CHAPTER 19
TWO-WAY STOP-CONTROLLED INTERSECTIONS

CONTENTS

LIST OF EXHIBITS

1. INTRODUCTION

Two-way STOP-controlled (TWSC) intersections are common in the United States. One typical configuration is a four-leg intersection, where one street—the *major street*—is uncontrolled, while the other street—the *minor street*—is controlled by STOP signs. The other typical configuration is a three-leg intersection, where the single minor-street approach (i.e., the stem of the T configuration) is controlled by a STOP sign. Minor street approaches can be public streets or private driveways. **Chapter 19, Two-Way STOP-Controlled Intersections,** presents concepts and procedures for analyzing these types of intersections. Chapter 9 provides a glossary and list of symbols, including those used for TWSC intersections.

Three-leg intersections are considered a standard type of TWSC intersection, when the stem of the T is controlled by a STOP sign.

Capacity analysis of TWSC intersections requires a clear description and understanding of the interaction between travelers on the minor, or STOP-controlled, approach with travelers on the major street. Both gap acceptance and empirical models have been developed to describe this interaction. Procedures described in this chapter rely primarily on field measurements of TWSC performance in the United States (*1*) that have been applied to a gap acceptance model developed and refined in Germany (*2*).

INTERSECTION ANALYSIS BOUNDARIES AND TRAVEL MODES

The intersection boundaries for a TWSC intersection analysis are assumed to be those of an isolated intersection (i.e., not affected by upstream or downstream intersections), with the exception of TWSC intersections that are located within 0.25 mi of a signalized intersection (for the major-street approaches). This chapter presents methodologies to assess TWSC intersections for both pedestrians and motor vehicles. A discussion of how the procedures for motor vehicles could potentially apply to an analysis of bicycle movements is also provided.

LEVEL-OF-SERVICE CRITERIA

Level of service (LOS) for a TWSC intersection is determined by the computed or measured control delay. For motor vehicles, LOS is determined for each minor-street movement (or shared movement) as well as major-street left turns by using criteria given in Exhibit 19-1. LOS is not defined for the intersection as a whole or for major-street approaches for three primary reasons: (*a*) major-street through vehicles are assumed to experience zero delay; (*b*) the disproportionate number of major-street through vehicles at a typical TWSC intersection skews the weighted average of all movements, resulting in a very low overall average delay for all vehicles; and (*c*) the resulting low delay can mask important LOS deficiencies for minor movements. As Exhibit 19-1 notes, LOS F is assigned to the movement if the volume-to-capacity ratio for the movement exceeds 1.0, regardless of the control delay.

LOS is not defined for the major-street approaches or for the overall intersection, as major-street through vehicles are assumed to experience no delay.

The LOS criteria for TWSC intersections are somewhat different from the criteria used in Chapter 18 for signalized intersections, primarily because user perceptions differ among transportation facility types. The expectation is that a signalized intersection is designed to carry higher traffic volumes and will present greater delay than an unsignalized intersection. Unsignalized intersections are also associated with more uncertainty for users, as delays are less predictable than they are at signals, which can reduce users' delay tolerance.

Exhibit 19-1
Level-of-Service Criteria: Automobile Mode

Control Delay (s/vehicle)	LOS by Volume-to-Capacity Ratio	
	$v/c \le 1.0$	$v/c > 1.0$
0–10	A	F
>10–15	B	F
>15–25	C	F
>25–35	D	F
>35–50	E	F
>50	F	F

Note: The LOS criteria apply to each lane on a given approach and to each approach on the minor street. LOS is not calculated for major-street approaches or for the intersection as a whole.

Pedestrian LOS at TWSC intersections is defined for pedestrians crossing a traffic stream not controlled by a STOP sign; it also applies to midblock pedestrian crossings. LOS criteria for pedestrians are given in Exhibit 19-2.

Exhibit 19-2
Level-of-Service Criteria: Pedestrian Mode

LOS	Control Delay (s/pedestrian)	Comments
A	0–5	Usually no conflicting traffic
B	5–10	Occasionally some delay due to conflicting traffic
C	10–20	Delay noticeable to pedestrians, but not inconveniencing
D	20–30	Delay noticeable and irritating, increased likelihood of risk taking
E	30–45	Delay approaches tolerance level, risk-taking behavior likely
F	>45	Delay exceeds tolerance level, high likelihood of pedestrian risk taking

Note: Control delay may be interpreted as s/pedestrian group if groups of pedestrians were counted as opposed to individual pedestrians.

LOS F for pedestrians occurs when there are not enough gaps of suitable size to allow waiting pedestrians to cross through traffic on the major street safely. This situation is typically evident from extremely long control delays. The method is based on a constant critical headway. In the field, however, LOS F may also appear in the form of crossing pedestrians selecting smaller-than-usual gaps. In such cases, safety could be a concern that warrants further study.

REQUIRED INPUT DATA

Analysis of a TWSC intersection requires the following data:

1. Number and configuration of lanes on each approach;
2. Percentage of heavy vehicles for each movement;
3. Either of the following:
   a. Demand flow rate for each entering vehicular movement and each pedestrian crossing movement during the peak 15 min, or
   b. Demand flow rate for each entering vehicular movement and each pedestrian crossing movement during the peak hour and a peak hour factor for the hour;
4. Special geometric factors such as
   a. Unique channelization aspects,
   b. Existence of a two-way left-turn lane or raised or striped median storage (or both),

  c. Approach grades,
  d. Existence of flared approaches on the minor street, and
  e. Existence of upstream signals;

5. The rate at which motorists yield to pedestrians and the degree of pedestrian platooning (for pedestrian LOS analysis); and
6. Length of analysis period, generally a peak 15-min period within the peak hour.

SCOPE OF THE METHODOLOGY

This chapter focuses on TWSC intersection operations. This version of the TWSC intersection analysis procedures is primarily based on studies conducted by National Cooperative Highway Research Program Project 3-46 (*1*).

LIMITATIONS OF THE METHODOLOGY

Automobile Mode

The methodologies in this chapter apply to TWSC intersections with up to three through lanes (either shared or exclusive) on the major-street approaches and up to three lanes on the minor-street approaches (with no more than one exclusive lane for each movement on the minor-street approach). Effects from other intersections are accounted for only in situations in which a TWSC intersection is located on an urban street segment between coordinated signalized intersections. In this situation, the intersection can be analyzed by using the procedures in Chapter 17, Urban Street Segments. The methodologies do not apply to TWSC intersections with more than four approaches.

The methodologies do not include a detailed method for estimating delay at YIELD-controlled intersections; however, with appropriate changes in the values of key parameters (e.g., critical headway and follow-up headway), the analyst could apply the TWSC method to YIELD-controlled intersections.

With appropriate changes in the values of critical headway and follow-up headway, the analyst could apply the TWSC method to YIELD-controlled intersections.

All the methods are for steady-state conditions (i.e., the demand and capacity conditions are constant during the analysis period); the methods are not designed to evaluate how fast or how often the facility transitions from one demand or capacity state to another. Analysts interested in that kind of information should consider applying alternative tools, as discussed later in this chapter.

Pedestrian Mode

The limitations of the pedestrian methodologies are somewhat different from those of the automobile mode, as the methods were developed in separate research efforts. In this chapter, pedestrian methodologies apply to TWSC intersections and midblock crossings where pedestrians cross up to four through lanes on the major street. The analysis procedure does not apply to undivided streets with more than four lanes, although it can accommodate up to four lanes in each direction separated by a median. The methodologies do not account for interaction effects of upstream signalized intersections. The analysis procedure assumes random arrivals on the major street and equal directional and lane distribution on the major street. It does not account for the effects of upstream signals.

The analysis procedure does not take into account pedestrian cross-flows (i.e., pedestrian flows approximately perpendicular to and crossing another pedestrian stream) and assumes that the pedestrian will reach the crossing without delay from pedestrians traveling parallel to the major street. Under high pedestrian volumes, this assumption may not be reasonable.

All the methods are for steady-state conditions (i.e., the demand and capacity conditions are constant during the analysis period); the methods are not designed to evaluate how fast or how often the facility transitions from one demand or capacity state to another.

Bicycle Mode

At the time of publication of this edition of the HCM, the current methodologies for analyzing LOS and delay at TWSC intersections apply to bicycles in limited situations that are not supported by research. As such, there are no established LOS standards for bicycles at TWSC intersections. Additional research on bicycle behavior and operations at TWSC intersections needs to be done before procedures that adequately address these issues can be developed. A discussion of qualitative effects is included in the methodology section of this chapter.

2. METHODOLOGY

OVERVIEW

TWSC intersections require only drivers on the minor-street approaches to stop before proceeding into the intersection. Left-turning drivers from the major street may have to yield to oncoming major-street through or right-turning traffic but are not required to stop in the absence of oncoming traffic.

The methodologies presented rely on the required input data listed previously to compute the potential capacity of each minor movement, which is ultimately adjusted, if appropriate, to compute a movement capacity for each movement. The movement capacity can be used to estimate the control delay by movement, by approach, and for the intersection as a whole. Queue lengths can also be estimated once movement capacities are determined.

The capacity of the controlled legs is based primarily on three factors: the distribution of gaps in the major stream, driver judgment in selecting the gaps, and the follow-up headways required by each driver in a queue.

At TWSC intersections, drivers on the STOP-controlled approaches are required to select gaps in the major-street flow in order to execute crossing or turning maneuvers. In the presence of a queue, each driver on the controlled approach must also use some time to move into the front-of-queue position and prepare to evaluate gaps in the major-street flow. Thus, the capacity of the controlled legs is based primarily on three factors: the distribution of gaps in the major-street traffic stream, driver judgment in selecting gaps through which to execute the desired maneuvers, and the follow-up headways required by each driver in a queue.

The basic capacity model assumes that gaps in the conflicting movements are randomly distributed. When traffic signals on the major street are within 0.25 mi of the subject intersection, flows may not be random but will likely have some platoon structure.

For the automobile mode analysis, the methodology addresses a number of special circumstances that may exist at TWSC intersections, including the following:

- Two-stage gap acceptance,
- Approaches with shared lanes,
- The presence of upstream traffic signals, and
- Flared approaches for minor-street right-turning vehicles.

THEORETICAL BASIS

Gap-acceptance models begin with the recognition that TWSC intersections give no positive indication or control to the driver on the minor street as to when it is appropriate to leave the stop line and enter the major street. The driver must determine when a gap on the major street is large enough to permit entry and when to enter, on the basis of the relative priority of the competing movements. This decision-making process has been formalized analytically into what is commonly known as gap-acceptance theory. Gap-acceptance theory includes three basic elements: the size and distribution (availability) of gaps on the major street, the usefulness of these gaps to the minor-street drivers, and the relative priority of the various movements at the intersection.

Availability of Gaps

The first element to consider is the proportion of gaps of a particular size on the major street offered to the driver entering from the minor street as well as the pattern of arrival times of vehicles. The distribution of gaps between the vehicles in the different streams has a major effect on the performance of the intersection.

Usefulness of Gaps

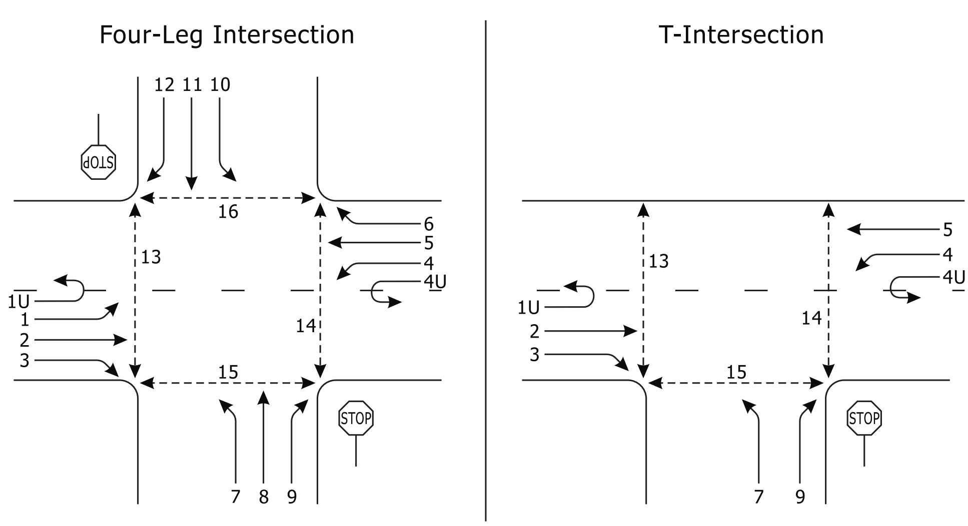
The second element to consider is the extent to which drivers find gaps of a particular size useful when they attempt to enter the intersection. It is generally assumed in gap-acceptance theory that drivers are both consistent and homogeneous. This assumption is not entirely correct. Studies have demonstrated that different drivers have different gap-acceptance thresholds and even that the gap-acceptance threshold of an individual driver often changes over time (*3*). In this manual, the critical headways and follow-up headways are considered representative of a statistical average of the driver population in the United States.

Relative Priority of Various Movements at the Intersection

Each movement has a different ranking in a priority hierarchy. The gap-acceptance process evaluates them with impedance terms through the order of departures. Typically, gap-acceptance processes assume that drivers on the major street are unaffected by the minor-street movements. If this assumption is not the case, the gap-acceptance process has to be modified.

In using the TWSC intersection methodology, the priority of right-of-way given to each movement must be identified. Some movements have absolute priority, while others have to give way or yield to higher-order movements. Exhibit 19-3 shows the assumed numbering of movements at both T- and four-leg intersections.

Exhibit 19-3
Vehicular and Pedestrian Movements at a TWSC Intersection



Movements can be categorized by right-of-way priority as follows:

- Movements of Rank 1 include through traffic on the major street, right-turning traffic from the major street, and pedestrian movements crossing the minor street.
- Movements of Rank 2 (subordinate to Rank 1) include left-turning and U-turning traffic from the major street, right-turning traffic onto the major street, and pedestrian movements crossing the major street (assumed for this procedure).
- Movements of Rank 3 (subordinate to Ranks 1 and 2) include through traffic on the minor street (in the case of a four-leg intersection) and left-turning traffic from the minor street (in the case of a T-intersection).
- Movements of Rank 4 (subordinate to all others) include left-turning traffic from the minor street. Rank 4 movements occur only at four-leg intersections.

The minor-street left-turn movement is assigned Rank 3 priority at a T-intersection and Rank 4 priority at a four-leg intersection.

As an example of application of the priority of right-of-way, assume the situation of a left-turning vehicle on the major street and a through vehicle from the minor street waiting to cross the major traffic stream. The first available gap of acceptable size would be taken by the left-turning vehicle. The minor-street through vehicle must wait for the second available gap. In aggregate terms, a large number of such left-turning vehicles could use up so many of the available gaps that minor-street through vehicles would be severely impeded or unable to make safe crossing movements.

Critical Headway and Follow-Up Headway

Critical headway defined.

