



Extensions of theoretical capacity models to account for special conditions

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Abstract

The computational procedures used to analyze two-way stop-controlled intersections were extended in the National Cooperative Highway Research Project 3-46 to account for a number of effects commonly observed at actual unsignalized intersections. This paper presents theoretical extensions that can account for commonly observed phenomena, such as two-stage gap acceptance when median storage is available; right-turn “sneakers” at flared minor-street approaches; non-random arrivals caused by upstream signals; impedance due to pedestrian crossings; and delay to major-street through vehicles using shared left-turn and through lanes. The individual effects are then combined into an analytical framework suitable for inclusion in the Unsignalized Intersections procedures of the 1997 “Highway Capacity Manual”. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Two way; Stop control; Intersection; Unsignalized; Two stage; Gap acceptance; Left turn lane; Median storage; Flared approach; Short lane; Upstream signal; Platoon arrival impedance; Pedestrian crossing shared lane; Highway capacity

1. Introduction

There are many commonly encountered real-world conditions that were not adequately accounted for in the capacity and delay models used in the 1994 Highway Capacity Manual (Transportation Research Board, 1994). These conditions include: the existence of a raised/striped median or a two-way left-turn lane (TWLTL) on the major street where a two-stage gap acceptance process is observed by some drivers, and a flared minor-street approach where right-turn sneakers are present. Other conditions that have not been accounted for include: the presence of upstream signals where heavy major-street platoons are observed, pedestrians who may

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affect the capacity and delay to vehicles, and a shared through and left-turn lane on the major street where left-turn vehicles may cause blockage of the through traffic.

These conditions need special consideration when applying the capacity and delay models. The purpose of this paper is to summarize some of the findings and recommendations regarding these special situations that were addressed as part of NCHRP Project 3-46 (see Kyte et al., 1996). Details of each procedure are covered in the cited references. Fig. 1 provides a numbering and ranking scheme for the individual movements at typical unsignalized intersections and will be referred to in the following discussions.

Combining these individual building blocks into a consistent procedure for analyzing the performance of two-way stop-controlled intersections was quite complex. However, the procedure, although tedious, can still be accomplished by means of a series of worksheets. Fig. 2(a–c) together represent a flowchart of the two-way stop-controlled procedure included in the 1997 version of the Highway Capacity Manual (Transportation Research Board, 1997). The procedure is divided into three separate modules. In the first module, *Initial Calculations*, the analyst computes the critical gap and follow-up time, and determines the flow patterns that result from any upstream signalized intersections that may affect the capacity of the subject intersection. For a subject movement, separate capacity analyses are performed for each proportion of the analysis period that is subject to each flow pattern. A weighted capacity estimate is obtained for the entire analysis period. The second module, *Capacity Calculations*, computes the capacity of each movement and makes adjustments for the effects of two-stage gap acceptance, shared lanes, or flared minor-street approaches. The third module, *Delay and LOS Calculations*, computes the

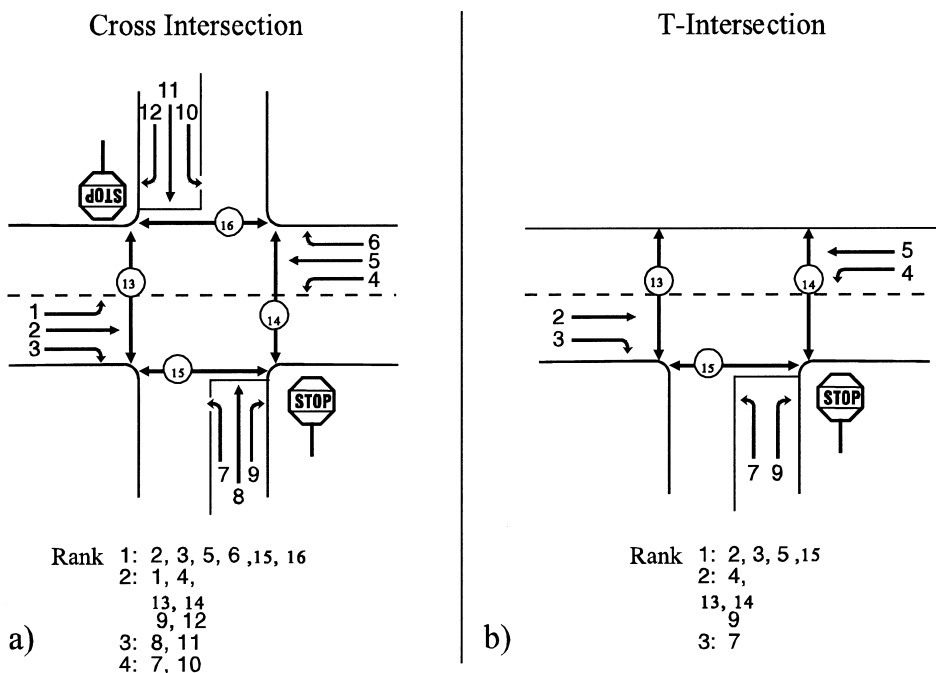


Fig. 1. Movement numbering and ranking scheme for two-way stop-controlled intersections.

