.30
900	0.00	0.02	0.06	0.09	0.11	0.14	0.17	0.20	0.23	0.26
1000	0.00	0.02	0.05	0.07	0.10	0.12	0.15	0.17	0.20	0.22
1100	0.00	0.02	0.04	0.04	0.09	0.11	0.13	0.15	0.17	0.20
1200	0.00	0.02	0.04	0.06	0.08	0.09	0.11	0.13	0.15	0.17
1300	0.00	0.02	0.03	0.05	0.07	0.08	0.10	0.12	0.13	0.15
1400	0.00	0.01	0.03	0.04	0.06	0.07	0.09	0.10	0.11	0.13
1500	0.00	0.01	0.02	0.04	0.05	0.06	0.07	0.09	0.10	0.11
2000	0.00	0.01	0.01	0.02	0.02	0.04	0.04	0.04	0.05	0.06
3000	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01
≥ 4000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

;[a]opposing vehicle volume, vehicles/h

TABLE 8 Intermediate Pedestrian-Bicycle Parameters: Permitted Phase Turning Adjustment *(A_{pbT};)* For Right And Left Turns

OCC_r[a]	N_{rec}[b] = N_{turn}[c]	$N_{rec} > N_{turn}$	OCC_r	$N_{rec} = N_{turn}$	$N_{rec} > N_{turn}$
0.00	1.00	1.00	0.50	0.50	0.70
0.05	0.95	0.97	0.55	0.45	0.67
0.10	0.90	0.94	0.60	0.40	0.64
0.15	0.85	0.91	0.65	0.35	0.61
0.20	0.80	0.88	0.70	0.30	0.58
0.25	0.75	0.85	0.75	0.25	0.55
0.30	0.70	0.82	0.80	0.20	0.52
0.35	0.65	0.79	0.85	0.15	0.49
0.40	0.60	0.76	0.90	0.10	0.46
0.45	0.55	0.73	0.95	0.05	0.43
			0.97	0.03	0.42

[a] relevant conflict zone occupancy from Table 5 or Table 7
[b] number of receiving lanes
[c] number of turning lanes

TABLE 9 Proposed Adjustment Factor For Pedestrian-Bicycle Effects On Right Turns (f_{Rpb})

Cases 1-6: Exclusive/Shared Lanes and Protected/Permitted Phasing

$f_{Rpb} = 1.0 - P_{RT} (1 - A_{pbT}) (1 - P_{RTA})$

$0.00 \leq P_{RT} \leq 1.0$ Proportion of RT in lane group = 1.00 for excl. RT lane (Cases 1-3);
≤ 1.00 for shared/single lane (Cases 4-6).

$0.03 \leq A_{pbT} \leq 1.0$ Permitted Phase Turning Adjustment
$0.00 \leq P_{RTA} \leq 1.0$ Proportion of RT using protected phase:
= 1.00 for protected phase (no peds);
≤ 1.00 for permitted phase (ped conflicts).

$f_{Rpb} = 1.0$ if $P_{RT} = 0.0$ $f_{Rpb} \geq 0.03$

Range of Variable Values

Case	RT Lane	RT Phase	P_{RT}[a]	P_{RTA}[b]	SIMPLIFIED FORMULA
1	Exclusive	Protected	1.0	1.0	1.0
2	Exclusive	Permitted	1.0	0.0	A_{pbT}[c]
3	Exclusive	Prot./Perm.	1.0	0.0 - 1.0	$1.0 - (1 - A_{pbT})(1 - P_{RTA})$
4	Shared	Protected	0 - 1.0	1.0	1.0
5	Shared	Permitted	0 - 1.0	0.0	$1.0 - P_{RT} (1 - A_{pbT})$
6	Shared	Prot./Perm.	0 - 1.0	0.0 - 1.0	$1.0 - P_{RT} (1 - A_{pbT})(1 - P_{RTA})$

[a] proportion of right turns in lane group
[b] proportion of right turns using protected phase
[c] permitted phase turning vehicle adjustment from phase 3 discussion

TABLE 10 Proposed Adjustment Factor For Pedestrian Effects On Left Turns (f_{Lpb})

