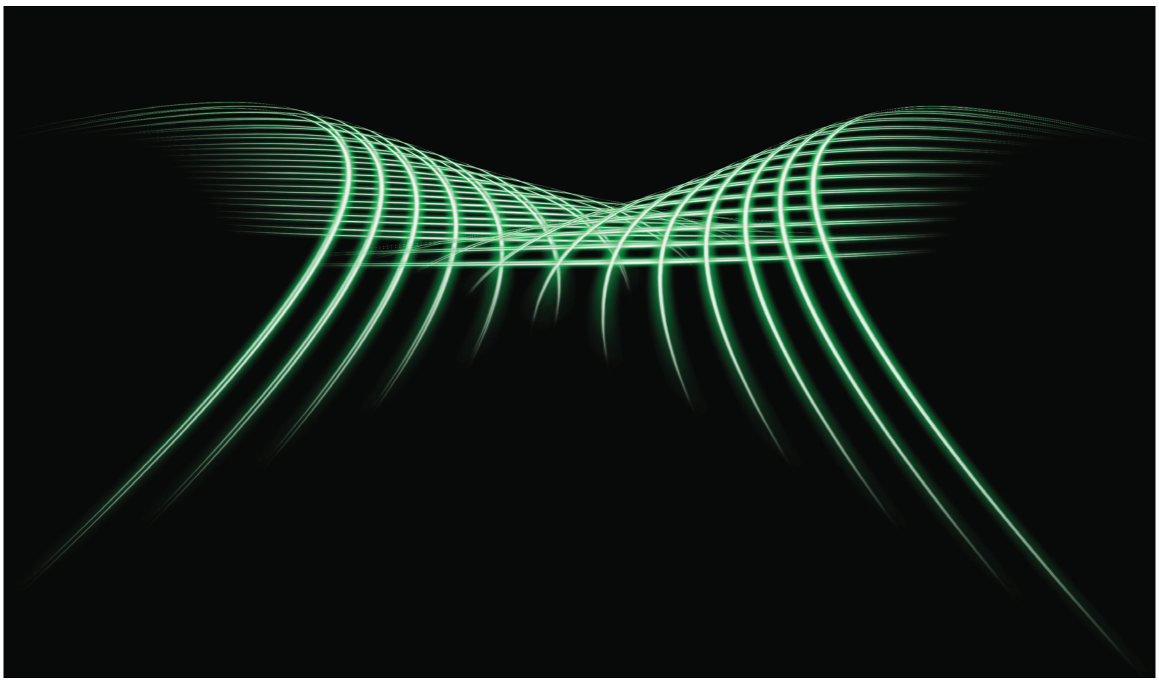
HCM2010

HIGHWAY CAPACITY MANUAL



CHAPTER 32

STOP-CONTROLLED INTERSECTIONS: SUPPLEMENTAL

TRB TRANSPORTATION RESEARCH BOARD
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HCM2010

HIGHWAY CAPACITY MANUAL

The HCM 2010 significantly enhances how engineers and planners assess the traffic and environmental effects of highway projects by

- Providing an integrated multimodal approach to the analysis and evaluation of urban streets from the points of view of automobile drivers, transit passengers, bicyclists, and pedestrians;
- Addressing the proper application of microsimulation analysis and the evaluation of the results;
- Examining active traffic management in relation to demand and capacity; and
- Exploring specific tools and generalized service volume tables to assist planners in quickly sizing future facilities.

The HCM 2010 consists of four volumes:

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Volume 4: Applications Guide (electronic only).

The four-volume format provides information at several levels of detail, to help users more easily apply and understand the concepts, methodologies, and potential applications.

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CHAPTER 32
STOP-CONTROLLED INTERSECTIONS: SUPPLEMENTAL

CONTENTS

LIST OF EXHIBITS

1. SUPPLEMENTAL MATERIAL ON TWSC POTENTIAL CAPACITY

The gap-acceptance model to estimate potential capacity (presented in Chapter 19, Equation 19-32) can be plotted for each of the non–Rank 1 movements by using values of critical headway and follow-up headway from Chapter 19 (Exhibit 19-10 and Exhibit 19-11). These graphs are presented in Exhibit 32-1, Exhibit 32-2, and Exhibit 32-3 for a major street with two lanes, four lanes, and six lanes, respectively. The potential capacity is expressed as vehicles per hour (veh/h). The exhibits indicate that the potential capacity is a function of the conflicting flow rate $v_{c,x}$, expressed as an hourly rate, as well as the type of minor-street movement.

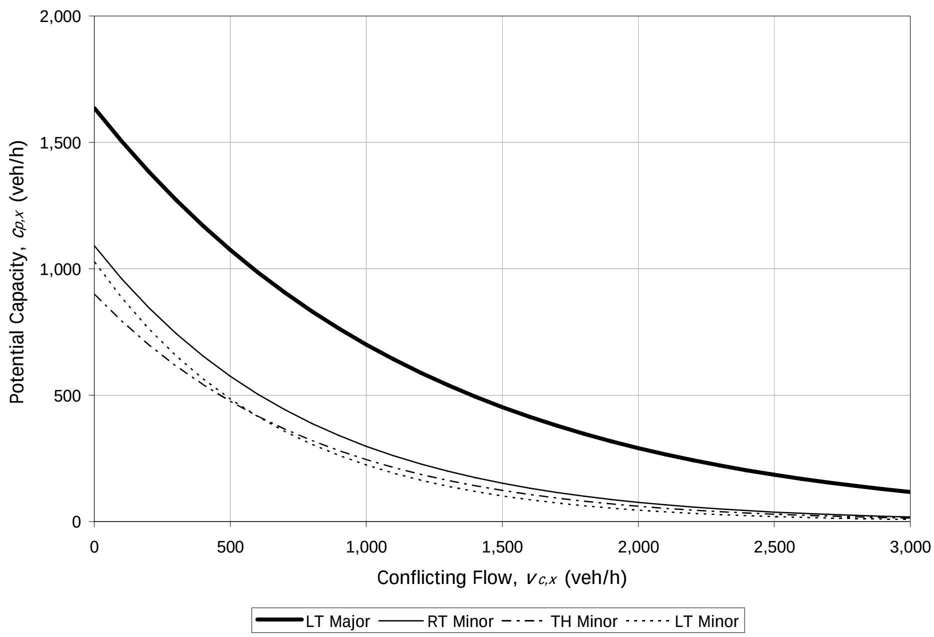


Exhibit 32-1
Potential Capacity, $c_{p,x}$, for Two-Lane Major Streets

Exhibit 32-2
Potential Capacity, $c_{p,x}$, for Four-Lane Major Streets

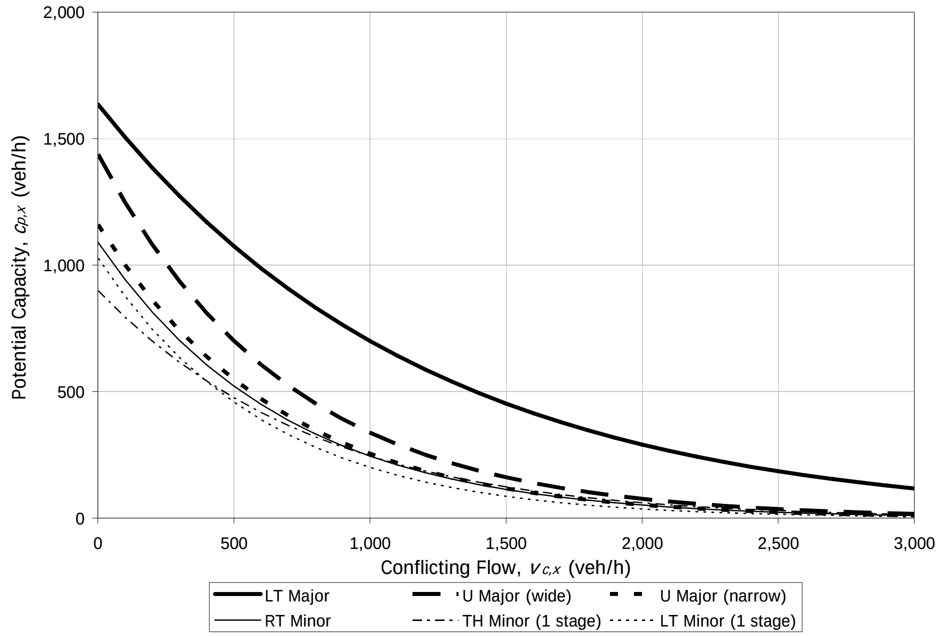
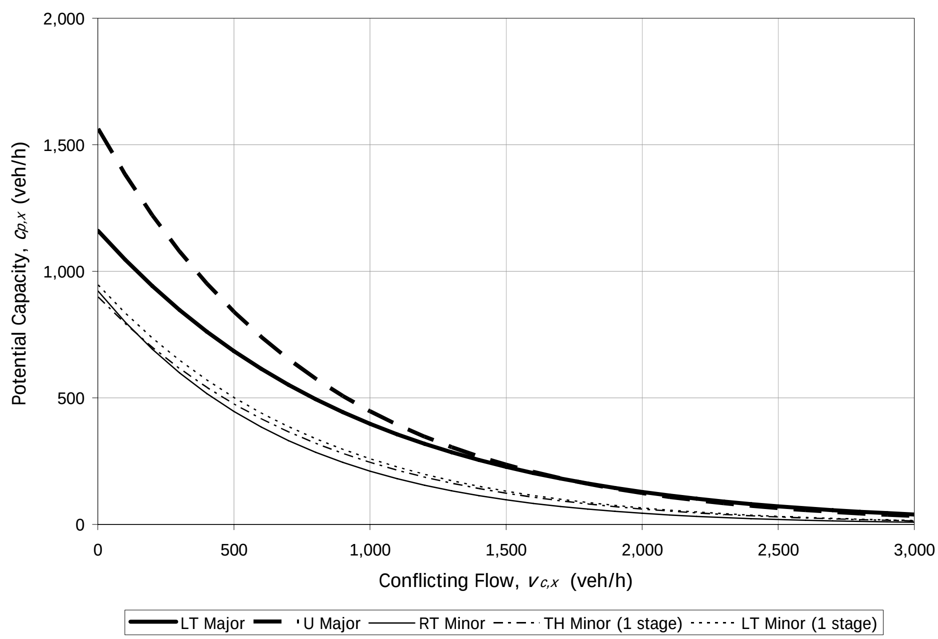


Exhibit 32-3
Potential Capacity, $c_{p,x}$, for Six-Lane Major Streets



2. TWSC MOVEMENT CAPACITY ACCOUNTING FOR PEDESTRIAN EFFECTS

The following text presents the methodological details of incorporating pedestrian effects on automobile capacity. These steps replace Steps 6 through 9 presented in Chapter 19.

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 occasionally occur, and they are accounted for by using adjustments provided later in this procedure.

For the purposes of this procedure, major-street movements of Rank 1 are assumed to be unimpeded by pedestrians at a TWSC intersection, even though research indicates some degree of Rank 1 vehicular yielding to pedestrians (see the pedestrian methodology in Chapter 19). This is a known limitation in the procedure.

STEP 7: RANK 2 MOVEMENT CAPACITY

Movements of Rank 2 (left 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 as well as conflicting pedestrian movements of Rank 1. The movement capacity of each Rank 2 movement is equal to its potential capacity, factored by any impedance due to pedestrians as indicated by Equation 32-3.

Step 7a: Pedestrian Impedance

Minor vehicular movements must yield to conflicting pedestrian movements at a TWSC intersection. A factor accounting for pedestrian blockage is computed by Equation 32-1 on the basis of pedestrian volume, pedestrian walking speed, and width of the lane the minor movement is negotiating into.

$$f_{pb} = \frac{(v_x)\left(\frac{w}{S_p}\right)}{3{,}600}$$

Equation 32-1

where

f_{pb} = pedestrian blockage factor or proportion of time that one lane on an approach is blocked during 1 h;

v_x = number of groups of pedestrians, where x is Movement 13, 14, 15, or 16;

w = width of the lane the minor movement is negotiating into (ft); and

S_p = pedestrian walking speed, assumed to be 3.5 ft/s.

The pedestrian impedance factor for pedestrian movement x, $p_{p,x}$, is computed by Equation 32-2.

Equation 32-2

$$p_{p,x} = 1 - f_{pb}$$

Exhibit 32-4 shows that Rank 2 movements v_1 and v_4 must yield to pedestrian movements v_{16} and v_{15}, respectively. Exhibit 32-4 also shows that Rank 2 movement v_9 must yield to pedestrian movements v_{15} and v_{14}, while Rank 2 movement v_{12} must yield to pedestrian movements v_{16} and v_{13}. Rank 2 U-turn movements v_{1U} and v_{4U} are assumed to not yield to pedestrians crossing the major street, consistent with the assumptions stated previously for Rank 1 vehicles.

Exhibit 32-4
Relative Pedestrian–Vehicle Hierarchy for Rank 2 Movements

Vehicular Movement (v_x)	Must Yield to Pedestrian Movement	Impedance Factor for Pedestrians ($p_{p,x}$)
v_1	v_{16}	$p_{p,16}$
v_{1U}	—	—
v_4	v_{15}	$p_{p,15}$
v_{4U}	—	—
v_9	v_{15}, v_{14}	$(p_{p,15})(p_{p,14})$
v_{12}	v_{16}, v_{13}	$(p_{p,16})(p_{p,13})$

Step 7b: Movement Capacity for Major Street Left-Turn Movements

Rank 2 major-street left-turn movements can be impeded only by conflicting pedestrians; therefore, the movement capacity for major-street left-turn movements is computed with Equation 32-3, where j denotes pedestrian movements of Rank 2 priority and i denotes movements of Rank 1 priority.

Equation 32-3

$$c_{m,j} = (c_{p,j})p_{p,i}$$

Step 7c: 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 impeded by two conflicting pedestrian movements. The capacity adjustment factors are denoted by f_9 and f_{12} for the minor-street right-turn Movements 9 and 12, respectively, and are given by Equation 32-4 and Equation 32-5, respectively.

Equation 32-4

$$f_9 = p_{p,15}p_{p,14}$$

Equation 32-5

$$f_{12} = p_{p,16}p_{p,13}$$

where

f_9, f_{12} = capacity adjustment factor for Rank 2 minor-street right-turn Movements 9 and 12, respectively; and

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

The movement capacity for minor-street right-turn movements is then computed with Equation 32-6:

Equation 32-6

$$c_{m,j} = (c_{p,j})f_j$$

where

$c_{m,j}$ = movement capacity for Movements 9 and 12,

$c_{p,j}$ = potential capacity for Movements 9 and 12 (from Step 5), and

f_j = capacity adjustment factor for Movements 9 and 12.

Step 7d: Movement Capacity for Major-Street U-Turn Movements

This step is the same as Step 7c in Chapter 19.

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

This step is the same as Step 7d in Chapter 19.

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 are normally available for use by Rank 3 movements, because some of them 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: Pedestrian Impedance

Exhibit 32-5 shows that Rank 3 movements v_8 and v_{11} must yield to pedestrian movements v_{15} and v_{16}.

Exhibit 32-5 Relative Pedestrian–Vehicle Hierarchy for Rank 3 Movements

Vehicular Movement (v_x)	Must Yield to Pedestrian Movement	Impedance Factor for Pedestrians ($p_{p,x}$)
v_8	v_{15}, v_{16}	$(p_{p,15})(p_{p,16})$
v_{11}	v_{15}, v_{16}	$(p_{p,15})(p_{p,16})$

The pedestrian impedance factor for Rank 3 movements is computed according to Equation 32-1 and Equation 32-2.

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

This step is the same as Step 8a in Chapter 19, except that the capacity adjustment factor, f_k, for all movements k and for all Rank 3 movements is given by Equation 32-7:

$$f_k = \prod_j (p_{0,j}) p_{p,x}$$

Equation 32-7

where

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

$p_{p,x}$ = probability of pedestrian movements of Rank 1 or Rank 2 priority,

k = Rank 3 movements, and

x = 13, 14, 15, 16 (pedestrian movements of both Rank 1 and Rank 2).

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

This step is the same as Step 8b in Chapter 19.

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 Pedestrian Impedance

Exhibit 32-6 shows that Rank 4 movement v_7 must yield to pedestrian movements v_{15} and v_{13}, and Rank 4 movement v_{10} must yield to pedestrian movements v_{16} and v_{14}.

Exhibit 32-6
Relative Pedestrian–Vehicle Hierarchy for Rank 4 Movements

Vehicular Movement (v_x)	Must Yield to Pedestrian Movement	Impedance Factor for Pedestrians ($p_{p,x}$)
v_7	v_{15}, v_{13}	$(p_{p,15})(p_{p,13})$
v_{10}	v_{16}, v_{14}	$(p_{p,16})(p_{p,14})$

The pedestrian impedance factor for Rank 4 movements is computed according to Equation 32-1 and Equation 32-2.

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

This step is the same as Step 9a in Chapter 19, except that the capacity adjustment factor for the Rank 4 minor-street left-turn movement can be computed by Equation 32-8:

Equation 32-8

$$f_l = (p')(p_{0,j})(p_{p,x})$$

where

l = minor-street left-turn movement of Rank 4,

j = conflicting Rank 2 minor-street right-turn movement, and

$p_{p,x}$ = the values shown in Equation 32-2 (the variable $p_{0,j}$ should be included only if movement j is identified as a conflicting movement).

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

This step is the same as Step 9b in Chapter 19.

3. TWSC SUPPLEMENTAL EXAMPLE PROBLEMS

Example Problems 1 and 2 appear in Chapter 19.

This part of the chapter provides additional example problems for use of the TWSC methodology. Exhibit 32-7 provides an overview of these problems. The examples focus on the operational analysis level. The planning and preliminary engineering analysis level is identical to the operations analysis level in terms of the calculations, except that default values are used where available.

Exhibit 32-7
TWSC Example Problems

Problem Number	Description	Analysis Level
3	TWSC intersection with flared approaches and median storage	Operational
4	TWSC intersection within a signalized urban street segment	Operational
5	TWSC intersection on a six-lane street with U-turns and pedestrians	Operational

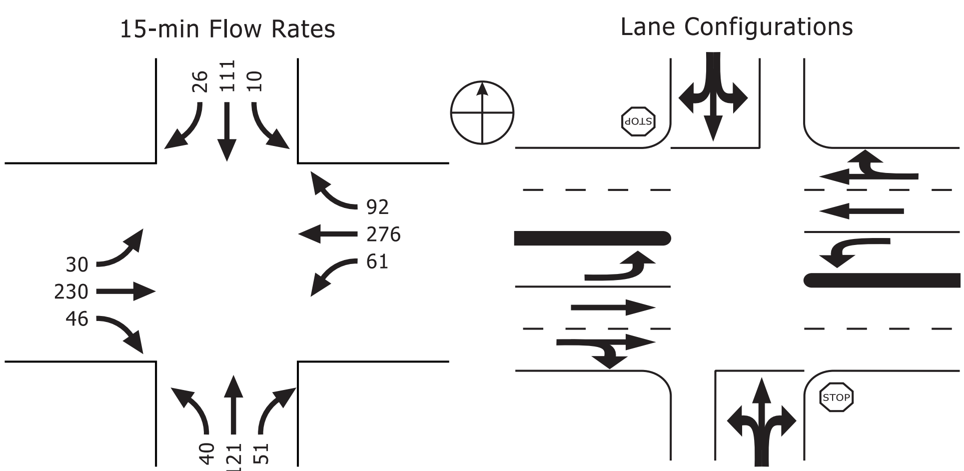
TWSC EXAMPLE PROBLEM 3: FLARED APPROACHES AND MEDIAN STORAGE

The Facts

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

- Major street with two lanes in each direction, minor street with one lane on each approach that flares with storage for one vehicle in the flare area, and median storage for two vehicles at one time available for minor-street through and left-turn movements;
- Level grade on all approaches;
- Percent heavy vehicles on all approaches = 10%;
- Peak hour factor on all approaches = 0.92;
- Length of analysis period = 0.25 h; and
- Volumes and lane configurations as shown in Exhibit 32-8.