The *critical headway* t_c is defined as the minimum time interval in the major-street traffic stream that allows intersection entry for one minor-street vehicle (*4*). Thus, the driver's critical headway is the minimum headway that would be acceptable. A particular driver would reject headways less than the critical headway and would accept headways greater than or equal to the critical headway. Critical headway can be estimated on the basis of observations of the largest rejected and smallest accepted headway for a given intersection.

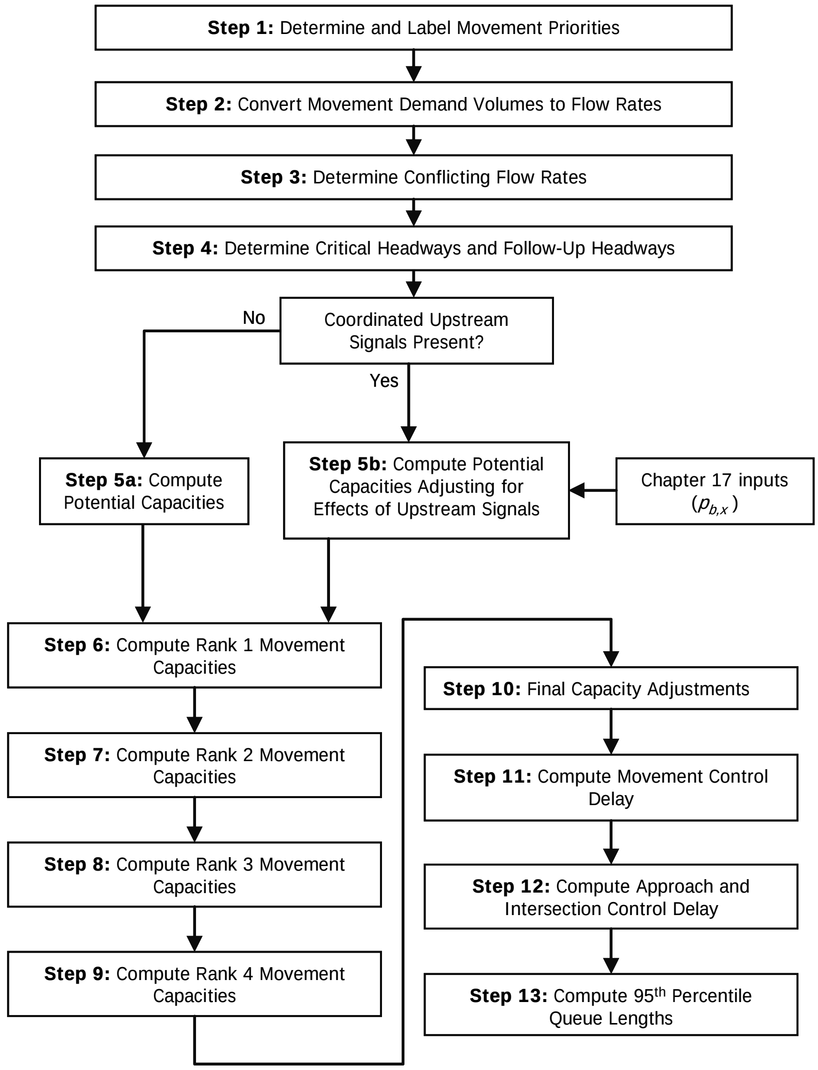
Follow-up headway defined.

The time between the departure of one vehicle from the minor street and the departure of the next vehicle using the same major-street headway, under a condition of continuous queuing on the minor street, is called the *follow-up headway* t_f. Thus, t_f is the headway that defines the saturation flow rate for the approach if there were no conflicting vehicles on movements of higher rank.

AUTOMOBILE MODE

The TWSC intersection methodology for the automobile mode is applied through a series of steps that require input data related to movement flow information and geometric conditions, prioritization of movements, computation of potential capacities and incorporation of adjustments to compute movement capacities, and estimation of control delays and queue lengths. These steps are illustrated in Exhibit 19-4.

Exhibit 19-4
TWSC Intersection Methodology



Step 1: Determine and Label Movement Priorities

The priority for each movement at a TWSC intersection must be identified to designate the appropriate rank of each movement for future steps in the analysis process. The process of this step also identifies for the analyst the sequence in which capacity computations will be completed. Because the methodology is based on prioritized use of gaps by vehicles at a TWSC intersection, it is important that the subsequent computations in the automobile mode be made in a precise order. The computational sequence is the same as the priority of gap use, and movements are considered in the following order:

1. Left turns from the major street,
2. Right turns from the minor street,
3. U-turns from the major street,
4. Through movements from the minor street, and
5. Left turns from the minor street.

Step 2: Convert Movement Demand Volumes to Flow Rates

For analysis of existing conditions where the peak 15-min period can be measured in the field, the volumes for the peak 15-min period are converted to a peak 15-min demand flow rate by multiplying the peak 15-min volumes by 4.

For analysis of projected conditions or when 15-min data are not available, hourly demand volumes for each movement are converted to peak 15-min demand flow rates in vehicles per hour, as shown in Equation 19-1, through use of the peak hour factor for the intersection.

Equation 19-1

$$v_i = \frac{V_i}{PHF}$$

where

v_i = demand flow rate for movement i (veh/h),

V_i = demand volume for movement i (veh/h), and

PHF = peak hour factor.

Step 3: Determine Conflicting Flow Rates

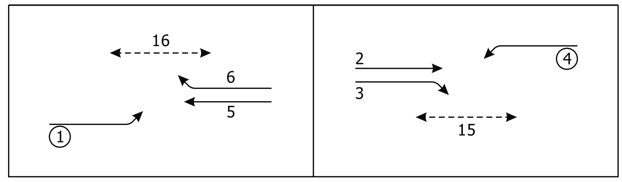
Each movement at a TWSC intersection faces a different set of conflicts that are directly related to the nature of the subject movement. The following subsections provide an illustration of the set of conflicts facing each minor movement (Rank 2 through Rank 4) at a TWSC intersection. These exhibits illustrate the computation of the parameter $v_{c,x}$, the conflicting flow rate for movement x—that is, the total flow rate [in vehicles per hour (veh/h)] that conflicts with movement x.

Pedestrians may also conflict with vehicular movements. Pedestrian flow rates, also defined as v_x, with x noting the leg of the intersection being crossed, should be included as part of the conflicting flow rates. Pedestrian flows are included because they define the beginning or ending of a gap that may be used by a minor-street movement. Although it recognizes some peculiarities associated with pedestrian movements, this method takes a uniform approach to vehicular and pedestrian movements.

Major-Street Left-Turn Movements (Rank 2—Movements 1 and 4)

Exhibit 19-5 illustrates the conflicting movements, while Equation 19-2 and Equation 19-3 compute the conflicting flow encountered by major-street left-turning drivers. The left-turn movement from the major street is in conflict with the total opposing through and right-turn flow, because those vehicles must cross the opposing through movement and merge with the right-turning vehicles. The method does not differentiate between crossing and merging conflicts. Left-turning vehicles from the major street and the opposing right turns from the major street are considered to merge, regardless of the number of lanes provided in the exit roadway.

Exhibit 19-5
Definition of Conflicting Movements for Major-Street Left-Turn Movements



Equation 19-2

$$v_{c,1} = v_5 + v_6 + v_{16}$$

Equation 19-3

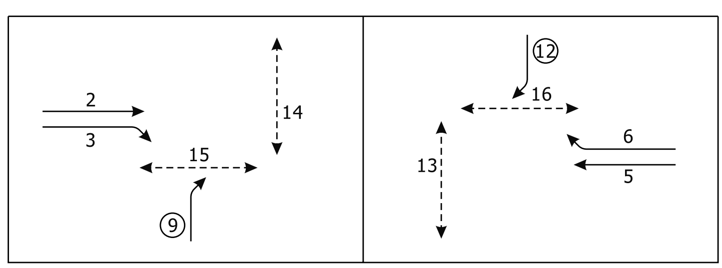
$$v_{c,4} = v_2 + v_3 + v_{15}$$

If the major-street right turn is separated by a triangular island and has to comply with a YIELD or STOP sign, the v_6 and v_3 terms in Equation 19-2 and Equation 19-3, respectively, may be assumed to be zero.

Minor-Street Right-Turn Movements (Rank 2—Movements 9 and 12)

Exhibit 19-6 illustrates the conflicting movements encountered by minor-street right-turning drivers. The right-turn movement from the minor street is assumed to be in conflict with only a portion of the major-street through movement where more than one major-street lane is present. Also, one-half of each right-turn movement from the major street is considered to conflict with the minor-street right-turn movement, as some of these turns tend to inhibit the subject movement. Because right-turning vehicles from the minor street commonly merge into gaps in the right-hand lane of the stream into which they turn, they typically do not require a gap across all lanes of the conflicting stream (this situation may not be true for some trucks and vans with long wheelbases that encroach on more than one lane in making their turn). Furthermore, a gap in the overall major-street traffic could be used simultaneously by another vehicle, such as a major-street left-turning vehicle. Exhibit 19-6 does not include major-street U-turns as conflicting vehicles. While these conflicts may be observed in practice, they are not assumed to be conflicts in this methodology.

Exhibit 19-6
Definition of Conflicting Movements for Minor-Street Right-Turn Movements



Equation 19-4 and Equation 19-5 compute the conflicting flow rate for minor-street right-turn movements entering two-lane major streets, Equation 19-6 and Equation 19-7 are used for four-lane major streets, and Equation 19-8 and Equation 19-9 are used for six-lane major streets. If the major-street right turn has its own lane, the corresponding v_3 or v_6 term in these equations may be assumed to be zero. Users may supply different lane distributions for the v_2 and v_5 terms in the equations for four- and six-lane major streets, when supported by field data.

Two-lane major streets:

$$v_{c,9} = v_2 + 0.5v_3 + v_{14} + v_{15}$$

Equation 19-4

$$v_{c,12} = v_5 + 0.5v_6 + v_{13} + v_{16}$$

Equation 19-5

Four-lane major streets:

$$v_{c,9} = 0.5v_2 + 0.5v_3 + v_{14} + v_{15}$$

Equation 19-6

$$v_{c,12} = 0.5v_5 + 0.5v_6 + v_{13} + v_{16}$$

Equation 19-7

Six-lane major streets:

$$v_{c,9} = 0.5v_2 + 0.5v_3 + v_{14} + v_{15}$$

Equation 19-8

$$v_{c,12} = 0.5v_5 + 0.5v_6 + v_{13} + v_{16}$$

Equation 19-9

Major-Street U-Turn Movements (Rank 2—Movements 1U and 4U)

Exhibit 19-7 illustrates the conflicting movements encountered by major-street U-turning drivers. The U-turn movement from the major street is in conflict with the total opposing through and right-turn flow, similar to the major-street left-turn movement. Research found that the presence of minor-street right-turning vehicles significantly affects the capacity of major-street U-turns (*5*). The methodology accounts for this effect in the impedance calculation rather than here in the calculation of conflicting flow. If a different priority order is desired (e.g., minor-street right turns yield to major-street U-turns), the analyst should adjust the computation procedure accordingly to replicate observed conditions.

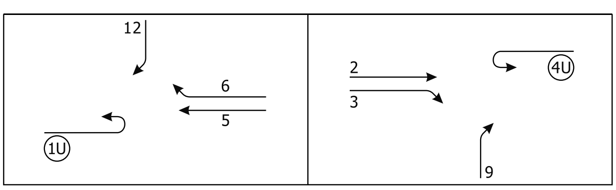


Exhibit 19-7
Definition of Conflicting Movements for Major-Street U-Turn Movements

Equation 19-10 and Equation 19-11 compute the conflicting flow rates for major-street U-turns, where the major street has four lanes. Equation 19-12 and Equation 19-13 compute the conflicting flow rates for major-street U-turns on six-lane major streets. (No field data are available for U-turns on major streets with fewer than four lanes.) If a major-street right turn has its own lane, the corresponding v_3 or v_6 term in these equations should be assumed to be zero.

Four-lane major streets:

$$v_{c,1U} = v_5 + v_6$$

Equation 19-10

$$v_{c,4U} = v_2 + v_3$$

Equation 19-11

Six-lane major streets:

$$v_{c,1U} = 0.73v_5 + 0.73v_6$$

Equation 19-12

$$v_{c,4U} = 0.73v_2 + 0.73v_3$$

Equation 19-13

Minor-Street Pedestrian Movements (Rank 2—Movements 13 and 14)

Minor-street pedestrian movements (those pedestrians crossing the major street) are in direct conflict with all vehicular movements on the major street except the right-turn and left-turn movements on the major street approaching from the far side of the intersection. The volume of minor-street pedestrians is an input parameter in the computation of the conflicting flow rates for all Rank 3 and Rank 4 movements.

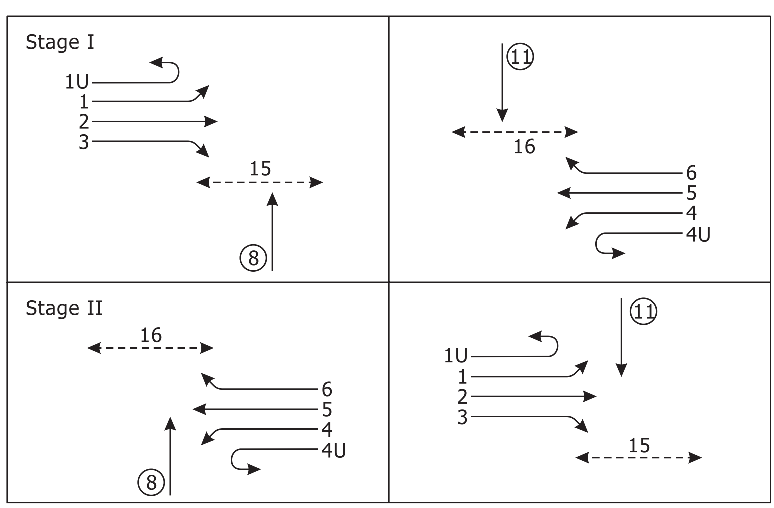
Minor-Street Through Movements (Rank 3—Movements 8 and 11)

Minor-street through movements have a direct crossing or merging conflict with all movements on the major street except the right turn into the subject approach. Similar to the minor-street right-turn movement, one-half of each right-turn movement from the major street is considered to conflict with the minor-street through movement. In addition, field research (*1*) has shown that the effect of left-turning vehicles is approximately twice their actual number.

Minor-street through movements may complete their maneuver in one or two stages. Single-stage gap acceptance assumes no median refuge area is available for minor-street drivers to store in and that the minor-street drivers will be evaluating gaps in both major-street directions simultaneously. Conversely, the two-stage gap-acceptance scenario assumes that a median refuge area is available for minor-street drivers. During Stage I, minor-street drivers evaluate major-street gaps in the near-side traffic stream (conflicting traffic from the left); during Stage II, minor-street drivers evaluate major-street gaps in the far-side traffic stream (conflicting traffic from the right). For one-stage crossings, the conflicting flows for Stage I and Stage II are combined; for two-stage crossings, the conflicting flows are considered separately.

