CHAPTER 32
STOP-CONTROLLED INTERSECTIONS: SUPPLEMENTAL

CONTENTS

LIST OF EXHIBITS

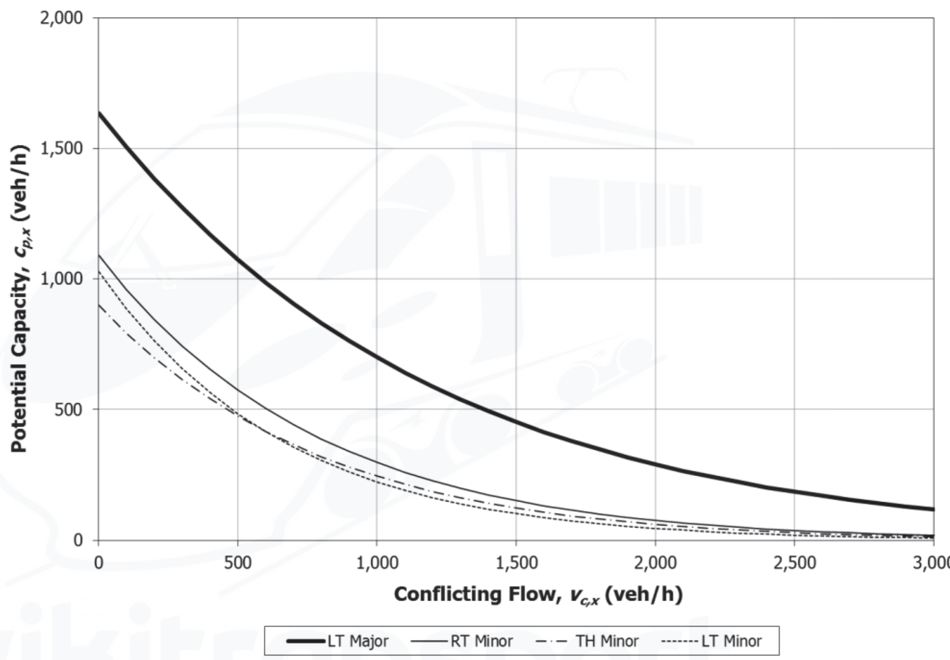
1. INTRODUCTION

Chapter 32 is the supplemental chapter for Chapter 20, Two-Way STOP-Controlled Intersections, and Chapter 21, All-Way STOP-Controlled Intersections, which are found in Volume 3 of the *Highway Capacity Manual*. This chapter provides supplemental material on (*a*) determining the potential capacity of two-way STOP-controlled (TWSC) intersections and (*b*) identifying the 512 combinations of degree-of-conflict cases for all-way STOP-controlled (AWSC) intersections with three-lane approaches. The chapter also provides example problems demonstrating the application of the TWSC and AWSC methodologies.

2. TWSC POTENTIAL CAPACITY

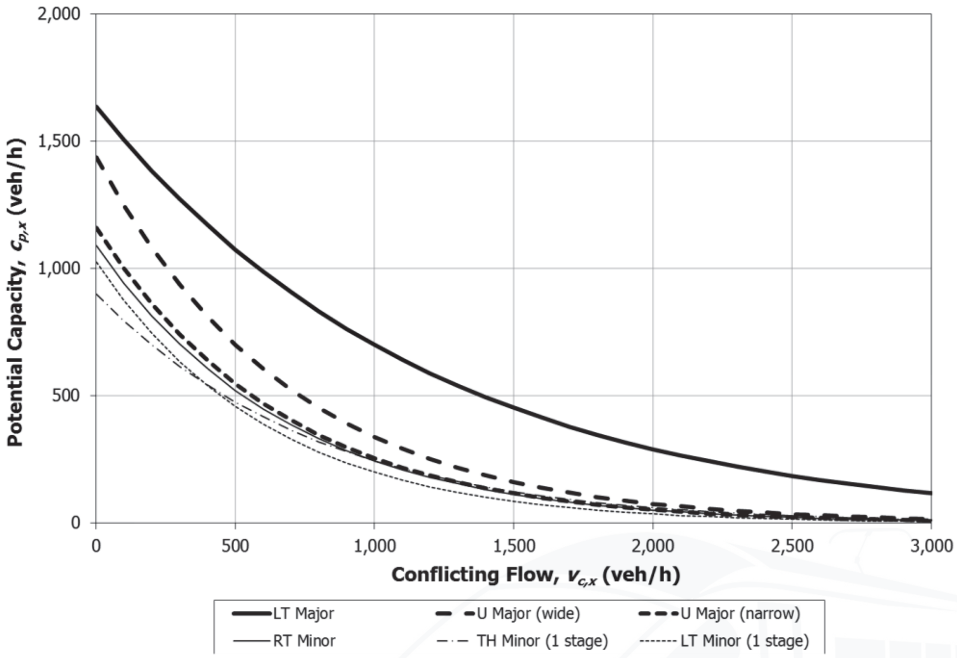
The gap acceptance model to estimate potential capacity (presented in Chapter 20, Equation 20-32) can be plotted for each of the non–Rank 1 movements by using values of critical headway and follow-up headway from Chapter 20 (Exhibit 20-12 and Exhibit 20-13, respectively). These graphs are presented in 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. The exhibits indicate 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



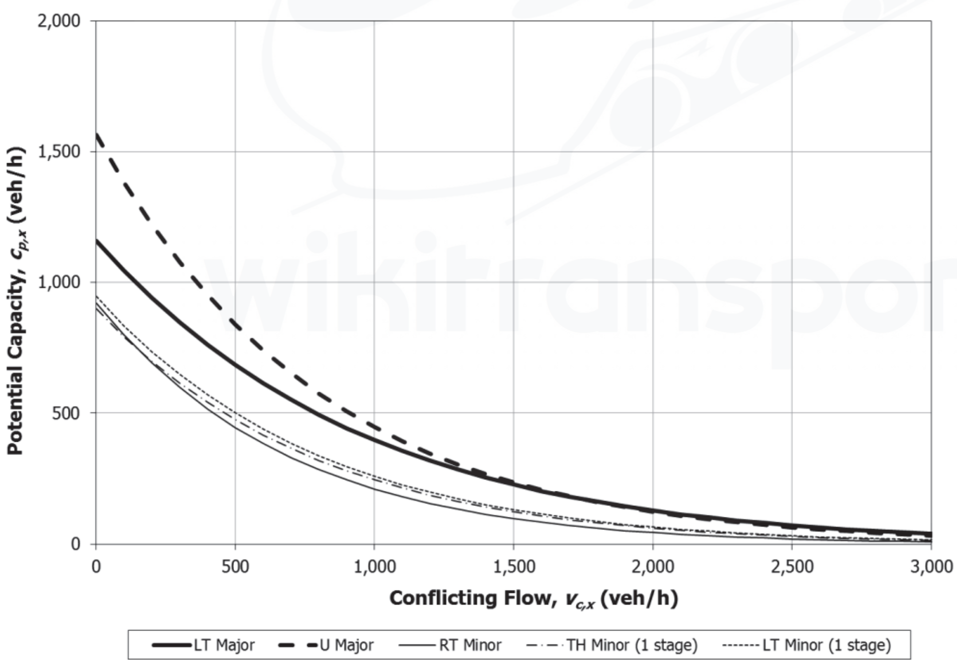
Note: LT = left turn, RT = right turn, and TH = through.

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



Note: LT = left turn, U = U-turn, RT = right turn, and TH = through.

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



Note: LT = left turn, U = U-turn, RT = right turn, and TH = through.

3. TWSC EXAMPLE PROBLEMS

This section provides example problems for use of the TWSC methodology. Exhibit 32-4 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 when available.

Exhibit 32-4
TWSC Example Problems

Problem Number	Description	Analysis Level
1	TWSC at an intersection with three legs	Operational
2	Pedestrian crossing at a TWSC intersection	Operational
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

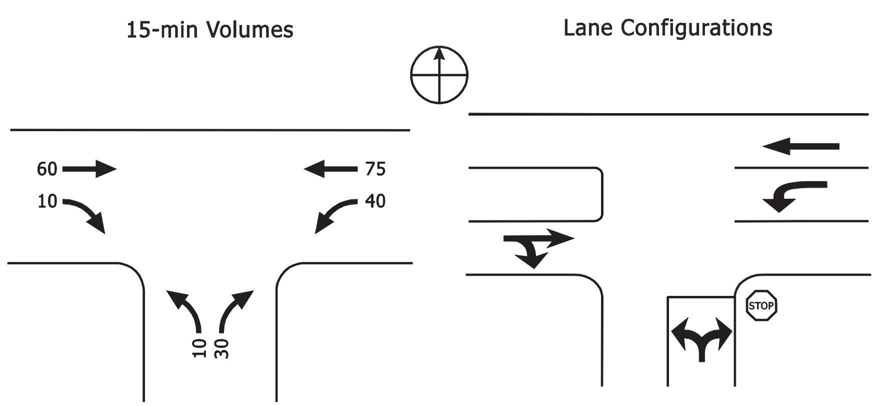
TWSC EXAMPLE PROBLEM 1: TWSC AT AN INTERSECTION WITH THREE LEGS

The Facts

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

- T-intersection,
- Major street with one lane in each direction,
- Minor street with one lane in each direction and STOP-controlled on the minor-street approach,
- Level grade on all approaches,
- Percentage heavy vehicles on all approaches = 10%,
- No other unique geometric considerations or upstream signal considerations,
- No pedestrians,
- Length of analysis period = 0.25 h, and
- Volumes during the peak 15-min period and lane configurations as shown in Exhibit 32-5.

Exhibit 32-5
TWSC Example Problem 1: 15-min Volumes and Lane Configurations



Comments

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

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

Because peak 15-min volumes have been provided, each volume is multiplied by four to determine a peak 15-min flow rate (in vehicle per hour) for each movement. These values, along with the associated movement numbers, are shown in Exhibit 32-6.