Cases 1-6 : Exclusive/Shared Lanes and Protected/Permitted Phasing

$f_{Lpb} = 1.0 - P_{LT} (1 - A_{pbT}) (1 - P_{LTA})$

$0.0 \leq P_{LT} \leq 1.0$ Proportion of LT in lane group = 1.00 for excl. LT lane (Cases 1-3);
≤ 1.00 for shared lane (Cases 4-6).
$0.1 \leq A_{pbT} \leq 1.0$ Permitted Phase Turning Adjustment
$0.0 \leq P_{LTA} \leq 1.0$ Proportion of LT using protected phase:
= 1.00 for protected phase (no peds);
≤ 1.00 for permitted phase (ped conflicts).

$f_{Lpb} = 1.00$ if $P_{LT} = 0.0$
$f_{Lpb} \geq 0.10$

Range of Variable Values

Case	LT Lane	LT Phase	P_{LT}[a]	P_{LTA}[b]	SIMPLIFIED FORMULA
1	Exclusive	Protected	1.0	1.0	1.0
2	Exclusive	Permitted	1.0	0.0	A_{pbT}[c]
3	Exclusive	Prot./Perm.	1.0	0.0 - 1.0	$1.0 - (1 - A_{pbT})(1 - P_{LTA})$
4	Shared	Protected	0 - 1.0	1.0	1.0
5	Shared	Permitted	0 - 1.0	0.0	$1.0 - P_{LT}(1 - A_{pbT})$
6	Shared	Prot./Perm.	0 - 1.0	0.0 - 1.0	$1.0 - P_{LT}(1 - A_{pbT})(1 - P_{LTA})$

[a] proportion of left turns in lane group
[b] proportion of left turns using protected phase
[c] permitted phase turning vehicle adjustment from phase 3 discussion

Figure 11 compares the saturation flow adjustment for turning vehicles from this procedure with those discussed in the background section, using a green time of 30 s and a cycle length of 60 s. As the figure shows, the two proposed models lie near the middle of the other models. They generally follow the Polish method (for C=90 and g=30), although they predict less effect of pedestrians on saturation flow than the Polish method for high pedestrian volumes. The graph for one net lane predicts more severe reductions in saturation flow than all except the Canadian methods until roughly 900 pedestrians/h (1800 per hour green at the assumed signal timing). The graph for more than one net lane predicts virtually the same effect as the *HCM* up to about 500 pedestrians/h (1000 per hour green). Beyond this level, it predicts substantially less effect than the *HCM*, and somewhat less effect than all methods except Zegeer above 800 pedestrians/h (1600 per hour green).

In the existing *HCM*, one adjusts right turns for both radius and pedestrians with f_{RT}. Under the proposed method of separating the effect of radius from pedestrians and bicycles, f_{RT} would only reflect the effect of radius on right turns (Table 11). Table 12 summarizes both the existing and proposed adjustment factors for lane groups containing turning vehicles.