Exhibit 19-8 illustrates the conflicting movements encountered by minor-street through-movement drivers.

Exhibit 19-8
Definition of Conflicting Movements for Minor-Street Through Movements



Equation 19-14 and Equation 19-15 compute the conflicting flow encountered by minor-street through-movement drivers during Stage I. If there is a right-turn lane on the major street, the corresponding v_3 or v_6 term in these equations may be assumed to be zero.

$$v_{c,I,8} = 2(v_1 + v_{1U}) + v_2 + 0.5v_3 + v_{15}$$

Equation 19-14

$$v_{c,I,11} = 2(v_4 + v_{4U}) + v_5 + 0.5v_6 + v_{16}$$

Equation 19-15

Equation 19-16 and Equation 19-17 compute the conflicting flow encountered by minor-street through-movement drivers during Stage II. If the major-street right turn is separated by a triangular island and has to comply with a YIELD or STOP sign, the corresponding v_3 or v_6 term in these equations may be assumed to be zero.

$$v_{c,II,8} = 2(v_4 + v_{4U}) + v_5 + v_6 + v_{16}$$

Equation 19-16

$$v_{c,II,11} = 2(v_1 + v_{1U}) + v_2 + v_3 + v_{15}$$

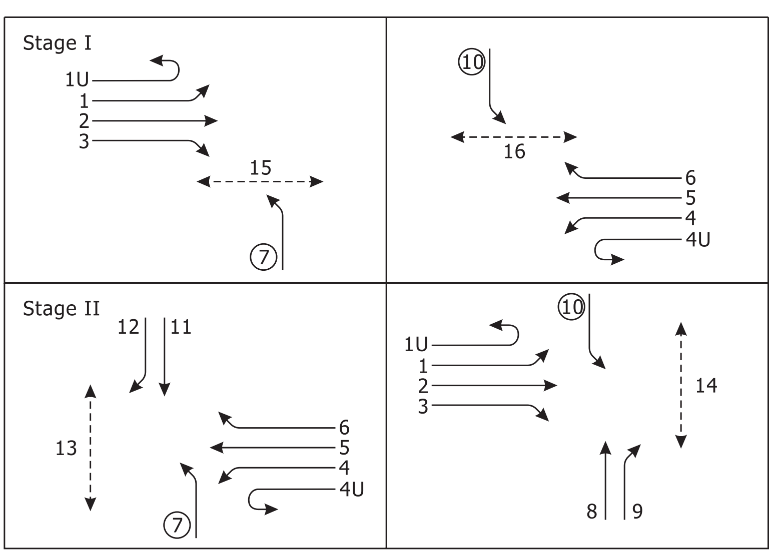
Equation 19-17

Minor-Street Left-Turn Movements (Rank 4—Movements 7 and 10)

The left-turn movement from the minor street is the most difficult maneuver to execute at a TWSC intersection, and it faces the most complex set of conflicting movements, which include all major-street movements in addition to the opposing right-turn and through movements on the minor street. Only one-half of the opposing right-turn and through-movement flow rate is included as conflicting flow rate because both movements are STOP-controlled, which diminishes their effect on left turns. The additional capacity impedance effects of the opposing right-turn and through-movement flow rates are taken into account elsewhere in the procedure.

Similar to minor-street through movements, minor-street left-turn movements may be completed in one or two stages. Exhibit 19-9 illustrates the conflicting movements encountered by minor-street left-turning drivers.

Exhibit 19-9
Conflicting Movements for Minor-Street Left-Turn Movements



During Stage I, Equation 19-18 and Equation 19-19 compute the conflicting flow rate for minor-street left-turn movements entering two-lane major streets, while Equation 19-20 and Equation 19-21 are used for four-lane major streets, and Equation 19-22 and Equation 19-23 are used for six-lane major streets. If a right-turn lane exists on the major street, the corresponding v_3 or v_6 term in these equations may be assumed to be zero.

Two-lane major streets:

Equation 19-18

$$v_{c,I,7} = 2v_1 + v_2 + 0.5v_3 + v_{15}$$

Equation 19-19

$$v_{c,I,10} = 2v_4 + v_5 + 0.5v_6 + v_{16}$$

Four-lane major streets:

Equation 19-20

$$v_{c,I,7} = 2(v_1 + v_{1U}) + v_2 + 0.5v_3 + v_{15}$$

Equation 19-21

$$v_{c,I,10} = 2(v_4 + v_{4U}) + v_5 + 0.5v_6 + v_{16}$$

Six-lane major streets:

Equation 19-22

$$v_{c,I,7} = 2(v_1 + v_{1U}) + v_2 + 0.5v_3 + v_{15}$$

Equation 19-23

$$v_{c,I,10} = 2(v_4 + v_{4U}) + v_5 + 0.5v_6 + v_{16}$$

During Stage II, Equation 19-24 and Equation 19-25 compute the conflicting flow rate for minor-street left-turn movements entering two-lane major streets, while Equation 19-26 and Equation 19-27 are used for four-lane major streets, and Equation 19-28 and Equation 19-29 are used for six-lane major streets. If the minor-street right turn is separated by a triangular island and has to comply with a YIELD or STOP sign, the corresponding v_9 or v_{12} term in these equations may be assumed to be zero.

Two-lane major streets:

Equation 19-24

$$v_{c,II,7} = 2v_4 + v_5 + 0.5v_6 + 0.5v_{12} + 0.5v_{11} + v_{13}$$

Equation 19-25

$$v_{c,II,10} = 2v_1 + v_2 + 0.5v_3 + 0.5v_9 + 0.5v_8 + v_{14}$$

Four-lane major streets:

Equation 19-26

$$v_{c,II,7} = 2(v_4 + v_{4U}) + 0.5v_5 + 0.5v_{11} + v_{13}$$

Equation 19-27

$$v_{c,II,10} = 2(v_1 + v_{1U}) + 0.5v_2 + 0.5v_8 + v_{14}$$

Six-lane major streets:

Equation 19-28

$$v_{c,II,7} = 2(v_4 + v_{4U}) + 0.4v_5 + 0.5v_{11} + v_{13}$$

Equation 19-29

$$v_{c,II,10} = 2(v_1 + v_{1U}) + 0.4v_2 + 0.5v_8 + v_{14}$$

Step 4: Determine Critical Headways and Follow-Up Headways

The critical headways $t_{c,x}$ and follow-up headways $t_{f,x}$ must be determined for the major-street left turns ($v_{c,1}$ and $v_{c,4}$), the minor-street right turns ($v_{c,9}$ and $v_{c,12}$), the major-street U-turns ($v_{c,1U}$ and $v_{c,4U}$), the minor-street through movements ($v_{c,8}$ and $v_{c,11}$), and the minor-street left turns ($v_{c,7}$ and $v_{c,10}$) as they occur at a TWSC intersection.

To compute the critical headways for each movement, the analyst begins with the base critical headway given in Exhibit 19-10 and makes movement-specific adjustments relating to the percentage of heavy vehicles, the grade encountered, and a three-leg versus four-leg intersection, as shown in Equation 19-30:

Equation 19-30

$$t_{c,x} = t_{c,base} + t_{c,HV} P_{HV} + t_{c,G} G - t_{3,LT}$$

where

$t_{c,x}$ = critical headway for movement x (s);

$t_{c,base}$ = base critical headway from Exhibit 19-10 (s);

$t_{c,HV}$ = adjustment factor for heavy vehicles (1.0 for major streets with one lane in each direction; 2.0 for major streets with two or three lanes in each direction) (s);

P_{HV} = proportion of heavy vehicles for movement (expressed as a decimal; e.g., $P_{HV} = 0.02$ for 2% heavy vehicles);

$t_{c,G}$ = adjustment factor for grade (0.1 for Movements 9 and 12; 0.2 for Movements 7, 8, 10, and 11) (s);

G = percent grade (expressed as an integer; e.g., $G = -2$ for a 2% downhill grade); and

$t_{3,LT}$ = adjustment factor for intersection geometry (0.7 for minor-street left-turn movement at three-leg intersections; 0.0 otherwise) (s).

$t_{3,LT}$ *is applicable to Movements 7, 8, 10, and 11*

Exhibit 19-10
Base Critical Headways for TWSC Intersections

	Base Critical Headway, $t_{c,base}$ (s)		
Vehicle Movement	**Two Lanes**	**Four Lanes**	**Six Lanes**
Left turn from major	4.1	4.1	5.3
U-turn from major	N/A	6.4 (wide) 6.9 (narrow)	5.6
Right turn from minor	6.2	6.9	7.1
Through traffic on minor	1-stage: 6.5 2-stage, Stage I: 5.5 2-stage, Stage II: 5.5	1-stage:6.5 2-stage, Stage I: 5.5 2-stage, Stage II: 5.5	1-stage: 6.5* 2-stage, Stage I: 5.5* 2-stage, Stage II: 5.5*
Left turn from minor	1-stage: 7.1 2-stage, Stage I: 6.1 2-stage, Stage II: 6.1	1-stage: 7.5 2-stage, Stage I: 6.5 2-stage, Stage II: 6.5	1-stage: 6.4 2-stage, Stage I: 7.3 2-stage, Stage II: 6.7

* Use caution; values estimated.
Note: "Narrow" U-turns have a median nose width < 21 ft; "wide" U-turns have a median nose width ≥21 ft.

The critical headway data for four- and six-lane sites account for the actual lane distribution of traffic flows measured at each site. For six-lane sites, minor-street left turns were commonly observed beginning their movement while apparently conflicting vehicles in the far-side major-street through stream pass. The values for critical headway for minor-street through movements at six-lane streets are estimated, as the movement is not frequently observed in the field.

Similar to the computation of critical headways, the analyst begins the computation of follow-up headways with the base follow-up headways given in Exhibit 19-11. The analyst then makes movement-specific adjustments to the base follow-up headways with information gathered on heavy vehicles and the geometrics of the major street per the adjustment factors given in Equation 19-31.

Equation 19-31

$$t_{f,x} = t_{f,base} + t_{f,HV} P_{HV}$$

where

$t_{f,x}$ = follow-up headway for movement x (s),

$t_{f,base}$ = base follow-up headway from Exhibit 19-11 (s),

$t_{f,HV}$ = adjustment factor for heavy vehicles (0.9 for major streets with one lane in each direction, 1.0 for major streets with two or three lanes in each direction), and

P_{HV} = proportion of heavy vehicles for movement (expressed as a decimal; e.g., P_{HV} = 0.02 for 2% heavy vehicles).

Exhibit 19-11
Base Follow-Up Headways for TWSC Intersections

Vehicle Movement	Base Follow-Up Headway, $t_{f,base}$ (s) Two Lanes	Four Lanes	Six Lanes
Left turn from major	2.2	2.2	3.1
U-turn from major	N/A	2.5 (wide) 3.1 (narrow)	2.3
Right turn from minor	3.3	3.3	3.9
Through traffic on minor	4.0	4.0	4.0
Left turn from minor	3.5	3.5	3.8

Note: "Narrow" U-turns have a median nose width < 21 ft; "wide" U-turns have a median nose width ≥21 ft.

Values from Exhibit 19-10 and Exhibit 19-11 are based on studies throughout the United States and are representative of a broad range of conditions. If smaller values for t_c and t_f are observed, capacity will be increased. If larger values for t_c and t_f are used, capacity will be decreased.

Step 5: Compute Potential Capacities

Step 5a: Potential Capacity If No Upstream Signal Effects Are Present

The potential capacity $c_{p,x}$ of a movement is computed according to the gap-acceptance model provided in Equation 19-32 (*6*). This model requires the analyst to input the conflicting flow rate $v_{c,x}$, the critical headway $t_{c,x}$, and the follow-up headway $t_{f,x}$, for movement x.

Equation 19-32

$$c_{p,x} = v_{c,x} \frac{e^{-v_{c,x} t_{c,x}/3{,}600}}{1 - e^{-v_{c,x} t_{f,x}/3{,}600}}$$

where

$c_{p,x}$ = potential capacity of movement x (veh/h),

$v_{c,x}$ = conflicting flow rate for movement x (veh/h),

$t_{c,x}$ = critical headway for minor movement x (s), and

$t_{f,x}$ = follow-up headway for minor movement x (s).

For two-stage Rank 3 or 4 movements, the potential capacity is computed three times: $c_{p,x}$ assuming one-stage operation, $c_{p,I,x}$ for Stage I, and $c_{p,II,x}$ for Stage II. The conflicting flow definitions for each calculation are as provided in Step 4.

Step 5b: Potential Capacity If Upstream Signal Effects Are Present

To evaluate the impact of coordinated upstream signals, the urban street segments methodology (Chapter 17) is used to estimate the proportion of time that each Rank 2 or lower movement will be effectively blocked by a platoon. The proportion of time blocked is denoted by $p_{b,x}$, where x is the movement using the movement conventions provided in Exhibit 19-3.

With these values, the proportion of the analysis period that is blocked for each minor movement can be computed by using Exhibit 19-12:

Exhibit 19-12
Proportion of Analysis Period Blocked for Each Movement

Movement(s) x	Proportion Blocked for Movement, $p_{b,x}$ One-Stage Movements	Two-Stage Movements Stage I	Two-Stage Movements Stage II
1, 1U	$p_{b,1}$	N/A	N/A
4, 4U	$p_{b,4}$	N/A	N/A
7	$p_{b,7}$	$p_{b,4}$	$p_{b,1}$
8	$p_{b,8}$	$p_{b,4}$	$p_{b,1}$
9	$p_{b,9}$	N/A	N/A
10	$p_{b,10}$	$p_{b,1}$	$p_{b,4}$
11	$p_{b,11}$	$p_{b,1}$	$p_{b,4}$
12	$p_{b,12}$	N/A	N/A

The flow for the unblocked period (no platoons) is determined in this step. This flow becomes the conflicting flow for the subject movement and is used to compute the capacity for this movement. The minimum platooned flow rate $v_{c,min}$ is approximately 1,000N, where N is the number of through lanes per direction on the major street (*7*).

The conflicting flow for movement x during the unblocked period is given by Equation 19-33:

Equation 19-33

$$v_{c,u,x} = \begin{cases} \dfrac{v_{c,x} - 1.5 v_{c,\min} p_{b,x}}{1 - p_{b,x}} & \text{if } v_{c,x} > 1.5 v_{c,\min} p_{b,x} \\ 0 & \text{otherwise} \end{cases}$$

where

$v_{c,u,x}$ = conflicting flow for movement x during the unblocked period (veh/h);

$v_{c,x}$ = total conflicting flow for movement x as determined from Step 3 (veh/h);

$v_{c,min}$ = minimum platooned flow rate (veh/h), assumed to be 1,000N, where N is the number of through lanes per direction on the major street; and

$p_{b,x}$ = proportion of time the subject movement x is blocked by the major-street platoon, which is determined from Exhibit 19-12.