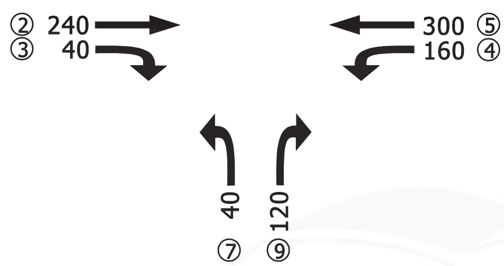


Exhibit 32-6
TWSC Example Problem 1: Movement Numbers and Calculation of Peak 15-min Flow Rates

Step 3: Compute Conflicting Flow Rates

The conflicting flow rates for each minor movement at the intersection are computed according to Equation 20-3, Equation 20-4, Equation 20-18, and Equation 20-24. The conflicting flow for the major-street left-turn $v_{c,4}$ is

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

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

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

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

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

Finally, the conflicting flow for the minor-street left-turn movement $v_{c,7}$ is computed. Because two-stage gap acceptance is not present at this intersection, the conflicting flow rates shown in Stage I (Equation 20-18) and Stage II (Equation 20-24) are added together and considered as one conflicting flow rate. The conflicting flow for $v_{c,7}$ is computed as follows:

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

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

Step 4: Determine Critical Headways and Follow-Up Headways

The critical headway for each minor movement is computed beginning with the base critical headway given in Exhibit 20-12. The base critical headway for each movement is then adjusted according to Equation 20-30. The critical headway for the major-street left-turn movement $t_{c,4}$ is computed as follows:

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

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

Similarly, the critical headway for the minor-street right-turn movement $t_{c,9}$ is

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

Finally, the critical headway for the minor-street left-turn movement $t_{c,7}$ is

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

The follow-up headway for each minor movement is computed beginning with the base follow-up headway given in Exhibit 20-13. The base follow-up headway for each movement is then adjusted according to Equation 20-31. The follow-up headway for the major-street left-turn movement $t_{f,4}$ is computed as follows:

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

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

Similarly, the follow-up headway for the minor-street right-turn movement $t_{f,9}$ is

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

Finally, the follow-up headway for the minor-street left-turn movement $t_{f,7}$ is

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

Step 5: Compute Potential Capacities

The computation of a potential capacity for each movement provides the analyst with a definition of capacity under the assumed base conditions. The potential capacity will be adjusted in later steps to estimate the movement capacity for each movement. The potential capacity for each movement is a function of the conflicting flow rate, critical headway, and follow-up headway computed in the previous steps. The potential capacity for the major-street left-turn movement $c_{p,4}$ is computed as follows from Equation 20-32:

$$c_{p,4} = v_{c,4} \frac{e^{-v_{c,4}t_{c,4}/3{,}600}}{1 - e^{-v_{c,4}t_{f,4}/3{,}600}}$$

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

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

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

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

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

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

Step 6: Compute Rank 1 Movement Capacities

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

Step 7: Compute Rank 2 Movement Capacities

The movement capacity for the major-street left-turn movement (Rank 2) $c_{m,4}$ is computed as follows from Equation 20-36:

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

Similarly, the movement capacity for the minor-street right-turn movement (Rank 2) $c_{m,9}$ is computed with Equation 20-37:

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

Step 8: Compute Rank 3 Movement Capacities

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

Major-street movements of Rank 1 and Rank 2 are assumed to be unimpeded by other vehicular movements. Minor-street movements of Rank 3 can be impeded by major-street left-turn movements due to a major-street left-turning vehicle waiting for an acceptable gap at the same time as vehicles of Rank 3. The magnitude of this impedance depends on the probability that major-street left-turning vehicles will be waiting for an acceptable gap at the same time as vehicles of Rank 3. In this example, only the minor-street left-turn movement is defined as a Rank 3 movement. Therefore, the probability of the major-street left-turn movement operating in a queue-free state ($p_{0,4}$) is computed from Equation 20-42:

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

The movement capacity for the minor-street left-turn movement (Rank 3) $c_{m,7}$ is found by first computing a capacity adjustment factor that accounts for the impeding effects of higher-ranked movements. The capacity adjustment factor for the minor-street left-turn movement f_7 is computed with Equation 20-46:

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

The movement capacity for the minor-street left-turn movement (Rank 3) $c_{m,7}$ is computed with Equation 20-47:

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

Step 9: Compute Rank 4 Movement Capacities

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

Step 10: Compute Capacity Adjustment Factors

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

The shared-lane capacity for the northbound minor-street approach $c_{SH,NB}$ is computed from Equation 20-59:

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

No other adjustments apply.

Step 11: Compute Control Delay

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

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

The control delay for the major-street left-turn movement (Rank 2) d_4 is computed with Equation 20-64:

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

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

$$d_4 = 8.3 \text{ s}$$

On the basis of Exhibit 20-2, the westbound left-turn movement is assigned level of service (LOS) A.

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

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

$$d_{SH,NB} = 14.9 \text{ s}$$

On the basis of Exhibit 20-2, the northbound approach is assigned LOS B.

Step 11b: Compute Control Delay to Rank 1 Movements

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

Step 12: Compute Approach and Intersection Control Delay

The control delays to all vehicles on the eastbound approach are assumed to be negligible as described in Step 11b. The control delay for the westbound approach $d_{A,WB}$ is computed with Equation 20-66:

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

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

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

The intersection control delay d_I is computed from Equation 20-67:

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

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

As noted in Chapter 20, neither major-street approach LOS nor intersection LOS is defined.

Step 13: Compute 95th Percentile Queue Lengths

The 95th percentile queue length for the major-street westbound left-turn movement $Q_{95,4}$ is computed from Equation 20-68:

$$Q_{95,4} \approx 900T \left[\frac{v_4}{c_{m,4}} - 1 + \sqrt{\left(\frac{v_4}{c_{m,4}} - 1\right)^2 + \frac{\left(\frac{3{,}600}{c_{m,4}}\right)\left(\frac{v_x}{c_{m,4}}\right)}{150T}} \right] \left(\frac{c_{m,4}}{3{,}600}\right)$$

$$Q_{95,4} \approx 900(0.25) \left[\frac{160}{1{,}238} - 1 + \sqrt{\left(\frac{160}{1{,}238} - 1\right)^2 + \frac{\left(\frac{3{,}600}{1{,}238}\right)\left(\frac{160}{1{,}238}\right)}{150(0.25)}} \right] \left(\frac{1{,}238}{3{,}600}\right)$$

$$Q_{95,4} = 0.4 \text{ veh}$$

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

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

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

$$Q_{95,NB} = 1.3 \text{ veh}$$

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

Discussion

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

TWSC EXAMPLE PROBLEM 2: PEDESTRIAN CROSSING AT A TWSC INTERSECTION

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

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

The Facts

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

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

Comments

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

Step 1: Identify Two-Stage Crossings

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

Step 2: Determine Critical Headway

Because there is no pedestrian platooning, the critical headway t_c is determined with Equation 20-77:

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

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

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

Step 3: Estimate Probability of a Delayed Crossing

Equation 20-81 and Equation 20-82 are used to calculate P_b, the probability of a blocked lane, and P_d, the probability of a delayed crossing, respectively. In the case of Scenario A, the crossing consists of four lanes. Scenarios B and C have only two lanes, given the two-stage crossing opportunity.

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

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

Scenario A:

$$P_b = 1 - e^{\frac{-t_{c,G}v}{N_L}}$$
$$P_d = 1 - (1 - P_b)^{N_L}$$

$$P_b = 1 - e^{\frac{-14.5(0.47)}{4}} = 0.82$$
$$P_d = 1 - (1 - 0.18)^4 = 0.999$$

Scenario B:

$$P_b = 1 - e^{\frac{-8(0.24)}{2}} = 0.61$$
$$P_d = 1 - (1 - 0.39)^2 = 0.85$$

Scenario C:

$$P_b = 1 - e^{\frac{-8(0.24)}{2}} = 0.61$$
$$P_d = 1 - (1 - 0.39)^2 = 0.85$$

Step 4: Calculate Average Delay to Wait for Adequate Gap

Average gap delay d_g and average gap delay when delay is nonzero d_{gd} are calculated by Equation 20-83 and Equation 20-84, respectively.

Scenario A:

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

$$d_g = \frac{1}{0.47}\left(e^{0.47(14.5)} - 0.47(14.5) - 1\right) = 1{,}977\ s$$

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

Scenario B:

$$d_g = \frac{1}{0.24}\left(e^{0.24(8)} - 0.24(8) - 1\right) = 15.8\ s$$

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

Scenario C:

$$d_g = \frac{1}{0.24}\left(e^{0.24(8)} - 0.24(8) - 1\right) = 15.8\ s$$

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

Step 5: Estimate Delay Reduction Due to Yielding Vehicles

Under Scenarios A and B, the motorist yield rates are approximately 0%. Therefore, there is no reduction in delay due to yielding vehicles, and average delay is the same as that shown in Step 4. Under Scenario C, motorist yield rates are 50%. The two-stage crossing requires the use of Equation 20-88 to determine $P(Y_i)$:

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

$$P(Y_1) = [0.85 - 0]\left[\frac{(2[0.61][1-0.61][0.5]) + (0.61^2 0.50^2)}{0.85}\right] = 0.33$$

$$P(Y_2) = [0.85 - 0.33]\left[\frac{(2[0.61][1-0.61][0.5]) + (0.61^2 0.50^2)}{0.85}\right] = 0.20$$

The results of Equation 20-88 are substituted into Equation 20-85 to determine average pedestrian delay.