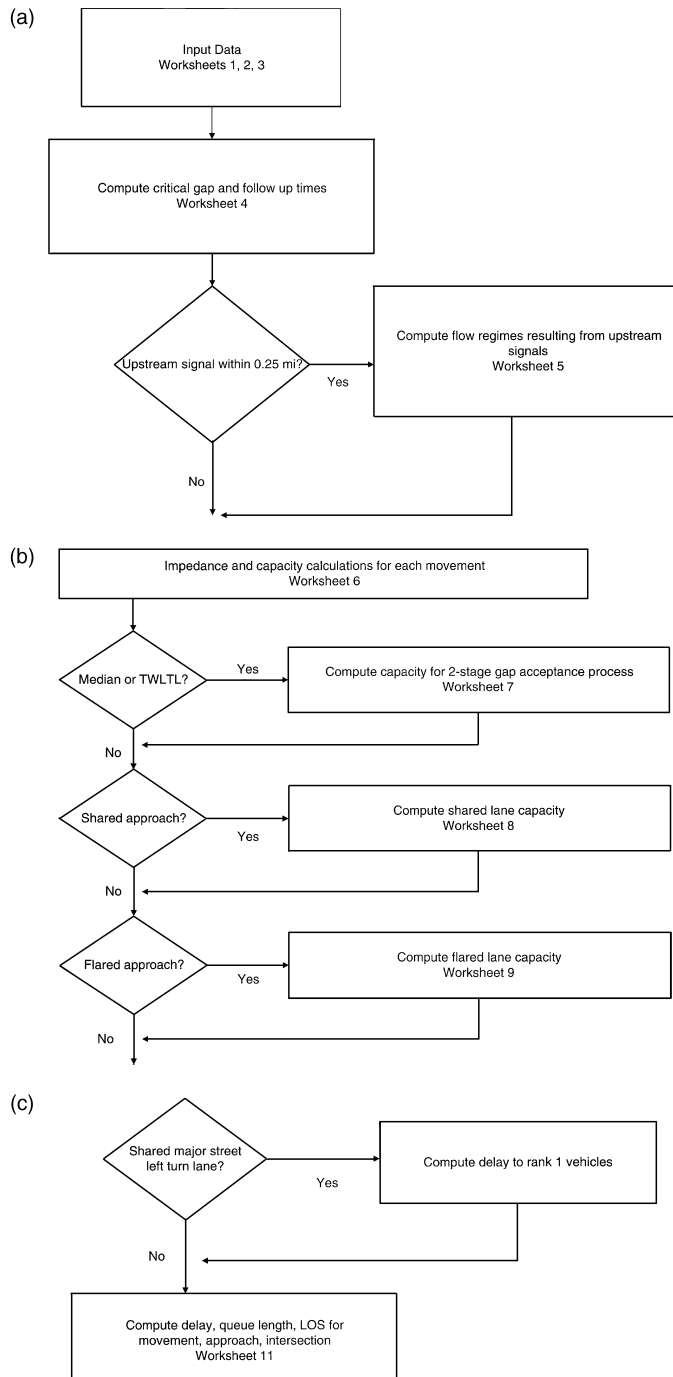


Fig. 2. (a) TWSC intersection capacity and LOS computation procedure, initial calculations. (Worksheets refer to Chapter 10 of 1997 HCM.); (b) TWSC intersection capacity and LOS computation procedure, capacity calculations. (Worksheets refer to Chapter 10 of 1997 HCM.); (c) TWSC intersection capacity and LOS computation procedure, delay, LOS calculations. (Worksheets refer to Chapter 10 of 1997 HCM.)

delay, queue length, and level of service for the intersection. Further research into the combined effects of these phenomena will be necessary to confirm this schema.

2. Two-stage gap acceptance

The existence of a raised or striped median or a TWLTL on the major street, in combination with moderate to heavy traffic flows, often causes some degree of special gap-acceptance phenomena known as two-stage gap acceptance. For example, the existence of a raised or striped median may cause a significant proportion of the minor-street drivers to first cross part of the major-street approach and then pause in the middle of the road to wait for another gap in the other approach. When a TWLTL exists on the major street, the minor-street left-turn vehicle may merge into the TWLTL first, then seek a usable gap on the other approach while slowly moving for some distance along the TWLTL. Both of these behaviors can contribute to increased capacity as is evident from empirical observations (Fig. 3).

In this procedure (Wu and Brilon, 1995), the intersection is assumed to consist of two parts, with the minor-street traffic crossing the major street in two phases. Between the partial intersections I and II (Fig. 4) there is a storage space for m vehicles. This area has to be passed by the left turners from the major street and the minor through or left-turn traffic. It is assumed that drivers at the intersections apply the usual rules for TWSC intersections. Thus the major through traffic has priority over all other movements. For example, Fig. 4 illustrates the two-stage gap acceptance process for a northbound minor movement (i.e. a vehicle from the bottom of the figure). Here, movement 1 vehicles must give way to priority movement 5, whereas northbound minor movements have to give the right-of-way to all other movements.

Considering the central area of the intersection as a closed storage system, which is limited by the input line and output line, the capacity properties of the storage system are restricted by the maximum input and maximum output. There are four different states of the system:

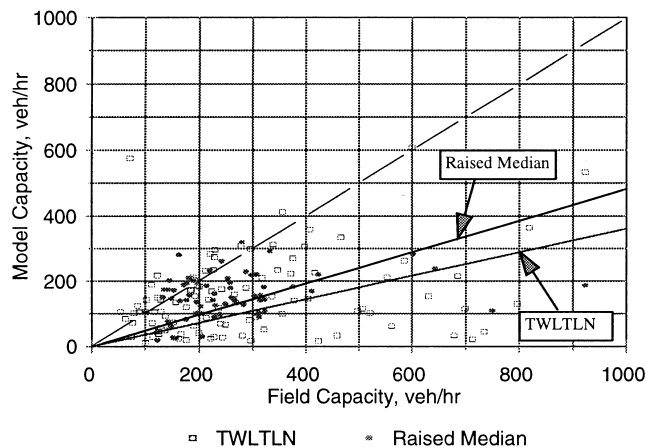


Fig. 3. Model testing results for sites with twltn or raised median (minor LT capacity) (Kyte, 1996).