The potential capacity of the subject movement x, accounting for the effect of platooning, is given by Equation 19-34 and Equation 19-35:

Equation 19-34

$$c_{p,x} = (1 - p_{b,x})c_{r,x}$$

Equation 19-35

$$c_{r,x} = v_{c,u,x} \frac{e^{-v_{c,u,x} t_{c,x} / 3{,}600}}{1 - e^{-v_{c,u,x} t_{f,x} / 3{,}600}}$$

where

$c_{p,x}$ = potential capacity of movement x (veh/h),

$p_{b,x}$ = proportion of time that movement x is blocked by a platoon, and

$c_{r,x}$ = capacity of movement x assuming random flow during the unblocked period.

This equation uses the same critical headway and follow-up headway inputs as does a normal calculation but uses only the conflicting flow during the unblocked period.

Steps 6–9: Compute Movement Capacities

For clarity, these steps assume that pedestrian impedance effects can be neglected, and in many cases this is a reasonable assumption. However, pedestrians can be accounted for in the analysis of the automobile mode by replacing these steps with those provided in Chapter 32, STOP-Controlled Intersections: Supplemental, that incorporate the effects of pedestrian impedance.

Step 6: Rank 1 Movement Capacity

Rank 1 major-street movements are assumed to be unimpeded by any movements of lower rank. This rank also implies that major-street movements of Rank 1 are not expected to incur delay or slowing as they travel through the TWSC intersection. Empirical observations have shown that such delays do occasionally occur, and they are accounted for by using adjustments provided later in this procedure.

Step 7: Rank 2 Movement Capacity

Movements of Rank 2 (left turns and U-turns from the major street and right turns from the minor street) must yield to conflicting major-street through and right-turning vehicular movements of Rank 1. Minor-street right turns are assumed to yield to major-street U-turns, although sometimes the reverse occurs.

Step 7a: Movement Capacity for Major-Street Left-Turn Movement

The movement capacity of each Rank 2 major-street left-turn movement (1 and 4) is equal to its potential capacity, as shown in Equation 19-36.

Equation 19-36

$$c_{m,j} = c_{p,j}$$

Step 7b: Movement Capacity for Minor-Street Right-Turn Movements

The movement capacity, $c_{m,j}$, for Rank 2 minor-street right-turn movements (9 and 12) is equal to its potential capacity, as shown in Equation 19-37.

Equation 19-37

$$c_{m,j} = c_{p,j}$$

Step 7c: Movement Capacity for Major-Street U-turn Movements

The movement capacity, $c_{m,j}$, for Rank 2 major-street U-turn movements (1U and 4U) is found by first computing a capacity adjustment factor that accounts for the impeding effects of higher-ranked movements. Field observations are mixed in terms of the degree to which major-street U-turn movements yield to minor-street right-turn movements and vice versa (5). It is assumed that the presence of minor-street right-turning vehicles will impede U-turning vehicles from accepting gaps in the major-street traffic stream; therefore, the capacity of the U-turn movement is affected by the probability that the minor-street right-turning traffic will operate in a queue-free state. The capacity adjustment factors are denoted by f_{1U} and f_{4U} for the major-street U-turn movements 1U and 4U, respectively, and are given by Equation 19-38 and Equation 19-39, respectively.

$$f_{1U} = p_{0,12} = 1 - \frac{v_{12}}{c_{m,12}}$$

Equation 19-38

$$f_{4U} = p_{0,9} = 1 - \frac{v_9}{c_{m,9}}$$

Equation 19-39

where

f_{1U}, f_{4U} = capacity adjustment factor for Rank 2 major-street U-turn movements 1 and 4, respectively;

$p_{0,j}$ = probability that conflicting Rank 2 minor-street right-turn movement j will operate in a queue-free state;

v_j = flow rate of movement j;

$c_{m,j}$ = capacity of movement j; and

j = 9 and 12 (minor-street right-turn movements of Rank 2).

The movement capacity for major-street U-turn movements is then computed with Equation 19-40:

$$c_{m,jU} = (c_{p,jU}) f_{JU}$$

Equation 19-40

In almost all cases, major-street left-turning vehicles share a lane with U-turning vehicles. Therefore, if Rank 2 major-street U-turn movements are present to a significant degree, then Equation 19-59 should be used to compute the shared-lane capacity.

where

$c_{m,jU}$ = movement capacity for Movements 1U and 4U,

$c_{p,jU}$ = potential capacity for Movements 1U and 4U (from Step 5), and

f_{jU} = capacity adjustment factor for Movements 1U and 4U.

Since the left-turn and U-turn movements are typically conducted from the same lane, their shared-lane capacity is computed with Equation 19-41:

$$c_{SH} = \frac{\sum_y v_y}{\sum_y \left(\frac{v_y}{c_{m,y}} \right)}$$

Equation 19-41

where

c_{SH} = capacity of the shared lane (veh/h),

v_y = flow rate of the y movement in the subject shared lane (veh/h), and

$c_{m,y}$ = movement capacity of the y movement in the subject shared lane (veh/h).

Step 7d: Effect of Major-Street Shared Through and Left-Turn Lane

The probability that the major-street left-turning traffic will operate in a queue-free state is expressed by Equation 19-42:

Equation 19-42

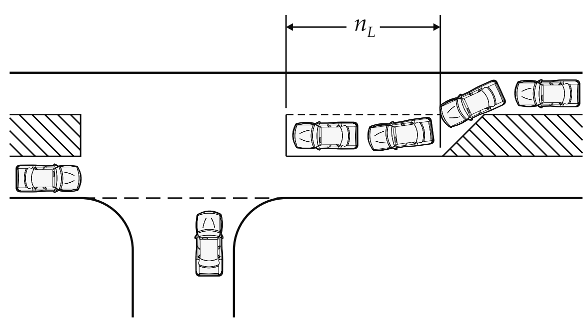
$$p_{0,j} = 1 - \frac{v_j}{c_{m,j}}$$

If major-street through and left-turn movements are shared, use Equation 19-43. Also, use Equation 19-42 to compute the probability of a queue-free state for Rank 3 movements.

where j = 1 and 4 (major-street left-turn and U-turn movements of Rank 2, using shared volume and capacity as appropriate).

If, however, a shared left-turn lane or a short left-turn pocket is present on a major-street approach (as in Exhibit 19-13), the analyst accounts for this occurrence by computing the probability that there will be no queue in the major-street shared lane, $p^*_{0,j}$, according to Equation 19-43. This probability is then used by the analyst in lieu of $p_{0,j}$ (as computed by Equation 19-42).

Exhibit 19-13
Short Left-Turn Pocket



The methodology implicitly assumes that an exclusive lane is provided to all left-turning traffic from the major street. If a left-turn lane is not provided or the left-turn pocket is not long enough to accommodate all queuing left-turn and U-turn vehicles, major-street through (and possibly right-turning) traffic could be delayed by left-turning vehicles waiting for an acceptable gap in opposing major-street through traffic. To account for this occurrence, the factors $p^*_{0,1}$ and $p^*_{0,4}$ may be computed according to Equation 19-43 and Equation 19-44 as an indication of the probability that there will be no queue in the respective major-street shared or short lanes (*8*).

Equation 19-43

$$p^*_{0,j} = 1 - \left(1 - p_{0,j}\right)\left[\sqrt[(n_L+1)]{1 + \frac{x_{i,1+2}^{(n_L+1)}}{1 - x_{i,1+2}}}\right]$$

Equation 19-44

$$x_{i,1+2} = \frac{v_{i1}}{s_{i1}} + \frac{v_{i2}}{s_{i2}}$$

where

$p_{0,j}$ = probability of queue-free state for movement j assuming an exclusive left-turn lane on the major street (per Equation 19-42);

j = 1 and 4 (major-street left-turning vehicular movements);

$i1$ = 2 and 5 (major-street through vehicular movements);

$i2$ = 3 and 6 (major-street right-turning vehicular movements);

$x_{i,1+2}$ = combined degree of saturation for the major-street through and right-turn movements;

s_{i1} = saturation flow rate for the major-street through movements (default assumed to be 1,800 veh/h; however, this parameter can be measured in the field);

s_{i2} = saturation flow rate for the major-street right-turn movements (default assumed to be 1,500 veh/h; however, this parameter can be measured in the field);

v_{i1} = major-street through-movement flow rate (veh/h);

v_{i2} = major-street right-turn flow rate (veh/h) (0 if an exclusive right-turn lane is provided); and

n_L = storage places in the left-turn pocket (see Exhibit 19-13).

When j = 1, $i1$ = 2 and $i2$ = 3; when j = 4, $i1$ = 5 and $i2$ = 6.

For the special situation of shared lanes (n_L = 0), Equation 19-43 becomes Equation 19-45 as follows:

$$p^*_{0,j} = 1 - \frac{1 - p_{0,j}}{1 - x_{i,1+2}}$$

Equation 19-45

where all terms are as previously defined.

By using $p^*_{0,1}$ and $p^*_{0,4}$ in lieu of $p_{0,1}$ and $p_{0,4}$ (as computed by Equation 19-42), the potential for queues on a major street with shared or short left-turn lanes may be taken into account.

Step 8: Compute Movement Capacities for Rank 3 Movements

Rank 3 minor-street traffic movements (minor-street through movements at four-leg intersections and minor-street left turns at three-leg intersections) must yield to conflicting Rank 1 and Rank 2 movements. Not all gaps of acceptable length that pass through the intersection will normally be available for use by Rank 3 movements, because some of these gaps are likely to be used by Rank 2 movements.

If the Rank 3 movement is a two-stage movement, the movement capacity for the one-stage movement is computed as an input to the two-stage calculation.

Step 8a: Rank 3 Movement Capacity for One-Stage Movements

For Rank 3 movements, the magnitude of vehicle impedance depends on the probability that major-street left-turning vehicles will be waiting for an acceptable gap at the same time as vehicles of Rank 3. A higher probability that this situation will occur means greater capacity-reducing effects of the major-street left-turning traffic on all Rank 3 movements.

The movement capacity $c_{m,k}$ for all Rank 3 movements is found by first computing a capacity adjustment factor that accounts for the impeding effects of higher-ranked movements. The capacity adjustment factor is denoted by f_k for all movements k and for all Rank 3 movements and is given by Equation 19-46:

Equation 19-46

$$f_k = \prod_j p_{0,j}$$

where

$p_{0,j}$ = probability that conflicting Rank 2 movement j will operate in a queue-free state, and

k = Rank 3 movements.

The movement capacity for Rank 3 minor-street movements is computed with Equation 19-47, where f_k is the capacity adjustment factor that accounts for the impeding effects of higher-ranked movements computed according to Equation 19-46.

Equation 19-47

$$c_{m,k} = (c_{p,k}) f_k$$

Step 8b: Rank 3 Capacity for Two-Stage Movements

If the Rank 3 movement is a two-stage movement, the procedure for computing the total movement capacity for the subject movement considering the two-stage gap-acceptance process is as follows. An adjustment factor a and an intermediate variable y are computed with Equation 19-48 and Equation 19-49, respectively.

Equation 19-48

$$a = 1 - 0.32e^{-1.3\sqrt{n_m}} \quad \text{for } n_m > 0$$

Equation 19-49

$$y = \frac{c_I - c_{m,x}}{c_{II} - v_L - c_{m,x}}$$

where

n_m = number of storage spaces in the median;

c_I = movement capacity for the Stage I process (veh/h);

c_{II} = movement capacity for the Stage II process (veh/h);

v_L = major left-turn or U-turn flow rate, either $v_1 + v_{1U}$ or $v_4 + v_{4U}$ (veh/h); and

$c_{m,x}$ = capacity of subject movement, considering the total conflicting flow rate for both stages of a two-stage gap-acceptance process (from Step 8a).

The total capacity c_T for the subject movement, considering the two-stage gap-acceptance process, is computed by using Equation 19-50 and Equation 19-51 and incorporating the adjustment factors derived from Equation 19-48 and Equation 19-49.

For $y \neq 1$:

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

Equation 19-50

For $y = 1$:

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

Equation 19-51

Step 9: Compute Movement Capacities for Rank 4 Movements

Rank 4 movements occur only at four-leg intersections. Rank 4 movements (i.e., only the minor-street left turns at a four-leg intersection) can be impeded by all higher-ranked movements (Ranks 1, 2, and 3).

Step 9a: Rank 4 Capacity for One-Stage Movements

The probability that higher-ranked traffic movements will operate in a queue-free state is central to determining their overall impeding effects on the minor street left-turn movement. At the same time, it must be recognized that not all these probabilities are independent of each other. Specifically, queuing in the major-street left-turning movement affects the probability of a queue-free state in the minor-street crossing movement. Applying the simple product of these two probabilities will likely overestimate the impeding effects on the minor-street left-turning traffic.

Exhibit 19-14 can be used to adjust for the overestimate caused by the statistical dependence between queues in streams of Ranks 2 and 3. The mathematical representation of this curve is determined with Equation 19-52.

$$p' = 0.65p'' - \frac{p''}{p'' + 3} + 0.6\sqrt{p''}$$

Equation 19-52

where

p' = adjustment to the major-street left, minor-street through impedance factor;

p'' = $(p_{0,j})(p_{0,k})$;

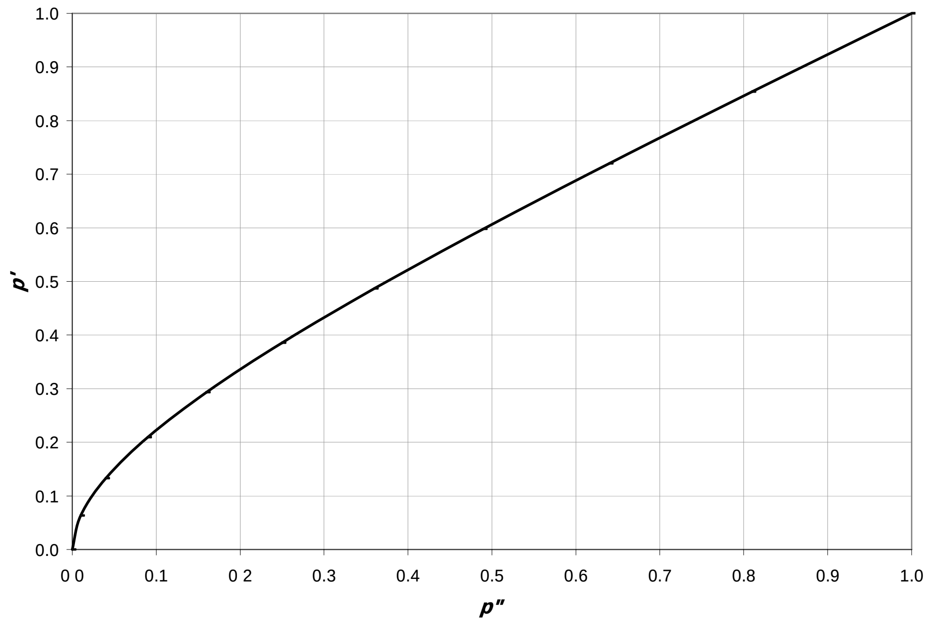
$p_{0,j}$ = probability of a queue-free state for the conflicting major-street left-turning traffic; and

$p_{0,k}$ = probability of a queue-free state for the conflicting minor-street crossing traffic.