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

$$h = \frac{N_L}{v} = \frac{2}{(0.24)} = 8.3\ \mathrm{s}$$

$$n = \mathrm{int}\left(\frac{d_{gd}}{h}\right) = \mathrm{int}\left(\frac{18.6}{8.3}\right) = 2$$

$$d_p = (8.3)(1 - 0.5)(0.33) + (8.3)(2 - 0.5)(0.20) + (0.85 - 0.53)(18.6) = 9.8\ \mathrm{s}$$

Step 6: Calculate LOS

Average pedestrian delays and the corresponding pedestrian LOS under each of the three scenarios are determined from Exhibit 20-3 as follows:

Scenario A = 1,979 s = LOS F

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

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

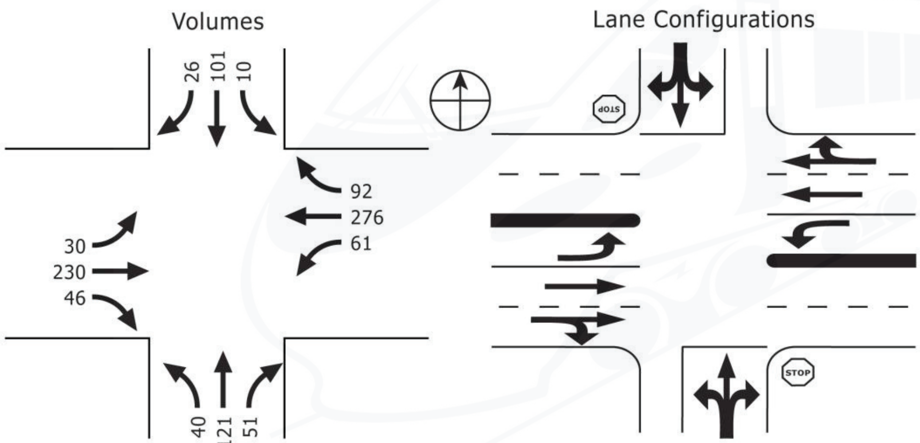
TWSC EXAMPLE PROBLEM 3: FLARED APPROACHES AND MEDIAN STORAGE

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;
- Percentage 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 32-7.

Exhibit 32-7
TWSC Example Problem 3: 15-min Volumes and Lane Configurations



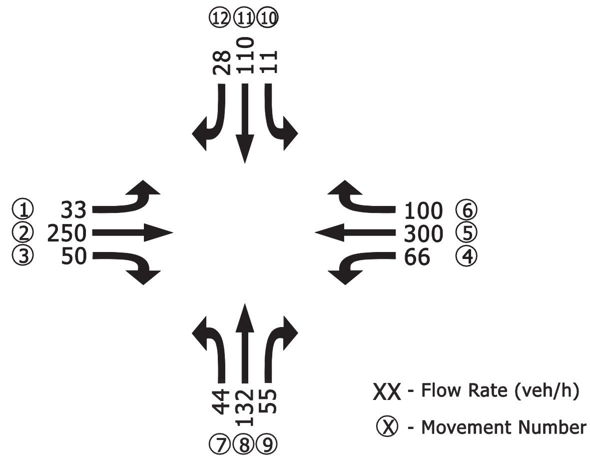
Comments

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 vehicles per hour) for each movement. These values are shown in Exhibit 32-8.

Exhibit 32-8
TWSC Example Problem 3: Movement Numbers and Calculation of Peak 15-min Flow Rates



Step 3: Compute Conflicting Flow Rates

The conflicting flow rates for each minor movement at the intersection are computed according to the equations in Chapter 20. The conflicting flow for the eastbound major-street left-turn movement $v_{c,1}$ is computed according to Equation 20-2 as follows:

$$v_{c,1} = v_5 + v_6 + v_{16} = 300 + 100 + 0 = 400 \text{ veh/h}$$

Similarly, the conflicting flow for the westbound major-street left-turn movement $v_{c,4}$ is computed according to Equation 20-3 as follows:

$$v_{c,4} = v_2 + v_3 + v_{15} = 250 + 50 + 0 = 300 \text{ veh/h}$$

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 with Equation 20-6 and Equation 20-7, respectively, as follows (with no U-turns and pedestrians, the last three terms can be assigned zero):

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

$$v_{c,9} = 0.5(250) + 0.5(50) + 0 + 0 + 0 = 150 \text{ veh/h}$$

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

$$v_{c,12} = 0.5(300) + 0.5(100) + 0 + 0 + 0 = 200 \text{ veh/h}$$

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 $v_{c,\mathrm{I},8}$ is computed from Equation 20-14:

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

$$v_{c,\mathrm{I},8} = 2(33 + 0) + 250 + 0.5(50) + 0 = 341 \text{ veh/h}$$

The conflicting flow for Stage II $v_{c,\mathrm{II},8}$ is computed from Equation 20-16:

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

$$v_{c,\mathrm{II},8} = 2(66 + 0) + 300 + 100 + 0 = 532 \text{ veh/h}$$

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

$$v_{c,8} = v_{c,\mathrm{I},8} + v_{c,\mathrm{II},8} = 341 + 532 = 873 \text{ veh/h}$$

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

$$v_{c,\mathrm{I},11} = 2(66 + 0) + 300 + 0.5(100) + 0 = 482 \text{ veh/h}$$

$$v_{c,\mathrm{II},11} = 2(33 + 0) + 250 + 50 + 0 = 366 \text{ veh/h}$$

$$v_{c,11} = v_{c,\mathrm{I},11} + v_{c,\mathrm{II},11} = 482 + 366 = 848 \text{ veh/h}$$

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 $v_{c,\mathrm{I},7}$ is computed with Equation 20-20 as follows:

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

$$v_{c,\mathrm{I},7} = 2(33 + 0) + 250 + 0.5(50) + 0 = 341 \text{ veh/h}$$

The conflicting flow for Stage II $v_{c,\mathrm{II},7}$ is computed with Equation 20-26 as follows:

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

$$v_{c,\mathrm{II},7} = 2(66 + 0) + 0.5(300) + 0.5(110) + 0 = 337 \text{ veh/h}$$

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

$$v_{c,7} = v_{c,\mathrm{I},7} + v_{c,\mathrm{II},7} = 341 + 337 = 678 \text{ veh/h}$$

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

$$v_{c,\mathrm{I},10} = 2(66 + 0) + 300 + 0.5(100) + 0 = 482 \text{ veh/h}$$

$$v_{c,\mathrm{II},10} = 2(33 + 0) + 0.5(250) + 0.5(132) + 0 = 257 \text{ veh/h}$$

$$v_{c,10} = v_{c,\mathrm{I},10} + v_{c,\mathrm{II},10} = 482 + 257 = 739 \text{ veh/h}$$

Step 4: Determine Critical Headways and Follow-Up Headways

The critical headway for each minor movement is computed beginning with the base critical headway given in Exhibit 20-12. The base critical headway for each movement is then adjusted according to Equation 20-30. 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:

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

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

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:

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

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, $t_{c,\mathrm{I},8}$, $t_{c,I,11}$ and $t_{c,\mathrm{II},8}$, $t_{c,\mathrm{II},11}$, respectively (in this case, $t_{c,\mathrm{I},8} = t_{c,\mathrm{II},8} = t_{c,\mathrm{I},11} = t_{c,\mathrm{II},11}$), are computed as follows:

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

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:

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

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, $t_{c,\mathrm{I},7}$, $t_{c,\mathrm{I},10}$ and $t_{c,\mathrm{II},7}$, $t_{c,\mathrm{II},10}$, respectively (in this case, $t_{c,\mathrm{I},7} = t_{c,\mathrm{II},7} = t_{c,\mathrm{I},10} = t_{c,\mathrm{II},10}$), are computed as follows:

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

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:

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

The follow-up headway for each minor movement is computed beginning with the base follow-up headway given in Exhibit 20-13. The base follow-up headway for each movement is then adjusted according to Equation 20-31. 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:

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

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

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:

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

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:

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 because they apply only to vehicles as they exit the approach and enter the intersection.

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

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:

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

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 movement $c_{p,1}$ is computed from Equation 20-32:

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

$$c_{p,1} = 400 \frac{e^{-(400)(4.3)/3{,}600}}{1 - e^{-(400)(2.3)/3{,}600}} = 1{,}100 \text{ veh/h}$$

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

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

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

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

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:

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

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

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

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

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:

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

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

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

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

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:

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

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

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

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

Steps 6–9: Compute Movement Capacities

Because no pedestrians are present, the procedures given in Chapter 20 are followed.

Step 6: Compute Rank 1 Movement Capacities

There is no computation for this step.

Step 7: Compute Rank 2 Movement Capacities

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

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

$$c_{m,1} = c_{p,1} = 1,100 \text{ veh/h}$$

$$c_{m,4} = c_{p,4} = 1,202 \text{ veh/h}$$

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

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

$$c_{m,9} = c_{p,9} = 845 \text{ veh/h}$$

$$c_{m,12} = c_{p,12} = 783 \text{ veh/h}$$

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

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: Compute Rank 3 Movement Capacities

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 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 20-42:

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

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

Next, by using the probabilities computed above, capacity adjustment factors f_8 and f_{11} can be computed according to Equation 20-46:

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

Finally, under the single-stage gap-acceptance assumption, the movement capacities $c_{m,8}$ and $c_{m,11}$ can be computed according to Equation 20-47:

$$c_{m,8} = c_{p,8} \times f_8 = (273)(0.917) = 250 \text{ veh/h}$$

$$c_{m,11} = c_{p,11} \times f_{11} = (283)(0.917) = 260 \text{ veh/h}$$

Because Movements 8 and 11 will operate under two-stage gap acceptance, 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 probabilities of queue-free states on conflicting Rank 2 movements calculated above are entered into Equation 20-46 as before, but this time capacity adjustment factors are estimated for each individual stage as follows:

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

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

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

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

The Stage I movement capacities are then computed as follows:

$$c_{m,\mathrm{I},8} = c_{p,\mathrm{I},8} \times f_{I,8} = (618)(0.970) = 599 \text{ veh/h}$$

$$c_{m,\mathrm{I},11} = c_{p,\mathrm{I},11} \times f_{\mathrm{I},11} = (532)(0.945) = 503 \text{ veh/h}$$

The Stage II movement capacities are then computed as follows:

$$c_{m,\mathrm{II},8} = c_{p,\mathrm{II},8} \times f_{\mathrm{II},8} = (504)(0.945) = 476 \text{ veh/h}$$

$$c_{m,\mathrm{II},11} = c_{p,\mathrm{II},11} \times f_{\mathrm{II},11} = (601)(0.970) = 583 \text{ veh/h}$$

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 20-48, under the assumption 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 20-49:

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

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

Finally, the total capacity for each movement $c_{T,8}$ and $c_{T,11}$ is computed according to Equation 20-50, because $y \neq 1$:

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

$$c_{m,T,8} = \frac{0.949}{1.808^{2+1} - 1}[(1.808)(1.808^2 - 1)(476 - 33) + (1.808 - 1)(250)]$$

$$c_{m,T,8} = 390 \text{ veh/h}$$

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

$$c_{m,T,11} = \frac{0.949}{0.946^{2+1} - 1}[(0.946)(0.946^2 - 1)(583 - 66) + (0.946 - 1)(260)]$$

$$c_{m,T,11} = 405 \text{ veh/h}$$

Step 9: Compute Rank 4 Movement Capacities

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

The vehicle impedance effects for Rank 4 movements are first estimated by assuming single-stage gap acceptance. Rank 4 movements are impeded by all 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 probabilities that the minor-street right-turn movements will operate in a queue-free state ($p_{0,9}$ and $p_{0,12}$) are computed as follows:

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

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

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 k represents Rank 3 movements. The values for $p_{0,k}$ are computed as follows:

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

$$p_{0,11} = 1 - \frac{110}{405} = 0.728$$

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:

$$p''_7 = p_{0,11} \times f_{11} = (0.728)(0.917) = 0.668$$

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

With the values for p'', the probability of a simultaneous queue-free state for each movement can be computed by using Equation 20-52 as follows:

$$p'_7 = 0.65p''_7 - \frac{p''_7}{p''_7 + 3} + 0.6\sqrt{p''_7}$$

$$p'_7 = 0.65(0.668) - \frac{0.668}{0.668 + 3} + 0.6\sqrt{0.668} = 0.742$$

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

Next, with the probabilities computed above, capacity adjustment factors f_7 and f_{10} can be computed according to Equation 20-53:

$$f_7 = p'_7 \times p_{0,12} = (0.742)(0.964) = 0.715$$

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

Finally, under the single-stage gap-acceptance assumption, the movement capacities $c_{m,7}$ and $c_{m,10}$ can be computed according to Equation 20-54:

$$c_{m,7} = c_{p,7} \times f_7 = (323)(0.715) = 231 \text{ veh/h}$$

$$c_{m,10} = c_{p,10} \times f_{10} = (291)(0.649) = 189 \text{ veh/h}$$

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. 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 20-46, 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:

$$c_{m,\mathrm{I},7} = c_{p,\mathrm{I},7} \times f_{\mathrm{I},7} = (626)(0.970) = 607 \text{ veh/h}$$

$$c_{m,\mathrm{I},10} = c_{p,\mathrm{I},10} \times f_{\mathrm{I},10} = (514)(0.945) = 486 \text{ veh/h}$$

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 20-46. 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 20-42:

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

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

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

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

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

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

$$c_{m,\mathrm{II},7} = c_{p,\mathrm{II},7} \times f_{\mathrm{II},7} = (629)(0.711) = 447 \text{ veh/h}$$

$$c_{m,\mathrm{II},10} = (703)(0.707) = 497 \text{ veh/h}$$

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 20-55, under the assumption 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 20-56:

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

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

Finally, the total capacity for each movement, $c_{T,7}$ and $c_{T,10}$, is computed according to Equation 20-57, as $y \neq 1$:

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

$$c_{T,7} = \frac{0.949}{2.055^{2+1} - 1}\left[(2.055)(2.055^2 - 1)(447 - 33) + (2.055 - 1)(231)\right]$$

$$c_{T,7} = 369 \text{ veh/h}$$

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

$$c_{T,10} = \frac{0.949}{1.227^{2+1} - 1}[(1.227)(1.227^2 - 1)(497 - 66) + (1.227 - 1)(189)]$$

$$c_{T,10} = 347 \text{ veh/h}$$

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; after these computations are completed, 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 20-59:

$$c_{SH,NB} = \frac{\sum_y v_y}{\sum_y \frac{v_y}{c_{m,y}}} = \frac{v_7 + v_8 + v_9}{\frac{v_7}{c_{m,7}} + \frac{v_8}{c_{m,8}} + \frac{v_9}{c_{m,9}}} = \frac{44 + 132 + 55}{\frac{44}{369} + \frac{132}{390} + \frac{55}{845}} = 442 \text{ veh/h}$$

$$c_{SH,SB} = \frac{\sum_y v_y}{\sum_y \frac{v_y}{c_{m,y}}} = \frac{11 + 110 + 28}{\frac{11}{347} + \frac{110}{405} + \frac{28}{783}} = 439 \text{ veh/h}$$

Step 10b: 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 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. Although the flow rates are known input data, the control delays have not yet been computed. Therefore, the control delay for each movement, assuming a 15-min analysis period and separate lanes for each movement, is computed with Equation 20-64:

$$d_7 = \frac{3{,}600}{c_7} + 900T\left[\frac{v_7}{c_{m,7}} - 1 + \sqrt{\left(\frac{v_7}{c_{m,7}} - 1\right)^2 + \frac{\left(\frac{3{,}600}{c_{m,7}}\right)\left(\frac{v_7}{c_{m,7}}\right)}{450T}}\right] + 5$$

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

$$d_7 = 16.07 \text{ s}$$

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

$$d_8 = 18.88 \text{ s}$$

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

$$d_9 = 9.57 \text{ s}$$

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

$$d_{10} = 15.71 \text{ s}$$

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

$$d_{11} = 17.17 \text{ s}$$

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

$$d_{12} = 9.77 \text{ s}$$

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 from Equation 20-60:

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

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

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

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

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

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

Next, the required length of the storage area so that each approach would operate effectively as separate lanes is computed with Equation 20-61:

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

$$n_{Max,NB} = \max_{NB}[\text{round}(Q_{sep,7} + 1), \text{round}(Q_{sep,8} + 1), \text{round}(Q_{sep,9} + 1)]$$

$$n_{Max,NB} = \max_{NB}[\text{round}(0.20 + 1), \text{round}(0.69 + 1), \text{round}(0.15 + 1)] = 2$$

$$n_{Max,SB} = \max_{SB}[\text{round}(0.05 + 1), \text{round}(0.53 + 1), \text{round}(0.08 + 1)] = 2$$

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 20-59:

$$c_{L+TH,NB} = \frac{\sum_y v_y}{\sum_y \frac{v_y}{c_{m,y}}} = \frac{v_7 + v_8}{\frac{v_7}{c_{m,7}} + \frac{v_8}{c_{m,8}}} = \frac{44 + 132}{\frac{44}{369} + \frac{132}{390}} = 385 \text{ veh/h}$$

$$c_{L+TH,SB} = \frac{\sum_y v_y}{\sum_y \frac{v_y}{c_{m,y}}} = \frac{v_{10} + v_{11}}{\frac{v_{10}}{c_{m,10}} + \frac{v_{11}}{c_{m,11}}} = \frac{11 + 110}{\frac{11}{347} + \frac{110}{405}} = 399 \text{ veh/h}$$

Then, the capacity of the separate lane condition c_{sep} for each approach can be computed according to Equation 20-62:

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

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

$$c_{sep,NB} = \min\left[(845)\left(1 + \frac{44 + 132}{55}\right), (385)\left(1 + \frac{55}{44 + 132}\right)\right] = 505 \text{ veh/h}$$

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

$$c_{sep,SB} = \min\left[(783)\left(1 + \frac{11 + 110}{28}\right), (399)\left(1 + \frac{28}{11 + 110}\right)\right] = 491 \text{ veh/h}$$

Finally, the capacities of the flared minor-street lanes are computed according to Equation 20-63:

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

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

$$c_{R,NB} = (505 - 442)\left(\frac{1}{2}\right) + 442 = 474 \text{ veh/h}$$

Similarly,

$$c_{R,SB} = (491 - 439)\left(\frac{1}{2}\right) + 439 = 465 \text{ veh/h}$$

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 with Equation 20-64:

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

$$d_1 = 8.4 \text{ s}$$

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

$$d_4 = 8.2 \text{ s}$$

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

$$d_{NB} = 19.6 \text{ s}$$

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

$$d_{SB} = 16.3 \text{ s}$$

According to Exhibit 20-2, 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, and
- 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 with Equation 20-66:

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

$$d_{A,EB} = \frac{0(50) + 0(250) + 8.2(33)}{50 + 250 + 33} = 0.8 \text{ s}$$

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

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

The intersection delay d_I is computed from Equation 20-67:

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

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

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 from Equation 20-68:

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

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

$$Q_{95,1} \approx 0.1 \text{ veh}$$

The result of 0.1 vehicles for the 95th percentile queue indicates 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:

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

$$Q_{95,4} \approx 0.2 \text{ veh}$$

The result of 0.2 vehicles for the 95th percentile queue indicates 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.

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

$$Q_{95,NB} \approx 2.6 \text{ veh}$$

The result of 2.6 vehicles for the 95th percentile queue indicates 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.

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

$$Q_{95,SB} \approx 1.4 \text{ veh}$$

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

Discussion

Overall, the results indicate 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 A SIGNALIZED URBAN STREET SEGMENT

The Facts

This problem analyzes the performance of the TWSC intersection at Access Point 1 (AP1) from Example Problem 1 in Chapter 30, Urban Street Segments: Supplemental, which looks at the motor vehicle performance of the urban street segment bounded by two signalized intersections, as shown in Exhibit 32-9. The street has a four-lane cross section with two lanes in each direction.

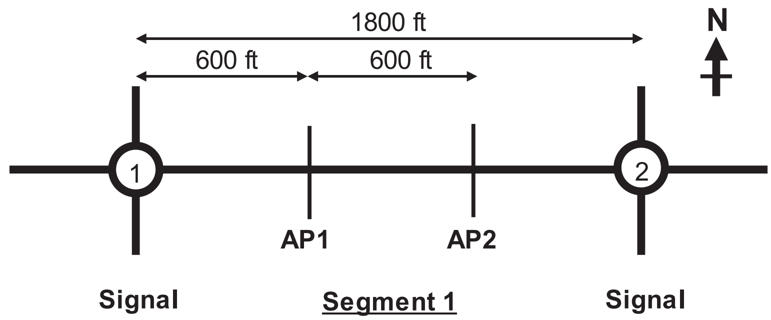


Exhibit 32-9
TWSC Example Problem 4: TWSC Intersection Within a Signalized Urban Street Segment

From Example Problem 1 in Chapter 30, 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 control on minor-street approach,
- Level grade on all approaches,
- Percentage heavy vehicles on all approaches = 1%,
- Length of analysis period = 0.25 h, and
- Flow rates and lane configurations as shown in Exhibit 32-10.