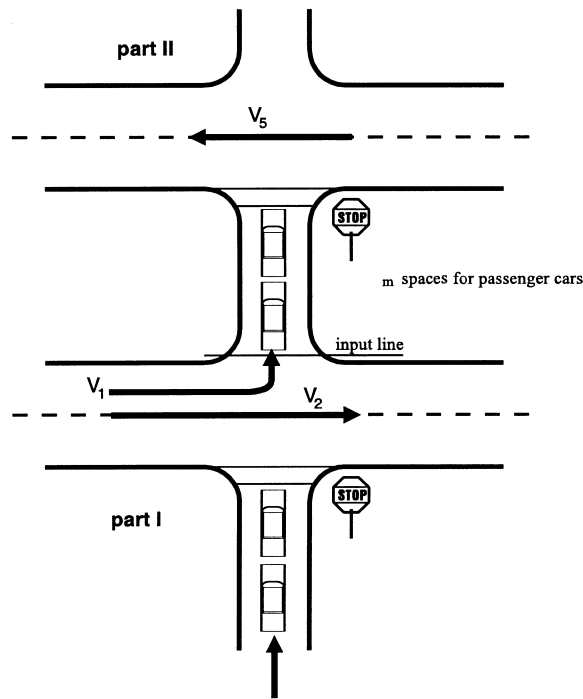


Fig. 4. Illustration of an intersection with two-stage gap acceptance process.

State 1: Part 1 of the intersection limits the input of vehicles to the storage area. The number of vehicles in the storage area is less than the maximum possible queue length. During this state a minor-street vehicle can enter the storage space if the major streams of part I provide sufficient gaps. During state 1, major-stream left-turning vehicles can also enter the storage space.

State 2: For this state it is assumed that the median storage area is fully occupied. In this state no minor-street vehicle or major-stream left-turning vehicles can get into the storage area. If, however, a sufficient gap for the passage of one minor-street vehicle can be accommodated at both parts (I and II) of the intersection simultaneously, then an additional vehicle can get into the storage area. State 1 and state 2 are mutually exclusive.

State 3: Considering the output of the storage area, concentrate on part II of the intersection. When a vehicle is present in the median, each possibility for a departure from the storage area provided by the major stream of part II can be used. No major-stream left-turning vehicles can pass directly through the storage area in this state.

State 4: For an empty storage area, no vehicle can depart the storage area even if the major stream of part II allowed a departure. If, however, a sufficient gap is provided in the major streams of both parts of the intersection simultaneously, a minor-street through vehicle can pass through the whole intersection without being queued somewhere in the storage area. This is the same situation as exists with single-stage gap acceptance. Also major-stream left-turning vehicles can pass through the storage area in this state. States 3 and 4 are mutually exclusive. During

times when the entire intersection is operating at capacity, for reasons of continuity, the maximum input and output of the storage area must be equal.

The conflicting volumes must be carefully defined for each minor-stream movement that uses the two-stage gap-acceptance process for both the first-stage and second-stage movements. For the first stage, the conflicting flows consist of the major-street flows from the left. For the second stage, the conflicting flows consist of the major street flows from the right. The specific streams that are included in each conflicting flow, and the critical gaps and follow-up times, will be provided in the 1997 HCM procedure (Transportation Research Board, 1997).

First, the capacity for the subject movement is computed assuming a single-stage gap-acceptance process through the entire intersection. Next, the capacity for stage one, c_I , and the capacity for stage two, c_{II} , are computed using appropriate values of critical gap and follow-up time for the two-stage gap acceptance; c_I is the capacity considering conflicting flows in part I. c_{II} is the capacity considering conflicting flows in part II.

The capacity for the subject movement considering the two-stage gap-acceptance process is computed as follows. For a complete derivation, see Wu and Brilon (1995). An adjustment factor a (obtained from calibration using simulation) and an intermediate variable y are computed.

$$a = 1 - 0.32e - 1.3\sqrt{m} \quad \text{for } m > 0 \quad (1)$$

$$y = \frac{c_I - c_{m,x}}{c_{II} - v_L - c_{m,x}} \quad (2)$$

where

- m = the number of storage spaces in the median;
- C_I = the capacity for the stage-one process;
- c_{II} = the capacity for the stage-two process;
- v_L = the major left-turn volume, either v_1 , or v_4 ;
- $c_{m,x}$ = capacity of subject movement considering the total conflicting volume for both stages of a two-stage gap-acceptance process

The total capacity c_T of the intersection for subject movement considering the two-stage gap acceptance process is computed.

For $y \neq 1$:

$$c_T = \frac{a}{y^{m+1} - 1} [y(y^m - 1)(c_{II} - v_L) + (y - 1)c_{m,x}] \quad (3)$$

For $y = 1$:

$$c_T = \frac{a}{m + 1} [m(c_{II} - v_L) + c_{m,x}] \quad (4)$$

3. Flared minor-street approach short lane

The geometric elements near the stop line on the stop-controlled approaches of many intersections may result in a higher capacity than the shared-lane capacity formula predicts. This is because, at such approaches, two vehicles may occupy or depart from the stop line simultaneously as a result of a large curb radius, a tapered curb, or a parking prohibition. The magnitude of this effect will depend in part on the turning-movement volumes and the resultant probability of two vehicles simultaneously at the stop line, and on the storage length available to feed the second position at the stop line.

If k is defined as the number of spaces for passenger cars belonging to one movement that can queue at the stop line without obstructing the access to the stop line for other movements, it is clear that with $k > 0$, the capacity of the minor-street approach is increased compared with the shared-lane condition. With an increase in k , the total capacity approaches the case that each movement has its own individual lane of infinite length. Fig. 5 shows a situation where the curb