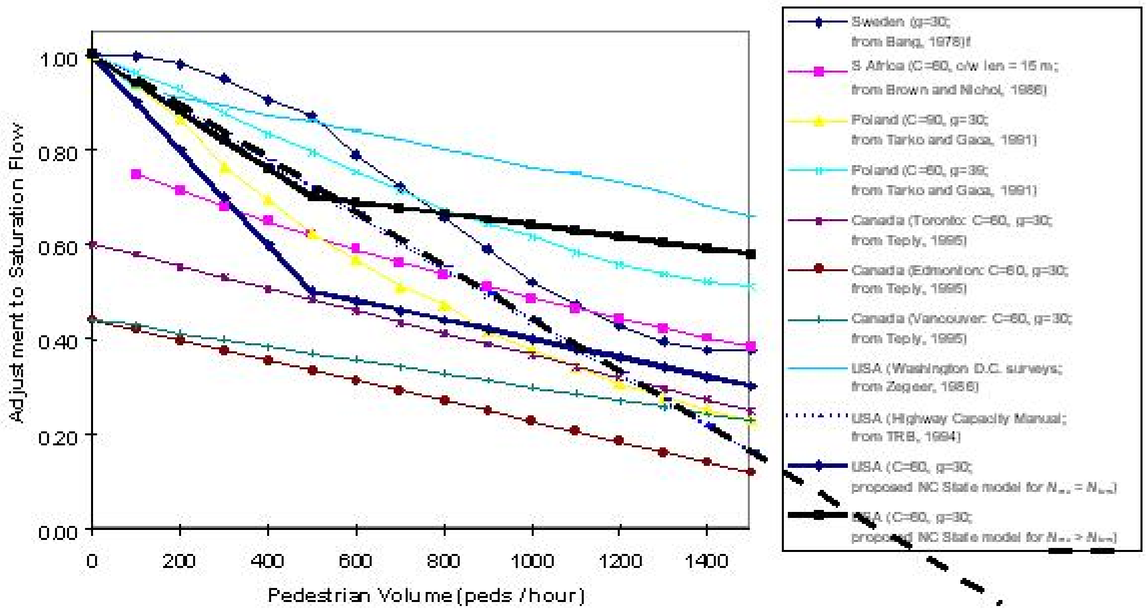

Figure 11: Comparison of A pbT with other adjustment factors for pedestrians.

TABLE 11 Proposed Adjustment Factor for Radius Effects on Right Turns (f_{RT})

P_{RT}[a]	f_{RT}	P_{RT}	f_{RT}	P_{RT}	f_{RT}
0.00[b]	1.000	;0.35	;*0.948*	0.70	0.895
0.05	0.992	0.40	0.940	0.75	0.888
0.10	0.985	0.45	0.932	0.80	0.880
0.15	0.978	0.50	0.925	0.85	0.872
0.20	0.970	0.55	0.918	0.90	0.865
0.25	0.962	0.60	0.910	0.95	0.858
0.30	0.955	0.65	0.902	1.00	0.850

NOTE: $f_{RT} = 1.0 - P_{RT}(0.15)$ $0.0 \le P_{RT} \le 1.0$

[a] proportion of right turns in lane group

[b] **no right turns from the lane group**

TABLE 12 Existing and proposed saturation flow adjustment factors for lane groups containing turning vehicles

Source of Impedance to Turning Vehicles

Procedure	Movement	Radius	Opposing Vehicles	Pedestrians	Bicycles
Existing	Left-Turn	f_{LT}	f_{LT}	ignored	ignored
	Right-Turn	f_{RT}	N/A	f_{RT}	1 bike = 1 ped
Proposed	Left-Turn	f_{LT}	f_{LT}	f_{Lpb}[a]	ignored
	Right-Turn	f_{RT}[a]	N/A	f_{Rpb}[a]	$f_{R\,pb}$[a]

[a] **new or changed factor**

EXAMPLE PROBLEMS

Table 13 provides several examples of the proposed procedure. For each example, the signal timing is held constant, with an effective pedestrian green time, g_p, of 30 s, an overall effective green time (applied to bicycles as well as opposing vehicles), g, of 30 s, and a cycle length, C, of 60 s. To facilitate comparisons, the examples are grouped in pairs. Examples 1a and 1b refer to right turns, while Examples 2a, 2b, 2c, and 2d pertain to the opposed left turn case, which is not addressed in the current HCM.

Figure 12: Through Bicycles delay right-turning vehicle in Gainesville, Florida

Examples 1a and 1b compare the effect on right turns of adding a moderate bicycle volume, V_{bike}, to a constant pedestrian volume, V_{ped}, of 500 pedestrians/h. Example 1a contains no bicycles, while Example 1b adds 175 bicycles/h (Figure 12). With conflicting bicycles, the saturation flow adjustment, f_{Rpb}, decreases from 0.50 to 0.43, and the capacity, c, decreases from 291 to 247 vehicles/h. Of note here, as the overall relevant occupancy, OCC_r, increased from 50 to 57 percent with the additional bicycles, the difference between the existing and proposed methods decreased from 232 to 205 vehicles/h.