When determining p' for Rank 4 Movement 7 in Equation 19-53, $p'' = (p_{0,1})(p_{0,4})(p_{0,11})$. Likewise, when determining p' for Rank 4 Movement 10, $p'' = (p_{0,1})(p_{0,4})(p_{0,8})$.

Exhibit 19-14
Adjustment to Impedance Factors for Major Left-Turn Movement and Minor Crossing Movement

LIVE GRAPH
Click here to view



The movement capacity $c_{m,l}$ for all Rank 4 movements is found by first computing a capacity adjustment factor that accounts for the impeding effects of higher-ranked movements. The capacity adjustment factor for the Rank 4 minor-street left-turn movement can be computed with Equation 19-53:

Equation 19-53

$$f_{p,l} = (p')(p_{0,j})$$

where

l = minor-street left-turn movement of Rank 4 (Movements 7 and 10 in Exhibit 19-3), and

j = conflicting Rank 2 minor-street right-turn movement (Movements 9 and 12 in Exhibit 19-3).

Finally, the movement capacity for the minor-street left-turn movements of Rank 4 is determined with Equation 19-54, where $f_{p,l}$ is the capacity adjustment factor that accounts for the impeding effects of higher-ranked movements.

Equation 19-54

$$c_{m,l} = (c_{p,l}) f_{p,l}$$

Step 9b: Rank 4 Capacity for Two-Stage Movements

The procedure for computing the total movement capacity for the subject movement considering the two-stage gap-acceptance process is as follows: An adjustment factor a and an intermediate variable y are computed with Equation 19-55 and Equation 19-56, respectively:

Equation 19-55

$$a = 1 - 0.32e^{-1.3\sqrt{n_m}} \quad \text{for } n_m > 0$$

Equation 19-56

$$y = \frac{c_I - c_{m,x}}{c_{II} - v_L - c_{m,x}}$$

where

n_m = number of storage spaces in the median;

c_I = movement capacity for the Stage I process (veh/h);

c_{II} = movement capacity for the Stage II process (veh/h);

v_L = major left-turn or U-turn flow rate, either $v_1 + v_{1U}$ or $v_4 + v_{4U}$ (veh/h); and

$c_{m,x}$ = capacity of subject movement, including the total conflicting flow rate for both stages of a two-stage gap-acceptance process (from Step 9a).

The total capacity c_T for the subject movement considering the two-stage gap-acceptance process is computed by using Equation 19-57 and Equation 19-58 and incorporating the adjustment factors computed in Equation 19-55 and Equation 19-56.

For $y \neq 1$:

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

Equation 19-57

For $y = 1$:

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

Equation 19-58

Step 10: Final Capacity Adjustments

Step 10a: Shared-Lane Capacity of Minor-Street Approaches

Where several movements share the same lane and cannot stop side by side at the stop line, Equation 19-59 is used to compute shared-lane capacity:

$$c_{SH} = \frac{\sum_y v_y}{\sum_y \left(\frac{v_y}{c_{m,y}}\right)}$$

Equation 19-59

where

c_{SH} = capacity of the shared lane (veh/h),

v_y = flow rate of the y movement in the subject shared lane (veh/h), and

$c_{m,y}$ = movement capacity of the y movement in the subject shared lane (veh/h).

Step 10b: Compute Flared Minor-Street Lane Effects

To estimate the capacity of a flared right-turn lane (as in Exhibit 19-15), the average queue length for each movement sharing the right lane on the minor-street approach must first be computed with Equation 19-60. This computation assumes that the right-turn movement operates in one lane and that the other traffic in the right lane (upstream of the flare) operates in another, separate lane.

Equation 19-60

$$Q_{sep} = \frac{d_{sep} v_{sep}}{3{,}600}$$

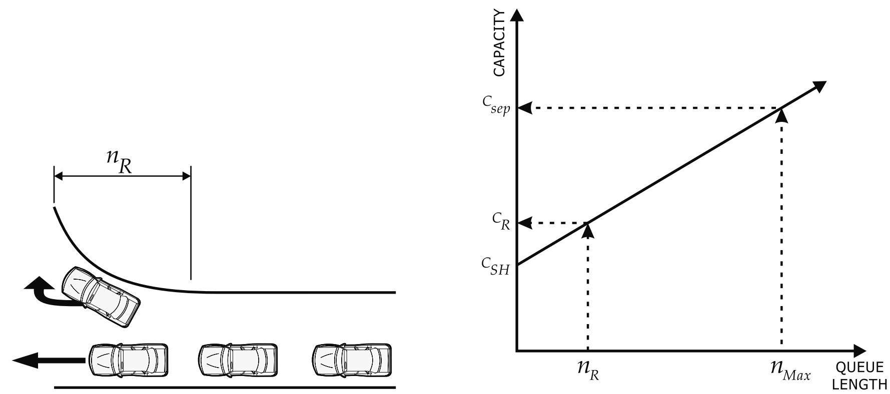
where

Q_{sep} = average queue length for the movement considered as a separate lane (veh),

d_{sep} = control delay for the movement considered as a separate lane (as described in Step 11), and

v_{sep} = flow rate for the movement (veh/h).

Exhibit 19-15
Capacity of a Flared-Lane Approach



Next, the required length of the storage area such that the approach would operate effectively as separate lanes is computed with Equation 19-61. This is the maximum value of the queue lengths computed for each separate movement plus one vehicle.

Equation 19-61

$$n_{Max} = \operatorname*{Max}_{i}\left[\text{round}\left(Q_{sep,i} + 1\right)\right]$$

where

$Q_{sep,i}$ = average queue length for movement i considered as a separate lane;

round = round-off operator, rounding the quantity in parentheses to the nearest integer; and

n_{Max} = length of the storage area such that the approach would operate as separate lanes.

Next, the capacity of a separate lane condition c_{sep} must be computed and is assumed to be the capacity of right-turning traffic operating as a separate lane and the capacity of the other traffic in the right lane (upstream of the flare) operating as a separate lane. The capacity of a separate lane condition is calculated according to Equation 19-62, as shown:

Equation 19-62

$$c_{sep} = \text{Min}\left[c_R\left(1 + \frac{v_{L+TH}}{v_R}\right), c_{L+TH}\left(1 + \frac{v_R}{v_{L+TH}}\right)\right]$$

where

c_{sep} = sum of the capacities of the right-turning traffic operating as a separate lane and the capacity of the other traffic in the right lane (upstream of the flare) operating in a separate lane (veh/h),

c_R = capacity of the right-turn movement (veh/h),

c_{L+TH} = capacity of the through and left-turn movements as a shared lane (veh/h),

v_R = right-turn movement flow rate (veh/h), and

v_{L+TH} = through and left-turn movement combined flow rate (veh/h).

Finally, the capacity of the lane is computed, taking into account the flare. The capacity is interpolated as shown in Exhibit 19-15. A straight line is established by using values of two points: (c_{sep}, n_{Max}) and (c_{SH}, 0). The interpolated value of the actual value of the flared-lane capacity c_R is computed with Equation 19-63.

$$c_R = \begin{cases} \left(c_{sep} - c_{SH}\right)\dfrac{n_R}{n_{Max}} + c_{SH} & \text{if } n_R \le n_{Max} \\ c_{sep} & \text{if } n_R > n_{Max} \end{cases}$$

Equation 19-63

where

c_R = actual capacity of the flared lane (veh/h),

c_{sep} = capacity of the lane if both storage areas were infinitely long (refer to Equation 19-62) (veh/h),

c_{SH} = capacity of the lane when all traffic is sharing one lane (veh/h), and

n_R = actual storage area for right-turning vehicles as defined in Exhibit 19-15.

The actual capacity c_{act} must be greater than c_{SH} but less than or equal to c_{sep}.

Step 11: Compute Movement Control Delay

The delay experienced by a motorist is made up of a number of factors that relate to control type, geometrics, traffic, and incidents. In the TWSC intersection methodology, only that portion of delay attributed to the STOP-control aspect of the intersection, referred to as control delay, is quantified.

Control delay includes delay due to deceleration to a stop at the back of the queue from free-flow speed, move-up time within the queue, stopped delay at the front of the queue, and delay due to acceleration back to free-flow speed. With respect to field measurements, control delay is defined as the total time that elapses from the time a vehicle stops at the end of the queue to the time the vehicle departs from the stop line. This total elapsed time includes the time required for the vehicle to travel from the last-in-queue position to the first-in-queue position, including deceleration of vehicles from free-flow speed to the speed of vehicles in queue.

Step 11a: Compute Control Delay to Rank 2 Through Rank 4 Movements

Average control delay for any particular minor movement is a function of the capacity of the approach and the degree of saturation. The analytical model used to estimate control delay (Equation 19-64) assumes that demand is less than capacity for the period of analysis. If the degree of saturation is greater than about 0.9, average control delay is significantly affected by the length of the analysis period. In most cases, the recommended analysis period is 15 min. If demand exceeds capacity during a 15-min period, the delay results computed by the procedure may not be accurate. In this case, the period of analysis should be lengthened to include the period of oversaturation.

Equation 19-64

$$d = \frac{3600}{c_{m,x}} + 900T\left[\frac{v_x}{c_{m,x}} - 1 + \sqrt{\left(\frac{v_x}{c_{m,x}} - 1\right)^2 + \frac{\left(\frac{3600}{c_{m,x}}\right)\left(\frac{v_x}{c_{m,x}}\right)}{450T}}\right] + 5$$

where

d = control delay (s/veh),

v_x = flow rate for movement x (veh/h),

$c_{m,x}$ = capacity of movement x (veh/h), and

T = analysis time period (equals 0.25 h for a 15-min period) (h).

A constant value of 5 s/veh is used to reflect delay during deceleration to and acceleration from a stop.

The constant 5 s/veh is included in Equation 19-64 to account for the deceleration of vehicles from free-flow speed to the speed of vehicles in queue and the acceleration of vehicles from the stop line to free-flow speed.

Step 11b: Compute Control Delay to Rank 1 Movements

The effect of a shared lane on the major-street approach where left-turning vehicles may block Rank 1 through or right-turning vehicles can be significant. 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. This will delay not only Rank 1 vehicles but also lower-ranked movements. While the delayed Rank 1 vehicles are discharging from the queue formed behind a left-turning vehicle, they impede lower-ranked conflicting movements.

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 by or bypass the left-turning vehicle. At a minimum, incorporating this effect requires estimating the proportion of Rank 1 vehicles being blocked and computing the average delay to the major-street left-turning vehicles that are blocking through vehicles.

In the simplest procedure, the proportion of Rank 1 major-street vehicles not being blocked (i.e., in a queue-free state) is given by $p^*_{0,j}$ in Equation 19-43 ($p^*_{0,j}$ should be substituted for the major left-turn factor $p_{0,j}$ in Equation 19-43 in computing the capacity of lower-ranked movements that conflict). Therefore, the proportion of Rank 1 vehicles being blocked is $1 - p^*_{0,j}$.

The average delay to Rank 1 vehicles is computed with Equation 19-65.

$$d_{Rank1} = \begin{cases} \dfrac{\left(1-p^*_{0,j}\right)d_{M,LT}\left(\dfrac{v_{i,1}}{N}\right)}{v_{i,1}+v_{i,2}} & N>1 \\ \\ \left(1-p^*_{0,j}\right)d_{M,LT} & N=1 \end{cases}$$

Equation 19-65

where

d_{Rank1} = delay to Rank 1 vehicles (s/veh);

N = number of through lanes per direction on the major street;

$p^*_{0,j}$ = proportion of Rank 1 vehicles not blocked, from Equation 19-43;

$d_{M,LT}$ = delay to major left-turning vehicles, from Equation 19-64 (s/veh);

$v_{i,1}$ = major-street through vehicles in shared lane (veh/h); and

$v_{i,2}$ = major-street turning vehicles in shared lane (veh/h).

On a multilane road, only the major-street volumes in the lane that may be blocked should be used in the computation as $v_{i,1}$ and $v_{i,2}$. On multilane roads, if it is assumed that blocked Rank 1 vehicles do not bypass the blockage by moving into other through lanes (a reasonable assumption under conditions of high major-street flows), then $v_{i,1} = v_2/N$. Because of the unique characteristics associated with each site, the decision on whether to account for this effect is left to the analyst.

Step 12: Compute Approach and Intersection Control Delay

The control delay for all vehicles on a particular approach can be computed as the weighted average of the control delay estimates for each movement on the approach. Equation 19-66 is used for the computation.

$$d_A = \frac{d_r v_r + d_t v_t + d_l v_l}{v_r + v_t + v_l}$$

Equation 19-66

where

d_A = control delay on the approach (s/veh);

d_r, d_t, d_l = computed control delay for the right-turn, through, and left-turn movements, respectively (s/veh); and

v_r, v_t, v_l = volume or flow rate of right-turn, through, and left-turn traffic on the approach, respectively (veh/h).

Similarly, the intersection control delay can be computed with

$$d_I = \frac{d_{A,1}v_{A,1} + d_{A,2}v_{A,2} + d_{A,3}v_{A,3} + d_{A,4}v_{A,4}}{v_{A,1} + v_{A,2} + v_{A,3} + v_{A,4}}$$

Equation 19-67

where

$d_{A,x}$ = control delay on approach x (s/veh), and

$v_{A,x}$ = volume or flow rate on approach x (veh/h).

In applying Equation 19-66 and Equation 19-67, the delay for all Rank 1 major-street movements is assumed to be 0 s/veh. LOS is not defined for an overall intersection because major-street movements with 0 s of delay typically result in a weighted average delay that is extremely low. As such, total intersection control delay calculations are typically used only when comparing control delay among different types of traffic control, such as two-way STOP control versus all-way STOP control.

Step 13: Compute 95th Percentile Queue Lengths

Queue length is an important consideration at unsignalized intersections. Theoretical studies and empirical observations have demonstrated that the probability distribution of queue lengths for any minor 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. Equation 19-68 can be used to estimate the 95th percentile queue length for any minor movement at an unsignalized intersection during the peak 15-min period on the basis of these two parameters as follows (*9*):

Equation 19-68

$$Q_{95} \approx 900T\left[\frac{v_x}{c_{m,x}} - 1 + \sqrt{\left(\frac{v_x}{c_{m,x}} - 1\right)^2 + \frac{\left(\frac{3{,}600}{c_{m,x}}\right)\left(\frac{v_x}{c_{m,x}}\right)}{150T}}\,\right]\left(\frac{c_{m,x}}{3{,}600}\right)$$

where

Q_{95} = 95th percentile queue (veh),

v_x = flow rate for movement x (veh/h),

$c_{m,x}$ = capacity of movement x (veh/h), and

T = analysis time period (0.25 h for a 15-min period) (h).

The mean queue length 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 vehicles during the hour.