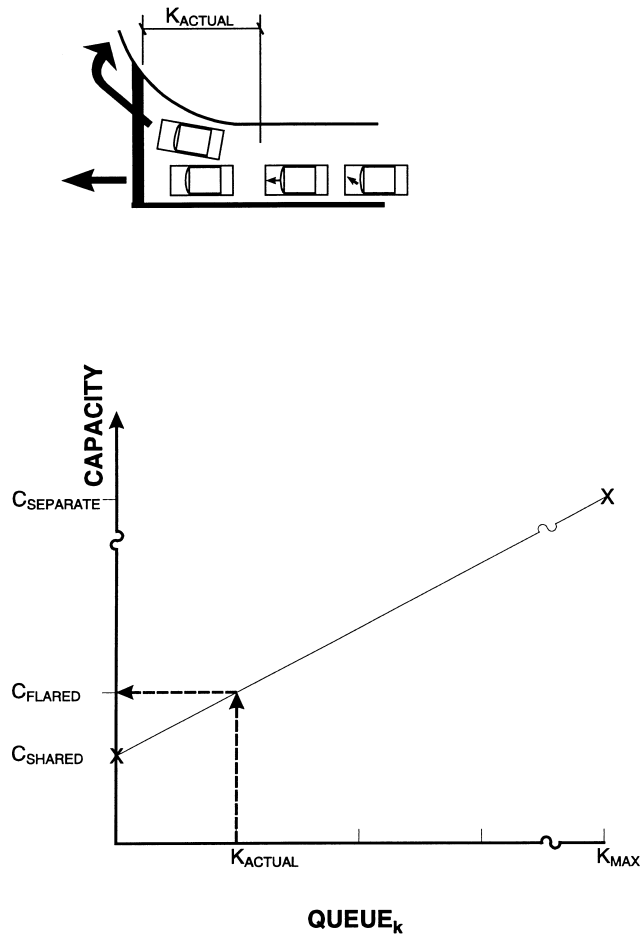


Fig. 5. Capacity approximation at intersections with flared minor-street approach.

line provides space for two vehicles to proceed to the stop line, one beside the other. In this case, the storage can be defined as $k = 1$, since one additional vehicle is able to use the stop line.

The actual capacity resulting from this configuration will be greater than the case where the right-turn vehicles must share the lane and less than the case where the vehicles have separate lanes. The average queue length for each movement must be computed considering the separate lane case and the actual storage available in the flared lane area for the intersection approach under study. Fig. 5 shows how the actual capacity can be interpolated using this information.

First, the average queue length for each movement sharing the right lane of the approach is computed, assuming that each movement operates as a separate lane. The movement with the maximum average queue length is identified.

$$Q_{\text{sep}} = \frac{D_{\text{sep}} v_{\text{sep}}}{3600} \quad (5)$$

where

- Q_{sep} = the average queue length for the movement considered as a separate lane;
- D_{sep} = the control delay for the movement considered as a separate lane;
- v_{sep} = the flow rate for the movement.

Next, the length of the storage area required is computed such that the approach would operate effectively as separate lanes. This is the maximum value of the queue lengths computed for each separate movement plus one vehicle.

$$k_{\text{max}} = \max_i \text{round} [Q_{\text{sep},i} + 1] \quad (6)$$

where

- $Q_{\text{sep},i}$ = the average queue length for movement i considered as a separate lane;
- round = the round-off operator, rounding the quantity in parentheses to the nearest integer;
- max = an operator determining the maximum value of the various values of $Q_{\text{sep},i}$;
- k_{max} = is the length of the storage area (in number of vehicles) such that the approach would operate as separate lanes.

Finally, the capacity of the approach is computed, taking into account the flare. The capacity is interpolated, as shown in Fig. 5. A straight line is established using values of two points: $(c_{\text{sep}}, k_{\text{max}})$ and $(c_{\text{sh}}, 0)$. The interpolated value of c_{act} is computed using the following equation:

$$c_{\text{act}} = (c_{\text{sep}} - c_{\text{SH}}) \frac{k}{k_{\text{max}}} + c_{\text{SH}} \quad (7)$$

where

- c_{act} = actual capacity of flared approach;
- c_{sep} = capacity for the separate lane case;
- c_{SH} = capacity of the shared lane case.

Note that this procedure requires knowledge of queue length, obtained from control delay computations. Queue length estimation is an important consideration at unsignalized intersections. Theoretical studies and empirical observations have demonstrated that the probability distribution function for queue lengths for any minor-stream movement at an unsignalized intersection is a function of the capacity of the movement and the volume of traffic being served during the analysis period. Fig. 10-9 of the 1994 HCM (Transportation Research Board, 1994) can be used to estimate the 95th-percentile queue length for any minor-stream movement at an unsignalized intersection during the peak 15-min period on the basis of these two parameters. See Wu (1994).

The mean queue length selected for approximating the capacity of flared approaches is computed as the product of the average delay per vehicle and the flow rate for the movement of interest. The expected total delay (vehicle hours per hour) equals the expected number of vehicles in the average queue; that is, the total hourly delay and the average queue are numerically identical. For example, four vehicle hours per hour of delay can be used interchangeably with an average queue length of four during the hour.

4. Upstream signals

The existence of nearby upstream signalized intersections (i.e. traffic signals on the major street within 1/4 mile of the subject intersection) usually causes vehicles to arrive at the intersection in platoons. Major-street vehicles arriving at a TWSC intersection in platoons from a single direction may cause an increase in the minor-street capacity compared with the case of random arrivals. The greater the number of vehicles travelling in platoons, the higher the minor-street capacity for a given opposing volume because there is a greater proportion of large gap sizes, which more than one minor-street vehicle can use. When signalized intersections exist upstream of the subject TWSC intersection in both directions, the effect is much more complex. When a traffic signal is more than 1/4 mile from the subject intersection, the effect on capacity is greatly diminished, because the major-street gaps are once again negative-exponentially distributed as the platoons disperse.

The method described here considers the flow patterns that result from traffic signals located upstream of the subject TWSC intersection and the headway distribution that results from the platooned flow. The method is based on a platoon dispersion algorithm as defined in the TRANSYT signal optimization software. The queues that form at each signalized intersection during their respective red phases will disperse as they travel downstream away from the signalized intersection.

Four flow regimes, and thus four headway distributions, result as the platoons arrive at the subject intersection. These include the following: regime 1: no platoons; regime 2: platoon from the left only; regime 3: platoon from the right only; and regime 4: platoons from both directions. During regime 1, minor-stream vehicles enter the subject TWSC intersection as described by the traditional gap-acceptance process. While platoons are present from both directions, during regime 4, no minor-stream vehicles are able to enter the subject intersection because the mean headways of the platoon are assumed to be less than the critical gap. Some of the minor-stream movements are *blocked* by the platoon during regimes 2 and 3 and are unable to enter the subject intersection. A minor stream is considered to be *blocked* if a conflicting platoon is travelling

through the TWSC intersection; the stream is considered to be *unblocked* if no conflicting platoons are travelling through the TWSC intersection.