Table 13 Examples showing impact of proposed adjustment factors on capacity

Example	PART 1					PART 2												
	USER INPUT			*Calculated*		USER INPUT				*Calc'd*	USER INPUT		*Calculated*					
	C	g_p	V_{ped}	V_{pedg}	OCC_{pedg}	L-turn or R-turn	1-way or 2-way	bikes or no bikes	[2][a]	[2a] OCC_r	[2b] g_q	[2b] V_o	[2b] g_q/g_p	[2b] $g_q/g_p \geq 1$	[2b] occ_{pedu}	[2b] P_{nscr}	[2b] occ_r
	sec	sec	ped/hr	ped/hr grn							sec	veh/hr					
1a	60	30	500	1000	**0.50**	R-turn	2-way	no bikes	**2a**	**0.50**	---	---	- - -	- - -	- - -	- - -	- - -
1b	60	30	500	1000	**0.50**	R-turn	2-way	bikes	**2c**	- - -	---	---	- - -	- - -	- - -	- - -	- - -
2a	60	30	1000	2000	**0.60**	L-turn	2-way	no bikes	**2b**	- - -	10	600	0.33	NO	0.50	0.43	**0.22**
2b	60	30	1000	2000	**0.60**	L-turn	2-way	no bikes	**2b**	- - -	10	600	0.33	NO	0.50	0.43	**0.22**
3a	60	30	2000	4000	**0.80**	L-turn	2-way	no bikes	**2b**	- - -	10	600	0.33	NO	0.67	0.43	**0.29**
3b	60	30	2000	4000	**0.80**	L-turn	2-way	no bikes	**2b**	- - -	10	600	0.33	NO	0.67	0.43	**0.29**

[a] [2a: Basic Left- or Right-turn] [2b: Left-turns with opposing vehicles] [2c: Right-turns with conflicting bicycles]

Table 13 (continued) Examples showing impact of proposed adjustment factors on capacity

Example	PART 2 (continued)						PART 3				PART 4					
	USER INPUT		*Calculated*			*Calc'd*	USER INPUT		*Calc'd*		USER INPUT					*Calc'd*
	[2c] g	[2c] V_{bike}	[2c] V_{bikeg}	[2c] OCC_{bike}	[2c] OCC_r	[2] OCC_r	N_t	N_{dep}	N_{net}	A_{pbt}	lane type[b]	signal phasing[c]	Case[d]	P_{LT}; P_{RT}	P_{LTA}; P_{RTA}	f_{Rpb} or f_{Lpb}
	sec	bike/hr	bike/hr green													
1a	---	---	---	---	---	**0.50**	1	1	1	**0.50**	EX	PER	**R-turn 2**	1	0	**0.50**
1b	30	175	350.0	0.15	**0.57**	**0.57**	1	1	1	**0.43**	EX	PER	**R-turn 2**	1	0	**0.43**
2a	---	---	---	---	---	**0.22**	1	1	1	**0.78**	EX	PER	**L-turn 2**	1	0	**0.78**
2b	---	---	---	---	---	**0.22**	1	2	2	**0.87**	EX	PER	**L-turn 2**	1	0	**0.87**
3a	---	---	---	---	---	**0.29**	1	1	1	**0.71**	EX	PER	**L-turn 2**	1	0	**0.71**
3b	---	---	---	---	---	**0.29**	1	2	2	**0.83**	EX	PER	**L-turn 2**	1	0	**0.83**

[b] EXclusive or SHared turn lane approach

[c] PROtected, PERmitted, or Protected/Permitted Signal Phasing

[d] See Table 9 for Right-Turns and Table 10 for Left-Turns

Table 13 (continued) Examples showing impact of proposed adjustment factors on capacity