PEDESTRIAN MODE

The TWSC intersection methodology for the pedestrian mode is applied through a series of steps requiring input data related to vehicle and pedestrian volumes, geometric conditions, and motorist yield rates to pedestrians. These data are used to calculate the average pedestrian delay associated with pedestrian crossings of unsignalized and non-STOP-controlled roadways. The required steps are illustrated in Exhibit 19-16.

Step 1: Identify Two-Stage Crossings

↓

Step 2: Determine Critical Headway

↓

Step 3: Estimate Probability of a Delayed Crossing

↓

Step 4: Calculate Average Delay to Wait for Adequate Gap

↓

Step 5: Estimate Delay Reduction due to Yielding Vehicles

↓

Step 6: Calculate Average Pedestrian Delay and Determine LOS

Exhibit 19-16
TWSC Pedestrian Methodology

Step 1: Identify Two-Stage Crossings

When a raised pedestrian-median refuge island is available, pedestrians typically cross in two stages, similar to the two-stage gap-acceptance described for automobiles earlier in this chapter. Determination of whether a pedestrian-median refuge exists may require engineering judgment. The main issue to determine is whether pedestrians cross the traffic streams in one or two stages. When pedestrians cross in two stages, pedestrian delay should be estimated separately for each stage of the crossing by using the procedures described in Steps 2 to 6. To determine pedestrian LOS, the pedestrian delay for each stage should be summed to establish the average pedestrian delay associated with the entire crossing. This service measure is used to determine pedestrian LOS for a TWSC intersection with two-stage crossings.

Step 2: Determine Critical Headway

Critical headway for pedestrians.

The procedure for estimating the critical headway is similar to that described for automobiles. The critical headway is the time in seconds below which a pedestrian will not attempt to begin crossing the street. Pedestrians use their judgment to determine whether the available headway between conflicting vehicles is long enough for a safe crossing. If the available headway is greater than the critical headway, it is assumed that the pedestrian will cross, but if the available headway is less than the critical headway, it is assumed that the pedestrian will not cross.

For a single pedestrian, critical headway is computed with Equation 19-69:

$$t_c = \frac{L}{S_p} + t_s$$

Equation 19-69

where

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

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

L = crosswalk length (ft), and

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

Pedestrian platooning.

If pedestrian platooning is observed in the field, then the spatial distribution of pedestrians should be computed with Equation 19-70. If no platooning is observed, the spatial distribution of pedestrians is assumed to be 1.

Equation 19-70

$$N_p = \mathrm{Int}\left[\frac{8.0(N_c - 1)}{W_c}\right] + 1$$

where

N_p = spatial distribution of pedestrians (ped);

N_c = total number of pedestrians in the crossing platoon, from Equation 19-71 (ped);

W_c = crosswalk width (ft); and

8.0 = default clear effective width used by a single pedestrian to avoid interference when passing other pedestrians (ft).

To compute spatial distribution, the analyst must make field observations or estimate the platoon size by using Equation 19-71:

Equation 19-71

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

where

N_c = total number of pedestrians in the crossing platoon (ped),

v_p = pedestrian flow rate (ped/s),

v = vehicular flow rate (veh/s), and

t_c = single pedestrian critical headway (s).

Group critical headway is determined with Equation 19-72:

Equation 19-72

$$t_{c,G} = t_c + 2(N_p - 1)$$

where

$t_{c,G}$ = group critical headway (s),

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

N_p = spatial distribution of pedestrians (ped).

Step 3: Estimate Probability of a Delayed Crossing

On the basis of calculation of the critical headway t_G, the probability that a pedestrian will not incur any crossing delay is equal to the likelihood that a pedestrian will encounter a gap greater than or equal to the critical headway immediately upon arrival at the intersection.

Assuming random arrivals of vehicles on the major street, and equal distribution of vehicles among all through lanes on the major street, the probability of encountering a headway exceeding the critical headway in any given lane can be estimated by using a Poisson distribution. The likelihood that a gap in a given lane does not exceed the critical headway is thus the complement as shown in Equation 19-73. Because traffic is assumed to be distributed independently in each through lane, Equation 19-74 shows the probability that a pedestrian incurs nonzero delay at a TWSC crossing.

$$P_b = 1 - e^{\frac{-t_{c,G} v}{L}}$$

Equation 19-73

$$P_d = 1 - (1 - P_b)^L$$

Equation 19-74

where

P_b = probability of a blocked lane,

P_d = probability of a delayed crossing,

L = number of through lanes crossed,

$t_{c,G}$ = group critical headway (s), and

v = vehicular flow rate (veh/s).

Step 4: Calculate Average Delay to Wait for Adequate Gap

Research indicates that average delay to pedestrians at unsignalized crossings, assuming that no motor vehicles yield and the pedestrian is forced to wait for an adequate gap, depends on the critical headway, the vehicular flow rate of the subject crossing, and the mean vehicle headway (*10*). The average delay per pedestrian to wait for an adequate gap is given by Equation 19-75.

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

Equation 19-75

where

d_g = average pedestrian gap delay (s),

$t_{c,G}$ = group critical headway (s), and

v = vehicular flow rate (veh/s).

The average delay for any pedestrian who is unable to cross immediately upon reaching the intersection (e.g., any pedestrian experiencing nonzero delay) is thus a function of P_d and d_g, as shown in Equation 19-76:

$$d_{gd} = \frac{d_g}{P_d}$$

Equation 19-76

where

d_{gd} = average gap delay for pedestrians who incur nonzero delay,

d_g = average pedestrian gap delay (s), and

P_d = probability of a delayed crossing.

Step 5: Estimate Delay Reduction due to Yielding Vehicles

When a pedestrian arrives at a crossing and finds an inadequate gap, that pedestrian is delayed until one of two situations occurs: (*a*) a gap greater than the critical headway is available, or (*b*) motor vehicles yield and allow the pedestrian to cross. Equation 19-75 estimates pedestrian delay when motorists on the major approaches do not yield to pedestrians. Where motorist yield rates are significantly higher than zero, pedestrians will experience considerably less delay than that estimated by Equation 19-75.

In the United States, motorists are legally required to yield to pedestrians, under most circumstances, in both marked and unmarked crosswalks. However, actual motorist yielding behavior varies considerably. Motorist yield rates are influenced by a range of factors, including roadway geometry, travel speeds, pedestrian crossing treatments, local culture, and law enforcement practices.

Research (*11*, *12*) provides information on motorist responses to typical pedestrian crossing treatments, as shown in Exhibit 19-17. The exhibit shows results from two separate data collection methods. Staged data were collected with pedestrians trained by the research team to maintain consistent positioning, stance, and aggressiveness in crossing attempts. Unstaged data were collected through video recordings of the general population. The values shown in Exhibit 19-17 are based on a limited number of sites and do not encompass the full range of available crossing treatments. As always, practitioners should supplement these values with local knowledge and engineering judgment.

Exhibit 19-17
Effect of Pedestrian Crossing Treatments on Motorist Yield Rates

Crossing Treatment	Staged Pedestrians		Unstaged Pedestrians	
	Number of Sites	Mean Yield Rate, %	Number of Sites	Mean Yield Rate, %
Overhead flashing beacon (push button activation)	3	47	4	49
Overhead flashing beacon (passive activation)	3	31	3	67
Pedestrian crossing flags	6	65	4	74
In-street crossing signs (25–30 mi/h)	3	87	3	90
High-visibility signs and markings (35 mi/h)	2	17	2	20
High-visibility signs and markings (25 mi/h)	1	61	1	91
Rectangular rapid-flash beacon	N/A	N/A	17	81

Source: Fitzpatrick et al. (*11*) and Shurbutt et al. (*12*).

Depending on the crossing treatment and other factors, motorist behavior varies significantly.

It is possible for pedestrians to incur less actual delay than d_g because of yielding vehicles. The likelihood of this situation occurring is a function of vehicle volumes, motorist yield rates, and number of through lanes on the major street. Consider a pedestrian waiting for a crossing opportunity at a TWSC intersection, with vehicles in each conflicting through lane arriving every h seconds. On average, a potential yielding event will occur every h seconds, where $P(Y)$ represents the probability of motorists yielding for a given event. As vehicles are assumed to arrive randomly, each potential yielding event is considered to be independent.

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

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

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

Thus, average pedestrian delay can be calculated with Equation 19-77, where the first term in the equation represents expected delay from crossings occurring when motorists yield, and the second term represents expected delay from crossings where pedestrians wait for an adequate gap.

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

Equation 19-77

where

d_p = average pedestrian delay (s),

i = crossing event (i = 1 to n),

h = average headway for each through lane,

$P(Y_i)$ = probability that motorists yield to pedestrian on crossing event i, and

n = Int(d_{gd}/h), average number of crossing events before an adequate gap is available.

Equation 19-77 requires the calculation of $P(Y_i)$. The probabilities $P(Y_i)$ that motorists will yield for a given crossing event are considered below for pedestrian crossings of one, two, three, and four through lanes.

One-Lane Crossing

Under the scenario in which a pedestrian crosses one through lane, $P(Y_i)$ is found simply. When $i = 1$, $P(Y_i)$ is equal to the probability of a delayed crossing P_d multiplied by the motorist yield rate, M_y. For $i = 2$, $P(Y_i)$ is equal to M_y multiplied by the probability that the second yielding event occurs (i.e., that the pedestrian did not cross on the first yielding event), $P_d^*(1 - M_y)$. Equation 19-78 gives $P(Y_i)$ for any i.

$$P(Y_i) = P_d M_y (1 - M_y)^{i-1}$$

Equation 19-78

where

M_y = motorist yield rate (decimal), and

i = crossing event (i = 1 to n).

Two-Lane Crossing

For a two-lane pedestrian crossing at a TWSC intersection, $P(Y_i)$ requires either (*a*) motorists in both lanes to yield simultaneously if both lanes are blocked, or (*b*) a single motorist to yield if only one lane is blocked. Because these cases are mutually exclusive, where $i = 1$, $P(Y_i)$ is equal to Equation 19-79:

Equation 19-79

$$P(Y_1) = 2P_b(1-P_b)M_y + P_b{}^2 M_y{}^2$$

Equation 19-80 shows $P(Y_i)$ where i is greater than 1. Equation 19-80 is equivalent to Equation 19-79 if $P(Y_0)$ is set to equal 0.

Equation 19-80

$$P(Y_i) = \left[P_d - \sum_{j=0}^{i-1} P(Y_j) \right] \left[\frac{(2P_b(1-P_b)M_y) + (P_b^2 M_y^2)}{P_d} \right]$$

Three-Lane Crossing

A three-lane crossing follows the same principles as a two-lane crossing. Equation 19-81 shows the calculation for $P(Y_i)$:

Equation 19-81

$$P(Y_i) = \left[P_d - \sum_{j=0}^{i-1} P(Y_j) \right] \times \left[\frac{P_b^3 M_y^3 + 3P_b^2(1-P_b)M_y^2 + 3P_b(1-P_b)^2 M_y}{P_d} \right]$$

where $P(Y_0) = 0$.

Four-Lane Crossing

A four-lane crossing follows the same principles as above. Equation 19-82 shows the calculation for $P(Y_i)$:

Equation 19-82

$$P(Y_i) = \left[P_d - \sum_{j=0}^{i-1} P(Y_j) \right] \times \left[\frac{P_b^4 M_y^4 + 4P_b^3(1-P_b)M_y^3 + 6P_b^2(1-P_b)^2 M_y^2 + 4P_b(1-P_b^3)M_y}{P_d} \right]$$

where $P(Y_0) = 0$.

Step 6: Calculate Average Pedestrian Delay and Determine LOS

The delay experienced by a pedestrian is the service measure. Exhibit 19-2 lists LOS criteria for pedestrians at TWSC intersections based on pedestrian delay. Pedestrian delay at TWSC intersections with two-stage crossings is equal to the sum of the delay for each stage of the crossing.

BICYCLE MODE

As of the publication date of this edition of the HCM, no methodology specific to bicyclists has been developed to assess the performance of bicyclists at TWSC intersections, as few data are available in the United States to support model calibration or LOS definitions. Depending on individual comfort level, ability, geometric conditions, and traffic conditions, bicyclists may travel through the intersection either as a motor vehicle or as a pedestrian. Critical headway distributions have been identified in the research (*13*, *14*) for bicycles crossing two-lane major streets. Data on critical headways for bicycles under many circumstances are not readily available, however. Bicycles also differ from motor vehicles in that they normally do not queue linearly at a STOP sign. Instead, multiple bicycles often use the same gap in the vehicular traffic stream. This fact probably affects the determination of bicycle follow-up time. This phenomenon and others described in this section have not been adequately researched and are not explicitly included in the methodology.

3. APPLICATIONS

DEFAULT VALUES

A comprehensive presentation of potential default values for interrupted flow facilities is provided elsewhere (*15*), with specific recommendations summarized in its Chapter 3, Recommended Default Values. These defaults cover the key characteristics of *PHF* and percent heavy vehicles (%HV). Recommendations are based on geographic region, population, and time of day. All general default values for interrupted-flow facilities may be applied to the analysis of TWSC intersections in the absence of field data or projected conditions.

The following general default values may be applied to a TWSC intersection analysis:

- *PHF* = 0.92
- %HV = 3

Additional default values are sometimes required. For the analysis of shared or short major-street left-turn lanes, the following assumed default values may be applied for the saturation flow rates of the major-street through and right-turn movements:

- Major-street through movement, s_{i1} = 1,800 veh/h
- Major-street right-turn movement, s_{i2} = 1,500 veh/h

For analysis of pedestrians at TWSC intersections, the following default values may be applied:

- Average pedestrian walking speed, S_p = 3.5 ft/s
- Pedestrian start-up time and end clearance time, t_s = 3 s

As the number of default values used in any analysis increases, its accuracy becomes more approximate, and the result may be significantly different from the actual outcome, depending on local conditions.

ESTABLISH INTERSECTION BOUNDARIES

This methodology assumes that the TWSC intersection under investigation is isolated, with the exception of a TWSC intersection that is located within 0.25 mi of a signalized intersection (for the major-street approaches). When interaction effects are likely between the subject TWSC intersection and other intersections (e.g., queue spillback, demand starvation), the use of alternative tools may result in more accurate analysis. Analysis boundaries may also include different demand scenarios related to the time of day or to different development scenarios that produce various demand flow rates.

TYPES OF ANALYSIS

The methodology of this chapter can be used in three types of analysis: operational analysis, design analysis, and planning and preliminary engineering analysis.

Operational Analysis

The methodology is most easily applied in the operational analysis mode. In operational analysis, all traffic and geometric characteristics of the analysis segment must be specified, including analysis-hour demand volumes for each turning movement in vehicles per hour, %HV for each approach, *PHF* for all demand volumes, lane configurations, specific geometric conditions, and upstream signal information. The outputs of an operational analysis are estimates of capacity, control delay, and queue lengths. The steps of the methodology, described in this chapter's methodology section, are followed directly without modification.

Design Analysis

The operational analysis described earlier in this chapter can be used for design purposes by using a given set of traffic flow data and iteratively determining the number and configuration of lanes that would be required to produce a given LOS.