If the traffic signals at the two upstream intersections are coordinated, these patterns are predictable and occur at regular intervals during the hour. Based on the flow pattern that exists during each regime, the capacity can be estimated. If one or both of the signals are actuated, or if the signal cycle lengths are different, the patterns are less predictable.

The following data are required for each upstream signal: cycle length (s), major-street effective green time (s), and saturation flow rate (vphg). Other essential data are the distance from the signalized intersection to the subject TWSC intersection; the speed of the platoon as it progresses from the signalized intersection to the TWSC intersection; and the upstream volume, including the through volume from the major-street approach. If applicable and significant, the left-turn volume from the side-street during an exclusive left-turn phase; and the arrival type of vehicles at the signalized intersection are also considered.

The method used here includes five sets of computations, including: the time for the queue to clear at each upstream signalized intersection, the proportion of time that the subject TWSC intersection is blocked as a result of platoons from each upstream intersection, the duration of the defining platoon events for each of the four flow regimes, the conflicting flows during each unblocked period, and the weighted capacity for each movement.

4.1. Computation 1. The time for the queue to clear at each upstream signalized intersection

In a typical four-leg intersection, three movements combine to constitute the exit leg flow (V_{out}) in the direction of the subject TWSC intersection, as shown in Fig. 6.

The flow v_{out} consists of two components. One component is a stable platoon discharging at the saturation flow rate when the signal changes from red to green. The second component is more or less random arrivals and departures, or a platoon from another upstream signal passing through on green. The first component includes both the portion of v_T that arrives during red and the portion that arrives during green when the standing queue is clearing. It also includes v_L for the same periods if v_L has an exclusive left-turn lane and a protected green phase. The second component includes the portion of v_T (and v_L , if applicable) that arrives after the queue has cleared, and v_R .

The time that it takes for a standing queue to clear is dependent on the pattern of vehicles arriving at the upstream signalized intersection. The arrival pattern, designated *arrival type* in Chapter 9 of the HCM (Transportation Research Board, 1994), is determined by the proportion

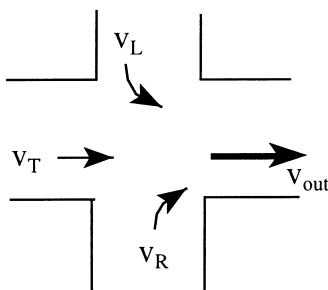


Fig. 6. Traffic flow components at an upstream signalized intersection.

of vehicles arriving during the green phase. For v_T , the arrival type ranges from 1 (very poor progression, few vehicles arrive on green) to 6 (exceptional progression, most vehicles arrive on green in a structured platoon).

The proportion of vehicles arriving on green is computed as follows:

$$P = R_p(g/C), P \leq 1 \quad (8)$$

where R_p is a function of the arrival type (Transportation Research Board, 1994, Table 9-2); g is green time, s ; and C is cycle length, s .

The time to discharge the vehicles that arrive during red is given by:

$$g_{q1} = \frac{v(1 - P)}{s} \quad (9)$$

where v is either v_T or v_L , and s is the saturation flow rate (in the same units as v).

The time to discharge the vehicles that arrive on green and join the back of the queue is given by:

$$g_{q2} = \frac{vCPg_{q1}}{sg - vCP} \quad (10)$$

where v is either v_T or v_L .

The total time to discharge the queue is

$$g_q = g_{q1} + g_{q2} \quad (11)$$

where g_q is less than or equal to g_{eff} , the effective green time, if the movement is over-saturated.

4.2. Computation 2. The proportion of time that the subject twsc intersection is blocked as a result of each upstream platoon

The discharging queue from the upstream signal will disperse as it travels downstream toward the subject TWSC intersection. The TRANSYT platoon dispersion model is used to determine the time duration that the TWSC intersection is blocked by the densest part of the platoon. The platoon headways are smaller than the critical gap, and thus no movement at the TWSC intersection can enter the intersection. See Fig. 7.

The basic platoon dispersion model parameters are listed below:

- a = the platoon dispersion factor; it is obtained from Table 1;
- β = $(1 + \alpha)^{-1}$;
- t_a = D/S_{prog} , the travel time from the signalized intersection to the subject TWSC intersection; where D is the distance from the upstream signal to the subject movement and S_{prog} is the average platoon running speed;
- F = $(1 + \alpha\beta t_a)^{-1}$;

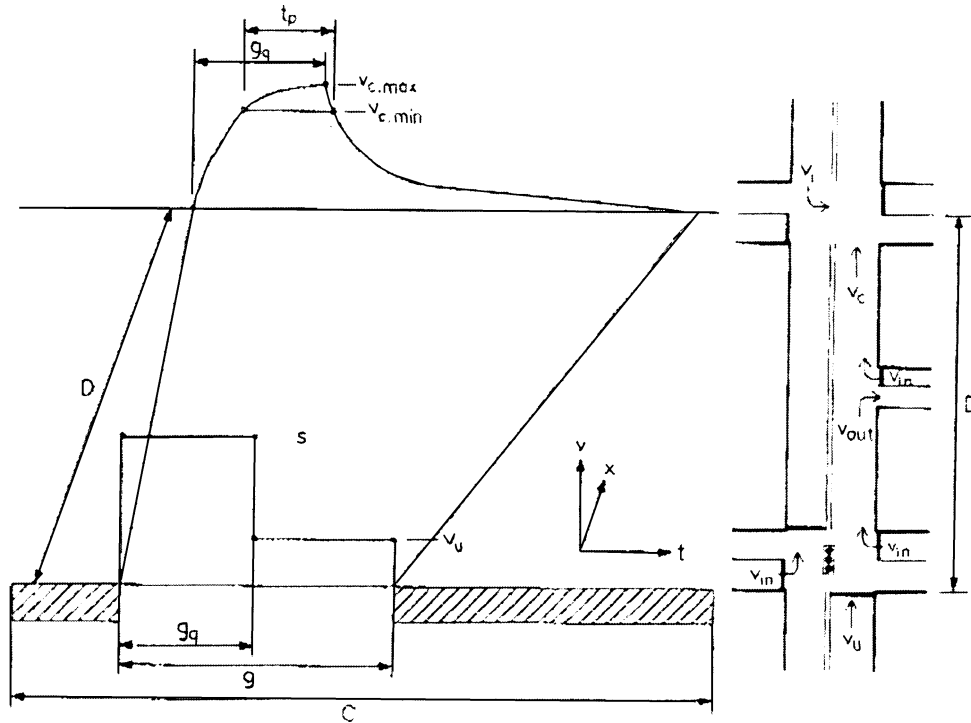


Fig. 7. Platoon dispersion model(Bonneson and Fitts, 1997).