Example	Determination of Capacity by Proposed and *HCM* Methods (External to f_{pb} Computational Procedure)											
	USER INPUT		*Calculated*									
	g	f_a [e]	PROP f_{LT} [f]	PROP f_{RT} [g]	PROP s	PROP c	EXIST peds [h]	EXIST f_{LT} [f]	EXIST f_{RT} [g]	EXIST s	EXIST c	Capacity Difference Between Methods = c(PROP) - c(EXIST)
	sec				pcphgpl	veh/hr	ped/hr			pcphgpl	veh/hr	veh/hr
1a	30	0.90	0.80	0.85	581	**291**	500	1.00	0.61	1046	**523**	**-232**
1b	30	0.90	0.80	0.85	494	**247**	675	1.00	0.53	904	**452**	**-205**
2a	30	0.90	0.80	1.00	1071	**535**	1000	0.80	1.00	1368	**684**	**-149**
2b	30	0.90	0.80	1.00	1190	**595**	1000	0.80	1.00	1368	**684**	**-89**
3a	30	0.90	0.80	1.00	972	**486**	2000	0.80	1.00	1368	**684**	**-198**
3b	30	0.90	0.80	1.00	1130	**565**	2000	0.80	1.00	1368	**684**	**-119**

[e] area type factor (from HCM Table 9-10, page 9-15); f_a = 0.9 if Central Business District and 1.0 otherwise

[f] proposed f_{LT} adjustment will only apply for the effect of turning radius or opposing vehicles on left-turns; the existing f_{LT} adjustment can also use right-turn equation for conflicting peds but no opposing traffic

[g] proposed f_{RT} adjustment will only adjust for radius; existing f_{RT} also adjusts for pedestrians (and bicycles)

[h] existing *HCM* method simply adds pedestrian volume and bicycle volume together

Examples 2a and 2b compare the effect on left turns of varying the number of receiving lanes for a constant, medium-high pedestrian volume, V_{ped}, of 1000/h, and moderate opposing volume, V_o, of 600 vehicles/h. While both examples use a single left-turn lane, Example 2a contains one receiving lane while Example 2b adds a second receiving lane (Figure 13). With the additional receiving lane, the saturation flow adjustment, f_{Lpb}, increases from 0.78 to 0.87, and the capacity, c, increases from 535 to 595 vehicles/h. In addition, as the number of receiving lanes increased, the difference between the existing and proposed methods decreased from 149 to 89 vehicles/h.

Examples 3a and 3b compare the effect on left turns of varying the number of receiving lanes for a constant, high pedestrian volume, V_{ped}, of 2000/h, and moderate opposing volume, V_o, of 600 vehicles/h. While both examples use a single left-turn lane, Example 3a contains one receiving lane while Example 3b adds a second receiving lane. With the additional receiving lane, the saturation flow adjustment, f_{Lpb}, increases from 0.71 to 0.83, and the capacity, c, increases from 486 to 565 vehicles/h. In addition, as the number of receiving lanes increased, the difference between the existing and proposed methods decreased from 198 to 119 vehicles/h.

Each of these examples shows a slight to moderate decrease in capacity using the new approach. Since the existing HCM does not consider the effect of pedestrians on opposed left turns, the resulting decrease in capacity is obviously not surprising. However, even though the pedestrian volume doubled from Example 2 to Example 3, the capacity only slightly decreased, because opposing traffic is screening the conflict zone for much of the time. In addition, since the proposed method only applies during the permitted phase, the capacity of a protected-only approach will not change under the proposed procedure. Finally, it is possible for the proposed method to predict more capacity than the existing HCM methodology if the pedestrian volume reaches a certain level.

Figures 14, 15, and 16 offer an example that illustrates the potential impact of using f_{pb} on level of service (LOS). Figure 14 depicts an intersection with vehicle volumes as shown for the eastbound, westbound, and southbound approaches. A total of 500 pedestrians/h use the crosswalk on the southbound approach, conflicting with right turns from the eastbound approach and left turns from the westbound approach. The intersection uses a simple two-phase signal as shown, with 30 s of green allocated to the major street and a 60-s cycle length.

Figure 13: Turning driver having two receiving lanes to choose from in Portland, Oregon.

The existing HCM procedure predicts that all movements and approaches for this example operate at LOS B (Figure 15). However, the current procedures underestimate the effect of pedestrians on right turns in many cases, including this example, and they ignore the effect of pedestrians on left turns. The revised procedure predicts that the major approaches will fall to LOS C, as will the intersection as a whole (Figure 16). The westbound left-turn lane group, in fact, drops from LOS B with the existing method to LOS E for the proposed method.