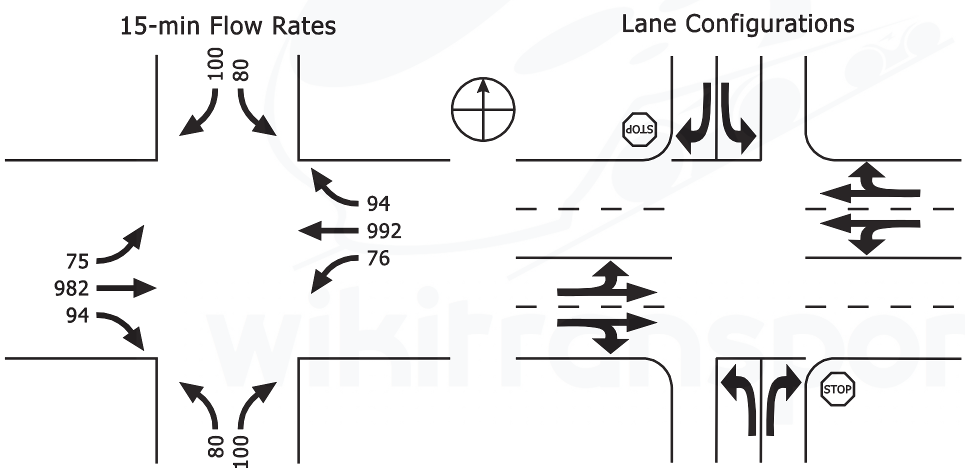


Exhibit 32-10
TWSC Example Problem 4: 15-min Flow Rates and Lane Configurations

The proportion time blocked and delay to through vehicles from the methodology of Chapter 18, Urban Street Segments, are as shown in Exhibit 32-11.

Access Point Data Segment 1 Movement:	EB L 1	EB T 2	EB R 3	WB L 4	WB T 5	WB R 6	NB L 7	NB T 8	NB R 9	SB L 10	SB T 11	SB R 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											

Exhibit 32-11
TWSC Example Problem 4: Movement-Based Access Point Output (from Chapter 30, Example Problem 1)

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:

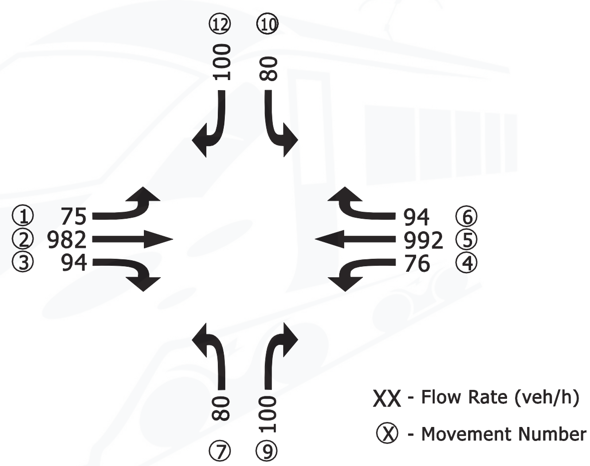
- Major-street through movement, s_{i1} = 1,800 veh/h; and
- Major-street right-turn movement, s_{i2} = 1,500 veh/h.

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 methodology of Chapter 17, Urban Street Reliability and ATDM. They are assigned movement numbers as shown in Exhibit 32-12.

Exhibit 32-12
TWSC Example Problem 4: Movement Numbers and Calculation of Peak 15-min Flow Rates



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 from Equation 20-2 and Equation 20-3 as follows:

$$v_{c,1} = v_5 + v_6 + v_{16} = 992 + 94 + 0 = 1{,}086 \text{ veh/h}$$

$$v_{c,4} = v_2 + v_3 + v_{15} = 982 + 94 + 0 = 1{,}076 \text{ veh/h}$$

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

The conflicting flows for minor-street right-turn movements are computed from Equation 20-6 and Equation 20-7 as follows:

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

$$v_{c,9} = 0.5(982) + 0.5(94) + 0 + 0 + 0 = 538 \text{ veh/h}$$

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

$$v_{c,12} = 0.5(992) + 0.5(94) + 0 + 0 + 0 = 543 \text{ veh/h}$$

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.

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

$$v_{c,7} = 2(75 + 0) + 982 + 0.5(94) + 0 + 2(76 + 0) + 0.5(992) + 0.5(0) + 0$$

$$v_{c,7} = 1{,}827 \text{ veh/h}$$

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

$$v_{c,10} = 2(76 + 0) + 992 + 0.5(94) + 0 + 2(75 + 0) + 0.5(982) + 0.5(0) + 0$$

$$v_{c,10} = 1{,}832 \text{ veh/h}$$

Step 4: Determine Critical Headways and Follow-Up Headways

Critical headways for each movement are computed from Equation 20-30:

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

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

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

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

Follow-up headways for each movement are computed from Equation 20-31:

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

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

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

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

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 18 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 20-33). 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:

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

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

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

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

Similar calculations are made for the other movements:

$$v_{c,u,4} = \frac{1{,}076 - 1.5(2{,}000)(0.170)}{1 - 0.170} = 682 \text{ veh/h}$$

$$v_{c,u,9} = \frac{538 - 1.5(2{,}000)(0.170)}{1 - 0.170} = 34 \text{ veh/h}$$

$$v_{c,u,12} = \frac{543 - 1.5(2{,}000)(0.170)}{1 - 0.170} = 40 \text{ veh/h}$$

$$v_{c,u,7} = \frac{1{,}827 - 1.5(2{,}000)(0.260)}{1 - 0.260} = 1{,}415 \text{ veh/h}$$

$$v_{c,u,10} = \frac{1{,}832 - 1.5(2{,}000)(0.260)}{1 - 0.260} = 1{,}422 \text{ veh/h}$$

The potential capacity for each movement is then calculated with Equation 20-34 and Equation 20-35 (combined) as follows:

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

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

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

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

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

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

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

Steps 6–9: Compute Movement Capacities

Because no pedestrians are present, the procedures given in Chapter 20 are followed.

Step 6: Compute Rank 1 Movement Capacities

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: Compute Rank 2 Movement Capacities

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

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

$$c_{m,1} = c_{p,1} = 750 \text{ veh/h}$$
$$c_{m,4} = c_{p,4} = 758 \text{ veh/h}$$

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

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

$$c_{m,9} = c_{p,9} = 859 \text{ veh/h}$$
$$c_{m,12} = c_{p,12} = 851 \text{ veh/h}$$

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

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 the left-turn movement occupies its own lane, is calculated with Equation 20-42 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 in Equation 20-45:

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

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

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 Rank 3 Movement Capacities

Step 8a: Rank 3 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 Rank 4 Movement Capacities

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 k represents Rank 3 movements. 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:

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

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

By using the values for p'', the probability of a simultaneous queue-free state for each movement can be computed with Equation 20-52 as follows:

$$p'_7 = 0.65p''_7 - \frac{p''_7}{p''_7 + 3} + 0.6\sqrt{p''_7}$$

$$p'_7 = 0.65(0.552) - \frac{(0.552)}{0.552 + 3} + 0.6\sqrt{0.552} = 0.649$$

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

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

$$f_7 = p'_7 \times p_{0,12} = (0.649)(0.882) = 0.572$$

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

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

$$c_{m,7} = c_{p,7} \times f_7 = (73)(0.572) = 42 \text{ veh/h}$$

$$c_{m,10} = c_{p,10} \times f_{10} = (72)(0.574) = 41 \text{ veh/h}$$

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: 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 from Equation 20-64:

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

$$d_1 = 10.3 \text{ s}$$

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

$$d_4 = 10.3 \text{ s}$$

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

$$d_9 = 9.7 \text{ s}$$

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

$$d_{12} = 9.8 \text{ s}$$

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

$$d_7 = 633 \text{ s}$$

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

$$d_{10} = 657 \text{ s}$$

According to Exhibit 20-2, 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, and
- 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 computed with Equation 20-65 as follows:

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

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

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, $v_{i,2} = 76$.

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

The procedures in Chapter 18 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:

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

$$d_{A,EB} = \frac{0(94) + 1.1(982) + 10.3(75)}{94 + 982 + 75} = 1.6 \text{ s}$$

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

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

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

The intersection delay d_I is computed as follows:

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

$$d_I = \frac{1.6(1{,}151) + 1.7(1{,}162) + 287(180) + 297(180)}{1{,}151 + 1{,}162 + 180 + 180} = 40.8 \text{ s}$$

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 by using Equation 20-68:

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

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

$$Q_{95,1} \approx 0.3 \text{ veh}$$

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

$$Q_{95,4} \approx 0.3 \text{ veh}$$

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

$$Q_{95,9} \approx 0.4 \text{ veh}$$

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

$$Q_{95,12} \approx 0.4 \text{ veh}$$

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

$$Q_{95,7} \approx 8.3 \text{ veh}$$

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

$$Q_{95,10} \approx 8.4 \text{ veh}$$

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 with room for storage of one vehicle),
- Level grade on all approaches,
- Percentage 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 his or her 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 32-13.

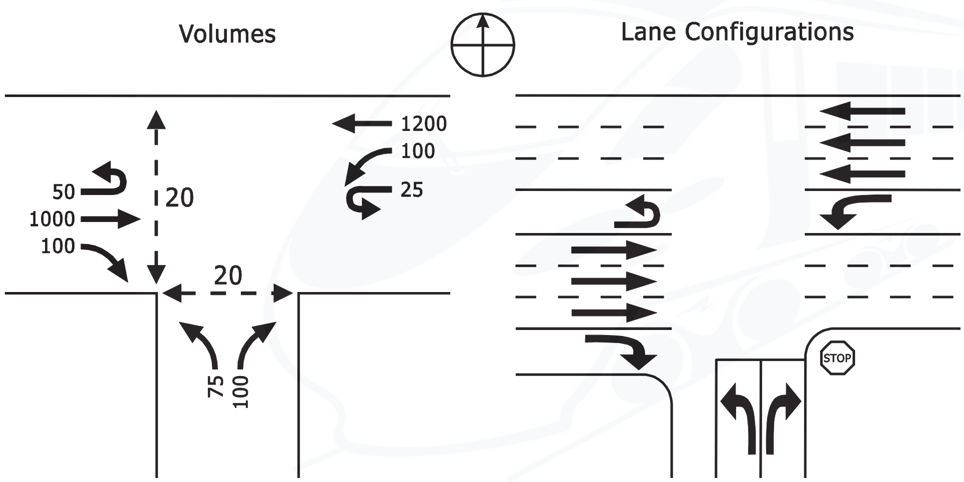


Exhibit 32-13
TWSC Example Problem 5: Volumes and Lane Configurations

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 32-14.