Table 1
Platoon dispersion factor, a

Median type	Through traffic lanes		
	2	4	6
Undivided	0.55	0.50	0.40
Raised curb	0.45	0.40	0.35
TWLTL	0.40	0.35	0.30

- f = v/v_c the proportion of the conflicting stream flow that originated at the upstream signal, where v is the flow rate of progressed flow;
- s = saturation flow rate, veh/s of green per lane (vpsgpl).

The maximum platooned flow rate in the conflicting stream is given by:

$$v_{c,max} = sf[1 - (1 - F)^{g_q}] \tag{12}$$

The minimum platooned flow rate, $V_{c,min}$, is at least larger than $1/t_c$. It is assumed to be equal to 0.278 veh/s per lane (vpspl), based on simulation data in Bonneson and Fitts (1997).

The duration of the blocked period for either the through movement or the protected left-turn movement is computed using Eq. (13):

$$t_p = \left[\begin{array}{l} gq - \frac{\ln\left[1 - \frac{v_{c,\min}}{sf}\right] \left(\frac{v_{c,\max} - v_{ul}}{v_{c,\min} - v_{ul}}\right)}{\ln(1-F)}; sf > v_{c,\min} \\ 0; sf \leq v_{c,\min} \end{array} \right] \quad (13)$$

with all variables defined above.

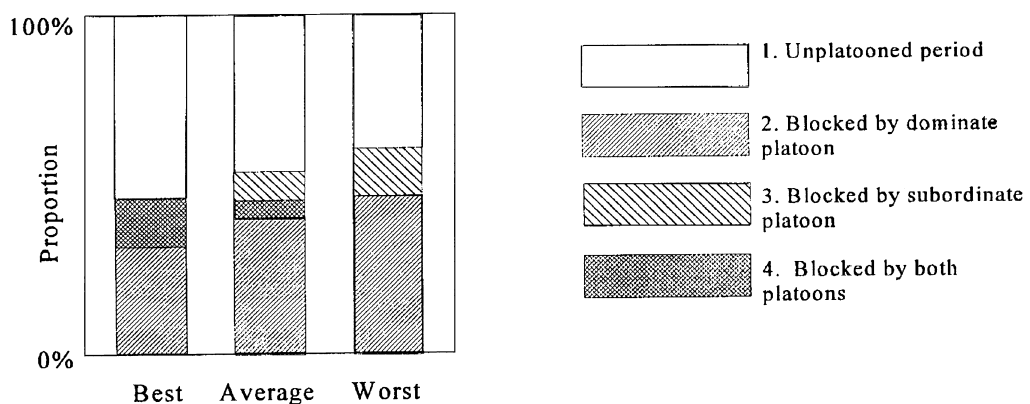
The proportion of time blocked by both through and protected left-turn movements is computed using Eq. (14):

$$p = \frac{t_{p,T} + t_{p,L}}{C} \quad (14)$$

4.3. Computation 3. Determine platoon event periods

The purpose of this computation is to determine the proportion of the study period during which each of the four flow regimes exists. In particular, it is important to determine for each minor-stream movement, the proportion of the study period that is unblocked.

The presence of a traffic signal on both upstream approaches will result in an overlapping platoon structure at the subject TWSC intersection. Depending on the signal timing parameters, a range of cases may present themselves, from a “best case” of simultaneous platoons from both directions to a “worst case” of alternating platoons from each direction. An “average case” results in a partial overlap of the platoons as shown in Fig. 8. Fig. 8 can also be interpreted to represent the expected pattern averaged over the analysis period.



Best case: platoons completely overlap so unplatooned period is minimum.
 Worst case: platoons alternate so unplatooned period is maximum.
 Average case: one-half of subordinate platoon is subsumed by dominant platoon.

Fig. 8. Various platoon overlap cases.

If p_2 and p_5 represent the proportion of the study period that movements 2 and 5 (and their corresponding turning movements) are blocking the TWSC intersection, respectively, the proportion of the study period during which blockages exist can be computed.

The dominant and subordinate platoons are determined:

$$p_{\text{dom}} = \max[p_2, p_5] \tag{15}$$

$$p_{\text{subo}} = \min[p_2, p_5] \tag{16}$$

Two cases exist. The *unconstrained* case exists when there is some period of time during which neither platoon is present. This case is defined when

$$p_{\text{dom}} + \frac{p_{\text{subo}}}{2} \leq 1 \tag{17}$$

The *constrained* case exists when one or both platoons are always present:

$$p_{\text{dom}} + \frac{p_{\text{subo}}}{2} > 1 \tag{18}$$

Table 2 shows the proportion of the study period for each of the four flow regimes for the average case.

Table 2 is used to determine the proportion of the study period that is blocked and unblocked for each minor movement. The results for each minor-stream movement for the average case are shown in Table 3.

4.4. Computation 4. Conflicting flows for each movement during unblocked period

The flow for the unblocked period (that is, the time periods when no platoons are present) is determined. This flow becomes the conflicting flow for the subject movement and is used to compute the capacity for this movement.