Exhibit 32-8
TWSC Example Problem 3: Volumes and Lane Configurations



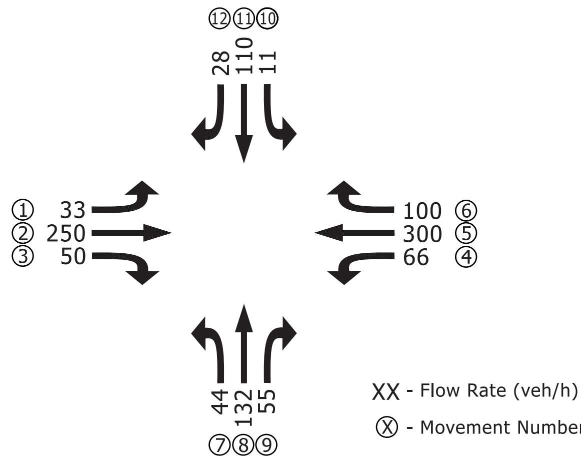
Comments

All relevant 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 hourly volumes and a peak hour factor have been provided, each hourly volume is divided by the peak hour factor to determine a peak 15-min flow rate (in veh/h) for each movement. They are shown in Exhibit 32-9.

Exhibit 32-9
TWSC Example Problem 3: Calculation of Peak 15-min Flow Rates, Movement Priorities



Step 3: Compute Conflicting Flow Rates

The conflicting flow rates for each minor movement at the intersection are computed according to the equations in Chapter 19. The conflicting flow for the eastbound major-street left-turn movement $v_{c,1}$ is computed according to Equation 19-2 as follows:

$$v_{c,1} = v_5 + v_6 + v_{16} = 300 + 100 + 0 = 400$$

Similarly, the conflicting flow for the westbound major-street left-turn movement $v_{c,4}$ is computed according to Equation 19-3 as follows:

$$v_{c,4} = v_2 + v_3 + v_{15} = 250 + 50 + 0 = 300$$

The conflicting flows for the northbound minor-street right-turn movement $v_{c,9}$ and southbound minor-street right-turn movement $v_{c,12}$ are computed using Equation 19-6 and Equation 19-7, respectively, as follows (with no U-turns and pedestrians, which allows the last three terms to be assigned zero):

$$v_{c,9} = 0.5v_2 + 0.5v_3 + v_{4U} + v_{14} + v_{15}$$

$$= 0.5(250) + 0.5(50) + 0 + 0 + 0 = 150$$

$$v_{c,12} = 0.5v_5 + 0.5v_6 + v_{1U} + v_{13} + v_{16}$$

$$= 0.5(300) + 0.5(100) + 0 + 0 + 0 = 200$$

Next, the conflicting flow for the northbound minor-street through movement $v_{c,8}$ is computed. Because two-stage gap acceptance is available for this movement, the conflicting flow rates shown in Stage I and Stage II must be computed separately. The conflicting flow for Stage I $v_{c,I,8}$ is computed as follows:

$$v_{c,I,8} = 2(v_1 + v_{1U}) + v_2 + 0.5v_3 + v_{15}$$
$$= 2(33+0) + 250 + 0.5(50) + 0 = 341$$

The conflicting flow for Stage II $v_{c,II,8}$ is computed as follows:

$$v_{c,II,8} = 2(v_4 + v_{4U}) + v_5 + v_6 + v_{16}$$
$$= 2(66+0) + 300 + 100 + 0 = 532$$

The total conflicting flow for the northbound through movement $v_{c,8}$ is computed as follows:

$$v_{c,8} = v_{c,I,8} + v_{c,II,8} = 341 + 532 = 873$$

Similarly, the conflicting flow for the southbound minor-street through movement $v_{c,11}$ is computed in two stages as follows:

$$v_{c,I,11} = 2(66+0) + 300 + 0.5(100) + 0 = 482$$
$$v_{c,II,11} = 2(33+0) + 250 + 50 + 0 = 366$$
$$v_{c,11} = 482 + 366 = 848$$

Next, the conflicting flow for the northbound minor-street left-turn movement $v_{c,7}$ is computed. Because two-stage gap acceptance is available for this movement, the conflicting flow rates shown in Stage I and Stage II must be computed separately. The conflicting flow for Stage I $v_{c,I,7}$ is computed with Equation 19-20 as follows:

$$v_{c,I,7} = 2(v_1 + v_{1U}) + v_2 + 0.5v_3 + v_{15}$$
$$v_{c,I,7} = 2(33+0) + 250 + 0.5(50) + 0 = 341$$

The conflicting flow for Stage II $v_{c,II,7}$ is computed with Equation 19-26 as follows:

$$v_{c,II,7} = 2(v_4 + v_{4U}) + 0.5v_5 + 0.5v_{11} + v_{13}$$
$$= 2(66+0) + 0.5(300) + 0.5(110) + 0 = 337$$

The total conflicting flow for the northbound left-turn movement $v_{c,7}$ is computed as follows:

$$v_{c,7} = v_{c,I,7} + v_{c,II,7}$$
$$v_{c,7} = 341 + 337 = 678$$

Similarly, the conflicting flow for the southbound minor-street left-turn movement $v_{c,10}$ is computed in two stages as follows:

$$v_{c,I,10} = 2(66+0) + 300 + 0.5(100) + 0 = 482$$
$$v_{c,II,10} = 2(33+0) + 0.5(250) + 0.5(132) + 0 = 257$$
$$v_{c,10} = 482 + 257 = 739$$

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 headways for the eastbound and westbound major-street left turns $t_{c,1}$ and $t_{c,4}$ (in this case $t_{c,1} = t_{c,4}$), are computed as follows:

$$t_{c,1} = t_{c,4} = t_{c,base} + t_{c,HV} P_{HV} + t_{c,G} G - t_{3,LT}$$

$$t_{c,1} = t_{c,4} = 4.1 + 2.0(0.1) + 0(0) - 0 = 4.3$$

Next, the critical headways for the northbound and southbound minor-street right-turn movements $t_{c,9}$ and $t_{c,12}$ (in this case $t_{c,9} = t_{c,12}$) are computed as follows:

$$t_{c,9} = t_{c,12} = 6.9 + 2.0(0.1) + 0.1(0) - 0 = 7.1$$

Next, the critical headways for the northbound and southbound minor-street through movements $t_{c,8}$ and $t_{c,11}$ (in this case, $t_{c,8} = t_{c,11}$) are computed. Because two-stage gap acceptance is available for these movements, the critical headways for Stage I and Stage II must be computed, along with the critical headways for these movements assuming single-stage gap acceptance. The critical headways for Stage I and Stage II $t_{c,I,8}$, $t_{c,II,8}$ and $t_{c,I,11}$, $t_{c,II,11}$ (in this case, $t_{c,I,8} = t_{c,II,8} = t_{c,I,11} = t_{c,II,11}$) are computed as follows:

$$t_{c,I,8} = t_{c,II,8} = t_{c,I,11} = t_{c,II,11} = 5.5 + 2.0(0.1) + 0.2(0) - 0 = 5.7$$

The critical headways for $t_{c,8}$ and $t_{c,11}$ (in this case, $t_{c,8} = t_{c,11}$), assuming single-stage gap acceptance, are computed as follows:

$$t_{c,8} = t_{c,11} = 6.5 + 2.0(0.1) + 0.2(0) - 0 = 6.7$$

Finally, the critical headways for the northbound and southbound minor-street left-turn movements $t_{c,7}$ and $t_{c,10}$ (in this case, $t_{c,7} = t_{c,10}$) are computed. Because two-stage gap acceptance is available for these movements, the critical headways for Stage I and Stage II must be computed, along with the critical headways for these movements assuming single-stage gap acceptance. The critical headways for Stage I and Stage II $t_{c,I,7}$, $t_{c,II,7}$ and $t_{c,I,10}$, $t_{c,II,10}$ (in this case, $t_{c,I,7} = t_{c,II,7} = t_{c,I,10} = t_{c,II,10}$) are computed as follows:

$$t_{c,I,7} = t_{c,II,7} = t_{c,I,10} = t_{c,II,10} = 6.5 + 2.0(0.1) + 0.2(0) - 0 = 6.7$$

The critical headways for $t_{c,7}$ and $t_{c,10}$ (in this case $t_{c,7} = t_{c,10}$), assuming single-stage gap acceptance, are computed as follows:

$$t_{c,7} = t_{c,10} = 7.5 + 2.0(0.1) + 0.2(0) - 0 = 7.7$$

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 headways for the northbound and southbound major-street left-turn movements $t_{f,1}$ and $t_{f,4}$ (in this case, $t_{f,1} = t_{f,4}$) are computed as follows:

$$t_{f,1} = t_{f,4} = t_{f,base} + t_{f,HV} P_{HV}$$

$$t_{f,1} = t_{f,4} = 2.2 + 1.0(0.1) = 2.3$$

Next, the follow-up headways for the northbound and southbound minor-street right-turn movements $t_{f,9}$ and $t_{f,12}$ (in this case, $t_{f,9} = t_{f,12}$) are computed as follows:

$$t_{f,9} = t_{f,12} = 3.3 + 1.0(0.1) = 3.4$$

Next, the follow-up headways for the northbound and southbound minor-street through movements $t_{f,8}$ and $t_{f,11}$ (in this case, $t_{f,8} = t_{f,11}$) are computed as follows:

$$t_{f,8} = t_{f,11} = 4.0 + 1.0(0.1) = 4.1$$

Follow-up headways for the minor-street through and left-turn movements are computed for the movement as a whole. Follow-up headways are not broken up by stage, since they apply only to vehicles as they exit the approach and enter the intersection.

Finally, the follow-up headways for the northbound and southbound minor-street left-turn movements $t_{f,7}$ and $t_{f,10}$ (in this case, $t_{f,7} = t_{f,10}$), are computed as follows:

$$t_{f,7} = t_{f,10} = 3.5 + 1.0(0.1) = 3.6$$

Step 5: Compute Potential Capacities

Because no upstream signals are present, the procedure in Step 5a is followed.

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 northbound major-street left-turn $c_{p,1}$ is computed as follows:

$$c_{p,1} = v_{c,1} \frac{e^{-v_{c,1} t_{c,1} / 3,600}}{1 - e^{-v_{c,1} t_{f,1} / 3,600}} = 400 \frac{e^{-(400)(4.3)/3,600}}{1 - e^{-(400)(2.3)/3,600}} = 1,100$$

Similarly, the potential capacities for Movements 4, 9, and 12, $c_{p,4}$, $c_{p,9}$, and $c_{p,12}$, are computed as follows:

$$c_{p,4} = 300 \frac{e^{-(300)(4.3)/3,600}}{1 - e^{-(300)(2.3)/3,600}} = 1,202$$

$$c_{p,9} = 150 \frac{e^{-(150)(7.1)/3,600}}{1 - e^{-(150)(3.4)/3,600}} = 845$$

$$c_{p,12} = 200 \frac{e^{-(200)(7.1)/3,600}}{1 - e^{-(200)(3.4)/3,600}} = 783$$

Because the two-stage gap-acceptance adjustment procedure will be implemented for estimating the capacity of the minor-street movements, three potential capacity values must be computed for each of Movements 7, 8, 10, and 11. First, the potential capacity must be computed for Stage I, $c_{p,I,8}$, $c_{p,I,11}$, $c_{p,I,7}$, and $c_{p,I,10}$, for each movement as follows:

$$c_{p,I,8} = 341 \frac{e^{-(341)(5.7)/3,600}}{1 - e^{-(341)(4.1)/3,600}} = 618$$

$$c_{p,I,11} = 482 \frac{e^{-(482)(5.7)/3,600}}{1 - e^{-(482)(4.1)/3,600}} = 532$$

$$c_{p,I,7} = 341 \frac{e^{-(341)(6.7)/3,600}}{1 - e^{-(341)(3.6)/3,600}} = 626$$

$$c_{p,I,10} = 482 \frac{e^{-(482)(6.7)/3,600}}{1 - e^{-(482)(3.6)/3,600}} = 514$$

Next, the potential capacity must be computed for Stage II for each movement $c_{p,II,8}$, $c_{p,II,11}$, $c_{p,II,7}$, and $c_{p,II,10}$ as follows:

$$c_{p,II,8} = 532 \frac{e^{-(532)(5.7)/3,600}}{1 - e^{-(532)(4.1)/3,600}} = 504$$

$$c_{p,II,11} = 366 \frac{e^{-(366)(5.7)/3,600}}{1 - e^{-(366)(4.1)/3,600}} = 601$$

$$c_{p,II,7} = 337 \frac{e^{-(337)(6.7)/3,600}}{1 - e^{-(337)(3.6)/3,600}} = 629$$

$$c_{p,II,10} = 257 \frac{e^{-(257)(6.7)/3,600}}{1 - e^{-(257)(3.6)/3,600}} = 703$$

Finally, the potential capacity must be computed assuming single-stage gap acceptance for each movement, $c_{p,8}$, $c_{p,11}$, $c_{p,7}$, and $c_{p,10}$, as follows:

$$c_{p,8} = 873 \frac{e^{-(873)(6.7)/3,600}}{1 - e^{-(873)(4.1)/3,600}} = 273$$

$$c_{p,11} = 848 \frac{e^{-(848)(6.7)/3,600}}{1 - e^{-(848)(4.1)/3,600}} = 283$$

$$c_{p,7} = 678 \frac{e^{-(678)(7.7)/3,600}}{1 - e^{-(678)(3.6)/3,600}} = 323$$

$$c_{p,10} = 739 \frac{e^{-(739)(7.7)/3,600}}{1 - e^{-(739)(3.6)/3,600}} = 291$$

Steps 6–9: Compute Movement Capacities

Because no pedestrians are present, the procedures given in Chapter 19 are followed.

Steps 6: Rank 1 Movement Capacity

There is no computation for this step.

Step 7: Rank 2 Movement Capacity

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

The movement capacity of each Rank 2 major-street left-turn movement is equal to its potential capacity:

$$c_{m,1} = c_{p,1} = 1{,}100$$

$$c_{m,4} = c_{p,4} = 1{,}202$$

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

The movement capacity of each minor-street right-turn movement is equal to its potential capacity:

$$c_{m,9} = c_{p,9} = 845$$

$$c_{m,12} = c_{p,12} = 783$$

Step 7c: Movement Capacity for Major-Street U-Turn Movement

No U-turns are present, so this step is skipped.

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

Separate major-street left-turn lanes are provided, so this step is skipped.

Step 8: Rank 3 Movement Capacity

The movement capacity of each Rank 3 movement is equal to its potential capacity, factored by any impedance due to conflicting pedestrian or vehicular movements.

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

As there are no pedestrians assumed at this intersection, the Rank 3 movements will be impeded only by other vehicular movements. Specifically, the Rank 3 movements will be impeded by major-street left-turning traffic, and as a first step in determining the impact of this impedance, the probability that these movements will operate in a queue-free state must be computed according to Equation 19-42:

$$p_{0,1} = 1 - \frac{v_1}{c_{m,1}} = 1 - \frac{33}{1{,}100} = 0.970$$

$$p_{0,4} = 1 - \frac{v_4}{c_{m,4}} = 1 - \frac{66}{1{,}202} = 0.945$$

Next, by using the probabilities computed above, capacity adjustment factors f_8 and f_{11} can be computed according to Equation 19-46:

$$f_8 = f_{11} = p_{0,1} p_{0,4} = (0.970)(0.945) = 0.917$$

Finally, under the single-stage gap-acceptance assumption, the movement capacities $c_{m,8}$ and $c_{m,11}$ can be computed according to Equation 19-47:

$$c_{m,8} = (c_{p,8}) f_8 = (273)(0.917) = 250$$

$$c_{m,11} = (c_{p,11}) f_{11} = (283)(0.917) = 260$$

Movements 8 and 11 will operate under two-stage gap acceptance. Therefore, the capacity adjustment procedure for estimating the capacity of Stage I and Stage II of these movements must be completed.

To begin the process of estimating Stage I and Stage II movement capacities, the probability of queue-free states on conflicting Rank 2 movements calculated above are entered into Equation 19-46 as before, but this time capacity adjustment factors are estimated for each individual stage as follows:

$$f_{I,8} = p_{0,1} = 0.970$$

$$f_{I,11} = p_{0,4} = 0.945$$

$$f_{II,8} = p_{0,4} = 0.945$$

$$f_{II,11} = p_{0,1} = 0.970$$

The Stage I movement capacities are then computed as follows:

$$c_{m,I,8} = (c_{p,I,8}) f_{I,8} = (618)(0.970) = 599$$

$$c_{m,I,11} = (c_{p,I,11}) f_{I,11} = (532)(0.945) = 503$$

The Stage II movement capacities are then computed as follows:

$$c_{m,II,8} = (c_{p,II,8}) f_{II,8} = (504)(0.945) = 476$$

$$c_{m,II,11} = (c_{p,II,11}) f_{II,11} = (601)(0.970) = 583$$

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

The two-stage gap-acceptance procedure will result in a total capacity estimate for Movements 8 and 11. To begin the procedure, an adjustment factor a must be computed for each movement by using Equation 19-48, under the assumption that there is storage for two vehicles in the median refuge area; thus, $n_m = 2$:

$$a_8 = a_{11} = 1 - 0.32e^{-1.3\sqrt{n_m}} = 1 - 0.32e^{-1.3\sqrt{2}} = 0.949$$

Next, an intermediate variable, y, must be computed for each movement by using Equation 19-49:

$$y_8 = \frac{c_{m,I,8} - c_{m,8}}{c_{m,II,8} - v_1 - c_{m,8}} = \frac{599 - 250}{476 - 33 - 250} = 1.808$$

$$y_{11} = \frac{c_{m,I,11} - c_{m,11}}{c_{m,II,11} - v_4 - c_{m,11}} = \frac{503 - 260}{583 - 66 - 260} = 0.946$$

Finally, the total capacity for each movement $c_{T,8}$ and $c_{T,11}$ is computed according to Equation 19-50, since $y \neq 1$:

$$c_{m,T,8} = \frac{a_8}{y_8^{\,n_m+1} - 1}\left[y_8\left(y_8^{\,n_m} - 1\right)\left(c_{m,II,8} - v_1\right) + \left(y_8 - 1\right)c_{m,8}\right]$$

$$= \frac{0.949}{1.808^{2+1} - 1}\left[(1.808)\left(1.808^2 - 1\right)(476 - 33) + (1.808 - 1)(250)\right] = 390$$

$$c_{m,T,11} = \frac{a_{11}}{y_{11}^{\;n_m+1} - 1}\left[y_{11}\left(y_{11}^{\;n_m} - 1\right)\left(c_{m,II,11} - v_4\right) + \left(y_{11} - 1\right)c_{m,11}\right]$$

$$= \frac{0.949}{0.946^{2+1} - 1}\left[(0.946)\left(0.946^2 - 1\right)(583 - 66) + (0.946 - 1)(260)\right] = 405$$

Step 9: Rank 4 Movement Capacity

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

The vehicle impedance effects for Rank 4 movements will first be estimated by assuming single-stage gap acceptance. Rank 4 movements are impeded by all of the same movements impeding Rank 2 and Rank 3 movements with the addition of impedances due to the minor-street crossing movements and minor-street right-turn movements. The probability that these movements will operate in a queue-free state must be incorporated into the procedure.