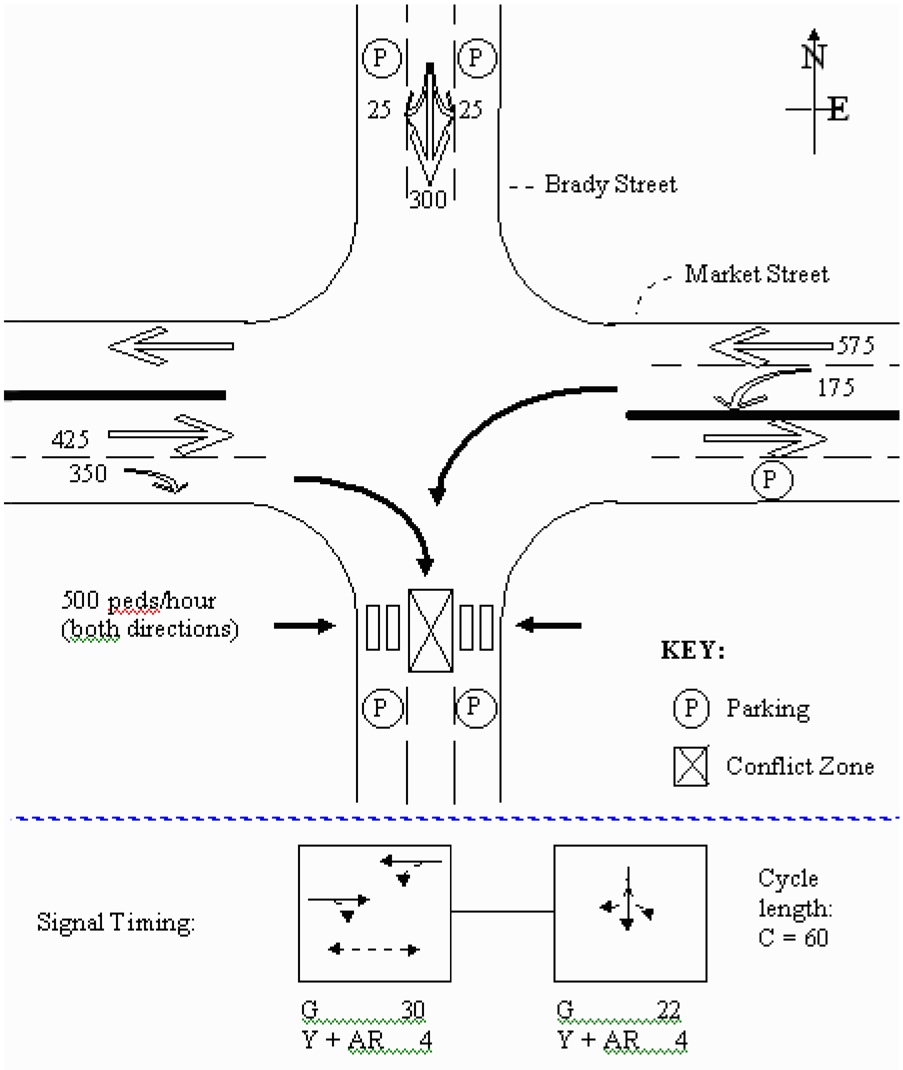

Figure 14: Example sketch

```
HCM: SIGNALIZED INTERSECTION SUMMARY   Version 2.4a       11-08-1996
              Center For Microcomputers In Transportation
======================================================================
Streets: (E-W) Market Street           (N-S) Brady Street
Analyst: JSM2                          File Name: PB-EXIST.HC9
Area Type: CBD                         11-8-96 8-9 am
Comment: Blairsville, PA

---->  EXISTING HCM METHOD
======================================================================
           |  Eastbound   |  Westbound   |  Northbound  |  Southbound
           | L    T    R  | L    T    R  | L    T    R  | L    T    R
           |---- ---- ----|---- ---- ----|---- ---- ----|---- ---- ----
No. Lanes  |      1    1  | 1    1       |              |    > 1  <
Volumes    |    425  350| 175  575       |              |  25  300   25
Lane Width |   12.0 12.0|12.0 12.0       |              |     12.0
RTOR Vols  |           0|             0|              |            0
Lost Time  |   3.00 3.00|3.00 3.00       |              |3.00 3.00 3.00
----------------------------------------------------------------------
                         Signal Operations
Phase Combination 1     2     3     4 |          5     6     7     8
EB  Left                              |NB  Left
    Thru          *                   |    Thru
    Right         *                   |    Right
    Peds          *                   |    Peds
WB  Left          *                   |SB  Left    *
    Thru          *                   |    Thru    *
    Right                             |    Right   *
    Peds          *                   |    Peds
NB  Right                             |EB  Right
SB  Right                             |WB  Right
Green          30.0P                  |Green    22.0P
Yellow/AR       4.0                   |Yellow/AR 4.0
Cycle Length:  60 secs  Phase combination order: #1 #5
----------------------------------------------------------------------
                   Intersection Performance Summary
     Lane  Group:  Adj Sat    v/c     g/C                    Approach:
     Mvmts   Cap    Flow     Ratio   Ratio   Delay  LOS   Delay   LOS
     -----  ----  --------   -----   -----   -----  ---   -----   ---
EB   T       818    1583     0.520   0.517     7.8   B     8.7     B
     R       540    1046     0.648   0.517     9.9   B
WB   L       249     482     0.703   0.517    14.2   B    13.8     B
     T       716    1385     0.804   0.517    13.7   B
SB   LTR     509    1328     0.688   0.383    14.5   B    14.5     B
              Intersection Delay =  11.8 sec/veh Intersection LOS = B
Lost Time/Cycle, L =   6.0 sec   Critical v/c(x)     = 0.754
----------------------------------------------------------------------
```