The conflicting flow for movement x during the unblocked period is given by

$$V_{c,u,x} = \frac{V_{c,x} - V_{c,b,x}P_x}{1 - p_x} \tag{19}$$

Table 2
Proportion of study period for each flow regime for the average case

Flow regime	Unconstrained case	Constrained case
1-no platoons	$1 - (p_{\text{dom}} + p_{\text{subo}}/2)$	0
2-dominant platoon only	$p_{\text{dom}} - p_{\text{subo}}/2$	$1 - p_{\text{subo}}$
3-subordinate platoon only	$p_{\text{subo}}/2$	$1 - p_{\text{dom}}$
4-both platoons	$p_{\text{subo}}/2$	$p_{\text{dom}} + p_{\text{subo}} - 1$

Table 3
Proportion of study period unblocked for each minor movement for average case

Proportion unblocked for movement, p_x	Unconstrained	Constrained
p_1	$1 - p_5$	$1 - p_5$
p_4	$1 - p_2$	$1 - p_2$
p_7	$1 - (p_{\text{dom}} + p_{\text{subo}}/2)$	0
p_8	$1 - (p_{\text{dom}} + p_{\text{subo}}/2)$	0
p_9	$1 - p_2$	$1 - p_2$
p_{10}	$1 - (p_{\text{dom}} + p_{\text{subo}}/2)$	0
p_{11}	$1 - (p_{\text{dom}} + p_{\text{subo}}/2)$	0
p_{12}	$1 - p_5$	$1 - p_5$

where

- $v_{c,x}$ = total conflicting flow for movement x as determined from HCM Fig. 10-2 (Transportation Research Board, 1994);
- $V_{c,b,x}$ = conflicting flow for movement x during the blocked period; this is the platooned flow and is assumed to be the product of the saturation flow rate for that movement and the number of lanes in which that movement travels;
- P_x = proportion of time that the subject movement x is blocked by the major street platoon; this is determined from Table 3.

4.5. Computation 5. Determine the capacity for the subject movement during the unblocked period

The capacity of the subject movement x accounting for the effect of platooning is given by

$$c_{\text{plat},x} = 3600(1 - p_x)c_{r,x} \quad (20)$$

where

- p_x = the proportion of time that movement x is blocked by a platoon;
- $C_{r,x}$ = the capacity of movement x assuming random flow during the unblocked period, using the conflicting flow computed for this unblocked period.

5. Pedestrian crossings

5.1. Pedestrian conflicting volumes

Pedestrians may also conflict with vehicular traffic streams. Pedestrian volumes should be included as part of the conflicting volumes, because they, like vehicular flows, define the beginning or ending of a gap that may be used by a minor-stream vehicle. While recognizing some peculiarities associated with pedestrian flows, this method takes a uniform approach to both vehicular and pedestrian movements at an intersection.

Referring to Fig. 1, pedestrian volumes are also defined as v_x , with x noting the leg of the intersection being crossed. Note that the terminology “pedestrian volumes” v_x implies *pedestrian groups*, because when more than one pedestrian is present, they may use the same gap (the analyst is required to input the pedestrian volumes as groups based on observations or reasonable assumptions). While regulations or practices may vary among jurisdictions, this methodology assumes that pedestrians crossing the subject or opposing approaches have rank 1 status, while pedestrians crossing the two conflicting approaches to the left or right of the subject minor-street approach have rank 2 status. The conflicting pedestrian volumes of higher rank for each subject movement must be determined and added to the conflicting vehicular volume.

5.2. Pedestrian impedance

With reference to Fig. 1, minor-street traffic streams must yield to pedestrian streams. Table 4 shows the relative hierarchy between pedestrian and vehicular streams that is assumed in this procedure.

Pedestrian groups crossing an intersection thus impede lower-ranked minor-street vehicles, but only one lane at a time. This is because vehicles performing a given through or turning movement tend to pass in front of or behind pedestrians once a driver’s target lane is clear. Pedestrian flows are counted somewhat differently than vehicle flows. If the typical pattern is for pedestrians to walk individually, then each pedestrian should be counted individually in the pedestrian flow. However, if pedestrians tend to cross in groups, then the number of groups should be counted in the pedestrian flow. The important factor is to determine the number of blockages that occur. In most cases, this will be a combination of individual pedestrians and groups of pedestrians. Thus, as defined for the purposes of determining the pedestrian impedance, the pedestrian volume is the sum of individual pedestrians crossing individually and groups of pedestrians crossing together during the time period of study.

A factor accounting for pedestrian blockage is computed based on the pedestrian volume, the pedestrian walking speed, and the lane width.

$$f_p = \frac{(v_x)(w/s)}{3600} \tag{21}$$

Table 4
Relative pedestrian vehicle hierarchy

Vehicle stream	Must yield to pedestrian stream
v_1	v_{16}
v_4	v_{15}
v_7	v_{15}, v_{13}
v_8	v_{15}, v_{16}
v_9	v_{15}, v_{14}
v_{10}	v_{16}, v_{14}
v_{11}	v_{15}, v_{16}
v_{12}	v_{16}, v_{13}

where

- f_p = pedestrian blockage factor, or the proportion of time that one lane on an approach is blocked during 1 h;
- v_x = pedestrian volume, where x is either 13, 14, 15, or 16;
- w = lane width;
- s = pedestrian walking speed, assumed to be 4 ft/s.

The impedance factor $p_{p,x}$, the pedestrian impedance factor for pedestrian movement x , is

$$p_{p,x} = 1 - f_p \quad (22)$$

If pedestrians are present to a significant degree, $p_{p,x}$ should be included as a factor in the impedance equations of the HCM.

6. Delay to major-street through vehicles

Traffic engineers are also interested in knowing the effect of a shared lane on the major-street approach where left-turning vehicles may block rank 1 through or right-turning vehicles. If no exclusive left-turn pocket is provided on the major street, a delayed left-turning vehicle may block the rank 1 vehicles behind it and cause them some delay. This effect delays not only rank 1 vehicles, but lower-ranked streams as well. While the delayed rank 1 vehicles are discharging from the queue formed behind a major-stream left-turning vehicle, they impede lower-ranked movements with which they conflict. This section uses the impedance for major-stream left-turning vehicles in a shared lane to estimate delay to rank 1 vehicles.