The probability that the minor-street right-turn movement will operate in a queue-free state, $p_{0,9}$ and $p_{0,12}$, can be computed as follows:

$$p_{0,9} = 1 - \frac{v_9}{c_{m,9}} = 1 - \frac{55}{845} = 0.935$$

$$p_{0,12} = 1 - \frac{v_{12}}{c_{m,12}} = 1 - \frac{28}{783} = 0.964$$

To compute p', the probability that both the major-street left-turn movements and the minor-street crossing movements will operate in a queue-free state simultaneously, the analyst must first compute $p_{0,k}$, which is done in the same manner as the computation of $p_{0,j}$, except that k represents Rank 3 movements. Therefore, the values for $p_{0,k}$, are computed as follows:

$$p_{0,8} = 1 - \frac{v_8}{c_{m,T,8}} = 1 - \frac{132}{390} = 0.662$$

$$p_{0,11} = 1 - \frac{v_{11}}{c_{m,T,11}} = 1 - \frac{110}{405} = 0.728$$

Next, the analyst must compute p'', which, under the single-stage gap-acceptance assumption, is simply the product of f_j and $p_{0,k}$. The value for $f_8 = f_{11} =$ 0.917 is as computed above. The value for $p_{0,11}$ is computed by using the total capacity for Movement 11 calculated in the previous step:

$$p_7'' = (p_{0,11})(f_{11}) = (0.728)(0.917) = 0.668$$

$$p_{10}'' = (p_{0,8})(f_8) = (0.662)(0.917) = 0.607$$

With the values for p'', the probability of a simultaneous queue-free state for each movement can be computed by using Equation 19-52 as follows:

$$p_7' = 0.65p_7'' - \frac{p_7''}{p_7''+3} + 0.6\sqrt{p_7''} = 0.65(0.668) - \frac{0.668}{0.668+3} + 0.6\sqrt{0.668} = 0.742$$

$$p_{10}' = 0.65(0.607) - \frac{0.607}{0.607+3} + 0.6\sqrt{0.607} = 0.694$$

Next, with the probabilities computed above, capacity adjustment factors f_7 and f_{10} can be computed according to Equation 19-53:

$$f_7 = (p_7')(p_{0,12}) = (0.742)(0.964) = 0.715$$

$$f_{10} = (p_{10}')(p_{0,9}) = (0.694)(0.935) = 0.649$$

Finally, under the single-stage gap-acceptance assumption, the movement capacities $c_{m,7}$ and $c_{m,10}$ can be computed according to Equation 19-54:

$$c_{m,7} = (c_{p,7})f_7 = (323)(0.715) = 231$$

$$c_{m,10} = (c_{p,10})f_{10} = (291)(0.649) = 189$$

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

Similar to the minor-street crossing movements at this intersection, Movements 7 and 10 will also operate under two-stage gap acceptance. Therefore, the capacity adjustment procedure for estimating the capacity of Stage I and Stage II of these movements must be completed.

Under the assumption of two-stage gap acceptance with a median refuge area, the minor-street left-turn movements operate as Rank 3 movements in each individual stage of completing the left-turn maneuver. Therefore, to begin the process of estimating two-stage movement capacities, the probabilities of queue-free states on conflicting Rank 2 movements for Stage I of the minor-street left-turn movement are entered into Equation 19-46, and capacity adjustment factors for Stage I are computed as follows:

$$f_{I,7} = p_{0,1} = 0.970$$

$$f_{I,10} = p_{0,4} = 0.945$$

The Stage I movement capacities can then be computed as follows:

$$c_{m,I,7} = (c_{p,I,7})f_{I,7} = (626)(0.970) = 607$$

$$c_{m,I,10} = (c_{p,I,10})f_{I,10} = (514)(0.945) = 486$$

Next, the probabilities of queue-free states on conflicting Rank 2 movements for Stage II of the minor-street left-turn movement are entered into Equation 19-46. However, before estimating these probabilities, the probability of a queue-free state for the first stage of the minor-street crossing movement must be estimated as it impedes Stage II of the minor-street left-turn movement. These probabilities are estimated with Equation 19-42:

$$p_{0,I,8} = 1 - \frac{v_8}{c_{m,I,8}} = 1 - \frac{132}{599} = 0.780$$

$$p_{0,I,11} = 1 - \frac{v_{11}}{c_{m,I,11}} = 1 - \frac{110}{503} = 0.781$$

The capacity adjustment factors for Stage II are then computed as follows:

$$f_{II,7} = (p_{0,4})(p_{0,12})(p_{0,I,11}) = (0.945)(0.964)(0.781) = 0.711$$

$$f_{II,10} = (p_{0,1})(p_{0,9})(p_{0,I,8}) = (0.970)(0.935)(0.780) = 0.707$$

Finally, the movement capacities for Stage II are computed as follows:

$$c_{m,II,7} = (c_{p,II,7})f_{II,7} = (629)(0.711) = 447$$

$$c_{m,II,10} = (703)(0.707) = 497$$

The final result of the two-stage gap-acceptance procedure will be a total capacity estimate for Movements 7 and 10. To begin the procedure, an adjustment factor, a, must be computed for each movement by using Equation 19-55, under the assumption that there is storage for two vehicles in the median refuge area; thus, $n_m = 2$:

$$a_7 = a_{10} = 1 - 0.32e^{-1.3\sqrt{n_m}} = 1 - 0.32e^{-1.3\sqrt{2}} = 0.949$$

Next, an intermediate variable, y, must be computed for each movement by using Equation 19-56:

$$y_7 = \frac{c_{m,I,7} - c_{m,7}}{c_{m,II,7} - v_1 - c_{m,7}} = \frac{607 - 231}{447 - 33 - 231} = 2.055$$

$$y_{10} = \frac{c_{m,I,10} - c_{m,10}}{c_{m,II,10} - v_4 - c_{m,10}} = \frac{486 - 189}{497 - 66 - 189} = 1.227$$

Finally, the total capacity for each movement, $c_{T,8}$ and $c_{T,11}$, is computed according to Equation 19-57, as $y \neq 1$:

$$c_{T,7} = \frac{a_7}{y_7^{n_m+1} - 1}\left[y_7\left(y_7^{n_m} - 1\right)\left(c_{m,II,7} - v_1\right) + \left(y_7 - 1\right)c_{m,7}\right]$$

$$= \frac{0.949}{2.055^{2+1} - 1}\left[(2.055)\left(2.055^2 - 1\right)(447 - 33) + (2.055 - 1)(231)\right] = 369$$

$$c_{T,10} = \frac{a_{10}}{y_{10}^{n_m+1} - 1}\left[y_{10}\left(y_{10}^{n_m} - 1\right)\left(c_{m,II,10} - v_4\right) + \left(y_{10} - 1\right)c_{m,10}\right]$$

$$= \frac{0.949}{1.227^{2+1} - 1}\left[(1.227)\left(1.227^2 - 1\right)(497 - 66) + (1.227 - 1)(189)\right] = 347$$

Step 10: Compute Final Capacity Adjustments

In this example problem, several final capacity adjustments must be made to account for the effect of the shared lanes and the flared lanes on the minor-street approaches. Initially, the shared-lane capacities for each of the minor-street approaches must be computed on the assumption of no flared lanes; then the effects of the flare can be incorporated to compute an actual capacity for each minor-street approach.

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

In this example, both minor-street approaches have single-lane entries, meaning that all movements on the minor street share one lane. The shared-lane capacities for the minor-street approaches are computed according to Equation 19-59:

$$c_{SH,NB} = \frac{\sum_y v_y}{\sum_y \left(\frac{v_y}{c_{m,y}}\right)} = \frac{v_7 + v_8 + v_9}{\frac{v_7}{c_{m,7}} + \frac{v_8}{c_{m,8}} + \frac{v_9}{c_{m,9}}} = \frac{44 + 132 + 55}{\frac{44}{369} + \frac{132}{390} + \frac{55}{845}} = 442$$

$$c_{SH,SB} = \frac{11 + 110 + 28}{\frac{11}{347} + \frac{110}{405} + \frac{28}{783}} = 439$$

Step 10b: Compute Flared Minor-Street Lane Effects

In this example, the capacity of each minor-street approach will be greater than the shared capacities computed in the previous step due to the shared-lane condition on each approach. On each approach, it is assumed that one vehicle at a time can queue in the flared area; therefore, $n = 1$.

First, the analyst must estimate the average queue length for each movement sharing the lane on each approach. Required input data for this estimation include the flow rates and control delays for each movement. While the flow rates are known input data, the control delays have not yet been computed. Therefore, the control delays for each movement, assuming a 15-min analysis period and separate lanes for each movement, must first be computed according to Equation 19-64:

$$d_7 = \frac{3{,}600}{c_{m,7}} + 900T\left[\frac{v_7}{c_{m,7}} - 1 + \sqrt{\left(\frac{v_7}{c_{m,7}} - 1\right)^2 + \frac{\left(\frac{3{,}600}{c_{m,7}}\right)\left(\frac{v_7}{c_{m,7}}\right)}{450T}}\right] + 5$$

$$d_7 = \frac{3{,}600}{369} + 900(0.25)\left[\frac{44}{369} - 1 + \sqrt{\left(\frac{44}{369} - 1\right)^2 + \frac{\left(\frac{3{,}600}{369}\right)\left(\frac{44}{369}\right)}{450(0.25)}}\right] + 5 = 16.07$$

$$d_8 = \frac{3{,}600}{390} + 900(0.25)\left[\frac{132}{390} - 1 + \sqrt{\left(\frac{132}{390} - 1\right)^2 + \frac{\left(\frac{3{,}600}{390}\right)\left(\frac{132}{390}\right)}{450(0.25)}}\right] + 5 = 18.88$$

$$d_9 = \frac{3{,}600}{845} + 900(0.25)\left[\frac{55}{845} - 1 + \sqrt{\left(\frac{55}{845} - 1\right)^2 + \frac{\left(\frac{3{,}600}{845}\right)\left(\frac{55}{845}\right)}{450(0.25)}}\right] + 5 = 9.57$$

$$d_{10} = \frac{3{,}600}{347} + 900(0.25)\left[\frac{11}{347} - 1 + \sqrt{\left(\frac{11}{347} - 1\right)^2 + \frac{\left(\frac{3{,}600}{347}\right)\left(\frac{11}{347}\right)}{450(0.25)}}\right] + 5 = 15.71$$

$$d_{11} = \frac{3{,}600}{405} + 900(0.25)\left[\frac{110}{405} - 1 + \sqrt{\left(\frac{110}{405} - 1\right)^2 + \frac{\left(\frac{3{,}600}{405}\right)\left(\frac{110}{405}\right)}{450(0.25)}}\right] + 5 = 17.17$$

$$d_{12} = \frac{3{,}600}{783} + 900(0.25)\left[\frac{28}{783} - 1 + \sqrt{\left(\frac{28}{783} - 1\right)^2 + \frac{\left(\frac{3{,}600}{783}\right)\left(\frac{28}{783}\right)}{450(0.25)}}\right] + 5 = 9.77$$

In this example, all movements on the minor-street approach share one lane; therefore, the average queue lengths for each minor-street movement are computed as follows:

$$Q_{sep,7} = \frac{d_{sep,7} v_{sep,7}}{3{,}600} = \frac{(16.07)(44)}{3{,}600} = 0.20$$

$$Q_{sep,8} = \frac{(18.88)(132)}{3{,}600} = 0.69$$

$$Q_{sep,9} = \frac{(9.57)(55)}{3{,}600} = 0.15$$

$$Q_{sep,10} = \frac{(15.71)(11)}{3{,}600} = 0.05$$

$$Q_{sep,11} = \frac{(17.17)(110)}{3{,}600} = 0.53$$

$$Q_{sep,12} = \frac{(9.77)(28)}{3{,}600} = 0.08$$

Next, the required length of the storage area so that each approach would operate effectively as separate lanes is computed with Equation 19-61:

$$n_{Max,NB} = \underset{NB}{\mathrm{Max}}\left[\mathrm{round}\left(Q_{sep,7} + 1\right), \mathrm{round}\left(Q_{sep,8} + 1\right), \mathrm{round}\left(Q_{sep,9} + 1\right)\right]$$

$$n_{Max,NB} = \underset{NB}{\mathrm{Max}}\left[\mathrm{round}(0.20 + 1), \mathrm{round}(0.69 + 1), \mathrm{round}(0.15 + 1)\right] = 2$$

$$n_{Max,SB} = \underset{SB}{\mathrm{Max}}\left[\mathrm{round}(0.05 + 1), \mathrm{round}(0.53 + 1), \mathrm{round}(0.08 + 1)\right] = 2$$

The next step involves estimating separate lane capacities, with consideration of the limitation of the amount of right-turn traffic that could actually move into a separate right-turn lane given a queue before the location of the flare. To compute separate lane capacities, the shared-lane capacities of the through plus left-turn movement on each approach must first be estimated according to Equation 19-59:

$$c_{L+TH,NB} = \frac{\sum_y v_y}{\sum_y \left(\frac{v_y}{c_{m,y}}\right)} = \frac{v_7 + v_8}{\frac{v_7}{c_{m,7}} + \frac{v_8}{c_{m,8}}} = \frac{44+132}{\frac{44}{369} + \frac{132}{390}} = 385$$

$$c_{L+TH,SB} = \frac{v_{10} + v_{11}}{\frac{v_{10}}{c_{m,10}} + \frac{v_{11}}{c_{m,11}}} = \frac{11+110}{\frac{11}{347} + \frac{110}{405}} = 399$$

Then, the capacity of the separate lane condition c_{sep} for each approach can be computed according to Equation 19-62:

$$c_{sep,NB} = \text{Min}\left[c_{m,9}\left(1 + \frac{v_{L+TH,NB}}{v_9}\right), c_{L+TH,NB}\left(1 + \frac{v_9}{v_{L+TH,NB}}\right)\right]$$

$$= \text{Min}\left[845\left(1 + \frac{44+132}{55}\right), 385\left(1 + \frac{55}{44+132}\right)\right] = 505$$

$$c_{sep,SB} = \text{Min}\left[c_{m,12}\left(1 + \frac{v_{L+TH,SB}}{v_{12}}\right), c_{L+TH,SB}\left(1 + \frac{v_{12}}{v_{L+TH,SB}}\right)\right]$$

$$= \text{Min}\left[783\left(1 + \frac{11+110}{28}\right), 399\left(1 + \frac{28}{11+110}\right)\right] = 491$$

Finally, the capacities of the flared minor-street lanes are computed according to Equation 19-63:

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

Because $n_R = 1$ and $n_{Max} = 2$, the first condition is evaluated:

$$c_{R,NB} = (505 - 442)\frac{1}{2} + 442 = 474$$

Similarly,

$$c_{R,SB} = (491 - 439)\frac{1}{2} + 439 = 465$$

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 delays for the major-street left-turn movements (Rank 2), d_1 and d_4, and the minor-street approaches, d_{NB} and d_{SB}, are computed as follows:

$$d_1 = \frac{3{,}600}{c_{m,1}} + 900T\left[\frac{v_1}{c_{m,1}} - 1 + \sqrt{\left(\frac{v_1}{c_{m,1}} - 1\right)^2 + \frac{\left(\frac{3{,}600}{c_{m,1}}\right)\left(\frac{v_1}{c_{m,1}}\right)}{450T}}\right] + 5$$

$$d_1 = \frac{3{,}600}{1{,}100} + 900(0.25)\left[\frac{33}{1{,}100} - 1 + \sqrt{\left(\frac{33}{1{,}100} - 1\right)^2 + \frac{\left(\frac{3{,}600}{1{,}100}\right)\left(\frac{33}{1{,}100}\right)}{450(0.25)}}\right] + 5 = 8.4$$

$$d_4 = \frac{3{,}600}{1{,}202} + 900(0.25)\left[\frac{66}{1{,}202} - 1 + \sqrt{\left(\frac{66}{1{,}202} - 1\right)^2 + \frac{\left(\frac{3{,}600}{1{,}202}\right)\left(\frac{66}{1{,}202}\right)}{450(0.25)}}\right] + 5 = 8.2$$

$$d_{NB} = \frac{3{,}600}{474} + 900(0.25)\left[\frac{231}{474} - 1 + \sqrt{\left(\frac{231}{474} - 1\right)^2 + \frac{\left(\frac{3{,}600}{474}\right)\left(\frac{231}{474}\right)}{450(0.25)}}\right] + 5 = 19.6$$

$$d_{SB} = \frac{3{,}600}{465} + 900(0.25)\left[\frac{149}{465} - 1 + \sqrt{\left(\frac{149}{465} - 1\right)^2 + \frac{\left(\frac{3{,}600}{465}\right)\left(\frac{149}{465}\right)}{450(0.25)}}\right] + 5 = 16.3$$

According to Exhibit 19-1, the levels of service (LOS) for the major-street left-turn movements and the minor-street approaches are as follows:

- Eastbound major-street left-turn (Movement 1): LOS A
- Westbound major-street left-turn (Movement 4): LOS A
- Northbound minor-street approach: LOS C
- Southbound minor-street approach: LOS C

Step 11b: Compute Control Delay to Rank 1 Movements

This step is not applicable as the major-street through movements v_2 and v_5 and westbound major-street left-turn movements v_1 and v_4 have exclusive lanes at this intersection.

Step 12: Compute Approach and Intersection Control Delay

The control delay for the eastbound approach $d_{A,EB}$ is computed as follows:

$$d_{A,EB} = \frac{d_r v_r + d_t v_t + d_l v_l}{v_r + v_t + v_l} = \frac{(0)(50) + (0)(250) + (8.2)(33)}{50 + 250 + 33} = 0.8$$

The control delay for the westbound approach $d_{A,WB}$ is computed according to the same equation as for the eastbound approach:

$$d_{A,WB} = \frac{(0)(100) + (0)(300) + (8.4)(66)}{100 + 300 + 66} = 1.2$$

The intersection delay d_I is computed as follows:

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

$$d_I = \frac{(0.8)(333) + (1.2)(466) + (19.6)(231) + (16.3)(149)}{333 + 466 + 231 + 149} = 6.6$$

LOS is not defined for the intersection as a whole or for the major-street approaches.

Step 13: Compute 95th Percentile Queue Lengths

The 95th percentile queue length for the major-street eastbound left-turn movement $Q_{95,1}$ is computed as follows:

$$Q_{95,1} \approx 900T \left[\frac{v_1}{c_{m,1}} - 1 + \sqrt{\left(\frac{v_1}{c_{m,1}} - 1 \right)^2 + \frac{\left(\frac{3{,}600}{c_{m,1}} \right)\left(\frac{v_1}{c_{m,1}} \right)}{150T}} \right] \left(\frac{c_{m,1}}{3{,}600} \right)$$

$$Q_{95,1} \approx 900(0.25) \left[\frac{33}{1{,}100} - 1 + \sqrt{\left(\frac{33}{1{,}100} - 1 \right)^2 + \frac{\left(\frac{3{,}600}{1{,}100} \right)\left(\frac{33}{1{,}100} \right)}{150(0.25)}} \right] \left(\frac{1{,}100}{3{,}600} \right) = 0.1$$

The result of 0.1 veh for the 95th percentile queue indicates that a queue of more than one vehicle will occur very infrequently for the eastbound major-street left-turn movement.

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

$$Q_{95,4} \approx 900(0.25) \left[\frac{66}{1{,}202} - 1 + \sqrt{\left(\frac{66}{1{,}202} - 1 \right)^2 + \frac{\left(\frac{3{,}600}{1{,}202} \right)\left(\frac{66}{1{,}202} \right)}{150(0.25)}} \right] \left(\frac{1{,}202}{3{,}600} \right) = 0.2$$

The result of 0.2 veh for the 95th percentile queue indicates that a queue of more than one vehicle will occur very infrequently for the westbound major-street left-turn movement.

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

$$Q_{95,NB} \approx 900(0.25)\left[\frac{231}{474}-1+\sqrt{\left(\frac{231}{474}-1\right)^2+\frac{\left(\frac{3,600}{474}\right)\left(\frac{231}{474}\right)}{150(0.25)}}\right]\left(\frac{474}{3,600}\right)=2.6$$

The result of 2.6 veh for the 95th percentile queue indicates that a queue of more than two vehicles will occur occasionally for the northbound approach.

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

$$Q_{95,SB} \approx 900(0.25)\left[\frac{149}{465}-1+\sqrt{\left(\frac{149}{465}-1\right)^2+\frac{\left(\frac{3,600}{465}\right)\left(\frac{149}{465}\right)}{150(0.25)}}\right]\left(\frac{465}{3,600}\right)=1.4$$

The result of 1.4 veh for the 95th percentile queue indicates that a queue of more than one vehicle will occur occasionally for the southbound approach.