Figure 15: Existing HCM method of capturing the effect of pedestrians on lane groups containing turning vehicles

```
HCM: SIGNALIZED INTERSECTION SUMMARY   Version 2.4a       11-08-1996
              Center For Microcomputers In Transportation
======================================================================
Streets: (E-W) Market Street           (N-S) Brady Street
Analyst: JSM2                          File Name: PB-PROP.HC9
Area Type: CBD                         11-8-96 8-9 am
Comment: Blairsville, PA

---->  PROPOSED METHOD
======================================================================
           |  Eastbound  |  Westbound   |  Northbound  |  Southbound
           | L    T    R | L    T    R  | L    T    R  | L    T    R
           |---- ---- ----|---- ---- ----|---- ---- ----|---- ---- ----
No. Lanes  |      1    1  | 1    1        |              |    > 1  <
Volumes    |     425  350| 175  575      |              |  25  300   25
Lane Width |     12.0 12.0|12.0 12.0     |              |     12.0
RTOR Vols  |            0|             0|              |              0
Lost Time  |     3.00 3.00|3.00 3.00     |              |3.00 3.00 3.00
----------------------------------------------------------------------
                         Signal Operations
Phase Combination 1     2     3     4 |           5     6     7     8
EB  Left                              |NB  Left
    Thru          *                   |    Thru
    Right         *                   |    Right
    Peds          *                   |    Peds
WB  Left          *                   |SB  Left    *
    Thru          *                   |    Thru    *
    Right                             |    Right   *
    Peds          *                   |    Peds
NB  Right                             |EB  Right
SB  Right                             |WB  Right
Green          30.0P                  |Green    22.0P
Yellow/AR       4.0                   |Yellow/AR 4.0
Cycle Length:  60 secs  Phase combination order: #1 #5
----------------------------------------------------------------------
                   Intersection Performance Summary
     Lane  Group:  Adj Sat    v/c     g/C                     Approach:
     Mvmts   Cap    Flow     Ratio   Ratio   Delay   LOS   Delay   LOS
     -----  ----  --------   -----   -----   -----   ---   -----   ---
EB   T       818    1583     0.520   0.517     7.8    B    19.6     C
     R       371     718     0.943   0.517    33.9    D
WB   L       185     359     0.943   0.517    46.5    E    21.4     C
     T       716    1385     0.804   0.517    13.7    B
SB   LTR     509    1328     0.688   0.383    14.5    B    14.5     B
               Intersection Delay =  19.3 sec/veh Intersection LOS = C
Lost Time/Cycle, L =   6.0 sec   Critical v/c(x)    = 0.834
----------------------------------------------------------------------
```