Planning and Preliminary Engineering Analysis

The operational analysis method described earlier in this chapter provides a detailed procedure for evaluating the performance of a TWSC intersection. To estimate LOS for a future time horizon, a planning analysis based on the operational method is used. The planning method uses all the geometric and traffic flow data required for an operational analysis, and the computations are identical. However, input variables for %HV and *PHF* are typically estimated (or defaults are used) when planning applications are performed.

Interpreting Results

Analysis of TWSC intersections is commonly performed to determine whether an existing intersection or driveway can remain as a TWSC intersection or whether additional treatments are necessary. These treatments, including geometric modifications and changes in traffic control, are discussed in other references, including the presentation of traffic signal warrants in the *Manual on Uniform Traffic Control Devices for Streets and Highways* (MUTCD; *16*). This section discusses two common situations analysts face: the analysis of shared versus separate lanes and the interpretation of LOS F.

Interpretation of the effects of shared lanes should take into account both delay associated with individual movements and delay associated with all vehicles on a given approach.

Some movements, most often left-turn movements, can sometimes have a poorer LOS when given a separate lane than when they share a lane with another movement (usually a through movement). This is not inconsistent in terms of the stated criteria. Left-turn movements will generally experience longer control delays than other movements because of the nature and priority of the movement. If left turns are placed in a shared lane, the control delay for vehicles in that lane may be less than the control delay for left turns in a separate lane. However, if delay for all vehicles on the approach or at the intersection is considered, providing separate lanes will result in lower total delay.

PERFORMANCE MEASURES

LOS F occurs when there are not enough gaps of suitable size to allow minor-street vehicles to enter or cross through traffic on the major street, resulting in long average control delays (greater than 50 s/veh). Depending on the demand on the approach, long queues on the minor approaches may result. The method, however, is based on a constant critical headway.

LOS F may also appear in the form of drivers on the minor street selecting smaller-than-usual gaps. In such cases, safety issues may occur, and some disruption to the major traffic stream may result. With lower demands, LOS F may not always result in long queues.

At TWSC intersections, the critical movement, often the minor-street left turn, may control the overall performance of the intersection. The lower threshold for LOS F is set at 50 s of delay per vehicle. In some cases, the delay equations will predict delays greater than 50 s for minor-street movements under very low-volume conditions on the minor street (fewer than 25 veh/h). On the basis of the first term of the delay equation, the LOS F threshold is reached with a movement capacity of approximately 85 veh/h or less, regardless of the minor-street movement volume.

This analysis procedure assumes random arrivals on the major street. For a typical major street with two lanes in each direction and an average traffic volume in the range of 15,000 to 20,000 veh/day (roughly equivalent to a peak hour flow rate of 1,500 to 2,000 veh/h), the delay equation will predict greater than 50 s of delay (LOS F) for many urban TWSC intersections that allow minor-street left-turn movements. LOS F will be predicted regardless of the volume of minor-street left-turning traffic. Even with an LOS F estimate, most low-volume minor-street approaches would not meet any of the MUTCD volume or delay warrants for signalization. As a result, analysts who use the HCM LOS thresholds to determine the design adequacy of TWSC intersections should do so with caution.

In evaluating the overall performance of TWSC intersections, it is important to consider measures of effectiveness in addition to delay, such as volume-to-capacity (v/c) ratios for individual movements, average queue lengths, and 95th percentile queue lengths. By focusing on a single measure of effectiveness for the worst movement only, such as delay for the minor-street left turn, users may make less effective traffic control decisions.

USE OF ALTERNATIVE TOOLS

Strengths of the HCM Procedure

This chapter offers a set of comprehensive procedures for analyzing the performance of an intersection under two-way STOP control. Simulation-based tools offer a more detailed treatment of the arrival and departure of vehicles and their interaction with the roadway and the control system, but for most purposes the HCM procedure produces an acceptable approximation.

The HCM procedure offers the advantage of a deterministic evaluation of a TWSC intersection, the results of which have been accepted by a broad consensus of international experts. The HCM procedure also considers advanced concepts such as two-stage gap acceptance and flared approaches based on empirical evidence of their effects.

Limitations of the HCM Procedures That Might Be Addressed by Alternative Tools

The identified limitations for this chapter are shown in Exhibit 19-18, along with the potential for improved treatment by alternative tools.

Exhibit 19-18
Limitations of the HCM Signalized Intersection Procedure

Limitation	Potential for Improved Treatment by Alternative Tools
Effects of upstream intersections	Simulation tools can include an unsignalized intersection explicitly within a signalized arterial or network.
YIELD-controlled intersection operations	Treated explicitly by some tools. Can be approximated by varying the gap-acceptance parameters.
Non-steady-state conditions for demand and capacity	Most alternative tools provide for multiperiod variation of demand and, in some cases, capacity.
Macroscopic treatment of pedestrians and bicycles	Some simulation tools offer a microscopic modeling approach that provides explicit treatment of pedestrians and bicycles.

The most common application of alternative tools for TWSC involves an unsignalized intersection within a signalized arterial street.

Most analyses for isolated unsignalized intersections are intended to determine whether TWSC is a viable control alternative. Analyses of this type are handled adequately by the procedures described in this chapter. The main application for alternative tools at TWSC intersections involves coordinated arterial systems. Most intersections (i.e., those that are between the signals) operate under TWSC. These intersections tend to be ignored in the analysis of the system because their effect on the system operation is minimal. Occasionally, it is necessary to examine a TWSC intersection as a part of the arterial system. While the procedures in this chapter provide a method for approximating the operation of a TWSC intersection with an upstream signal, the operation of such an intersection is arguably best handled by including it in a complete simulation of the full arterial system. For example, queue backup from a downstream signal that blocks entry from the cross street for a portion of the cycle is not treated explicitly by the procedures contained in this chapter.

Development of HCM-Compatible Performance Measures Using Alternative Tools

The performance measure that determines LOS for unsignalized intersections is *control delay,* defined as that portion of the delay that is due to the existence of the control device—in this case, a STOP sign. Most simulation tools do not produce explicit estimates of control delay.

The best way to determine control delay at a STOP sign from simulation is to perform simulation runs with and without the control device(s) in place. The segment delays reported with no control represent the delays due to geometrics and interaction between vehicles. The additional delay reported in the run with the control in place is, by definition, the control delay.

Chapter 7, Interpreting HCM and Alternative Tool Results, discusses performance measures from various tools in more detail, and Chapter 24, Concepts: Supplemental, provides recommendations on how individual vehicle trajectories should be interpreted to produce specific performance measures. Of

Delay and LOS should be estimated only by using alternative tools that conform to these definitions and computations of queue delay presented in this manual.

particular interest to TWSC operation is the definition of a “queued” state and the development of queue delay from that definition. For alternative tools that conform to the queue delay definitions and computations presented in this manual, the queue delay will provide the best estimate of control delay for TWSC intersections. Delay and LOS should not be estimated by using alternative tools that do not conform to these definitions and computations.

Conceptual Differences Between the HCM and Simulation Modeling That Preclude Direct Comparison of Results

Deterministic tools and simulation tools both model TWSC operations as a gap-acceptance process that follows the rules of the road to determine the right-of-way hierarchy. To this extent, they are dealing in the same conceptual framework. Deterministic tools such as the HCM base their estimates of capacity and delay on expected values computed from analytical formulations that have been mathematically derived. Simulation tools take a more microscopic view, treating each vehicle as an independent object that is subject to the rules of the road as well as interaction with other vehicles. Differences in the treatment of randomness also exist, as explained in the Chapter 18, Signalized Intersections, guidance.

When the opposing movement volumes are very high, there is minimal opportunity for the STOP-controlled movements to accept gaps and these movements often have little or no capacity. Simulation tends to produce slightly higher capacities under these conditions because of overriding logic that limits the amount of time any driver is willing to wait for a gap. The overriding logic is somewhat tool specific.

In general, the simulation results for a specific TWSC intersection problem should be close to the results obtained from the procedures in this chapter. Some differences may, however, be expected among all the analysis tools.

Adjustment of Simulation Parameters to the HCM Parameters

The critical headways and follow-up headways are common to both deterministic and simulation models. It is therefore desirable that similar values be used for these parameters.

Sample Calculations Illustrating Alternative Tool Applications

It was mentioned previously that the most common application for TWSC simulation involves unsignalized intersections within a signalized arterial system. An example of this situation is presented in Chapter 29, Urban Street Facilities: Supplemental. An additional example involving blockage of a cross-street approach with STOP control by a queue from a nearby diamond interchange is presented in Chapter 34, Interchange Ramp Terminals: Supplemental.

4. EXAMPLE PROBLEMS

Exhibit 19-19
List of Example Problems

Example Problem	Title	Type of Analysis
1	TWSC T-intersection	Operational analysis
2	TWSC pedestrian crossing	Operational analysis

EXAMPLE PROBLEM 1: TWSC T-INTERSECTION

The Facts

The following data are available to describe the traffic and geometric characteristics of this location:

- T-intersection,
- Major street with one lane in each direction,
- Minor street with one lane in each direction and STOP-controlled on the minor-street approach,
- Level grade on all approaches,
- Percent heavy vehicles on all approaches = 10%,
- No other unique geometric considerations or upstream signal considerations,
- No pedestrians,
- Length of analysis period = 0.25 h, and
- Volumes during the peak 15-min period and lane configurations as shown in Exhibit 19-20.

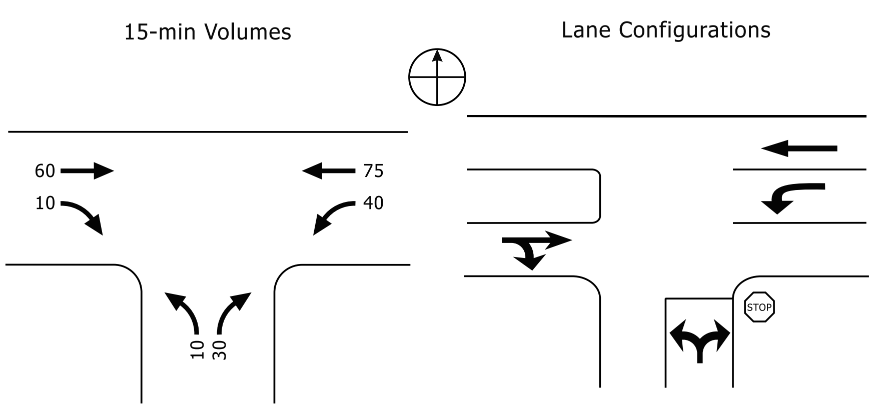


Exhibit 19-20
Example Problem 1 Movement Priorities, Lane Configurations, and Volumes

Comments

All input parameters are known, so no default values are needed or used.

Steps 1 and 2: Convert Movement Demand Volumes to Flow Rates and Label Movement Priorities

Because peak 15-min volumes have been provided, each volume is multiplied by 4 to determine a peak 15-min flow rate (in veh/h) for each movement. These values, along with the associated movement numbers, are shown in Exhibit 19-21.

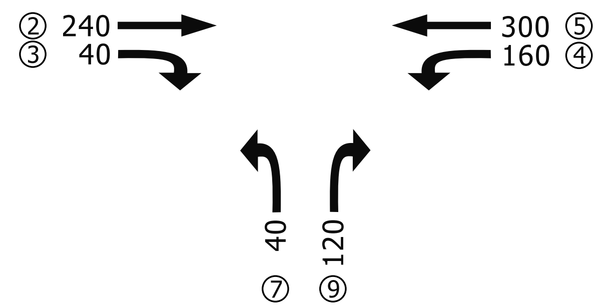


Exhibit 19-21
Example Problem 1: Calculation of Peak 15-min Flow Rates

Step 3: Compute Conflicting Flow Rates

The conflicting flow rates for each minor movement at the intersection are computed according to Equation 19-3, Equation 19-4, Equation 19-18, and Equation 19-24. The conflicting flow for the major-street left-turn $v_{c,4}$ is computed as follows:

$$v_{c,4} = v_2 + v_3 + v_{15}$$

$$v_{c,4} = 240 + 40 + 0 = 280 \text{ veh/h}$$

The conflicting flow for the minor-street right-turn movement $v_{c,9}$ is computed as follows:

$$v_{c,9} = v_2 + 0.5v_3 + v_{14} + v_{15}$$

$$v_{c,9} = 240 + 0.5(40) + 0 + 0 = 260 \text{ veh/h}$$

Finally, the conflicting flow for the minor-street left-turn movement $v_{c,7}$ is computed. Because two-stage gap acceptance is not present at this intersection, the conflicting flow rates shown in Stage I (Equation 19-18) and Stage II (Equation 19-24) are added together and considered as one conflicting flow rate. The conflicting flow for $v_{c,7}$ is computed as follows:

$$v_{c,7} = 2v_1 + v_2 + 0.5v_3 + v_{15} + 2v_4 + v_5 + 0.5v_6 + 0.5v_{12} + 0.5v_{11} + v_{13}$$

$$v_{c,7} = 2(0) + 240 + 0.5(40) + 0 + 2(160) + 300 + 0.5(0) + 0.5(0) + 0.5(0) + 0 = 880 \text{ veh/h}$$

Step 4: Determine Critical Headways and Follow-Up Headways

The critical headway for each minor movement is computed beginning with the base critical headway given in Exhibit 19-10. The base critical headway for each movement is then adjusted according to Equation 19-30. The critical headway for the major-street left-turn $t_{c,4}$ is computed as follows:

$$t_{c,4} = t_{c,base} + t_{c,HV}P_{HV} + t_{c,G}G - t_{3,LT}$$

$$t_{c,4} = 4.1 + 1.0(0.1) + 0(0) - 0 = 4.2 \text{ s}$$

Similarly, the critical headway for the minor-street right-turn $t_{c,9}$ is computed as follows:

$$t_{c,9} = 6.2 + 1.0(0.1) + 0.1(0) - 0 = 6.3 \text{ s}$$

Finally, the critical headway for the minor-street left-turn $t_{c,7}$ is computed as follows:

$$t_{c,7} = 7.1 + 1.0(0.1) + 0.2(0) - 0.7 = 6.5 \text{ s}$$

The follow-up headway for each minor movement is computed beginning with the base follow-up headway given in Exhibit 19-11. The base follow-up headway for each movement is then adjusted according to Equation 19-31. The follow-up headway for the major-street left-turn $t_{f,4}$ is computed as follows:

$$t_{f,4} = t_{f,base} + t_{f,HV} P_{HV}$$

$$t_{f,4} = 2.2 + 0.9(0.1) = 2.29 \text{ s}$$

Similarly, the follow-up headway for the minor-street right-turn $t_{f,9}$ is computed as follows:

$$t_{f,9} = 3.3 + 0.9(0.1) = 3.39 \text{ s}$$

Finally, the follow-up headway for the minor-street left-turn $t_{f,7}$ is computed as follows:

$$t_{f,7} = 3.5 + 0.9(0.1) = 3.59 \text{ s}$$

Step 5: Compute Potential Capacities

The computation of a potential capacity for each movement provides the analyst with a definition of capacity under the assumed base conditions. The potential capacity will be adjusted in later steps to estimate the movement capacity for each movement. The potential capacity for each movement is a function of the conflicting flow rate, critical headway, and follow-up headway computed in the previous steps. The potential capacity for the major-street left-turn $c_{p,4}$ is computed as follows:

$$c_{p,4} = v_{c,4} \frac{e^{-v_{c,4} t_{c,4} / 3{,}600}}{1 - e^{-v_{c,4} t_{f,4} / 3{,}600}} = 280 \frac{e^{-(280)(4.2)/3{,}600}}{1 - e^{-(280)(2.29)/3{,}600}} = 1{,}238 \text{ veh/h}$$

Similarly, the potential capacity for the minor-street right-turn movement $c_{p,9}$ is computed as follows:

$$c_{p,9} = 260 \frac{e^{-(260)(6.3)/3{,}600}}{1 - e^{-(260)(3.39)/3{,}600}} = 760 \text{ veh/h}$$

Finally, the potential capacity for the minor-street left-turn movement $c_{p,7}$ is computed as follows:

$$c_{p,7} = 880 \frac{e^{-(880)(6.5)/3{,}600}}{1 - e^{-(880)(3.59)/3{,}600}} = 308 \text{ veh/h}$$

There are no upstream signals, so the adjustments for upstream signals are ignored.