Discussion

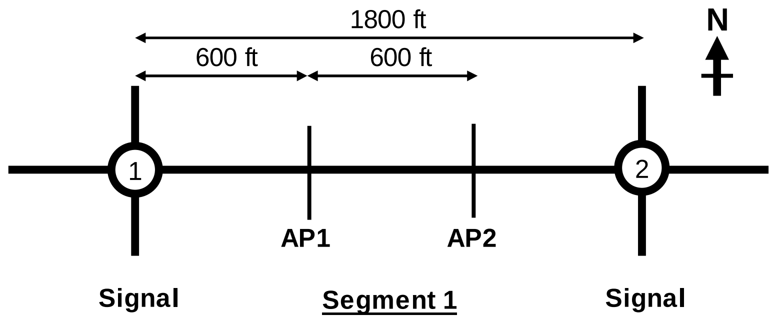
Overall, the results indicate that the four-leg TWSC intersection with two-stage gap-acceptance and flared minor-street approaches will operate satisfactorily with low delays for major-street movements and average delays for the minor-street approaches.

TWSC EXAMPLE PROBLEM 4: TWSC INTERSECTION WITHIN SIGNALIZED URBAN STREET SEGMENT

The Facts

This problem focuses on analyzing the performance of the TWSC intersection at Access Point 1 (AP1) from Example Problem 1 in Chapter 17, which looks at the automobile performance of the urban street segment bounded by two signalized intersections, as shown in Exhibit 32-10. The street has a four-lane cross section with two lanes in each direction.

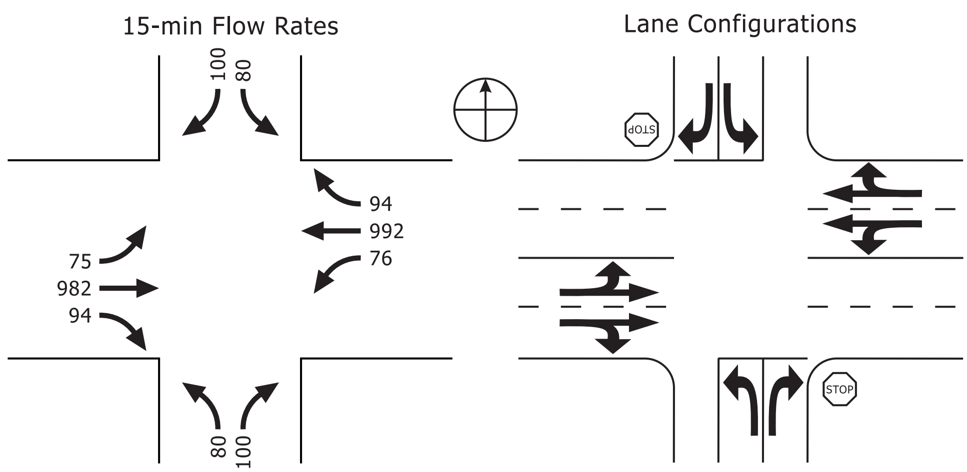
Exhibit 32-10
TWSC Example Problem 4: TWSC Intersection Within Signalized Urban Street Segment



From Example Problem 1 in Chapter 17, the following data are relevant:

- Major street with two lanes in each direction,
- Minor street with separate left-turn and right-turn lanes in each direction (through movements considered negligible) and STOP-controlled on minor-street approach,
- Level grade on all approaches,
- Percent heavy vehicles on all approaches = 1%,
- Length of analysis period = 0.25 h, and
- Flow rates and lane configurations as shown in Exhibit 32-11.

Exhibit 32-11
TWSC Example Problem 4: Flow Rates and Lane Configurations



The proportion time blocked and delay to through vehicles from the Chapter 17 methodology is as shown in Exhibit 32-12.

Exhibit 32-12
TWSC Example Problem 4: Movement-Based Access Point Output (from Chapter 17, Example Problem 1)

Access Point Data	**EB**	**EB**	**EB**	**WB**	**WB**	**WB**	**NB**	**NB**	**NB**	**SB**	**SB**	**SB**
Segment 1	**L**	**T**	**R**	**L**	**T**	**R**	**L**	**T**	**R**	**L**	**T**	**R**
Movement:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Access Point Intersection No. 1												
1: Volume, veh/h	74.80	981.71	93.50	75.56	991.70	94.45	80.00	0.00	100.00	80.00	0.00	100.00
1: Lanes	0	2	0	0	2	0	1	0	1	1	0	1
1: Proportion time blocked	0.170			0.170			0.260	0.260	0.170	0.260	0.260	0.170
1: Delay to through vehicles, s/veh		0.163			0.164							
1: Prob. inside lane blocked by left		0.101			0.101							
1: Dist. from West/South signal, ft	600											
Access Point Intersection No. 2												
2: Volume, veh/h	75.56	991.70	94.45	74.80	981.71	93.50	80.00	0.00	100.00	80.00	0.00	100.00
2: Lanes	0	2	0	0	2	0	1	0	1	1	0	1
2: Proportion time blocked	0.170			0.170			0.260	0.260	0.170	0.260	0.260	0.170
2: Delay to through vehicles, s/veh		0.164			0.163							
2: Prob. inside lane blocked by left		0.101			0.101							
2: Dist. from West/South signal, ft	1200											

Comments

Default values are needed for the saturation flow rates of the major-street through and right-turn movements for the analysis of shared or short major-street left-turn lanes:

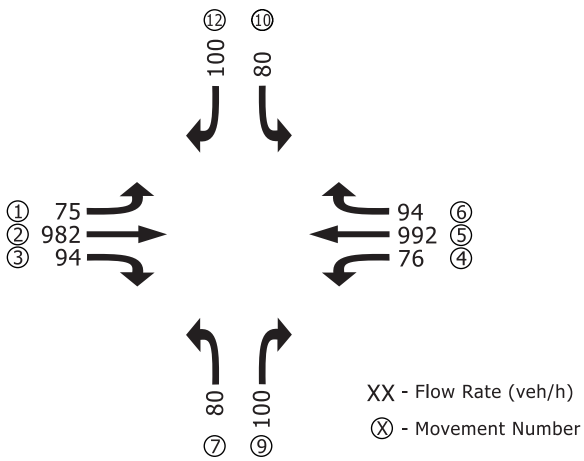
- Major-street through movement, s_{i1} = 1,800 veh/h; and
- Major-street right-turn movement, s_{i2} = 1,500 veh/h.

All other input parameters are known.

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

Flow rates for each turning movement have been provided from the Chapter 17 methodology. They are assigned movement numbers as shown in Exhibit 32-13.

Exhibit 32-13
TWSC Example Problem 4: Calculation of Peak 15-min Flow Rates, Movement Priorities



Step 3: Compute Conflicting Flow Rates

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

The conflicting flows for the major-street left-turn movements are computed as follows:

$$v_{c,1} = v_5 + v_6 + v_{16} = 992 + 94 + 0 = 1{,}086$$

$$v_{c,4} = v_2 + v_3 + v_{15} = 982 + 94 + 0 = 1{,}076$$

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

The conflicting flows for minor-street right-turn movements are computed as follows:

$$v_{c,9} = 0.5v_2 + 0.5v_3 + v_{4U} + v_{14} + v_{15} = 0.5(982) + 0.5(94) + 0 + 0 + 0 = 538$$

$$v_{c,12} = 0.5v_5 + 0.5v_6 + v_{1U} + v_{13} + v_{16} = 0.5(992) + 0.5(94) + 0 + 0 + 0 = 543$$

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

U-turns are assumed to be negligible.

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

Minor-street pedestrian movements are assumed to be negligible.

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

Because there are no minor-street through movements, this step can be skipped.

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

Because the major street has four lanes without left-turn lanes or other possible median storage, the minor-street left-turn movement is assumed to be conducted in one stage. As a result, the conflicting flows for Stages I and II can be combined.

$$v_{c,7} = 2(v_1 + v_{1U}) + v_2 + 0.5v_3 + v_{15} + 2(v_4 + v_{4U}) + 0.5v_5 + 0.5v_{11} + v_{13}$$

$$= 2(75 + 0) + 982 + 0.5(94) + 0 + 2(76 + 0) + 0.5(992) + 0.5(0) + 0 = 1{,}827$$

$$v_{c,10} = 2(v_4 + v_{4U}) + v_5 + 0.5v_6 + v_{16} + 2(v_1 + v_{1U}) + 0.5v_2 + 0.5v_8 + v_{14}$$

$$= 2(76 + 0) + 992 + 0.5(94) + 0 + 2(75 + 0) + 0.5(982) + 0.5(0) + 0 = 1{,}832$$

Step 4: Determine Critical Headways and Follow-Up Headways

Critical headways for each movement are computed as follows:

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

$$t_{c,1} = t_{c,4} = 4.1 + (2.0)(0.01) + 0 - 0 = 4.12$$

$$t_{c,9} = t_{c,12} = 6.9 + 2.0(0.01) + 0.1(0) - 0 = 6.92$$

$$t_{c,7} = t_{c,10} = 7.5 + 2.0(0.01) + 0.2(0) - 0 = 7.52$$

Follow-up headways for each movement are computed as follows:

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

$$t_{f,1} = t_{f,4} = 2.2 + 1.0(0.01) = 2.21$$

$$t_{f,9} = t_{f,12} = 3.3 + 1.0(0.01) = 3.31$$

$$t_{f,7} = t_{f,10} = 3.5 + 1.0(0.01) = 3.51$$

Step 5: Compute Potential Capacities

Because upstream signals are present, Step 5b is used. The proportion time blocked for each movement x is given as $p_{b,x}$ and has been computed by the Chapter 17 procedure.

The flow for the unblocked period (no platoons) is determined by first computing the conflicting flow for each movement during the unblocked period (Equation 19-40). The minimum platooned flow rate $v_{c,min}$ over two lanes is assumed to be equal to $1{,}000N = 1{,}000(2) = 2{,}000$. The flow rate assumed to occur during the blocked period is calculated as follows:

$$1.5v_{c,\min}p_{b,1} = 1.5(2{,}000)(0.170) = 510$$

The value for $v_{c,1}$ = 1,086 exceeds this value, which indicates that some of the conflicting flow occurs in the unblocked period. Therefore, $v_{c,u,1}$ is calculated as follows:

$$v_{c,u,1} = \frac{v_{c,1} - 1.5v_{c,\min}p_{b,1}}{1 - p_{b,1}} = \frac{1{,}086 - 1.5(2{,}000)(0.170)}{1 - 0.170} = 694$$

Similar calculations are made for the other movements as follows:

$$v_{c,u,4} = \frac{v_{c,4} - 1.5v_{c,\min}p_{b,4}}{1 - p_{b,4}} = \frac{1076 - 1.5(2{,}000)(0.170)}{1 - 0.170} = 682$$

$$v_{c,u,9} = \frac{v_{c,9} - 1.5v_{c,\min}p_{b,9}}{1 - p_{b,9}} = \frac{538 - 1.5(2{,}000)(0.170)}{1 - 0.170} = 34$$

$$v_{c,u,12} = \frac{v_{c,12} - 1.5v_{c,\min}p_{b,12}}{1 - p_{b,12}} = \frac{543 - 1.5(2{,}000)(0.170)}{1 - 0.170} = 40$$

$$v_{c,u,7} = \frac{v_{c,7} - 1.5v_{c,\min}p_{b,7}}{1 - p_{b,7}} = \frac{1{,}827 - 1.5(2{,}000)(0.260)}{1 - 0.260} = 1{,}415$$

$$v_{c,u,10} = \frac{v_{c,10} - 1.5v_{c,\min}p_{b,10}}{1 - p_{b,10}} = \frac{1{,}832 - 1.5(2{,}000)(0.260)}{1 - 0.260} = 1{,}422$$

The potential capacity for each movement is then calculated with Equation 19-34 and Equation 19-35 (combined) as follows:

$$c_{p,1} = (1 - p_{b,1})v_{c,u,1}\frac{e^{-v_{c,u,1}t_{c,1}/3{,}600}}{1 - e^{-v_{c,u,1}t_{f,1}/3{,}600}}$$

$$= (1 - 0.170)(694)\frac{e^{-(694)(4.12)/3{,}600}}{1 - e^{-(694)(2.21)/3{,}600}} = 750$$

$$c_{p,4} = (1 - 0.170)(682)\frac{e^{-(682)(4.12)/3{,}600}}{1 - e^{-(682)(2.21)/3{,}600}} = 758$$

$$c_{p,9} = (1 - 0.170)(34)\frac{e^{-(34)(6.92)/3{,}600}}{1 - e^{-(34)(3.31)/3{,}600}} = 859$$

$$c_{p,12} = (1 - 0.170)(40)\frac{e^{-(40)(6.92)/3{,}600}}{1 - e^{-(40)(3.31)/3{,}600}} = 851$$

$$c_{p,7} = (1 - 0.260)(1{,}415)\frac{e^{-(1415)(7.52)/3{,}600}}{1 - e^{-(1415)(3.51)/3{,}600}} = 73$$

$$c_{p,10} = (1 - 0.260)(1{,}422)\frac{e^{-(1422)(7.52)/3{,}600}}{1 - e^{-(1422)(3.51)/3{,}600}} = 72$$

Steps 6–9: Compute Movement Capacities

Because no pedestrians are present, the procedures given in Chapter 19 are followed.

Step 6: Rank 1 Movement Capacity

There is no computation for this step. The adjustment for the delay to through movements caused by left-turn movements in the shared left-through lane is accounted for by using adjustments provided later in this procedure.

Step 7: Rank 2 Movement Capacity

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 follows:

$$c_{m,1} = c_{p,1} = 750$$

$$c_{m,4} = c_{p,4} = 758$$

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

The movement capacity of each minor-street right-turn movement is equal to its potential capacity:

$$c_{m,9} = c_{p,9} = 859$$

$$c_{m,12} = c_{p,12} = 851$$

Step 7c: Movement Capacity for Major-Street U-Turn Movement

No U-turns are present, so this step is skipped.

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, assuming that the left-turn movement occupies its own lane, is calculated with Equation 19-51 as follows:

$$p_{0,1} = 1 - \frac{v_1}{c_{m,1}} = 1 - \frac{75}{750} = 0.900$$

$$p_{0,4} = 1 - \frac{v_4}{c_{m,4}} = 1 - \frac{76}{758} = 0.900$$

However, for this problem the major-street left-turn movement shares a lane with the through movement. First, the combined degree of saturation for the major-street through and right-turn movements is calculated as follows (using default values for s):

$$x_{2+3} = \frac{v_2}{s_2} + \frac{v_3}{s_3} = \frac{982}{1{,}800} + \frac{94}{1{,}500} = 0.608$$

$$x_{5+6} = \frac{v_5}{s_5} + \frac{v_6}{s_6} = \frac{992}{1{,}800} + \frac{94}{1{,}500} = 0.614$$

Next, the probability that there will be no queue in the major-street shared lane $p^*_{0,j}$ is calculated according to the special case ($n_L = 0$) given as follows:

$$p^*_{0,1} = 1 - \frac{1 - p_{0,1}}{1 - x_{2+3}} = 1 - \frac{1 - 0.900}{1 - 0.608} = 0.745$$

$$p^*_{0,4} = 1 - \frac{1 - p_{0,4}}{1 - x_{5+6}} = 1 - \frac{1 - 0.900}{1 - 0.614} = 0.741$$

These values of $p^*_{0,1}$ and $p^*_{0,4}$ are used in lieu of $p_{0,1}$ and $p_{0,4}$ for the remaining calculations.

Step 8: Compute Movement Capacities for Rank 3 Movements

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

Because there are no minor-street through movements, it is not necessary to compute the movement capacities for those movements. However, capacity adjustment factors f_8 and f_{11} are needed for subsequent steps and can be computed as follows:

$$f_8 = f_{11} = p^*_{0,1} p^*_{0,4} = (0.745)(0.741) = 0.552$$

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

No two-stage movements are present, so this step is skipped.

Step 9: Compute Movement Capacities for Rank 4 Movements

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

The probabilities that the minor-street right-turn movements will operate in the queue-free state $p_{0,9}$ and $p_{0,12}$ are computed as follows:

$$p_{0,9} = 1 - \frac{v_9}{c_{m,9}} = 1 - \frac{100}{859} = 0.884$$

$$p_{0,12} = 1 - \frac{v_{12}}{c_{m,12}} = 1 - \frac{100}{851} = 0.882$$

To compute p', the probability that both the major-street left-turn movements and the minor-street crossing movements will operate in a queue-free state simultaneously, the analyst must first compute $p_{0,k}$, which is done in the same manner as the computation of $p_{0,j}$, except that k represents Rank 3 movements. Therefore, the values for $p_{0,k}$ are computed as follows:

$$p_{0,8} = 1 - \frac{v_8}{c_{m,8}} = 1 - 0 = 1$$

$$p_{0,11} = 1 - \frac{v_{11}}{c_{m,11}} = 1 - 0 = 1$$

Next, the analyst must compute p'', which, under the single-stage gap-acceptance assumption, is simply the product of f_j and $p_{0,k}$. The value for $f_8 = f_{11} = 0.552$ is as computed above. The value for $p_{0,11}$ is computed by using the total capacity for Movement 11 calculated in the previous step:

$$p_7'' = (p_{0,11})(f_{11}) = (1)(0.552) = 0.552$$

$$p_{10}'' = (p_{0,8})(f_8) = (1)(0.552) = 0.552$$

By using the values for p'', the probability of a simultaneous queue-free state for each movement can be computed with Equation 19-52 as follows:

$$p_7' = 0.65 p_7'' - \frac{p_7''}{p_7''+3} + 0.6\sqrt{p_7''} = 0.65(0.552) - \frac{0.552}{0.552+3} + 0.6\sqrt{0.552} = 0.649$$

$$p_{10}' = 0.65(0.552) - \frac{0.552}{0.552+3} + 0.6\sqrt{0.552} = 0.649$$

Next, by using the probabilities computed above, capacity adjustment factors f_7 and f_{10} can be computed as follows:

$$f_7 = (p_7')(p_{0,12}) = (0.649)(0.882) = 0.572$$

$$f_{10} = (p_{10}')(p_{0,9}) = (0.649)(0.884) = 0.574$$

Finally, the movement capacities $c_{m,7}$ and $c_{m,10}$ can be computed as follows:

$$c_{m,7} = (c_{p,7}) f_7 = (73)(0.572) = 42$$

$$c_{m,10} = (c_{p,10}) f_{10} = (72)(0.574) = 41$$

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

No two-stage movements are present, so this step is skipped.

Step 10: Final Capacity Adjustments

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

No shared lanes are present on the side street, so this step is skipped.

Step 10b: Compute Flared Minor-Street Lane Effects

No flared lanes are present, so this step is skipped.