Figure 16: Impact of proposed method for capturing the effect of pedestrians on lane groups containg turning vehicles

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

As a result of this research, the following conclusions are offered:

- There is a wide variation among existing adjustments to vehicular saturation flow due to pedestrians.
- The *HCM* may not accurately predict the effect of a moderate pedestrian or bicycle volume on turning traffic.
- The procedures described herein should improve the analysis and performance of signalized intersections subject to nonmotorized interference of turning movements.

Recommendations

Based on the above conclusions, the following recommendations are made:

- It is recommended that the *HCM* include the proposed saturation flow adjustment factors f_{Rpb} and f_{Lpb} to account for the effect of pedestrians and bicycles on signalized intersections.
- It is recommended that the *HCM* simplify f_{RT} to account only for the effect of radius.

Based on the results of the *Literature Synthesis for Chapter 13, "Pedestrians," of the Highway Capacity Manual (Rouphail et al., 1998)*, the following additional recommendation is made:

As stated in the *Recommended Procedures for Chapter 13, "Pedestrians," of the Highway Capacity Manual (Rouphail et al., 1998)*, it is recommended that the *HCM* include pedestrian delay as a primary measure of effectiveness for pedestrian street corner analysis in Chapter 13 of the *HCM* (Table 14). This will result in easily comparable delay-based service measures at signalized crossings from the perspective of both drivers and pedestrians.

TABLE 14 Recommended HCM pedestrian Level of Service (LOS) criteria for signalized crossing delay

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

REFERENCES

Allen, D. Patrick. The Effect of Bicycles on the Capacity of Signalized Intersections. Master's Thesis, North Carolina State University, Raleigh, N.C., 1996.

Bang, Karl-Lennart. "Swedish Capacity Manual: Part 3- Capacity of Signalized Intersections," *Transportation Research Record* 667, 1978. (Excerpted from: Swedish Capacity Manual, National Swedish Road Administration, 1977.)

Brown, R.J. and R.D. Nicol. "Effect of Pedestrian Volumes on Left-Turning Traffic." *Second International Conference on Road Traffic Control*, pp 145-149, 1986.

Garber, Nicholas J. and Lester A. Hoel. *Traffic and Highway Engineering*. Boston: PWS Publishing Company, 1997, 2nd edition.

Milazzo II, Joseph. The Effect of Pedestrians on the Capacity of Signalized Intersections. Master's Thesis, North Carolina State University, Raleigh, N.C., 1996.

Rouphail, Nagui; Joseph Hummer, Joseph Milazzo II, and Patrick Allen. *Literature Synthesis for Chapter 13, "Pedestrians" of the Highway Capacity Manual*. Federal Highway Administration Report, February 1998.

Rouphail, Nagui; Joseph Hummer, Joseph Milazzo II, and Patrick Allen. *Recommended Procedures for Chapter 13, "Pedestrians" of the Highway Capacity Manual*. Federal Highway Administration Report, February 1998.

Tarko, Andrzej and Stanislaw Gaca. "Pedestrians at Signalized Intersections." *International Symposium on Highway Capacity and Level of Service at Karlsruhe, Germany*, pp. 367-376, July 1991.

Teply, Stan, editor. "Canadian Capacity Guide for Signalized Intersections," second edition, June 1995, excerpts from final draft.

Transportation Research Board. *Highway Capacity Manual*. Special Report 209, 1994 update to 1985 edition.

Wigan, Marcus. "Treatment of Walking as a Mode of Transportation." In *Transportation Research Record* 1487, Transportation Research Board, 1995.

Zegeer, John D. "Field Validation of Intersection Capacity Factors," *Transportation Research Record 1091, page 67*, 1986.