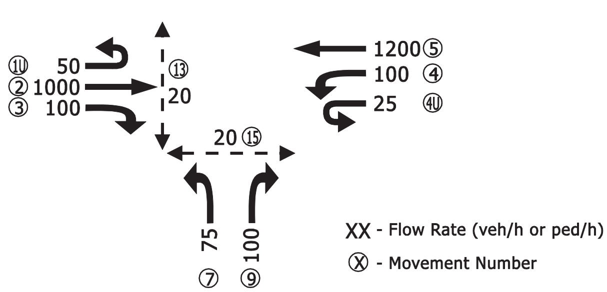


Exhibit 32-14
TWSC Example Problem 5: Movement Numbers and Calculation of Peak 15-min Flow Rates

Step 3: Compute Conflicting Flow Rates

Major-Street Left-Turn Movement (Rank 2, Movement 4)

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

$$v_{c,4} = v_2 + v_3 + v_{15} = 1{,}000 + 100 + 20 = 1{,}120 \text{ veh/h}$$

Minor-Street Right-Turn Movement (Rank 2, Movement 9)

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):

$$v_{c,9} = 0.5v_2 + 0.5v_3 + v_{4U} + v_{14} + v_{15}$$
$$v_{c,9} = 0.5(1{,}000) + 0.5(0) + 0 + 0 + 20 = 520 \text{ veh/h}$$

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):

$$v_{c,1U} = 0.73v_5 + 0.73v_6 = 0.73(1{,}200) + 0 = 876 \text{ veh/h}$$
$$v_{c,4U} = 0.73v_2 + 0.73v_3 = 0.73(1{,}000) + 0 = 730 \text{ veh/h}$$

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):

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

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

$$v_{c,\mathrm{II},7} = 2(v_4 + v_{4U}) + 0.4v_5 + 0.5v_{11} + v_{13}$$
$$v_{c,\mathrm{II},7} = 2(100 + 25) + 0.4(1{,}200) + 0 + 20 = 750 \text{ veh/h}$$
$$v_{c,7} = v_{c,\mathrm{I},7} + v_{c,\mathrm{II},7} = 1{,}120 + 750 = 1{,}870 \text{ veh/h}$$

Step 4: Determine Critical Headways and Follow-Up Headways

Critical headways for each minor movement are computed as follows:

$$t_{c,x} = t_{c,\text{base}} + t_{c,HV}P_{HV} + t_{c,G}G - t_{3,LT}$$
$$t_{c,1U} = 5.6 + 0 + 0 - 0 = 5.6 \text{ s}$$
$$t_{c,4} = 5.3 + 0 + 0 - 0 = 5.3 \text{ s}$$
$$t_{c,4U} = 5.6 + 0 + 0 - 0 = 5.6 \text{ s}$$
$$t_{c,9} = 7.1 + 0 + 0 - 0 = 7.1 \text{ s}$$
$$t_{c,7} = 6.4 + 0 + 0 - 0.7 = 5.7 \text{ s}$$
$$t_{c,I,7} = 7.3 + 0 + 0 - 0.7 = 6.6 \text{ s}$$
$$t_{c,II,7} = 6.7 + 0 + 0 - 0.7 = 6.0 \text{ s}$$

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

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

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

$$t_{f,4} = 3.1 + 0 = 3.1 \text{ s}$$

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

$$t_{f,9} = 3.9 + 0 = 3.9 \text{ s}$$

$$t_{f,7} = 3.8 + 0 = 3.8 \text{ s}$$

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:

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

$$c_{p,1U} = v_{c,1U} \frac{e^{-v_{c,1U} t_{c,1U}/3{,}600}}{1 - e^{-v_{c,1U} t_{f,1U}/3{,}600}} = 876 \frac{e^{-(876)(5{,}6)/3{,}600}}{1 - e^{-(876)(2.3)/3{,}600}} = 523 \text{ veh/h}$$

$$c_{p,4} = 1{,}120 \frac{e^{-(1{,}120)(5{,}3)/3{,}600}}{1 - e^{-(1{,}120)(3.1)/3{,}600}} = 348 \text{ veh/h}$$

$$c_{p,4U} = 730 \frac{e^{-(730)(5{,}6)/3{,}600}}{1 - e^{-(730)(2.3)/3{,}600}} = 629 \text{ veh/h}$$

$$c_{p,9} = 520 \frac{e^{-(520)(7.1)/3{,}600}}{1 - e^{-(520)(3.9)/3{,}600}} = 433 \text{ veh/h}$$

$$c_{p,7} = 1{,}870 \frac{e^{-(1{,}870)(5{,}7)/3{,}600}}{1 - e^{-(1{,}870)(3.8)/3{,}600}} = 112 \text{ veh/h}$$

$$c_{p,I,7} = 1{,}120 \frac{e^{-(1{,}120)(6.6)/3{,}600}}{1 - e^{-(1{,}120)(3.8)/3{,}600}} = 207 \text{ veh/h}$$

$$c_{p,II,7} = 750 \frac{e^{-(750)(6.0)/3{,}600}}{1 - e^{-(750)(3.8)/3{,}600}} = 393 \text{ veh/h}$$

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: Compute Rank 1 Movement Capacities

The methodology assumes Rank 1 vehicles are unimpeded by pedestrians.

Step 7: Compute Rank 2 Movement Capacities

Step 7a: Pedestrian Impedance

The factor accounting for pedestrian blockage is computed by Equation 20-69 as follows:

$$f_{pb} = \frac{v_x \times \frac{w}{S_p}}{3{,}600}$$

$$f_{pb,13} = \frac{v_{13} \times \frac{w}{S_p}}{3{,}600} = \frac{20 \times \frac{12}{3.5}}{3{,}600} = 0.019$$

$$f_{pb,15} = \frac{20 \times \frac{12}{3.5}}{3{,}600} = 0.019$$

The pedestrian impedance factor for each pedestrian movement x, $p_{p,x}$ is computed by Equation 20-70 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 20-18, 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:

$$c_{m,4} = c_{p,4} \times p_{p,15} = (348)(0.981) = 341 \text{ veh/h}$$

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:

$$c_{m,9} = c_{p,9} \times f_9 = (433)(0.981) = 425 \text{ veh/h}$$

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:

$$c_{m,1U} = c_{p,1U} \times f_{1U} = (523)(0.981) = 523 \text{ veh/h}$$

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:

$$c_{m,4U} = c_{p,4U} \times f_{4U} = (629)(0.765) = 481 \text{ veh/h}$$

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

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

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

This step is skipped.

Step 8: Compute Rank 3 Movement Capacities

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:

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

Step 8b: Rank 3 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:

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

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

$$c_{m,7} = c_{p,7} \times f_7 = (112)(0.570) = 64 \text{ veh/h}$$

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,

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

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

$$c_{m,\mathrm{I},7} = c_{p,\mathrm{I},7} \times f_{\mathrm{I},7} = (207)(0.581) = 120 \text{ veh/h}$$

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

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

$$c_{m,\mathrm{II},7} = c_{p,\mathrm{II},7} \times f_{\mathrm{II},7} = (393)(0.981) = 386 \text{ veh/h}$$

Next, an adjustment factor a and an intermediate variable y are computed for Movement 7 as follows:

$$a_7 = 1 - 0.32e^{-1.3\sqrt{n_m}} = 1 - 0.32e^{-1.3\sqrt{1}} = 0.913$$

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

Therefore, the total capacity c_T is computed as follows:

$$c_{m,T,7} = \frac{a_7}{y_7^{n_m+1} - 1}\left[y_7\left(y_7^{n_m} - 1\right)\left(c_{m,II,7} - v_{4+4U}\right) + (y_7 - 1)c_{m,7}\right]$$

$$c_{m,T,7} = \frac{0.913}{0.284^{1+1} - 1}[(0.284)(0.284^1 - 1)(386 - 125) + (0.284 - 1)(64)]$$

$$c_{m,T,7} = 98 \text{ veh/h}$$

Step 9: Compute Rank 4 Movement Capacities

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:

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

$$d_1 = 12.6 \text{ s}$$

This movement would be assigned LOS B.

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

$$d_{4+4U} = 20.1 \text{ s}$$

This movement would be assigned LOS C.

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

$$d_9 = 16.1 \text{ s}$$

This movement would be assigned LOS C.

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

$$d_1 = 113 \text{ s}$$

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:

$$d_{A,EB} = \frac{0(100) + 0(1{,}000) + 12.6(50)}{100 + 1{,}000 + 50} = 0.5 \text{ s}$$

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

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

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:

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

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

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 from Equation 20-68:

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

$$Q_{95,1} \approx 0.3 \text{ veh}$$

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

$$Q_{95,4+4U} \approx 1.5 \text{ veh}$$

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

$$Q_{95,9} \approx 0.9 \text{ veh}$$

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

$$Q_{95,7} \approx 4.1 \text{ veh}$$

Discussion

Overall, the results indicate that although 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. AWSC SUPPLEMENTAL ANALYSIS FOR THREE-LANE APPROACHES

Exhibit 32-15 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 a vehicle is in the lane; a 0 indicates a vehicle is not in the lane.