Step 11: Compute Movement Control Delay

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

The delay for each minor-street movement is calculated as follows:

$$d_1 = \frac{3{,}600}{750} + 900(0.25)\left[\frac{75}{750} - 1 + \sqrt{\left(\frac{75}{750} - 1\right)^2 + \frac{\left(\frac{3{,}600}{750}\right)\left(\frac{75}{750}\right)}{450(0.25)}}\right] + 5 = 10.3$$

$$d_4 = \frac{3{,}600}{758} + 900(0.25)\left[\frac{76}{758} - 1 + \sqrt{\left(\frac{76}{758} - 1\right)^2 + \frac{\left(\frac{3{,}600}{758}\right)\left(\frac{76}{758}\right)}{450(0.25)}}\right] + 5 = 10.3$$

$$d_9 = \frac{3{,}600}{859} + 900(0.25)\left[\frac{100}{859} - 1 + \sqrt{\left(\frac{100}{859} - 1\right)^2 + \frac{\left(\frac{3{,}600}{859}\right)\left(\frac{100}{859}\right)}{450(0.25)}}\right] + 5 = 9.7$$

$$d_{12} = \frac{3{,}600}{851} + 900(0.25)\left[\frac{100}{851} - 1 + \sqrt{\left(\frac{100}{851} - 1\right)^2 + \frac{\left(\frac{3{,}600}{851}\right)\left(\frac{100}{851}\right)}{450(0.25)}}\right] + 5 = 9.8$$

$$d_7 = \frac{3{,}600}{42} + 900(0.25)\left[\frac{80}{42} - 1 + \sqrt{\left(\frac{80}{42} - 1\right)^2 + \frac{\left(\frac{3{,}600}{42}\right)\left(\frac{80}{42}\right)}{450(0.25)}}\right] + 5 = 633$$

$$d_{10} = \frac{3{,}600}{41} + 900(0.25)\left[\frac{80}{41} - 1 + \sqrt{\left(\frac{80}{41} - 1\right)^2 + \frac{\left(\frac{3{,}600}{41}\right)\left(\frac{80}{41}\right)}{450(0.25)}}\right] + 5 = 657$$

According to Exhibit 19-1, the LOS for the major-street left-turn movements and the minor-street approaches are as follows:

- Eastbound major-street left turn (Movement 1): LOS B
- Westbound major-street left turn (Movement 4): LOS B
- Northbound minor-street right turn (Movement 9): LOS A
- Southbound minor-street right turn (Movement 12): LOS A
- Northbound minor-street left turn (Movement 7): LOS F
- Southbound minor-street left turn (Movement 10): LOS F

Step 11b: Compute Control Delay to Rank 1 Movements

The presence of a shared left through lane on the major street creates delay for Rank 1 movements (major-street through movements). Assuming that major-street through vehicles distribute equally across both lanes, then $v_{i,1} = v_2/N = 982/2$

= 491. The number of major-street turning vehicles in the shared lane is equal to the major-street left-turn flow rate; therefore, $v_{i,2}$ = 75.

The average delay to Rank 1 vehicles is therefore computed with Equation 19-65 as follows:

$$d_2 = \frac{\left(1-p^*_{0,1}\right)d_1\left(\frac{v_{i,1}}{N}\right)}{v_{i,1}+v_{i,2}} = \frac{(1-0.745)(10.3)\left(\frac{491}{2}\right)}{491+75} = 1.1$$

Similarly, for the opposite direction, $v_{i,1} = v_5/N$ = 992/2 = 496. The number of major-street turning vehicles in the shared lane is equal to the major-street left-turn flow rate; therefore, $v_{i,2}$ = 76.

$$d_5 = \frac{\left(1-p^*_{0,4}\right)d_4\left(\frac{v_{i,1}}{N}\right)}{v_{i,1}+v_{i,2}} = \frac{(1-0.741)(10.3)\left(\frac{496}{2}\right)}{496+76} = 1.2$$

The procedures in Chapter 17 provide a better estimate of delay to major-street through vehicles: d_2 = 0.2 and d_5 = 0.2. These values account for the likelihood of major-street through vehicles shifting out of the shared left through lane to avoid being delayed by major-street left-turning vehicles. These values are used in the calculations in Step 12.

Step 12: Compute Approach and Intersection Control Delay

The control delay for each approach is computed as follows:

$$d_{A,EB} = \frac{d_r v_r + d_t v_t + d_l v_l}{v_r + v_t + v_l} = \frac{(0)(94)+(1.1)(982)+(10.3)(75)}{94+982+75} = 1.6$$

$$d_{A,WB} = \frac{(0)(94)+(1.2)(992)+(10.3)(76)}{94+992+76} = 1.7$$

$$d_{A,NB} = \frac{(9.7)(100)+0+(633)(80)}{100+0+80} = 287$$

$$d_{A,SB} = \frac{(9.8)(100)+0+(657)(80)}{100+0+80} = 297$$

The intersection delay d_I is computed as follows:

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

$$d_I = \frac{(1.6)(1151)+(1.7)(1162)+(287)(180)+(297)(180)}{1151+1162+180+180} = 40.8$$

LOS is not defined for the intersection as a whole or for the major-street approaches. This fact is particularly important for this problem, as the assignment of LOS to the intersection as a whole would mask the severe LOS F condition on the minor-street left-turn movement.

Step 13: Compute 95th Percentile Queue Lengths

The 95th percentile queue length for each movement is computed as follows:

$$Q_{95,1} \approx 900(0.25)\left[\frac{75}{750} - 1 + \sqrt{\left(\frac{75}{750} - 1\right)^2 + \frac{\left(\frac{3{,}600}{750}\right)\left(\frac{75}{750}\right)}{150(0.25)}}\right]\left(\frac{750}{3{,}600}\right) = 0.3$$

$$Q_{95,4} \approx 900(0.25)\left[\frac{76}{758} - 1 + \sqrt{\left(\frac{76}{758} - 1\right)^2 + \frac{\left(\frac{3{,}600}{758}\right)\left(\frac{76}{758}\right)}{150(0.25)}}\right]\left(\frac{758}{3{,}600}\right) = 0.3$$

$$Q_{95,9} \approx 900(0.25)\left[\frac{100}{859} - 1 + \sqrt{\left(\frac{100}{859} - 1\right)^2 + \frac{\left(\frac{3{,}600}{859}\right)\left(\frac{100}{859}\right)}{150(0.25)}}\right]\left(\frac{859}{3{,}600}\right) = 0.4$$

$$Q_{95,12} \approx 900(0.25)\left[\frac{100}{851} - 1 + \sqrt{\left(\frac{100}{851} - 1\right)^2 + \frac{\left(\frac{3{,}600}{851}\right)\left(\frac{100}{851}\right)}{150(0.25)}}\right]\left(\frac{851}{3{,}600}\right) = 0.4$$

$$Q_{95,7} \approx 900(0.25)\left[\frac{80}{42} - 1 + \sqrt{\left(\frac{80}{42} - 1\right)^2 + \frac{\left(\frac{3{,}600}{42}\right)\left(\frac{80}{42}\right)}{150(0.25)}}\right]\left(\frac{42}{3{,}600}\right) = 8.3$$

$$Q_{95,10} \approx 900(0.25)\left[\frac{80}{41} - 1 + \sqrt{\left(\frac{80}{41} - 1\right)^2 + \frac{\left(\frac{3{,}600}{41}\right)\left(\frac{80}{41}\right)}{150(0.25)}}\right]\left(\frac{41}{3{,}600}\right) = 8.4$$

The results indicate that queues of more than one vehicle will rarely occur for the major-street left-turn and minor-street right-turn movements. Longer queues are expected for the minor-street left-turn movements, and these queues are likely to be unstable under the significantly oversaturated conditions.

Discussion

The results indicate that Access Point 1 will operate over capacity (LOS F) for the minor-street left-turn movements. All other movements are expected to operate at LOS B or better, with low average delays and short queue lengths.

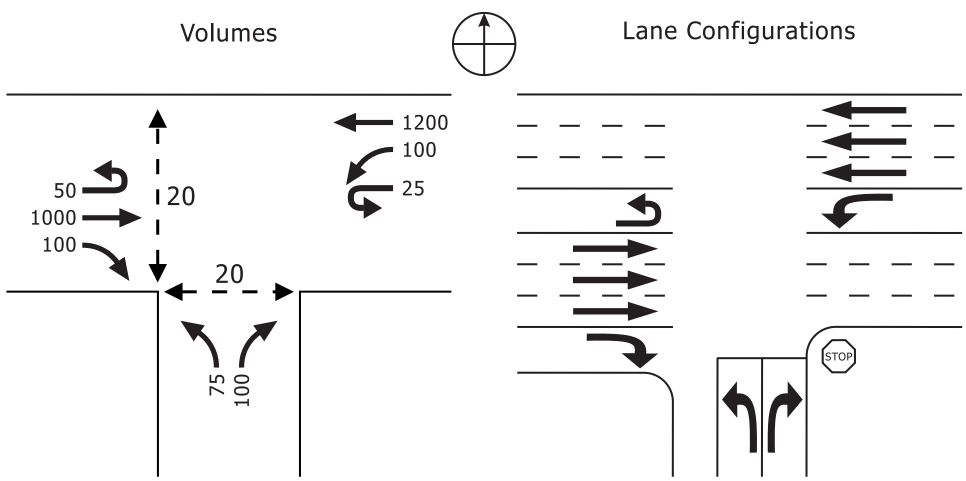
TWSC EXAMPLE PROBLEM 5: SIX-LANE STREET WITH U-TURNS AND PEDESTRIANS

The Facts

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

- T-intersection,
- Major street with three lanes in each direction,
- Minor street with separate left-turn and right-turn lanes and STOP control on the minor-street approach [minor-street left turns operate in two stages (room for storage of one vehicle)],
- Level grade on all approaches,
- Percent heavy vehicles on all approaches = 0%,
- Lane width = 12 ft,
- No other unique geometric considerations or upstream signal considerations,
- 20 p/h crossing both the west and south legs [each pedestrian is assumed to cross in its own group (i.e., independently)],
- Peak hour factor = 1.00,
- Length of analysis period = 0.25 h, and
- Hourly volumes and lane configurations as shown in Exhibit 32-14.

Exhibit 32-14
TWSC Example Problem 5: Volumes and Lane Configurations



Comments

The assumed walking speed of pedestrians is 3.5 ft/s.

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

Flow rates for each turning movement are the same as the peak hour volumes because the peak hour factor equals 1.0. These movements are assigned numbers as shown in Exhibit 32-15.

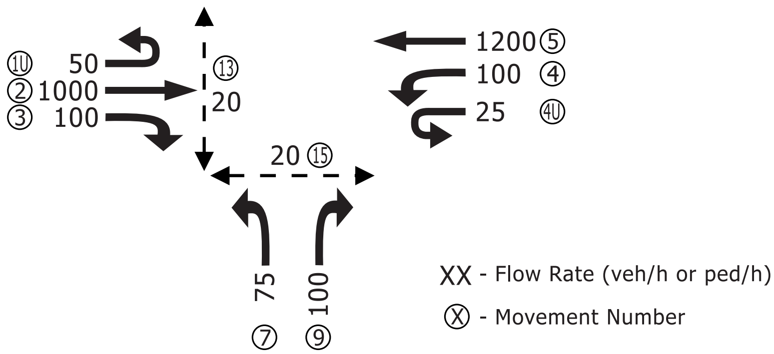


Exhibit 32-15
TWSC Example Problem 5: Calculation of Peak 15-min Flow Rates, Movement Priorities

Step 3: Compute Conflicting Flow Rates

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

The conflicting flow rate for the major-street left-turn movement is computed as follows:

$$v_{c,4} = v_2 + v_3 + v_{15} = 1{,}000 + 100 + 20 = 1{,}120$$

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

The conflicting flow rate for the minor-street right-turn movement is computed as follows (dropping the v_3 term due to a separate major-street right-turn lane):

$$v_{c,9} = 0.5v_2 + 0.5v_3 + v_{14} + v_{15} = 0.5(1{,}000) + 0 + 0 + 20 = 520$$

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

The conflicting flow rates for the major-street U-turns are computed as follows (again dropping the v_3 term):

$$v_{c,1U} = 0.73v_5 + 0.73v_6 = 0.73(1{,}200) + 0 = 876$$

$$v_{c,4U} = 0.73v_2 + 0.73v_3 = 0.73(1{,}000) + 0 = 730$$

Minor-Street Left-Turn Movements (Rank 3—Movement 7)

The conflicting flow rate for Stage I of the minor-street left-turn movement is computed as follows (the v_3 term in these equations is assumed to be zero because of the right-turn lane on the major street):

$$v_{c,I,7} = 2(v_1 + v_{1U}) + v_2 + 0.5v_3 + v_{15} = 2(0 + 50) + 1{,}000 + 0 + 20 = 1{,}120$$

The conflicting flow rate for Stage II of the minor-street left-turn movement is computed as follows:

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

$$v_{c,II,7} = 2(100 + 25) + 0.4(1{,}200) + 0 + 20 = 750$$

$$v_{c,7} = v_{c,I,7} + v_{c,II,7} = 1{,}120 + 750 = 1{,}870$$

Step 4: Determine Critical Headways and Follow-Up Headways

Critical headways for each minor movement are computed as follows:

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

$$t_{c,1U} = 5.6 + 0 + 0 - 0 = 5.6$$

$$t_{c,4} = 5.3 + 0 + 0 - 0 = 5.3$$

$$t_{c,4U} = 5.6 + 0 + 0 - 0 = 5.6$$

$$t_{c,9} = 7.1 + 0 + 0 - 0 = 7.1$$

$$t_{c,7} = 6.4 + 0 + 0 - 0.7 = 5.7$$

$$t_{c,I,7} = 7.3 + 0 + 0 - 0.7 = 6.6$$

$$t_{c,II,7} = 6.7 + 0 + 0 - 0.7 = 6.0$$

Follow-up headways for each minor movement are computed as follows:

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

$$t_{f,1U} = 2.3 + 0 = 2.3$$

$$t_{f,4} = 3.1 + 0 = 3.1$$

$$t_{f,4U} = 2.3 + 0 = 2.3$$

$$t_{f,9} = 3.9 + 0 = 3.9$$

$$t_{f,7} = 3.8 + 0 = 3.8$$

Step 5: Compute Potential Capacities

Because no upstream signals are present, Step 5a is used. The potential capacity $c_{p,x}$ for each movement is computed as follows:

$$c_{p,1U} = v_{c,1U}\frac{e^{-v_{c,1U}t_{c,1U}/3{,}600}}{1-e^{-v_{c,1U}t_{f,1U}/3{,}600}} = 876\frac{e^{-(876)(5.6)/3{,}600}}{1-e^{-(876)(2.3)/3{,}600}} = 523$$

$$c_{p,4} = v_{c,4}\frac{e^{-v_{c,4}t_{c,4}/3{,}600}}{1-e^{-v_{c,4}t_{f,4}/3{,}600}} = 1{,}120\frac{e^{-(1120)(5.3)/3{,}600}}{1-e^{-(1120)(3.1)/3{,}600}} = 348$$

$$c_{p,4U} = v_{c,4U}\frac{e^{-v_{c,4U}t_{c,4U}/3{,}600}}{1-e^{-v_{c,4U}t_{f,4U}/3{,}600}} = 730\frac{e^{-(730)(5.6)/3{,}600}}{1-e^{-(730)(2.3)/3{,}600}} = 629$$

$$c_{p,9} = v_{c,9}\frac{e^{-v_{c,9}t_{c,9}/3{,}600}}{1-e^{-v_{c,9}t_{f,9}/3{,}600}} = 520\frac{e^{-(520)(7.1)/3{,}600}}{1-e^{-(520)(3.9)/3{,}600}} = 433$$

$$c_{p,7} = v_{c,7}\frac{e^{-v_{c,7}t_{c,7}/3{,}600}}{1-e^{-v_{c,7}t_{f,7}/3{,}600}} = 1{,}870\frac{e^{-(1870)(5.7)/3{,}600}}{1-e^{-(1870)(3.8)/3{,}600}} = 112$$

$$c_{p,I,7} = v_{c,I,7}\frac{e^{-v_{c,I,7}t_{c,7}/3{,}600}}{1-e^{-v_{c,I,7}t_{f,7}/3{,}600}} = 1{,}120\frac{e^{-(1120)(6.6)/3{,}600}}{1-e^{-(1120)(3.8)/3{,}600}} = 207$$

$$c_{p,II,7} = v_{c,II,7} \frac{e^{-v_{c,II,7} t_{c,7}/3{,}600}}{1-e^{-v_{c,II,7} t_{f,7}/3{,}600}} = 750 \frac{e^{-(750)(6.0)/3{,}600}}{1-e^{-(750)(3.8)/3{,}600}} = 393$$

Steps 6–9: Compute Movement Capacities

Because of the presence of pedestrians, the computation steps provided earlier in this chapter should be used.

Step 6: Rank 1 Movement Capacity

The methodology assumes that Rank 1 vehicles are unimpeded by pedestrians.

Step 7: Rank 2 Movement Capacity

Step 7a: Pedestrian Impedance

The factor accounting for pedestrian blockage is computed by Equation 32-1 as follows:

$$f_{pb,13} = \frac{(v_{13})\left(\frac{w}{S_p}\right)}{3{,}600} = \frac{20\left(\frac{12}{3.5}\right)}{3{,}600} = 0.019$$

$$f_{pb,15} = \frac{(v_{15})\left(\frac{w}{S_p}\right)}{3{,}600} = \frac{20\left(\frac{12}{3.5}\right)}{3{,}600} = 0.019$$

The pedestrian impedance factor for each pedestrian movement x, $p_{p,x}$, is computed by Equation 32-2 as follows:

$$p_{p,13} = 1 - f_{pb,13} = 1 - 0.019 = 0.981$$

$$p_{p,15} = 1 - f_{pb,15} = 1 - 0.019 = 0.981$$

Step 7b: Movement Capacity for Major-Street Left-Turn Movements

On the basis of Exhibit 32-4, vehicular Movement 4 is impeded by pedestrian Movement 15. Therefore, the movement capacity for Rank 2 major-street left-turn movements is computed as follows:

$$c_{m,4} = (c_{p,4}) p_{p,15} = (348)(0.981) = 341$$

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

The northbound minor-street right-turn movement (Movement 9) is impeded by one conflicting pedestrian movement: Movement 15.

$$f_9 = p_{p,15} = 0.981$$

The movement capacity is then computed as follows:

$$c_{m,9} = (c_{p,9}) f_9 = (433)(0.981) = 425$$

Step 7d: Movement Capacity for Major-Street U-Turn Movements

The eastbound U-turn is unimpeded by queues from any other movement. Therefore, $f_{1U} = 1$, and the movement capacity is computed as follows:

$$c_{m,1U} = (c_{p,1U}) f_{1U} = (523)(1) = 523$$

For the westbound U-turn, the movement capacity is found by first computing a capacity adjustment factor that accounts for the impeding effects of minor-street right turns as follows:

$$f_{4U} = p_{0,9} = 1 - \frac{v_9}{c_{m,9}} = 1 - \frac{100}{425} = 0.765$$

The movement capacity is therefore computed as follows:

$$c_{m,4U} = (c_{p,4U}) f_{4U} = (629)(0.765) = 481$$

Because the westbound left-turn and U-turn movements are conducted from the same lane, their shared-lane capacity is computed as follows:

$$c_{m,4+4U} = \frac{v_4 + v_{4U}}{\frac{v_4}{c_{m,4}} + \frac{v_{4U}}{c_{m,4U}}} = \frac{100 + 25}{\frac{100}{341} + \frac{25}{481}} = 362$$

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

This step is skipped.

Step 8: Compute Movement Capacities for Rank 3 Movements

There are no minor-street through movements, so the minor-street left-turn movement is treated as a Rank 3 movement.

Step 8a: Pedestrian Impedance

The northbound minor-street left turn (Movement 7) must yield to pedestrian Movements 13 and 15. Therefore, the impedance factor for pedestrians is as follows:

$$p_{p,7} = (p_{p,15})(p_{p,13}) = (0.981)(0.981) = 0.962$$

Step 8b: Rank 3 Movement Capacity for One-Stage 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, assuming the movement operates in one stage. This value is computed as follows:

$$f_7 = (p_{0,1U})(p_{0,4+4U}) p_{p,7} = \left(1 - \frac{v_{1U}}{c_{m,1U}}\right)\left(1 - \frac{v_{4+4U}}{c_{m,4+4U}}\right) p_{p,7}$$

$$f_7 = \left(1 - \frac{50}{523}\right)\left(1 - \frac{100 + 25}{362}\right)(0.962) = 0.570$$

$$c_{m,7} = (c_{p,7}) f_7 = (112)(0.570) = 64$$

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

Because the minor-street left-turn movement operates in two stages, the procedure for computing the total movement capacity for the subject movement considering the two-stage gap-acceptance process is followed.