Field observations have shown that such a blockage effect is usually very small, because the major street usually provides enough space for the blocked rank 1 vehicle to sneak around. Models could be developed from a theoretical point of view when the major-street width does not allow a through vehicle to bypass the left-turning vehicle. At a minimum, incorporating this effect requires the following information: the proportion of rank 1 vehicles being blocked, and the average delay to the major-street left-turning vehicles that are blocking through vehicles.

The probability that the major-stream left-turning traffic will operate in a queue-free state can be expressed as:

$$p_{0,j} = 1 - \frac{v_i}{c_{m,j}} \quad (23)$$

where:

$$j = 1 \text{ or } 4 \text{ (major-street left-turn movements of rank 2).}$$

It is important to remember that the HCM methodology (Transportation Research Board, 1994) implicitly assumes an exclusive lane is provided to all left-turning traffic from the major street. In situations where a left-turn lane is not provided, it is possible for major-street through (and possibly right-turning) traffic to be delayed by left-turning vehicles waiting for an acceptable

gap. To account for this possibility, the factors $p_{0.1}^*$ and $P_{0.4}^*$ may be computed as an indication of the probability there will be no queue in the respective major-street shared lanes:

$$p_{0,j}^* = 1 - \frac{1 - p_{0,j}}{1 - \left[\frac{v_{i1}}{s_{i1}} - \frac{v_{i2}}{s_{i2}} \right]} \quad (24)$$

where:

- $p_{0,j}$ = probability of queue-free state for movement j as suming an exclusive left-turn lane on the major street;
- j = 1 or 4 (major-street left-turning traffic streams);
- il = 2 or 5 (major-street through traffic streams);
- $i2$ = 3 or 6 (major-street right-turning traffic streams);
- s_{i1} = saturation flow rate for the major-street through traffic streams, in vph; this is a parameter that can be measured in the field;
- s_{i2} = saturation flow rate for the major-street right-turning traffic, in vph; this is a parameter that can be measured in the field;
- v_{i1} = major-street through volume;
- v_{i2} = major-street right-turning volume, or 0 if an exclusive right-turn lane is provided.

By using $p_{0.1}^*$ and $P_{0.4}^*$ in lieu of $p_{0.1}$ and $p_{0.4}$ the additional influence of the potential for queues on a major street with shared left-turn lanes may be properly taken into account. In the simplest procedure, the proportion of major-stream rank 1 vehicles not being blocked (i.e. in a queue-free state) is given by p_{0j}^* in Eq. (24) (p_{0j}^* should be substituted for the major-stream left-turn factor $p_{0,j}$ when calculating the capacity of lower-ranked movements that conflict). Therefore, the proportion of rank 1 vehicles being blocked is $1 - p_{0j}^*$.

The average delay to rank 1 vehicles on this approach is given by:

$$d_{\text{rank1}} = \begin{cases} \frac{(1 - p_{0,j}^*) \times D_{\text{major left}} \times \left(\frac{V_{i1}}{N}\right)}{V_{i1} + V_{i2}} & N \geq 1 \\ (1 - P_{0,j}^*) \times D_{\text{major, left}} & N = 1 \end{cases} \quad (25)$$

where:

- d_{rank1} = delay to rank 1 vehicles;
- $p_{0,j}^*$ = proportion of rank 1 vehicles not blocked (Eq. (24));
- $D_{\text{major left}}$ = delay to major-stream left-turning vehicles;
- $v_{i,1}$ = major-street through vehicles in shared lane;
- $v_{i,2}$ = major-street right-turning vehicles in shared lane.

Note that on a multi-lane road, only the major-street volumes in the lane that may be blocked should be used in the calculation as v_{i1} and v_{i2} . On multi-lane roads, if it is assumed that blocked rank 1 vehicles do not bypass the blockage by moving across into other through lanes (a reasonable assumption under conditions of high major-street flows), then $v_{i1} = v_1/N$.

Because of the unique characteristics associated with each site, the decision whether or not to account for this effect should be left to the analyst. Geometric design features such as an adjacent exclusive right-turn lane, a large curb radius, or a wide shared left-turn and through travel lane may enable rank 1 vehicles to bypass the blockage caused by major left-turning vehicles. Also, conflicting traffic volumes in such adjacent bypass lanes must provide sufficient gaps to accept bypassing vehicles.

7. Conclusion

This paper has presented theoretical models to adjust the basic capacity or delay equations to account for some common occurrences at TWSC intersections: two-stage gap acceptance; flared minor-street approaches; effects of upstream signals; effects of pedestrians; and delay to major-street rank 1 vehicles. Singly or in combination, these effects can cause significant adjustments to the basic capacity and delay models. The user survey conducted as part of the NCHRP 3-46 study indicated that methods to account for all these effects are desirable. If one of these effects were to be included in the recommended computational procedure, then it was considered important to include all of them, if the conditions are present at a given site. This is because the sum of these effects may be either positive (two-stage gap-acceptance, flared approaches, and signals increase capacity), negative (pedestrians and shared major-stream left-turn and through lanes decrease capacity) or neutral. Some effects may require significant judgment or data to be provided by the analyst, while physical inputs such as flared, median, or shared-lane geometries may be easier to obtain or judge.

In many cases, these theoretical models have not been calibrated against empirical data; therefore, they represent initial attempts to explain such phenomena and should be subject to scrutiny and modifications as necessary. As mentioned in the introduction, how to combine the individual effects into a coherent procedure is not self-evident, and this systems aspect also deserves more attention in future research. For example, the effect of upstream signals on regulating flow is expected to reduce the random component of the delay equation. Referring to Fig. 2(a–c) it is not obvious whether the upstream signal effect contains, or should be contained within, the two-stage gap-acceptance effect. The authors hope that further research into these and other secondary effects will be stimulated by this paper.

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