Exhibit 32-15
Probability of Degree-of-Conflict Case: Multilane AWSC Intersections (Three-Lane Approaches, by Lane) (Cases 1–49)

i	DOC Case	No. of Vehicles	Opposing Approach			Conflicting Left Approach			Conflicting Right Approach		
			L1	L2	L3	L1	L2	L3	L1	L2	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 32-15 (cont'd.)
Probability of Degree-of-Conflict Case: Multilane AWSC Intersections (Three-Lane Approaches, by Lane) (Cases 50–112)

			Opposing Approach			Conflicting Left Approach			Conflicting Right Approach		
i	DOC Case	No. of 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 32-15 (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**	**No. 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 32-15 (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**	**No. 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 32-15 (cont'd.)
Probability of Degree-of-Conflict Case: Multilane AWSC Intersections (Three-Lane Approaches, by Lane) (Cases 239–301)

i	DOC Case	No. of Vehicles	Opposing Approach			Conflicting Left Approach			Conflicting Right Approach		
			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 32-15 (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	No. 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 32-15 (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	No. 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 32-15 (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	No. 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 32-15 (cont'd.)
Probability of Degree-of-Conflict Case: Multilane AWSC Intersections (Three-Lane Approaches, by Lane) (Cases 491–512)

i	DOC Case	No. 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 = degree-of-conflict; No. of vehicles = total number of vehicles on the opposing and conflicting approaches; L1, L2, and L3 = Lane 1, 2, and 3, respectively.

5. AWSC EXAMPLE PROBLEMS

This part of the chapter provides example problems for use of the AWSC methodology. Exhibit 32-16 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 default values are used when available.

Exhibit 32-16
AWSC Example Problems

Problem Number	Description	Analysis Level
1	Single-lane, three-leg AWSC intersection	Operational
2	Multilane, four-leg AWSC intersection	Operational

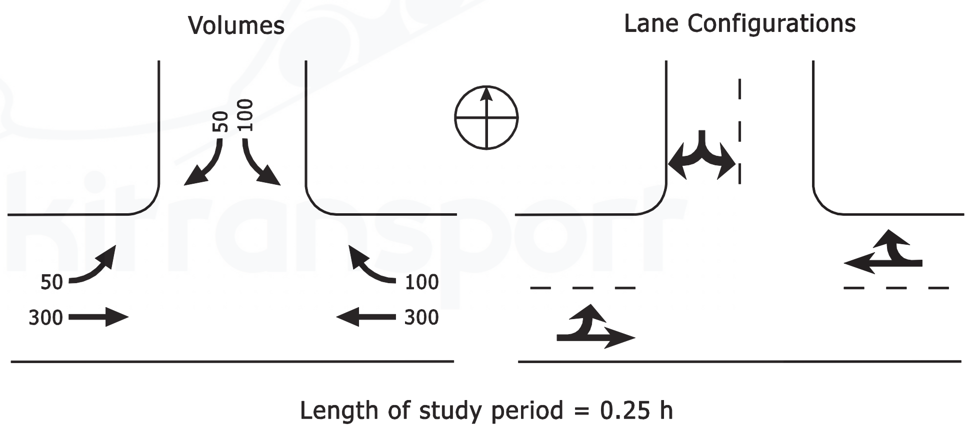
AWSC EXAMPLE PROBLEM 1: SINGLE-LANE, THREE-LEG INTERSECTION

The Facts

The following describes this location's traffic and geometric characteristics:

- Three legs (T-intersection),
- One-lane entries on each leg,
- Percentage heavy vehicles on all approaches = 2%,
- Peak hour factor = 0.95, and
- Volumes and lane configurations are as shown in Exhibit 32-17.

Exhibit 32-17
AWSC Example Problem 1: Volumes and Lane Configurations



Comments

The use of a spreadsheet or software for AWSC intersection analysis is recommended because of the repetitive and iterative computations required.

All input parameters are known, so no default values are needed or used. The use of a spreadsheet or software is recommended because of the repetitive computations required. Slight differences in reported values may result from rounding differences between manual and software computations. Because showing all the individual computations is not practical, this example problem shows how one or more computations are made. All computational results can be found in the spreadsheet output located in the Volume 4 Technical Reference Library section for Chapter 32.

Step 1: Convert Movement Demand Volumes to Flow Rates

Peak 15-min flow rates for each turning movement at the intersection are equal to the hourly volumes divided by the peak hour factor (Equation 21-12). For example, the peak 15-min flow rate for the eastbound through movement is as follows:

$$v_{EBTH} = \frac{V_{EBTH}}{PHF} = \frac{300}{0.95} = 316 \text{ veh/h}$$

Step 2: Determine Lane Flow Rates

This step does not apply because the intersection has one-lane approaches on all legs.

Step 3: Determine Geometry Group for Each Approach

Exhibit 21-11 shows each approach should be assigned to Geometry Group 1.

Step 4: Determine Saturation Headway Adjustments

Exhibit 21-12 shows the headway adjustments for left turns, right turns, and heavy vehicles are 0.2, –0.6, and 1.7, respectively. These values apply to all approaches because all are assigned to Geometry Group 1. The saturation headway adjustment for the eastbound approach is calculated from Equation 21-13 as follows:

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

$$h_{adj,EB} = 0.2\frac{53}{53+316} - 0.6(0) + 1.7(0.02) = 0.063$$

Similarly, the saturation headway adjustments for the westbound and northbound approaches are as follows:

$$h_{adj,WB} = 0.2(0) - 0.6\left(\frac{105}{105+316}\right) + 1.7(0.02) = -0.116$$

$$h_{adj,NB} = 0.2\frac{105}{105+53} - 0.6\left(\frac{53}{105+53}\right) + 1.7(0.02) = -0.034$$

Steps 5–11: Determine Departure Headways

These steps are iterative. The following narrative highlights some of the key calculations using the eastbound approach for Iteration 1.

Step 6: Calculate Initial Degree of Utilization

By using the lane flow rates from Step 2 and the assumed initial departure headway from Step 5, the initial degree of utilization x is computed as follows from Equation 21-14:

$$x_{EB} = \frac{vh_d}{3{,}600} = \frac{(368)(3.2)}{3{,}600} = 0.327$$

$$x_{WB} = \frac{(421)(3.2)}{3{,}600} = 0.374$$

$$x_{NB} = \frac{(158)(3.2)}{3{,}600} = 0.140$$

Step 7: Compute Probability States

The probability state of each combination i is determined with Equation 21-15.

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

For an intersection with single-lane approaches, only eight cases from Exhibit 21-14 apply, as shown in Exhibit 32-18:

Exhibit 32-18
AWSC Example Problem 1: Applicable Degree-of-Conflict Cases

i	DOC Case	No. of Vehicles	Opposing Approach	Conflicting Left Approach	Conflicting Right Approach
1	1	0	0	0	0
2	2	1	1	0	0
5	3	1	0	1	0
7	3	1	0	0	1
13	4	2	0	1	1
16	4	2	1	1	0
21	4	2	1	0	1
45	5	3	1	1	1

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:

$P(a_O) = 1 - x_O = 1 - 0.374 = 0.626$ (no opposing vehicle present)

$P(a_{CL}) = 1 - x_{CL} = 1 - 0.140 = 0.860$ (no conflicting vehicle from left)

$P(a_{CR}) = 1$ (no approach conflicting from right)

Therefore,

$$P(1) = P(a_O) \times P(a_{CL}) \times P(a_{CR}) = (0.626)(0.860)(1) = 0.538$$

Similarly,

$$P(2) = (0.374)(0.860)(1) = 0.322$$
$$P(5) = (0.626)(0.140)(1) = 0.088$$
$$P(7) = (0.626)(0.860)(0) = 0$$
$$P(13) = (0.626)(0.140)(0) = 0$$
$$P(16) = (0.374)(0.140)(1) = 0.052$$
$$P(21) = (0.374)(0.860)(0) = 0$$
$$P(45) = (0.374)(0.140)(0) = 0$$

Step 8: Compute Probability Adjustment Factors

The probability adjustment is computed as follows, using Equation 21-16 through Equation 21-20:

$$P(C_1) = P(1) = 0.538$$
$$P(C_2) = P(2) = 0.322$$
$$P(C_3) = P(5) + P(7) = 0.088 + 0 = 0.088$$
$$P(C_4) = P(13) + P(16) + P(21) = 0 + 0.052 + 0 = 0.052$$
$$P(C_5) = P(45) = 0$$

The probability adjustment factors for the nonzero cases are calculated from Equation 21-21 through Equation 21-25:

$$AdjP(1) = 0.01[0.322 + 2(0.088) + 3(0.052) + 0]/1 = 0.0065$$
$$AdjP(2) = 0.01[0.088 + 2(0.052) + 0 - 0.322]/3 = -0.0004$$
$$AdjP(5) = 0.01[0.052 + 2(0) - 3(0.088)]/6 = -0.0004$$
$$AdjP(16) = 0.01[0 - 6(0.052)]/27 = -0.0001$$

Therefore, the adjusted probability for Combination 1, for example, is as follows from Equation 21-16:

$$P'(1) = P(1) + AdjP(1) = 0.538 + 0.0065 = 0.5445$$

Step 9: Compute Saturation Headways

The base saturation headways for each combination can be determined with Exhibit 21-15. They are adjusted by using the adjustment factors calculated in Step 4 and added to the base saturation headways to determine saturation headways as shown in Exhibit 32-19 (eastbound illustrated):

Exhibit 32-19
AWSC Example Problem 1: Eastbound Saturation Headways

i	h_{base}	h_{adj}	h_{si}
1	3.9	0.063	3.963
2	4.7	0.063	4.763
5	5.8	0.063	5.863
7	7.0	0.063	7.063

Step 10: Compute Departure Headways

The departure headway of the lane is the sum of the products of the adjusted probabilities and the saturation headways as follows (eastbound illustrated):

$$h_d = \sum_{i=1}^{64} P'(i)h_{si}$$

$$h_{d,EB} = (0.5445)(3.963) + (0.3213)(4.763) + (0.0875)(5.863) + (0.0524)(7.063)$$

$$h_{d,EB} = 4.57 \text{ s}$$

Step 11: Check for Convergence

The calculated values of h_d are checked against the initial values assumed 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, four iterations are required for convergence, as shown in Exhibit 32-20.

Exhibit 32-20
AWSC Example Problem 1: Convergence Check

	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	

Step 12: Compute Capacities

The capacity of each lane in a subject 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 for a spreadsheet or software implementation.