First, the movement capacities for each stage of the left-turn movement are computed on the basis of the impeding movements for each stage. For Stage I, the left-turn movement is impeded by the major-street left and U-turns and by pedestrian Movement 15. Therefore:

$$f_{I,7} = (p_{0,1U})(p_{0,4+4U})p_{p,15} = \left(1 - \frac{v_{1U}}{c_{m,1U}}\right)\left(1 - \frac{v_{4+4U}}{c_{m,4+4U}}\right)p_{p,15}$$

$$f_{I,7} = \left(1 - \frac{50}{523}\right)\left(1 - \frac{100+25}{362}\right)(0.981) = 0.581$$

$$c_{m,I,7} = (c_{p,I,7})f_{I,7} = (207)(0.581) = 120$$

For Stage II, the left-turn movement is impeded only by pedestrian Movement 13. Therefore:

$$f_{II,7} = p_{p,13} = 0.981$$

$$c_{m,II,7} = (c_{p,II,7})f_{II,7} = (393)(0.981) = 386$$

Next, an adjustment factor a and an intermediate variable y are computed as follows:

$$a = 1 - 0.32e^{-1.3\sqrt{n_m}} = 1 - 0.32e^{-1.3\sqrt{1}} = 0.913$$

$$y_7 = \frac{c_{m,I,7} - c_{m,7}}{c_{m,II,7} - v_{4+4U} - c_{m,7}} = \frac{120 - 64}{386 - 125 - 64} = 0.284$$

Therefore, the total capacity c_T is computed as follows:

$$c_{T,7} = \frac{a}{y_7^{\,n_m+1} - 1}\left[y_7\left(y_7^{\,n_m} - 1\right)\left(c_{m,II,7} - v_{4+4U}\right) + \left(y_7 - 1\right)c_{m,7}\right]$$

$$= \frac{0.913}{(0.284)^{1+1} - 1}\left[(0.284)\left((0.284)^1 - 1\right)(386 - 125) + (0.284 - 1)(64)\right] = 98$$

Step 9: Compute Movement Capacities for Rank 4 Movements

Because there are no Rank 4 movements, this step is skipped.

Step 10: Final Capacity Adjustments

There are no shared or flared lanes on the minor street, so this step is skipped.

Step 11: Compute Movement Control Delay

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

The control delay for each minor movement is computed as follows:

$$d = \frac{3{,}600}{c_{m,x}} + 900T\left[\frac{v_x}{c_{m,x}} - 1 + \sqrt{\left(\frac{v_x}{c_{m,x}} - 1\right)^2 + \frac{\left(\frac{3{,}600}{c_{m,x}}\right)\left(\frac{v_x}{c_{m,x}}\right)}{450T}}\right] + 5$$

$$d_{1U} = \frac{3{,}600}{523} + 900(0.25)\left[\frac{50}{523} - 1 + \sqrt{\left(\frac{50}{523} - 1\right)^2 + \frac{\left(\frac{3{,}600}{523}\right)\left(\frac{50}{523}\right)}{450(0.25)}}\right] + 5 = 12.6$$

This movement would be assigned LOS B.

$$d_{4+4U} = \frac{3{,}600}{362} + 900(0.25)\left[\frac{125}{362} - 1 + \sqrt{\left(\frac{125}{362} - 1\right)^2 + \frac{\left(\frac{3{,}600}{362}\right)\left(\frac{125}{362}\right)}{450(0.25)}}\right] + 5 = 20.1$$

This movement would be assigned LOS C.

$$d_9 = \frac{3{,}600}{425} + 900(0.25)\left[\frac{100}{425} - 1 + \sqrt{\left(\frac{100}{425} - 1\right)^2 + \frac{\left(\frac{3{,}600}{425}\right)\left(\frac{100}{425}\right)}{450(0.25)}}\right] + 5 = 16.1$$

This movement would be assigned LOS C.

$$d_7 = \frac{3{,}600}{98} + 900(0.25)\left[\frac{75}{98} - 1 + \sqrt{\left(\frac{75}{98} - 1\right)^2 + \frac{\left(\frac{3{,}600}{98}\right)\left(\frac{75}{98}\right)}{450(0.25)}}\right] + 5 = 113$$

This movement would be assigned LOS F.

Step 11b: Compute Control Delay to Rank 1 Movements

No shared lanes are present on the major street, so this step is skipped.

Step 12: Compute Approach and Intersection Control Delay

The control delay for each approach is computed as follows:

$$d_{A,EB} = \frac{d_r v_r + d_t v_t + d_l v_l}{v_r + v_t + v_l} = \frac{(0)(100) + (0)(1{,}000) + (12.6)(50)}{100 + 1{,}000 + 50} = 0.5$$

$$d_{A,WB} = \frac{(0)(1{,}200) + (20.1)(125)}{1{,}200 + 125} = 1.9$$

$$d_{A,NB} = \frac{(16.1)(100) + (113)(75)}{100 + 75} = 57.6$$

The northbound approach is assigned LOS F. No LOS is assigned to the major-street approaches.

The intersection delay d_I is computed as follows:

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

$$= \frac{(0.5)(1{,}150) + (1.9)(1{,}325) + (57.6)(175)}{1{,}150 + 1{,}325 + 175} = 5.0$$

LOS is not defined for the intersection as a whole.

Step 13: Compute 95th Percentile Queue Lengths

The 95th percentile queue length for each movement is computed as follows:

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

$$Q_{95,1U} \approx 900(0.25)\left[\frac{50}{523} - 1 + \sqrt{\left(\frac{50}{523} - 1\right)^2 + \frac{\left(\frac{3{,}600}{523}\right)\left(\frac{50}{523}\right)}{150(0.25)}}\right]\left(\frac{523}{3{,}600}\right) = 0.3$$

$$Q_{95,4+4U} \approx 900(0.25)\left[\frac{125}{362} - 1 + \sqrt{\left(\frac{125}{362} - 1\right)^2 + \frac{\left(\frac{3{,}600}{362}\right)\left(\frac{125}{362}\right)}{150(0.25)}}\right]\left(\frac{362}{3{,}600}\right) = 1.5$$

$$Q_{95,9} \approx 900(0.25)\left[\frac{100}{425} - 1 + \sqrt{\left(\frac{100}{425} - 1\right)^2 + \frac{\left(\frac{3{,}600}{425}\right)\left(\frac{100}{425}\right)}{150(0.25)}}\right]\left(\frac{425}{3{,}600}\right) = 0.9$$

$$Q_{95,7} \approx 900(0.25)\left[\frac{75}{98} - 1 + \sqrt{\left(\frac{75}{98} - 1\right)^2 + \frac{\left(\frac{3{,}600}{98}\right)\left(\frac{75}{98}\right)}{150(0.25)}}\right]\left(\frac{98}{3{,}600}\right) = 4.1$$

Discussion

Overall, the results indicate that, while most minor movements are operating at low to moderate delays and at LOS C or better, the minor-street left turn experiences high delays and operates at LOS F.

4. METHODOLOGY FOR THREE-LANE AWSC APPROACHES

This section provides details for analyzing three-lane approaches at all-way STOP-controlled intersections. Exhibit 32-16 provides the 512 possible combinations of probability of degree-of-conflict cases when alternative lane occupancies are considered for three-lane approaches. A 1 indicates that a vehicle is in the lane; a 0 indicates that a vehicle is not in the lane.

The probability adjustment is computed with Equation 32-9 through Equation 32-13 to account for the serial correlation in the previous probability computation. First, the probability of each degree-of-conflict case must be determined (assuming the 512 cases presented in Exhibit 32-16).

Equation 32-9

$$P(C_1) = P(1)$$

Equation 32-10

$$P(C_2) = \sum_{i=2}^{8} P(i)$$

Equation 32-11

$$P(C_3) = \sum_{i=9}^{22} P(i)$$

Equation 32-12

$$P(C_4) = \sum_{i=23}^{169} P(i)$$

Equation 32-13

$$P(C_5) = \sum_{i=170}^{512} P(i)$$

The probability adjustment factors are then computed with Equation 32-14 through Equation 32-18.

Equation 32-14

$$AdjP(1) = \alpha\left[P(C_2) + 2P(C_3) + 3P(C_4) + 4P(C_5)\right]/1$$

Equation 32-15

$$AdjP(2) \text{ through } AdjP(8) = \alpha\left[P(C_3) + 2P(C_4) + 3P(C_5) - P(C_2)\right]/7$$

Equation 32-16

$$AdjP(9) \text{ through } AdjP(22) = \alpha\left[P(C_4) + 2P(C_5) - 3P(C_3)\right]/14$$

Equation 32-17

$$AdjP(23) \text{ through } AdjP(169) = \alpha\left[P(C_5) - 6P(C_4)\right]/147$$

Equation 32-18

$$AdjP(170) \text{ through } AdjP(512) = -\alpha\left[10P(C_5)\right]/343$$

where α equals 0.01 (or 0.00 if correlation among saturation headways is not taken into account).

The remaining part of the procedure is fundamentally the same as for two-lane approaches.

Exhibit 32-16
Probability of Degree-of-Conflict Case: Multilane AWSC Intersections (Three-Lane Approaches, by Lane) (Cases 1–49)

i	DOC Case	# of Vehicles	Opposing Approach L1	Opposing Approach L2	Opposing Approach L3	Conflicting Left Approach L1	Conflicting Left Approach L2	Conflicting Left Approach L3	Conflicting Right Approach L1	Conflicting Right Approach L2	Conflicting Right Approach L3
1	1	0	0	0	0	0	0	0	0	0	0
2	2	1	1	0	0	0	0	0	0	0	0
3			0	1	0	0	0	0	0	0	0
4			0	0	1	0	0	0	0	0	0
5		2	1	1	0	0	0	0	0	0	0
6			0	1	1	0	0	0	0	0	0
7			1	0	1	0	0	0	0	0	0
8		3	1	1	1	0	0	0	0	0	0
9	3	1	0	0	0	1	0	0	0	0	0
10			0	0	0	0	1	0	0	0	0
11			0	0	0	0	0	1	0	0	0
12			0	0	0	0	0	0	1	0	0
13			0	0	0	0	0	0	0	1	0
14			0	0	0	0	0	0	0	0	1
15		2	0	0	0	1	1	0	0	0	0
16			0	0	0	0	1	1	0	0	0
17			0	0	0	1	0	1	0	0	0
18			0	0	0	0	0	0	1	1	0
19			0	0	0	0	0	0	0	1	1
20			0	0	0	0	0	0	1	0	1
21		3	0	0	0	1	1	1	0	0	0
22			0	0	0	0	0	0	1	1	1
23	4	2	1	0	0	1	0	0	0	0	0
24			1	0	0	0	1	0	0	0	0
25			1	0	0	0	0	1	0	0	0
26			0	1	0	1	0	0	0	0	0
27			0	1	0	0	1	0	0	0	0
28			0	1	0	0	0	1	0	0	0
29			0	0	1	1	0	0	0	0	0
30			0	0	1	0	1	0	0	0	0
31			0	0	1	0	0	1	0	0	0
32			1	0	0	0	0	0	1	0	0
33			1	0	0	0	0	0	0	1	0
34			1	0	0	0	0	0	0	0	1
35			0	1	0	0	0	0	1	0	0
36			0	1	0	0	0	0	0	1	0
37			0	1	0	0	0	0	0	0	1
38			0	0	1	0	0	0	1	0	0
39			0	0	1	0	0	0	0	1	0
40			0	0	1	0	0	0	0	0	1
41			0	0	0	1	0	0	1	0	0
42			0	0	0	1	0	0	0	1	0
43			0	0	0	1	0	0	0	0	1
44			0	0	0	0	1	0	1	0	0
45			0	0	0	0	1	0	0	1	0
46			0	0	0	0	1	0	0	0	1
47			0	0	0	0	0	1	1	0	0
48			0	0	0	0	0	1	0	1	0
49			0	0	0	0	0	1	0	0	1

Exhibit 32-16 (cont'd.)
Probability of Degree-of-Conflict Case: Multilane AWSC Intersections (Three-Lane Approaches, by Lane) (Cases 50–112)

	DOC	# of	Opposing Approach			Conflicting Left Approach			Conflicting Right Approach		
i	Case	Vehicles	L1	L2	L3	L1	L2	L3	L1	L2	L3
50	4	3	1	1	0	1	0	0	0	0	0
51	(cont'd.)		1	1	0	0	1	0	0	0	0
52			1	1	0	0	0	1	0	0	0
53			0	1	1	1	0	0	0	0	0
54			0	1	1	0	1	0	0	0	0
55			0	1	1	0	0	1	0	0	0
56			1	0	1	1	0	0	0	0	0
57			1	0	1	0	1	0	0	0	0
58			1	0	1	0	0	1	0	0	0
59			1	1	0	0	0	0	1	0	0
60			1	1	0	0	0	0	0	1	0
61			1	1	0	0	0	0	0	0	1
62			0	1	1	0	0	0	1	0	0
63			0	1	1	0	0	0	0	1	0
64			0	1	1	0	0	0	0	0	1
65			1	0	1	0	0	0	1	0	0
66			1	0	1	0	0	0	0	1	0
67			1	0	1	0	0	0	0	0	1
68			1	0	0	1	1	0	0	0	0
69			1	0	0	0	1	1	0	0	0
70			1	0	0	1	0	1	0	0	0
71			0	1	0	1	1	0	0	0	0
72			0	1	0	0	1	1	0	0	0
73			0	1	0	1	0	1	0	0	0
74			0	0	1	1	1	0	0	0	0
75			0	0	1	0	1	1	0	0	0
76			0	0	1	1	0	1	0	0	0
77			0	0	0	1	1	0	1	0	0
78			0	0	0	1	1	0	0	1	0
79			0	0	0	1	1	0	0	0	1
80			0	0	0	0	1	1	1	0	0
81			0	0	0	0	1	1	0	1	0
82			0	0	0	0	1	1	0	0	1
83			0	0	0	1	0	1	1	0	0
84			0	0	0	1	0	1	0	1	0
85			0	0	0	1	0	1	0	0	1
86			1	0	0	0	0	0	1	1	0
87			1	0	0	0	0	0	0	1	1
88			1	0	0	0	0	0	1	0	1
89			0	1	0	0	0	0	1	1	0
90			0	1	0	0	0	0	0	1	1
91			0	1	0	0	0	0	1	0	1
92			0	0	1	0	0	0	1	1	0
93			0	0	1	0	0	0	0	1	1
94			0	0	1	0	0	0	1	0	1
95			0	0	0	1	0	0	1	1	0
96			0	0	0	1	0	0	0	1	1
97			0	0	0	1	0	0	1	0	1
98			0	0	0	0	1	0	1	1	0
99			0	0	0	0	1	0	0	1	1
100			0	0	0	0	1	0	1	0	1
101			0	0	0	0	0	1	1	1	0
102			0	0	0	0	0	1	0	1	1
103			0	0	0	0	0	1	1	0	1
104		4	1	1	0	1	1	0	0	0	0
105			1	1	0	0	1	1	0	0	0
106			1	1	0	1	0	1	0	0	0
107			0	1	1	1	1	0	0	0	0
108			0	1	1	0	1	1	0	0	0
109			0	1	1	1	0	1	0	0	0
110			1	0	1	1	1	0	0	0	0
111			1	0	1	0	1	1	0	0	0
112			1	0	1	1	0	1	0	0	0

Exhibit 32-16 (cont'd.)
Probability of Degree-of-Conflict Case: Multilane AWSC Intersections (Three-Lane Approaches, by Lane) (Cases 113–175)

			Opposing Approach			Conflicting Left Approach			Conflicting Right Approach		
i	DOC Case	# of Vehicles	L1	L2	L3	L1	L2	L3	L1	L2	L3
113	4	4	1	1	0	0	0	0	1	1	0
114	(cont'd.)	(cont'd.)	1	1	0	0	0	0	0	1	1
115			1	1	0	0	0	0	1	0	1
116			0	1	1	0	0	0	1	1	0
117			0	1	1	0	0	0	0	1	1
118			0	1	1	0	0	0	1	0	1
119			1	0	1	0	0	0	1	1	0
120			1	0	1	0	0	0	0	1	1
121			1	0	1	0	0	0	1	0	1
122			0	0	0	1	1	0	1	1	0
123			0	0	0	1	1	0	0	1	1
124			0	0	0	1	1	0	1	0	1
125			0	0	0	0	1	1	1	1	0
126			0	0	0	0	1	1	0	1	1
127			0	0	0	0	1	1	1	0	1
128			0	0	0	1	0	1	1	1	0
129			0	0	0	1	0	1	0	1	1
130			0	0	0	1	0	1	1	0	1
131			1	1	1	1	0	0	0	0	0
132			1	1	1	0	1	0	0	0	0
133			1	1	1	0	0	1	0	0	0
134			1	1	1	0	0	0	1	0	0
135			1	1	1	0	0	0	0	1	0
136			1	1	1	0	0	0	0	0	1
137			1	0	0	1	1	1	0	0	0
138			0	1	0	1	1	1	0	0	0
139			0	0	1	1	1	1	0	0	0
140			0	0	0	1	1	1	1	0	0
141			0	0	0	1	1	1	0	1	0
142			0	0	0	1	1	1	0	0	1
143			1	0	0	0	0	0	1	1	1
144			0	1	0	0	0	0	1	1	1
145			0	0	1	0	0	0	1	1	1
146			0	0	0	1	0	0	1	1	1
147			0	0	0	0	1	0	1	1	1
148			0	0	0	0	0	1	1	1	1
149		5	1	1	1	1	1	0	0	0	0
150			1	1	1	0	1	1	0	0	0
151			1	1	1	1	0	1	0	0	0
152			1	1	1	0	0	0	1	1	0
153			1	1	1	0	0	0	0	1	1
154			1	1	1	0	0	0	1	0	1
155			1	1	0	1	1	1	0	0	0
156			0	1	1	1	1	1	0	0	0
157			1	0	1	1	1	1	0	0	0
158			0	0	0	1	1	1	1	1	0
159			0	0	0	1	1	1	0	1	1
160			0	0	0	1	1	1	1	0	1
161			1	1	0	0	0	0	1	1	1
162			0	1	1	0	0	0	1	1	1
163			1	0	1	0	0	0	1	1	1
164			0	0	0	1	1	0	1	1	1
165			0	0	0	0	1	1	1	1	1
166			0	0	0	1	0	1	1	1	1
167		6	1	1	1	1	1	1	0	0	0
168			1	1	1	0	0	0	1	1	1
169			0	0	0	1	1	1	1	1	1
170	5	3	1	0	0	1	0	0	1	0	0
171			1	0	0	1	0	0	0	1	0
172			1	0	0	1	0	0	0	0	1
173			1	0	0	0	1	0	1	0	0
174			1	0	0	0	1	0	0	1	0
175			1	0	0	0	1	0	0	0	1

Exhibit 32-16 (cont'd.)
Probability of Degree-of-Conflict Case: Multilane AWSC Intersections (Three-Lane Approaches, by Lane) (Cases 176–238)