Step 6: Compute Movement Capacities for Rank 1 Movements

There are no pedestrians at the intersection; therefore, all pedestrian impedance factors are equal to 1.0 and this step can be ignored.

Step 7: Compute Movement Capacities for Rank 2 Movements

The movement capacity for the major-street left-turn movement (Rank 2) $c_{m,4}$ is computed as follows:

$$c_{m,4} = (c_{p,4}) = 1{,}238 \text{ veh/h}$$

Similarly, the movement capacity for the minor-street right-turn movement (Rank 2) $c_{m,9}$ is computed as follows:

$$c_{m,9} = (c_{p,9}) = 760 \text{ veh/h}$$

Step 8: Compute Movement Capacities for Rank 3 Movements

The computation of vehicle impedance effects accounts for the reduction in potential capacity due to the impacts of the congestion of a high-priority movement on lower-priority movements.

Major-street movements of Rank 1 and Rank 2 are assumed to be unimpeded by other vehicular movements. Minor-street movements of Rank 3 can be impeded by major-street left-turn movements due to a major-street left-turning vehicle waiting for an acceptable gap at the same time as vehicles of Rank 3. The magnitude of this impedance depends on the probability that major-street left-turning vehicles will be waiting for an acceptable gap at the same time as vehicles of Rank 3. In this example, only the minor-street left-turn movement is defined as a Rank 3 movement. Therefore, the probability of the major-street left-turn operating in a queue-free state, $p_{0,4}$, is computed as follows:

$$p_{0,4} = 1 - \frac{v_4}{c_{m,4}} = 1 - \frac{160}{1{,}238} = 0.871$$

The movement capacity for the minor-street left-turn movement (Rank 3), $c_{m,7}$, is found by first computing a capacity adjustment factor that accounts for the impeding effects of higher-ranked movements. The capacity adjustment factor for the minor-street left-turn movement f_7 is computed with Equation 19-46 as follows:

$$f_7 = \prod_j p_{0,j} = 0.871$$

The movement capacity for the minor-street left-turn movement (Rank 3) $c_{m,7}$ is computed as follows:

$$c_{m,7} = (c_{p,7}) f_7 = (308)0.871 = 268 \text{ veh/h}$$

Step 9: Compute Movement Capacities for Rank 4 Movements

There are no Rank 4 movements in this example problem, so this step does not apply.

Step 10: Compute Capacity Adjustment Factors

In this example, the minor-street approach is a single lane shared by right-turn and left-turn movements; therefore, the capacity of these two movements must be adjusted to compute an approach capacity based on shared-lane effects.

The shared-lane capacity for the northbound minor-street approach $c_{SH,NB}$ is computed as follows:

$$c_{SH,NB} = \frac{\sum_y v_y}{\sum_y \left(\frac{v_y}{c_{m,y}}\right)} = \frac{v_7 + v_9}{\frac{v_7}{c_{m,7}} + \frac{v_9}{c_{m,9}}} = \frac{40+120}{\frac{40}{268} + \frac{120}{760}} = 521 \text{ veh/h}$$

No other adjustments apply.

Step 11: Compute Control Delay

The control-delay computation for any movement includes initial deceleration delay, queue move-up time, stopped delay, and final acceleration delay.

Step 11a: Compute Control Delay to Rank 2 Through Rank 4 Movements

The control delay for the major-street left-turn movement (Rank 2) d_4 is computed as follows:

$$d_4 = \frac{3600}{c_{m,4}} + 900T\left[\frac{v_4}{c_{m,4}} - 1 + \sqrt{\left(\frac{v_4}{c_{m,4}} - 1\right)^2 + \frac{\left(\frac{3{,}600}{c_{m,4}}\right)\left(\frac{v_4}{c_{m,4}}\right)}{450T}}\right] + 5$$

$$d_4 = \frac{3{,}600}{1{,}238} + 900(.25)\left[\frac{160}{1{,}238} - 1 + \sqrt{\left(\frac{160}{1{,}238} - 1\right)^2 + \frac{\left(\frac{3{,}600}{1{,}238}\right)\left(\frac{160}{1{,}238}\right)}{450(0.25)}}\right] + 5 = 8.3 \text{ s}$$

On the basis of Exhibit 19-1, the westbound left-turn movement is assigned LOS A.

The control delay for the minor-street right-turn and left-turn movements is computed by using the same formula; however, one significant difference from the major-street left-turn computation of control delay is that these movements share the same lane. Therefore, the control delay is computed for the approach as a whole and the shared-lane volume and shared-lane capacity must be used as follows:

$$d_{SH,NB} = \frac{3{,}600}{521} + 900(0.25)\left[\frac{160}{521} - 1 + \sqrt{\left(\frac{160}{521} - 1\right)^2 + \frac{\left(\frac{3{,}600}{521}\right)\left(\frac{160}{521}\right)}{450(0.25)}}\right] + 5 = 14.9 \text{ s}$$

On the basis of Exhibit 19-1, the northbound approach is assigned LOS B.

Step 11b: Compute Control Delay to Rank 1 Movements

This step is not applicable as the westbound major-street through movement v_5 and westbound major-street left-turn movement v_4 have exclusive lanes at this intersection. It is assumed that the eastbound through movement v_2 and eastbound major-street right-turn movement v_3 do not incur any delay at this intersection.

Step 11c: Compute Approach and Intersection Control Delay

The control delays to all vehicles on the eastbound approach are assumed to be negligible as described in Step 11b. The control delay for the westbound approach $d_{A,WB}$ is computed as follows:

$$d_{A,WB} = \frac{d_r v_r + d_t v_t + d_l v_l}{v_r + v_t + v_l}$$

$$d_{A,WB} = \frac{0(0) + 0(300) + 8.3(160)}{0 + 300 + 160} = 2.9 \text{ s}$$

It is assumed that the westbound through movement incurs no control delay at this intersection. The control delay for the northbound approach was computed in Step 11a as $c_{SH,NB}$.

The intersection delay d_I is computed as follows:

$$d_I = \frac{d_{A,EB} v_{A,EB} + d_{A,WB} v_{A,WB} + d_{A,NB} v_{A,NB}}{v_{A,EB} + v_{A,WB} + v_{A,NB}}$$

$$d_I = \frac{0(280) + 2.9(460) + 14.9(160)}{280 + 460 + 160} = 4.1 \text{ s}$$

As noted previously, neither major-street approach LOS nor intersection LOS is defined.

Step 12: Compute 95th Percentile Queue Lengths

The 95th percentile queue length for the major-street westbound left-turn movement, $Q_{95,4}$, is computed as follows:

$$Q_{95,4} \approx 900T\left[\frac{v_4}{c_{m,4}} - 1 + \sqrt{\left(\frac{v_4}{c_{m,4}} - 1\right)^2 + \frac{\left(\frac{3600}{c_{m,4}}\right)\left(\frac{v_4}{c_{m,4}}\right)}{150T}}\right]\left(\frac{c_{m,4}}{3600}\right)$$

$$Q_{95,4} \approx 900(0.25)\left[\frac{160}{1238} - 1 + \sqrt{\left(\frac{160}{1238} - 1\right)^2 + \frac{\left(\frac{3600}{1238}\right)\left(\frac{160}{1238}\right)}{150(0.25)}}\right]\left(\frac{1238}{3600}\right) = 0.4 \text{ veh}$$

The result of 0.4 veh for the 95th percentile queue indicates that a queue of more than one vehicle will occur very infrequently for the major-street left-turn movement.

The 95th percentile queue length for the northbound approach is computed by using the same formula. Similar to the control-delay computation, the shared-lane volume and shared-lane capacity must be used as shown:

$$Q_{95,NB} \approx 900(0.25)\left[\frac{160}{521}-1+\sqrt{\left(\frac{160}{521}-1\right)^2+\frac{\left(\frac{3{,}600}{521}\right)\left(\frac{160}{521}\right)}{150(0.25)}}\right]\left(\frac{521}{3{,}600}\right)=1.3\text{ veh}$$

The result suggests that a queue of more than one vehicle will occur only occasionally for the northbound approach.

Discussion

Overall, the results indicate that the three-leg, TWSC intersection will operate well with small delays and little queuing for all minor movements.

EXAMPLE PROBLEM 2: TWSC PEDESTRIAN CROSSING

Calculate the pedestrian LOS of a pedestrian crossing of a major street at a TWSC intersection under the following circumstances:

- Scenario A: Unmarked crosswalk, no median refuge island;
- Scenario B: Unmarked crosswalk, median refuge island; and
- Scenario C: Marked crosswalk with high-visibility treatments, median refuge island.

The Facts

The following data are available to describe the traffic and geometric characteristics of this location:

- Four-lane major street;
- 1,700 peak hour vehicles, bidirectional;
- Crosswalk length without median = 46 ft;
- Crosswalk length with median = 40 ft;
- Observed pedestrian walking speed = 4 ft/s;
- Pedestrian start-up time = 3 s; and
- No pedestrian platooning.

Comments

In addition to the input data listed above, information is required on motor vehicle yield rates under the various scenarios. On the basis of an engineering study of similar intersections in the vicinity, it is determined that motor vehicle yield rates are 0% with unmarked crosswalks and 50% with high-visibility marked crosswalks.

Step 1: Identify Two-Stage Crossings

Scenario A does not have two-stage pedestrian crossings, as no median refuge is available. Analysis for Scenarios B and C should assume two-stage crossings. Thus, analysis for Scenarios B and C will combine two equidistant pedestrian crossings of 20 ft to determine the total delay.

Step 2: Determine Critical Headway

Because there is no pedestrian platooning, the critical headway is determined with Equation 19-69:

Scenario A: t_c = (46 ft/4 ft/s) + 3 s = 14.5 s

Scenario B: t_c = (20 ft/4 ft/s) + 3 s = 8 s

Scenario C: t_c = (20 ft/4 ft/s) + 3 s = 8 s

Step 3: Estimate Probability of a Delayed Crossing

Equation 19-73 and Equation 19-74 are used to calculate P_b, the probability of a blocked lane, and P_d, the probability of a blocked crossing, respectively. In the case of Scenario A, the crossing consists of four lanes. Scenarios B and C have only two lanes, given the two-stage crossing opportunity.

$$P_b = 1 - e^{\frac{-t_{c,G} v}{L}}$$

$$P_d = 1 - (1 - P_b)^L$$

where

P_b = probability of a blocked lane,

P_d = probability of a delayed crossing,

L = number of through lanes crossed,

$t_{c,G}$ = group critical headway (s), and

v = vehicular flow rate (veh/s).

For the single-stage crossing, v is (1,700 veh/h)/(3,600 s/h) = 0.47 veh/s.

For the two-stage crossing, without any information on directional flows, one-half the volume is used, and v is therefore (850 veh/h)/(3,600 s/h) = 0.24 veh/s.

Scenario A:

$$P_b = 1 - e^{\frac{-14.5 \times 0.47}{4}} = 0.82$$

$$P_d = 1 - (0.18)^4 = 0.999$$

Scenario B:

$$P_b = 1 - e^{\frac{-8 \times 0.24}{2}} = 0.61$$

$$P_d = 1 - (0.39)^2 = 0.85$$

Scenario C:

$$P_b = 1 - e^{\frac{-8\times0.24}{2}} = 0.61$$

$$P_d = 1 - (0.39)^2 = 0.85$$

Step 4: Calculate Average Delay to Wait for Adequate Gap

Average gap delay d_g and average gap delay when delay is nonzero d_{gd} are calculated by Equation 19-75 and Equation 19-76.

Scenario A:

$$d_g = \frac{1}{0.47} \times \left(e^{0.47\times14.5} - 0.47\times14.5 - 1\right) = 1{,}977 \text{ s}$$

$$d_{gd} = \frac{1{,}977}{0.999} = 1{,}979 \text{ s}$$

Scenario B:

$$d_g = \frac{1}{0.24}\left(e^{0.24\times8} - 0.24\times8 - 1\right) = 15.8 \text{ s}$$

$$d_{gd} = \frac{15.8}{0.85} = 18.6 \text{ s}$$

Scenario C:

$$d_g = \frac{1}{0.24}\left(e^{0.24\times8} - 0.24\times8 - 1\right) = 15.8 \text{ s}$$

$$d_{gd} = \frac{15.8}{0.85} = 18.6 \text{ s}$$

Step 5: Estimate Delay Reduction due to Yielding Vehicles

Under Scenarios A and B, the motorist yield rates are approximately 0%. Therefore, there is no reduction in delay due to yielding vehicles, and average delay is the same as that shown in Step 4. Under Scenario C, motorist yield rates are 50%. Because of the two-stage crossing, use Equation 19-80 to determine $P(Y_i)$:

$$P(Y_1) = [0.85 - 0]\left[\frac{(2\times0.61(1-0.61)0.50) + (0.61^2 0.50^2)}{0.85}\right] = 0.33$$

$$P(Y_2) = [0.85 - 0.33]\left[\frac{(2\times0.61(1-0.61)0.50) + (0.61^2 0.50^2)}{0.85}\right] = 0.20$$

The results of Equation 19-80 can be substituted into Equation 19-77 to determine average pedestrian delay.

$$d_p = \sum_{i=1}^{2} 8.5(i - 0.5)P(Y_i) + \left(0.85 - \sum_{i=1}^{2} P(Y_i)\right)18.6 = 9.8\,\mathrm{s}$$

Step 6: Calculate LOS

Average pedestrian delays and pedestrian LOS under each of the three scenarios are as follows:

Scenario A = 1,979 s = LOS F

Scenario B = 2 × 15.8 s = 31.6 s = LOS E

Scenario C = 2 × 9.8 s = 19.6 s = LOS C

5. REFERENCES

Some of these references are available in the Technical Reference Library in Volume 4.

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