Here, the eastbound lane capacity is approximately 720 veh/h, which is lower than the value that could be estimated by dividing the lane volume by the degree of utilization (368/0.492 = 748 veh/h). The difference is due to the interaction effects among the approaches: increases in eastbound traffic volume increase the departure headways of the lanes on the other approaches, which in turn increases the departure headways of the lane(s) on 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 21-29. For the eastbound lane (using a value for m of 2.0 for Geometry Group 1), the calculation is as follows:

$$t_{s,EB} = h_{d,EB} - m = 4.97 - 2.0 = 2.97 \text{ s}$$

Step 14: Compute Control Delay and Determine LOS for Each Lane

The control delay for each lane is computed with Equation 21-30 as follows (eastbound illustrated):

$$d_{EB} = t_{s,EB} + 900T\left[(x_{EB} - 1) + \sqrt{(x_{EB} - 1)^2 + \frac{h_{d,EB}x_{EB}}{450T}}\right] + 5$$

$$d_{EB} = 2.97 + 900(0.25)\left[(0.508 - 1) + \sqrt{(0.508 - 1)^2 + \frac{4.97(0.508)}{450(0.25)}}\right] + 5$$

$$d_{EB} = 13.0 \text{ s}$$

By using Exhibit 21-8, the eastbound lane (and thus approach) is assigned LOS B. A similar calculation for the westbound and southbound lanes (and thus approaches) yields 13.5 and 10.6 s, respectively.

Step 15: Compute Control Delay and Determine LOS for the Intersection

The control delays for the approaches can be combined into an intersection control delay by using a weighted average as follows:

$$d_{\text{intersection}} = \frac{\sum d_a v_a}{\sum v_a}$$

$$d_{\text{intersection}} = \frac{(13.0)(368) + (13.5)(421) + (10.6)(158)}{368 + 421 + 158} = 12.8 \text{ s}$$

This value of delay is assigned LOS B.

Step 16: Compute Queue Lengths

The 95th percentile queue for each lane is computed with Equation 21-33 as follows (eastbound approach illustrated):

$$Q_{95,EB} \approx \frac{900T}{h_{d,EB}}\left[(x_{EB} - 1) + \sqrt{(x_{EB} - 1)^2 + \frac{h_{d,EB}x_{EB}}{150T}}\right]$$

$$Q_{95,EB} \approx \frac{900(0.25)}{4.97}\left[(0.508 - 1) + \sqrt{(0.508 - 1)^2 + \frac{4.97(0.508)}{150(0.25)}}\right] = 2.9 \text{ veh}$$

This queue length would be reported as three vehicles.

Discussion

The results indicate the intersection operates well with brief delays.

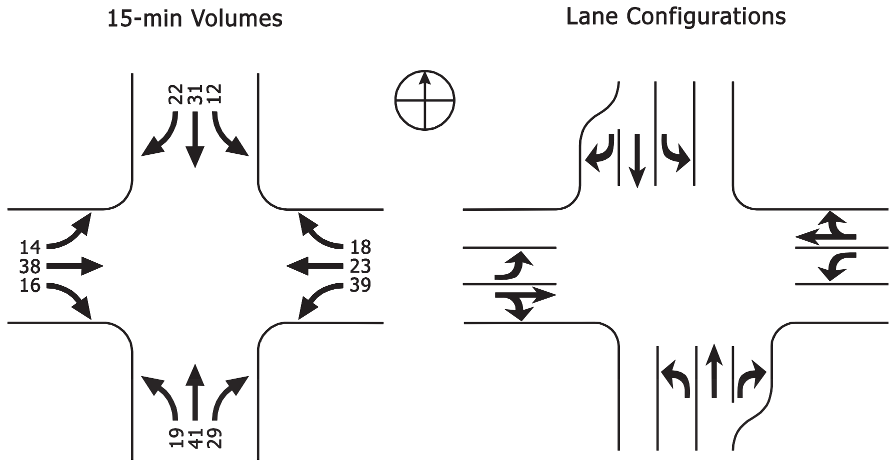
AWSC EXAMPLE PROBLEM 2: MULTILANE, FOUR-LEG INTERSECTION

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;
- Percentage 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 are as shown in Exhibit 32-21.

Exhibit 32-21
AWSC Example Problem 2: 15-min Volumes and Lane Configurations



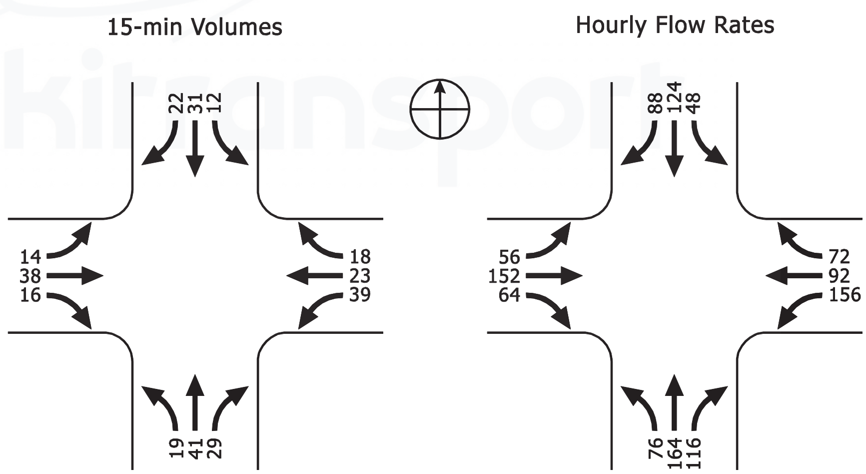
Comments

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 showing all the individual computations is not practical, this example problem shows how one or more computations are made. All computational results can be found in the spreadsheet output located in the Volume 4 Technical Reference Library section for Chapter 32.

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 32-22:

Exhibit 32-22
AWSC Example Problem 2: 15-min Volumes Converted to 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 21-11 shows each approach should be assigned to Geometry Group 6.

Step 4: Determine Saturation Headway Adjustments

Exhibit 21-12 shows 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):

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

$$h_{adj,EB,1} = 0.5(1.0) - 0.7(0) + 1.7(0.02) = 0.534$$

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

$$h_{adj,EB,2} = 0.5(0) - 0.7\left(\frac{64}{64+152}\right) + 1.7(0.02) = -0.173$$

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 5–11: Determine Departure Headways

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 it 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:

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

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

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

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

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

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

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

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

Step 7: Compute Probability States

Because three-lane approaches are involved, the modified methodology presented in Section 4 of Chapter 21 is used.

The probability state of each combination *i* is determined with Equation 21-34:

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

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 21-16):

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

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

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

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

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

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

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

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

Therefore,

$$P(1) = P(a_{O1}) \times P(a_{O2}) \times P(a_{CL1}) \times P(a_{CL2}) \times P(a_{CL3}) \times P(a_{CR1}) \times P(a_{CR2}) \times P(a_{CR3})$$

$$P(1) = (0.8613)(0.8542)(0.9573)(0.8898)(0.9218)(0.9324)(0.8542)(0.8969)$$

$$P(1) = 0.4127$$

To complete the calculations for Step 7, the computations are completed for the remaining 511 possible combinations. The full computational results for the eastbound leg (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 21-35 through Equation 21-39 to account for the serial correlation in the previous probability computation. First, the probability of each degree-of-conflict case must be determined. 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

$$P(C_1) = P(1) = 0.4127$$

$$P(C_2) = \sum_{i=2}^{8} P(i) = 0.1482$$

$$P(C_3) = \sum_{i=9}^{22} P(i) = 0.2779$$

$$P(C_4) = \sum_{i=23}^{169} P(i) = 0.1450$$

$$P(C_5) = \sum_{i=170}^{512} P(i) = 0.0162$$

The probability adjustment factors are then computed with Equation 21-40 through Equation 21-44, where α equals 0.01 (or 0.00 if correlation among saturation headways is not taken into account).

For example, by using Equation 21-35, $AdjP(1)$ is calculated as follows:

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

The results of the remaining computations 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 21-15. 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 lane 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, as shown in Exhibit 32-23.

Exhibit 32-23
AWSC Example Problem 2: Convergence Check

	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 lane in a subject 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 lane 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 lanes on the other approaches, which increases the departure headways of the lanes on 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 21-29. For the eastbound Lane 1 (using a value for m of 2.3 for Geometry Group 6), the calculation is as follows:

$$t_{s,EB,1} = h_{d,EB,1} - m = 8.19 - 2.3 = 5.89 \text{ s}$$

Step 14: Compute Control Delay and Determine LOS for Each Lane

The control delay for each lane is computed with Equation 21-30 as follows (eastbound Lane 1 illustrated):

$$d_{EB,1} = t_{s,EB,1} + 900T\left[\left(x_{EB,1} - 1\right) + \sqrt{(x_{EB,1} - 1)^2 + \frac{h_{d,EB,1}x_{EB,1}}{450T}}\right] + 5$$

$$d_{EB,1} = 5.89 + 900(0.25)\left[(0.1274 - 1) + \sqrt{(0.1274 - 1)^2 + \frac{8.19(0.1274)}{450(0.25)}}\right] + 5$$

$$d_{EB,1} = 12.1 \text{ s}$$

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

Step 15: Compute Control Delay and Determine LOS for Each Approach and the Intersection

The control delay for each approach is calculated using Equation 21-31 as follows (eastbound approach illustrated):

$$d_{EB} = \frac{(12.1)(272) + (16.1)(216)}{56 + 216} = 15.3 \text{ s}$$

This value of delay is assigned LOS C.

Similarly, the control delay for the intersection is calculated as follows:

$$d_{\text{intersection}} = \frac{(15.3)(272) + (14.3)(320) + (13.1)(356) + (12.6)(260)}{272 + 320 + 356 + 260} = 14.0 \text{ s}$$

This value of delay is assigned LOS B.

Step 16: Compute Queue Lengths

The 95th percentile queue for each lane is computed with Equation 21-33 as follows for eastbound Lane 1:

$$Q_{95,EB1} \approx \frac{900(0.25)}{8.19}\left[(0.1274 - 1) + \sqrt{(0.1274 - 1)^2 + \frac{8.19(0.1274)}{150(0.25)}}\right]$$

$$Q_{95,EB1} \approx 0.4 \text{ veh}$$

This queue length commonly would be rounded up to one 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. The intersection as a whole operates at LOS B, so the reporting of individual movements is important to avoid masking results caused by aggregating delays.