			Opposing Approach			Conflicting Left Approach			Conflicting Right Approach		
i	DOC Case	# of Vehicles	L1	L2	L3	L1	L2	L3	L1	L2	L3
176	5	3	1	0	0	0	0	1	1	0	0
177	(cont'd.)	(cont'd.)	1	0	0	0	0	1	0	1	0
178			1	0	0	0	0	1	0	0	1
179			0	1	0	1	0	0	1	0	0
180			0	1	0	1	0	0	0	1	0
181			0	1	0	1	0	0	0	0	1
182			0	1	0	0	1	0	1	0	0
183			0	1	0	0	1	0	0	1	0
184			0	1	0	0	1	0	0	0	1
185			0	1	0	0	0	1	1	0	0
186			0	1	0	0	0	1	0	1	0
187			0	1	0	0	0	1	0	0	1
188			0	0	1	1	0	0	1	0	0
189			0	0	1	1	0	0	0	1	0
190			0	0	1	1	0	0	0	0	1
191			0	0	1	0	1	0	1	0	0
192			0	0	1	0	1	0	0	1	0
193			0	0	1	0	1	0	0	0	1
194			0	0	1	0	0	1	1	0	0
195			0	0	1	0	0	1	0	1	0
196			0	0	1	0	0	1	0	0	1
197		4	1	1	0	1	0	0	1	0	0
198			1	1	0	1	0	0	0	1	0
199			1	1	0	1	0	0	0	0	1
200			1	1	0	0	1	0	1	0	0
201			1	1	0	0	1	0	0	1	0
202			1	1	0	0	1	0	0	0	1
203			1	1	0	0	0	1	1	0	0
204			1	1	0	0	0	1	0	1	0
205			1	1	0	0	0	1	0	0	1
206			0	1	1	1	0	0	1	0	0
207			0	1	1	1	0	0	0	1	0
208			0	1	1	1	0	0	0	0	1
209			0	1	1	0	1	0	1	0	0
210			0	1	1	0	1	0	0	1	0
211			0	1	1	0	1	0	0	0	1
212			0	1	1	0	0	1	1	0	0
213			0	1	1	0	0	1	0	1	0
214			0	1	1	0	0	1	0	0	1
215			1	0	1	1	0	0	1	0	0
216			1	0	1	1	0	0	0	1	0
217			1	0	1	1	0	0	0	0	1
218			1	0	1	0	1	0	1	0	0
219			1	0	1	0	1	0	0	1	0
220			1	0	1	0	1	0	0	0	1
221			1	0	1	0	0	1	1	0	0
222			1	0	1	0	0	1	0	1	0
223			1	0	1	0	0	1	0	0	1
224			1	0	0	1	1	0	1	0	0
225			1	0	0	1	1	0	0	1	0
226			1	0	0	1	1	0	0	0	1
227			1	0	0	0	1	1	1	0	0
228			1	0	0	0	1	1	0	1	0
229			1	0	0	0	1	1	0	0	1
230			1	0	0	1	0	1	1	0	0
231			1	0	0	1	0	1	0	1	0
232			1	0	0	1	0	1	0	0	1
233			0	1	0	1	1	0	1	0	0
234			0	1	0	1	1	0	0	1	0
235			0	1	0	1	1	0	0	0	1
236			0	1	0	0	1	1	1	0	0
237			0	1	0	0	1	1	0	1	0
238			0	1	0	0	1	1	0	0	1

Exhibit 32-16 (cont'd.)
Probability of Degree-of-Conflict Case: Multilane AWSC Intersections (Three-Lane Approaches, by Lane) (Cases 239–301)

			Opposing Approach			Conflicting Left Approach			Conflicting Right Approach		
i	DOC Case	# of Vehicles	L1	L2	L3	L1	L2	L3	L1	L2	L3
239	5	4	0	1	0	1	0	1	1	0	0
240	(cont'd.)	(cont'd.)	0	1	0	1	0	1	0	1	0
241			0	1	0	1	0	1	0	0	1
242			0	0	1	1	1	0	1	0	0
243			0	0	1	1	1	0	0	1	0
244			0	0	1	1	1	0	0	0	1
245			0	0	1	0	1	1	1	0	0
246			0	0	1	0	1	1	0	1	0
247			0	0	1	0	1	1	0	0	1
248			0	0	1	1	0	1	1	0	0
249			0	0	1	1	0	1	0	1	0
250			0	0	1	1	0	1	0	0	1
251			1	0	0	1	0	0	1	1	0
252			1	0	0	1	0	0	0	1	1
253			1	0	0	1	0	0	1	0	1
254			1	0	0	0	1	0	1	1	0
255			1	0	0	0	1	0	0	1	1
256			1	0	0	0	1	0	1	0	1
257			1	0	0	0	0	1	1	1	0
258			1	0	0	0	0	1	0	1	1
259			1	0	0	0	0	1	1	0	1
260			0	1	0	1	0	0	1	1	0
261			0	1	0	1	0	0	0	1	1
262			0	1	0	1	0	0	1	0	1
263			0	1	0	0	1	0	1	1	0
264			0	1	0	0	1	0	0	1	1
265			0	1	0	0	1	0	1	0	1
266			0	1	0	0	0	1	1	1	0
267			0	1	0	0	0	1	0	1	1
268			0	1	0	0	0	1	1	0	1
269			0	0	1	1	0	0	1	1	0
270			0	0	1	1	0	0	0	1	1
271			0	0	1	1	0	0	1	0	1
272			0	0	1	0	1	0	1	1	0
273			0	0	1	0	1	0	0	1	1
274			0	0	1	0	1	0	1	0	1
275			0	0	1	0	0	1	1	1	0
276			0	0	1	0	0	1	0	1	1
277			0	0	1	0	0	1	1	0	1
278		5	1	1	0	1	1	0	1	0	0
279			1	1	0	1	1	0	0	1	0
280			1	1	0	1	1	0	0	0	1
281			1	1	0	0	1	1	1	0	0
282			1	1	0	0	1	1	0	1	0
283			1	1	0	0	1	1	0	0	1
284			1	1	0	1	0	1	1	0	0
285			1	1	0	1	0	1	0	1	0
286			1	1	0	1	0	1	0	0	1
287			0	1	1	1	1	0	1	0	0
288			0	1	1	1	1	0	0	1	0
289			0	1	1	1	1	0	0	0	1
290			0	1	1	0	1	1	1	0	0
291			0	1	1	0	1	1	0	1	0
292			0	1	1	0	1	1	0	0	1
293			0	1	1	1	0	1	1	0	0
294			0	1	1	1	0	1	0	1	0
295			0	1	1	1	0	1	0	0	1
296			1	0	1	1	1	0	1	0	0
297			1	0	1	1	1	0	0	1	0
298			1	0	1	1	1	0	0	0	1
299			1	0	1	0	1	1	1	0	0
300			1	0	1	0	1	1	0	1	0
301			1	0	1	0	1	1	0	0	1

Exhibit 32-16 (cont'd.)
Probability of Degree-of-Conflict Case: Multilane AWSC Intersections (Three-Lane Approaches, by Lane) (Cases 302–364)

			Opposing Approach			Conflicting Left Approach			Conflicting Right Approach		
i	DOC Case	# of Vehicles	L1	L2	L3	L1	L2	L3	L1	L2	L3
302	5	5	1	0	1	1	0	1	1	0	0
303	(cont'd.)	(cont'd.)	1	0	1	1	0	1	0	1	0
304			1	0	1	1	0	1	0	0	1
305			1	1	0	1	0	0	1	1	0
306			1	1	0	0	1	0	1	1	0
307			1	1	0	0	0	1	1	1	0
308			1	1	0	1	0	0	0	1	1
309			1	1	0	0	1	0	0	1	1
310			1	1	0	0	0	1	0	1	1
311			1	1	0	1	0	0	1	0	1
312			1	1	0	0	1	0	1	0	1
313			1	1	0	0	0	1	1	0	1
314			0	1	1	1	0	0	1	1	0
315			0	1	1	0	1	0	1	1	0
316			0	1	1	0	0	1	1	1	0
317			0	1	1	1	0	0	0	1	1
318			0	1	1	0	1	0	0	1	1
319			0	1	1	0	0	1	0	1	1
320			0	1	1	1	0	0	1	0	1
321			0	1	1	0	1	0	1	0	1
322			0	1	1	0	0	1	1	0	1
323			1	0	1	1	0	0	1	1	0
324			1	0	1	0	1	0	1	1	0
325			1	0	1	0	0	1	1	1	0
326			1	0	1	1	0	0	0	1	1
327			1	0	1	0	1	0	0	1	1
328			1	0	1	0	0	1	0	1	1
329			1	0	1	1	0	0	1	0	1
330			1	0	1	0	1	0	1	0	1
331			1	0	1	0	0	1	1	0	1
332			1	0	0	1	1	0	1	1	0
333			1	0	0	1	1	0	0	1	1
334			1	0	0	1	1	0	1	0	1
335			1	0	0	0	1	1	1	1	0
336			1	0	0	0	1	1	0	1	1
337			1	0	0	0	1	1	1	0	1
338			1	0	0	1	0	1	1	1	0
339			1	0	0	1	0	1	0	1	1
340			1	0	0	1	0	1	1	0	1
341			0	1	0	1	1	0	1	1	0
342			0	1	0	1	1	0	0	1	1
343			0	1	0	1	1	0	1	0	1
344			0	1	0	0	1	1	1	1	0
345			0	1	0	0	1	1	0	1	1
346			0	1	0	0	1	1	1	0	1
347			0	1	0	1	0	1	1	1	0
348			0	1	0	1	0	1	0	1	1
349			0	1	0	1	0	1	1	0	1
350			0	0	1	1	1	0	1	1	0
351			0	0	1	1	1	0	0	1	1
352			0	0	1	1	1	0	1	0	1
353			0	0	1	0	1	1	1	1	0
354			0	0	1	0	1	1	0	1	1
355			0	0	1	0	1	1	1	0	1
356			0	0	1	1	0	1	1	1	0
357			0	0	1	1	0	1	0	1	1
358			0	0	1	1	0	1	1	0	1
359			1	1	1	1	0	0	1	0	0
360			1	1	1	1	0	0	0	1	0
361			1	1	1	1	0	0	0	0	1
362			1	1	1	0	1	0	1	0	0
363			1	1	1	0	1	0	0	1	0
364			1	1	1	0	1	0	0	0	1

Exhibit 32-16 (cont'd.)
Probability of Degree-of-Conflict Case: Multilane AWSC Intersections (Three-Lane Approaches, by Lane) (Cases 365–427)

			Opposing Approach			Conflicting Left Approach			Conflicting Right Approach		
i	DOC Case	# of Vehicles	L1	L2	L3	L1	L2	L3	L1	L2	L3
365	5	5	1	1	1	0	0	1	1	0	0
366	(cont'd.	(cont'd.)	1	1	1	0	0	1	0	1	0
367			1	1	1	0	0	1	0	0	1
368			1	0	0	1	1	1	1	0	0
369			1	0	0	1	1	1	0	1	0
370			1	0	0	1	1	1	0	0	1
371			0	1	0	1	1	1	1	0	0
372			0	1	0	1	1	1	0	1	0
373			0	1	0	1	1	1	0	0	1
374			0	0	1	1	1	1	1	0	0
375			0	0	1	1	1	1	0	1	0
376			0	0	1	1	1	1	0	0	1
377			1	0	0	1	0	0	1	1	1
378			1	0	0	0	1	0	1	1	1
379			1	0	0	0	0	1	1	1	1
380			0	1	0	1	0	0	1	1	1
381			0	1	0	0	1	0	1	1	1
382			0	1	0	0	0	1	1	1	1
383			0	0	1	1	0	0	1	1	1
384			0	0	1	0	1	0	1	1	1
385			0	0	1	0	0	1	1	1	1
386		6	1	1	0	1	1	0	1	1	0
387			1	1	0	1	1	0	0	1	1
388			1	1	0	1	1	0	1	0	1
389			1	1	0	0	1	1	1	1	0
390			1	1	0	0	1	1	0	1	1
391			1	1	0	0	1	1	1	0	1
392			1	1	0	1	0	1	1	1	0
393			1	1	0	1	0	1	0	1	1
394			1	1	0	1	0	1	1	0	1
395			0	1	1	1	1	0	1	1	0
396			0	1	1	1	1	0	0	1	1
397			0	1	1	1	1	0	1	0	1
398			0	1	1	0	1	1	1	1	0
399			0	1	1	0	1	1	0	1	1
400			0	1	1	0	1	1	1	0	1
401			0	1	1	1	0	1	1	1	0
402			0	1	1	1	0	1	0	1	1
403			0	1	1	1	0	1	1	0	1
404			1	0	1	1	1	0	1	1	0
405			1	0	1	1	1	0	0	1	1
406			1	0	1	1	1	0	1	0	1
407			1	0	1	0	1	1	1	1	0
408			1	0	1	0	1	1	0	1	1
409			1	0	1	0	1	1	1	0	1
410			1	0	1	1	0	1	1	1	0
411			1	0	1	1	0	1	0	1	1
412			1	0	1	1	0	1	1	0	1
413			1	1	1	1	1	0	1	0	0
414			1	1	1	1	1	0	0	1	0
415			1	1	1	1	1	0	0	0	1
416			1	1	1	0	1	1	1	0	0
417			1	1	1	0	1	1	0	1	0
418			1	1	1	0	1	1	0	0	1
419			1	1	1	1	0	1	1	0	0
420			1	1	1	1	0	1	0	1	0
421			1	1	1	1	0	1	0	0	1
422			1	1	1	1	0	0	1	1	0
423			1	1	1	1	0	0	0	1	1
424			1	1	1	1	0	0	1	0	1
425			1	1	1	0	1	0	1	1	0
426			1	1	1	0	1	0	0	1	1
427			1	1	1	0	1	0	1	0	1

Exhibit 32-16 (cont'd.)
Probability of Degree-of-Conflict Case: Multilane AWSC Intersections (Three-Lane Approaches, by Lane) (Cases 428–490)

			Opposing Approach			Conflicting Left Approach			Conflicting Right Approach		
i	DOC Case	# of Vehicles	L1	L2	L3	L1	L2	L3	L1	L2	L3
428	5	6	1	1	1	0	0	1	1	1	0
429	(cont'd.)	(cont'd.)	1	1	1	0	0	1	0	1	1
430			1	1	1	0	0	1	1	0	1
431			1	1	0	1	1	1	1	0	0
432			1	1	0	1	1	1	0	1	0
433			1	1	0	1	1	1	0	0	1
434			0	1	1	1	1	1	1	0	0
435			0	1	1	1	1	1	0	1	0
436			0	1	1	1	1	1	0	0	1
437			1	0	1	1	1	1	1	0	0
438			1	0	1	1	1	1	0	1	0
439			1	0	1	1	1	1	0	0	1
440			1	0	0	1	1	1	1	1	0
441			1	0	0	1	1	1	0	1	1
442			1	0	0	1	1	1	1	0	1
443			0	1	0	1	1	1	1	1	0
444			0	1	0	1	1	1	0	1	1
445			0	1	0	1	1	1	1	0	1
446			0	0	1	1	1	1	1	1	0
447			0	0	1	1	1	1	0	1	1
448			0	0	1	1	1	1	1	0	1
449			1	1	0	1	0	0	1	1	1
450			1	1	0	0	1	0	1	1	1
451			1	1	0	0	0	1	1	1	1
452			0	1	1	1	0	0	1	1	1
453			0	1	1	0	1	0	1	1	1
454			0	1	1	0	0	1	1	1	1
455			1	0	1	1	0	0	1	1	1
456			1	0	1	0	1	0	1	1	1
457			1	0	1	0	0	1	1	1	1
458			1	0	0	1	1	0	1	1	1
459			1	0	0	0	1	1	1	1	1
460			1	0	0	1	0	1	1	1	1
461			0	1	0	1	1	0	1	1	1
462			0	1	0	0	1	1	1	1	1
463			0	1	0	1	0	1	1	1	1
464			0	0	1	1	1	0	1	1	1
465			0	0	1	0	1	1	1	1	1
466			0	0	1	1	0	1	1	1	1
467		7	1	1	1	1	1	0	1	1	0
468			1	1	1	1	1	0	0	1	1
469			1	1	1	1	1	0	1	0	1
470			1	1	1	0	1	1	1	1	0
471			1	1	1	0	1	1	0	1	1
472			1	1	1	0	1	1	1	0	1
473			1	1	1	1	0	1	1	1	0
474			1	1	1	1	0	1	0	1	1
475			1	1	1	1	0	1	1	0	1
476			1	1	0	1	1	1	1	1	0
477			1	1	0	1	1	1	0	1	1
478			1	1	0	1	1	1	1	0	1
479			0	1	1	1	1	1	1	1	0
480			0	1	1	1	1	1	0	1	1
481			0	1	1	1	1	1	1	0	1
482			1	0	1	1	1	1	1	1	0
483			1	0	1	1	1	1	0	1	1
484			1	0	1	1	1	1	1	0	1
485			1	1	0	1	1	0	1	1	1
486			1	1	0	0	1	1	1	1	1
487			1	1	0	1	0	1	1	1	1
488			0	1	1	1	1	0	1	1	1
489			0	1	1	0	1	1	1	1	1
490			0	1	1	1	0	1	1	1	1

Exhibit 32-16 (cont'd.)
Probability of Degree-of-Conflict Case: Multilane AWSC Intersections (Three-Lane Approaches, by Lane) (Cases 491–512)

i	DOC Case	# of Vehicles	Opposing Approach L1	Opposing Approach L2	Opposing Approach L3	Conflicting Left Approach L1	Conflicting Left Approach L2	Conflicting Left Approach L3	Conflicting Right Approach L1	Conflicting Right Approach L2	Conflicting Right Approach L3
491	5	7	1	0	1	1	1	0	1	1	1
492	(cont'd.)	(cont'd.)	1	0	1	0	1	1	1	1	1
493			1	0	1	1	0	1	1	1	1
494			1	1	1	1	1	1	1	0	0
495			1	1	1	1	1	1	0	1	0
496			1	1	1	1	1	1	0	0	1
497			1	1	1	1	0	0	1	1	1
498			1	1	1	0	1	0	1	1	1
499			1	1	1	0	0	1	1	1	1
500			1	0	0	1	1	1	1	1	1
501			0	1	0	1	1	1	1	1	1
502			0	0	1	1	1	1	1	1	1
503		8	1	1	1	1	1	1	1	1	0
504			1	1	1	1	1	1	0	1	1
505			1	1	1	1	1	1	1	0	1
506			1	1	1	1	1	0	1	1	1
507			1	1	1	0	1	1	1	1	1
508			1	1	1	1	0	1	1	1	1
509			1	1	0	1	1	1	1	1	1
510			0	1	1	1	1	1	1	1	1
511			1	0	1	1	1	1	1	1	1
512		9	1	1	1	1	1	1	1	1	1

Note: "DOC Case" is the degree-of-conflict case, "# of vehicles" is the total number of vehicles on the opposing and conflicting approaches, L1 is Lane 1, L2 is Lane 2, and L3 is Lane 3.

5. AWSC SUPPLEMENTAL EXAMPLE PROBLEMS

Example Problem 1 appears in Chapter 20.

This part of the chapter provides additional example problems for use of the AWSC methodology. Exhibit 32-17 provides an overview of these problems. The examples focus on the operational analysis level. The planning and preliminary engineering analysis level is identical to the operations analysis level in terms of the calculations, except that default values are used where available.

Exhibit 32-17
AWSC Example Problems

Problem Number	Description	Analysis Level
1	Details for Example Problem 1 (Chapter 20)	Operational
2	Analyze a multilane, four-leg AWSC intersection	Operational

HEADWAY ADJUSTMENT FACTOR CALCULATION DETAILS FOR AWSC EXAMPLE PROBLEM 1

This section provides details of the calculations used to determine the headway adjustment factors in Example Problem 1 in Chapter 20, All-Way STOP-Controlled Intersections. In the following, EB means eastbound, WB means westbound, NB means northbound, SB means southbound, L1 means Lane 1, and L2 means Lane 2.

	EB L1	EB L2	WB L1	WB L2	NB L1	NB L2	SB L1	SB L2
Total lane flow rate	368		421				158	
LT flow rate in lane	53	0	0	0	0	0	105	0
RT flow rate in lane	0	0	105	0	0	0	53	0
Prop LT in lane	0.143		0.000				0.667	
Prop RT in lane	0.000		0.250				0.333	
Prop HV in Lane	0.02		0.02				0.02	
Geometry Group	1		1				1	
hL Tadj T 10-18	0.2		0.2				0.2	
hR Tadj T 10-18	-0.6		-0.6				-0.6	
hH Tadj T 10-18	1.7		1.7				1.7	
hadj	0.063		-0.116				-0.033	

	EB L1	EB L2	WB L1	WB L2	NB L1	NB L2	SB L1	SB L2
Total lane flow rate	368		421				158	
hd, initial value, Iteration 1	3.2		3.2				3.2	
x, initial, Iteration 1	0.327		0.374				0.140	
hd, computed value, Iteration 1	4.57		4.35				5.14	
Convergence?	N		N				N	
hd, initial value, Iteration 2	4.57		4.35				5.14	
x, initial, Iteration 2	0.468		0.509				0.225	
hd, computed value, Iteration 2	4.88		4.66				5.59	
Convergence?	N		N				N	
hd, initial value, Iteration 3	4.88		4.66				5.59	
x, initial, Iteration 3	0.499		0.545				0.245	
hd, computed value, Iteration 3	4.95		4.73				5.70	
Convergence?	Y		Y				N	
hd, initial value, Iteration 4	4.88		4.66				5.70	
x, initial, Iteration 4	0.499		0.545				0.250	
hd, computed value, Iteration 4	4.97		4.74				5.70	
Convergence?	Y		Y				Y	

Eastbound approach (EB L1), Iteration 1

	PaO1	PaCL1	PaCR1	P[Ci]	h_base	h_adj	h_si
1	0.6257	0.8596	1	0.5379	3.900	0.063	3.963
2	0.3743	0.8596	1	0.3217	4.700	0.063	4.763
5	0.6257	0.1404	1	0.0878	5.800	0.063	5.863
7	0.6257	0.8596	0	0	5.800		
13	0.6257	0.1404	0	0	7.000		
16	0.3743	0.1404	1	0.0525	7.000	0.063	7.063
21	0.3743	0.8596	0	0	7.000		
45	0.3743	0.1404	0	0	9.600		
						Sum:	4.571

DOC	SumPC1	SumPC2	SumPC3	SumPC4	SumPC5			Pcadj	PCiFinal
1	0.53791							0.006550	0.544459
2		0.32174						-0.000430	0.321310
3			0.08782					-0.000352	0.087470
3			0.00000					-0.000352	-0.000352
4				0.00000				-0.000117	-0.000117
4				0.05253				-0.000117	0.052412
4				0.00000				-0.000117	-0.000117
5					0.00000			0.000000	0.000000
PC	0.53791	0.32174	0.08782	0.05253	0.00000				
Count	1	3	6	27	27				
PCAdj	0.00655	-0.00043	-0.00035	-0.00012	0.00000	0.0057	Sum:	0.000000	1.000000

	EB L1	EB L2	WB L1	WB L2	NB L1	NB L2	SB L1	SB L2
Total lane flow rate	368		421				158	
Service time	2.97		2.74				3.70	
Degree of utilization, x	0.508		0.555				0.250	
Departure headway, hd	4.97		4.74				5.70	
Capacity								
Delay	13.0		13.5				10.6	
Level of service	B		B				B	
Delay, approach	13.0		13.5				10.6	
LOS approach	B		B				B	
Delay, intersection				12.8				
LOS intersection				B				
95th percentile queue length	2.9		3.5				1.0	

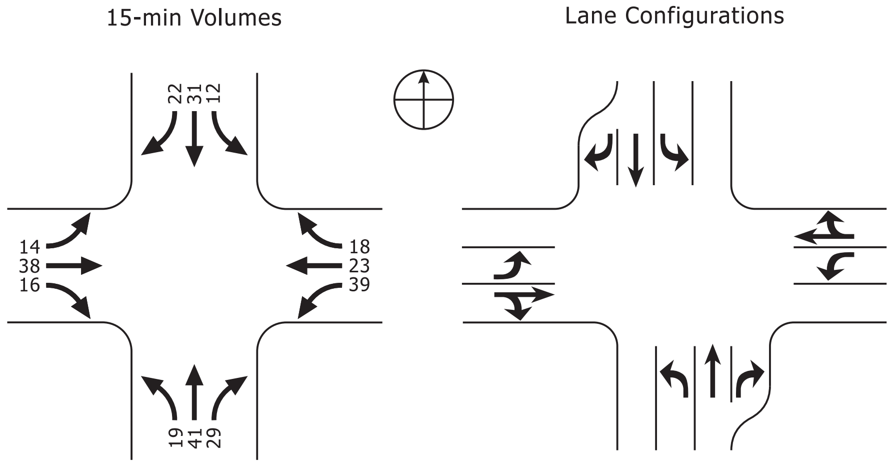
AWSC EXAMPLE PROBLEM 2: MULTILANE, FOUR-LEG INTERSECTION

The Facts

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

- Four legs;
- Two-lane approaches on the east and west legs;
- Three-lane approaches on the north and south legs;
- Percent heavy vehicles on all approaches = 2%;
- Demand volumes are provided in 15-min intervals (therefore, a peak hour factor is not required), and the analysis period length is 0.25 h; and
- Volumes and lane configurations as shown in Exhibit 32-18.

Exhibit 32-18
AWSC Example Problem 2: 15-min Volumes and Lane Configurations



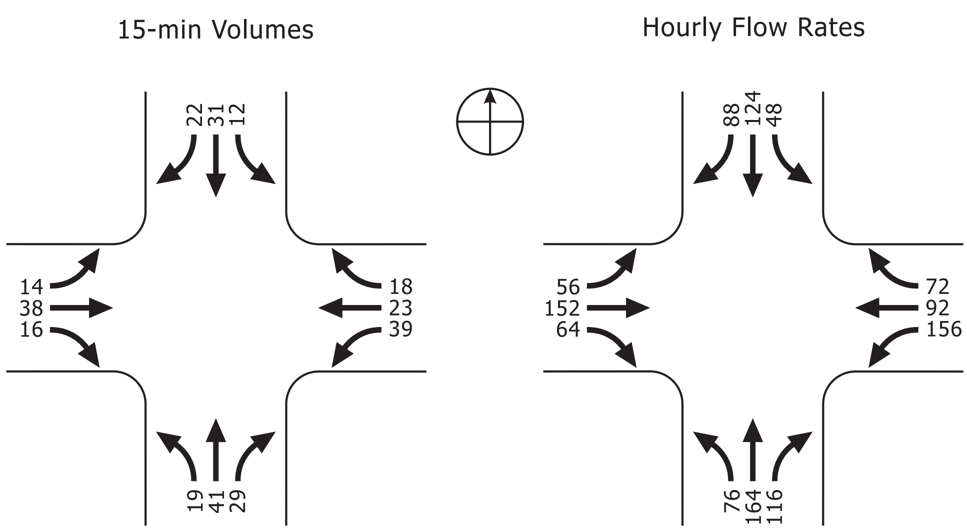
Comments

All input parameters are known, so no default values are needed or used. The use of a spreadsheet or software is required because of the several thousand repetitive computations needed. Slight differences in reported values may result from rounding differences between manual and software computations. Because it is not practical to show all the individual computations, this example problem will show how one or more computations are made. All the computational results can be found in the spreadsheet output, located in the Volume 4 Technical Reference Library for Chapter 20, All-Way STOP-Controlled Intersections.

Step 1: Convert Movement Demand Volumes to Flow Rates

To convert the peak 15-min demand volumes to hourly flow rates, the individual movement volumes are simply multiplied by four, as shown in Exhibit 32-19:

Exhibit 32-19
AWSC Example Problem 2: Hourly Flow Rates



Step 2: Determine Lane Flow Rates

This step simply involves assigning the turning movement volume to each of the approach lanes. The left-turn volume is assigned to the separate left-turn lane on each approach. For the east and west approaches, the through and right-turn volumes are assigned to the shared through and right lanes. For the north and south approaches, the through volumes are assigned to the through lanes and the right-turn volumes are assigned to the right-turn lanes.

Step 3: Determine Geometry Group for Each Approach

Exhibit 20-10 shows that each approach should be assigned to Geometry Group 6.

Step 4: Determine Saturation Headway Adjustments

Exhibit 20-11 shows that the headway adjustments for left turns, right turns, and heavy vehicles are 0.5, –0.7, and 1.7, respectively. These values apply to all approaches as all are assigned Geometry Group 6. The saturation headway adjustment for the eastbound approach is as follows for Lane 1 (the left-turn lane):

$$h_{adj} = h_{LT,adj}P_{LT} + h_{RT,adj}P_{RT} + h_{HV,adj}P_{HV}$$

$$h_{adj} = 0.5(1.0) - 0.7(0) + 1.7(0.02) = 0.534$$

Similarly, the saturation headway adjustment for Lane 2 of the eastbound approach is as follows:

$$h_{adj} = 0.2(0) - 0.6\frac{64}{64+216} + 1.7(0.02) = -0.173$$

The saturation headway adjustment for all the remaining lanes by approach is similarly calculated. The full computational results can be seen in the "HdwyAdj" spreadsheet tab.

Steps 5 Through 11: Determine Departure Headway

These steps are iterative and, for this example, involve several thousand calculations. The following narrative highlights some of the key calculations using the eastbound approach for Iteration 1 but does not attempt to reproduce all calculations for all iterations. The full computational results for each of the iterative computations can be seen in the "DepHdwyIterX" spreadsheet tab, where "X" is the iteration.

Step 6: Calculate Initial Degree of Utilization

The remainder of this example illustrates the calculations needed to evaluate Lane 1 on the eastbound approach (eastbound left turn). Step 6 requires calculating the initial degree of utilization for all the opposing and conflicting lanes. They are computed as follows:

$$x, WB(\text{Lane 1}) = \frac{vh_d}{3{,}600} = \frac{(156)(3.2)}{3{,}600} = 0.1387$$

$$x, WB(\text{Lane 2}) = \frac{vh_d}{3{,}600} = \frac{(164)(3.2)}{3{,}600} = 0.1458$$

$$x, NB(\text{Lane 1}) = \frac{vh_d}{3{,}600} = \frac{(76)(3.2)}{3{,}600} = 0.0676$$

$$x, NB(\text{Lane } 2) = \frac{vh_d}{3{,}600} = \frac{(164)(3.2)}{3{,}600} = 0.1458$$

$$x, NB(\text{Lane } 3) = \frac{vh_d}{3{,}600} = \frac{(116)(3.2)}{3{,}600} = 0.1031$$

$$x, SB(\text{Lane } 1) = \frac{vh_d}{3{,}600} = \frac{(48)(3.2)}{3{,}600} = 0.0427$$

$$x, SB(\text{Lane } 2) = \frac{vh_d}{3{,}600} = \frac{(124)(3.2)}{3{,}600} = 0.1102$$

$$x, SB(\text{Lane } 3) = \frac{vh_d}{3{,}600} = \frac{(88)(3.2)}{3{,}600} = 0.0782$$

Step 7: Compute Probability States

The probability state of each combination i is determined with Equation 20-15:

$$P(i) = \prod_j P(a_j) = P(a_O)P(a_{CL})P(a_{CR})$$

As illustrated in Example Problem 1 in Chapter 20, for an intersection with single-lane approaches, only eight cases from Exhibit 20-13 apply. However, to evaluate three-lane approaches, Exhibit 32-16 is required. Exhibit 32-16 is an expanded version of Exhibit 20-13 that provides the 512 possible combinations of probability of degree-of-conflict cases.

For example, the probability state for the eastbound leg under the condition of no opposing vehicles on the other approaches (Degree-of-Conflict Case 1, $i = 1$) is as follows (using Exhibit 20-6):

$P(a_{O1}) = 1 - x_{O1} = 1 - 0.1387 = 0.8613$ (opposing westbound Lane 1)

$P(a_{O2}) = 1 - x_{O2} = 1 - 0.1458 = 0.8542$ (opposing westbound Lane 2)

$P(a_{CL1}) = 1 - x_{CL1} = 1 - 0.0427 = 0.9573$ (conflicting from left Lane 1)

$P(a_{CL2}) = 1 - x_{CL2} = 1 - 0.1102 = 0.8898$ (conflicting from left Lane 2)

$P(a_{CL3}) = 1 - x_{CL3} = 1 - 0.0782 = 0.9218$ (conflicting from left Lane 3)

$P(a_{CR1}) = 1 - x_{CR1} = 1 - 0.0676 = 0.9324$ (conflicting from right Lane 1)

$P(a_{CR2}) = 1 - x_{CR2} = 1 - 0.1458 = 0.8542$ (conflicting from right Lane 2)

$P(a_{CR3}) = 1 - x_{CR3} = 1 - 0.1031 = 0.8969$ (conflicting from right Lane 3)

Therefore,

$$P(1) = P(a_{O1})P(a_{O2})P(a_{CL1})P(a_{CL2})P(a_{CL3})P(a_{CR1})P(a_{CR2})P(a_{CR3})$$
$$= (0.8613)(0.8542)(0.9573)(0.8898)(0.9218)(0.9324)(0.8542)(0.8969)$$
$$= 0.4127$$

To complete the calculations for Step 7, the computations are completed for the remaining 511 possible combinations. The full computational results for the eastbound (Lane 1) can be seen in the "DepHdwyIter1" spreadsheet tab, Rows 3118–3629 (Columns C–K).

Step 8: Compute Probability Adjustment Factors

The probability adjustment is computed with Equation 20-1 through Equation 20-5 to account for the serial correlation in the previous probability computation. First, the probability of each degree-of-conflict case must be determined (assuming the 512 cases presented in Exhibit 32-16):

$$P(C_1) = P(1)$$

$$P(C_2) = \sum_{i=2}^{8} P(i)$$

$$P(C_3) = \sum_{i=9}^{22} P(i)$$

$$P(C_4) = \sum_{i=23}^{169} P(i)$$

$$P(C_5) = \sum_{i=170}^{512} P(i)$$

Again for the example of eastbound (Lane 1), these computations are made by summing Rows 3118–3629 in the spreadsheet for each of the five cases (Columns R–V). The resulting computations are shown in Row 3630 (Columns R–V), where

$$P(C_1) = 0.4127$$

$$P(C_2) = 0.1482$$

$$P(C_3) = 0.2779$$

$$P(C_4) = 0.1450$$

$$P(C_5) = 0.0162$$

The probability adjustment factors are then computed with Equation 32-14 through Equation 32-18, where α equals 0.01 (or 0.00 if correlation among saturation headways is not taken into account).

For example, by using Equation 32-14:

$$AdjP(1) = 0.01[0.1482 + 2(0.2779) + 3(0.1450) + 4(0.0162)]/1 = 0.01204$$

The results of the remaining computations (Equation 32-15 to Equation 32-18) for eastbound Lane 1 are located in Row 3632 of the spreadsheet (Columns S–V).

Step 9: Compute Saturation Headways

The base saturation headways for each of the 512 combinations can be determined with Exhibit 20-14. They are adjusted by using the adjustment factors calculated in Step 4 and added to the base saturation headways to determine saturation headways.

For the example of eastbound (Lane 1), these computations are shown in Rows 3118–3629 of the spreadsheet (Columns M–O).

Step 10: Compute Departure Headways

The departure headway of the approach is the sum of the products of the adjusted probabilities and the saturation headways. For the example of eastbound (Lane 1), these computations are made by summing the product of Columns O and Y for Rows 3118–3629 in the example spreadsheet.

Step 11: Check for Convergence

The calculated values of h_d are checked against the assumed initial values for h_d. After one iteration, each calculated headway differs from the initial value by more than 0.1 s. Therefore, the new calculated headway values are used as initial values in a second iteration. For this problem, five iterations were required for convergence.

	EB L1	EB L2	EB L3	WB L1	WB L2	WB L3	NB L1	NB L2	NB L3	SB L1	SB L2	SB L3
Total lane flow rate	56	216		156	164		76	164	116	48	124	88
hd, initial value, Iteration 1	3.2	3.2		3.2	3.2		3.2	3.2	3.2	3.2	3.2	3.2
x, initial, Iteration 1	0.0498	0.192		0.1387	0.1458		0.0676	0.1458	0.1031	0.0427	0.1102	0.0782
hd, computed value, Iteration 1	6.463	5.755		6.405	5.597		6.440	5.935	5.228	6.560	6.055	5.347
Convergence?	N	N		N	N		N	N	N	N	N	N
hd, initial value, Iteration 2	6.463	5.755		6.405	5.597		6.440	5.935	5.228	6.560	6.055	5.347
x, initial, Iteration 2	0.1005	0.3453		0.2776	0.255		0.136	0.2704	0.1685	0.0875	0.2086	0.1307
hd, computed value, Iteration 2	7.550	6.838		7.440	6.629		7.537	7.027	6.313	7.740	7.230	6.515
Convergence?	N	N		N	N		N	N	N	N	N	N
hd, initial value, Iteration 3	7.550	6.838		7.440	6.629		7.537	7.027	6.313	7.740	7.230	6.515
x, initial, Iteration 3	0.1174	0.4103		0.3224	0.302		0.1591	0.3201	0.2034	0.1032	0.249	0.1593
hd, computed value, Iteration 3	7.970	7.257		7.854	7.041		7.954	7.442	6.725	8.187	7.675	6.957
Convergence?	N	N		N	N		N	N	N	N	N	N
hd, initial value, Iteration 4	7.970	7.257		7.854	7.041		7.954	7.442	6.725	8.187	7.675	6.957
x, initial, Iteration 4	0.124	0.4354		0.3404	0.3208		0.1679	0.339	0.2167	0.1092	0.2643	0.17
hd, computed value, Iteration 4	8.130	7.416		8.010	7.196		8.114	7.601	6.884	8.359	7.845	7.126
Convergence?	N	N		N	N		N	N	N	N	N	N
hd, initial value, Iteration 5	8.130	7.416		8.010	7.196		8.114	7.601	6.884	8.359	7.845	7.126
x, initial, Iteration 5	0.1265	0.445		0.3471	0.3278		0.1713	0.3463	0.2218	0.1115	0.2702	0.1742
hd, computed value, Iteration 5	8.191	7.476		8.069	7.255		8.174	7.661	6.943	8.424	7.910	7.190
Convergence?	Y	Y		Y	Y		Y	Y	Y	Y	Y	Y

Step 12: Compute Capacity

As noted in the procedure, the capacity of each approach is computed by increasing the given flow rate on the subject lane (assuming the flows on the opposing and conflicting approaches are constant) until the degree of utilization for the subject lane reaches 1. This level of calculation requires running an iterative procedure many times, which is practical only for a spreadsheet or software implementation.

For this example, the capacity of eastbound Lane 1 can be found to be approximately 420 veh/h. This value is lower than the value that could be estimated by dividing the approach volume by the degree of utilization (56/0.1265 = 443 veh/h). The difference is due to the interaction effects among the approaches: increases in eastbound traffic volume increase the departure headways of the other approaches, which increases the departure headway of the subject approach.

Step 13: Compute Service Times

The service time required to calculate control delay is computed on the basis of the final calculated departure headway and the move-up time by using Equation 20-29. For the eastbound Lane 1 (using a value for m of 2.3 for Geometry Group 6), the calculation is as follows:

$$t_s = h_d - m = 8.19 - 2.3 = 5.89$$

Step 14: Compute Control Delay

The control delay for each approach is computed with Equation 20-30 as follows (eastbound Lane 1 illustrated):

$$d = 5.89 + 900(0.25)\left[(0.1274-1) + \sqrt{(0.1274-1)^2 + \frac{(8.19)(0.1274)}{(450)(0.25)}}\right] + 5 = 12.1\ \text{s}$$

On the basis of Exhibit 20-2, eastbound Lane 1 is assigned LOS B.

Step 15: Compute Queue Length

The 95th percentile queue for each lane is computed with Equation 20-33 as follows for eastbound Lane 1:

$$Q_{95} \approx \frac{900(0.25)}{8.19}\left[(0.1274-1) + \sqrt{(0.1274-1)^2 + \frac{(8.19)(0.1274)}{(150)(0.25)}}\right] = 0.4\ \text{veh}$$

This queue length commonly would be rounded up to 1 vehicle.

Discussion

The overall results can be found in the "DelayLOS" spreadsheet tab. As indicated in the output, all movements at the intersection are operating well with small delays. The worst-performing movement is eastbound Lane 2, which is operating with a volume-to-capacity ratio of 0.45 and a control delay of 16.1 s/veh, which results in LOS C.