CHAPTER 19
SIGNALIZED INTERSECTIONS – PROTOTYPE CHAPTER

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1. INTRODUCTION

This prototype chapter illustrates an alternative way to present the HCM methods for analyzing signalized intersections. The chapter focuses on the needs of the practitioner, not the researcher or teacher, nor the software developer. It assumes that practitioners will conduct their analysis by applying either

- The basic method using the worksheets provided here or a software application, or
- The advanced method using a software application.

The chapter provides the analyst with the information that they need to conduct their analysis including the data they will need. It also:

- Explains the concepts of traffic flow and signal control that form the basis for the methods.
- Describes the basic method to predict the performance of a signalized intersection, when the method is appropriate for use, the data needed to use the method, and the performance measures predicted by the method.
- Provides an example calculation to illustrate the application of the basic method.
- Provides guidance as to when the advanced method is appropriate and the data needed to use the method.

The supplementary prototype chapter for signalized intersections (Chapter 31) provides information for researchers and teachers who need to have access to and understand the details of the computational procedures upon which the methods are based, so they can test them, extend them, and teach them. The supplementary chapter also provides unambiguous descriptions of the computational procedures that constitute the methods so that software developers can write the applications needed by practitioners, researchers, and teachers.

Highlights of the Basic and Advanced Methods

The HCM provides two methods for analyzing signalized intersections, a basic method and an advanced method. The basic method, described in section 3 of this chapter, is applied using the worksheets provided in that section or by using a software application. Guidance for using the advanced method is provided in section 5 of the chapter. The advanced method must be applied using a software application.

Exhibit 1 and Exhibit 2 provide highlights of the basic and advanced methods. The information provided in the exhibits help the analyst determine which method to choose for a particular traffic analysis problem.

<table>
<tr><th>Element</th><th>Basic Method</th><th>Advanced Method</th></tr>
<tr><td>Method is appropriate when…</td><td>Analyst desires to conduct a quick analysis of existing or proposed intersection conditions
Analyst has limited information on the conditions at an intersection
Focus is on future conditions</td><td>Analyst has detailed information on intersection conditions
Focus is on current or near term conditions
Analyst desires to make decisions about operating conditions such as lane configurations, signal timing, and signal phasing
Traffic demand exceeds capacity, and oversaturation, queue spillback, or demand starvation conditions result
Detailed analysis of actuated and/or coordinated signal timing is needed</td></tr>
<tr><td>Method helps analyst to…</td><td>Determine:
Adequacy of the lane geometry
Signal cycle length
Distribution of green times among the signal phases</td><td>Make decisions about operating conditions such as:
Lane configurations
Signal timing
Signal phasing</td></tr>
</table>

Exhibit 1. Elements of the Basic Method and the Advanced Method

Element	Basic Method	Advanced Method
Method should not be applied when…	• Intersection has actuated control • Intersection has actuated control but operation can't be modeled by pretimed control • Approach grades are not level, lane widths are not standard, and bus activity is present • Demand exceeds capacity	• Traffic overflows turn bay • Demand is starved for any movement • Queues spillback from downstream intersection • There are added lanes just upstream or downstream of intersection • There is storage of shared left turn vehicles within intersection to permit bypass of through vehicles in some lanes • There are multiple advance detectors in same lane • There is premature phase termination due to short passage times or detection zone lengths, or both • There is delay to movements not under signal control • There is rest-in-walk, signal preemption, signal priority, phase overlap, or gap reduction or variable initial timing parameters
Method is applied using…	• Manual calculations using worksheets, or • Software application	• Software application
The method predicts…	• Volume-to-capacity ratio for Intersection • Control delay for each movement and approach, and the intersection • Level of service for each movement and approach, and the intersection	• Capacity for each movement and approach • Volume-to-capacity ratio for each movement and approach, and the intersection • Control delay for each movement and approach, and the intersection • Level of service for each movement and approach, and the intersection • Queue storage ratio for each movement and approach
The method…	• Is based on critical movement analysis • Assumes a base saturation flow rate • Adjusts volumes based on given conditions • Approximates cycle length based on number of critical phases • Allocates green time to phases based on volumes • Accounts for protected or permitted left turn phasing	• Is based on deterministic queuing theory • Assumes a base saturation flow rate • Adjusts both volumes and saturation flow rate based on given conditions • Uses given green times (if pretimed control) or predicts green times (if actuated control) • Accounts for protected or permitted left turn phasing
Data required when applying the method are provided in…	• Section 3	• Section 5

Exhibit 2. Elements of the Basic Method and the Advanced Method

Roadmap to Chapter

Exhibit 3 provides a roadmap to this chapter. Use it find the information that you need, depending on the task that you want to complete.

If you want to…	**Go to page…**
Understand traffic flow and signal control concepts that are the foundation of the basic and advanced method	
• Representing traffic flow	4
• Representing signal control	4
• Determining capacity	4
• Determining delay	4
Learn about and apply the basic method	
• Introduction and overview to the method	5
• Data needed to use the method	7
• Applying the method	7
• Performance measures predicted by the method	5
• Example calculation illustrating application of the method	19
Learn about the advanced method	
• Introduction and overview to the method	33
• Data needed need to use the method	34
• Performances measures predicted by the method	35

Exhibit 3. Roadmap to Chapter 19

2. TRAFFIC FLOW AND SIGNAL CONTROL CONCEPTS

This section presents the concepts of traffic flow and signal control that are the basis for the signalized intersection method.

Representing Traffic Flow

Time space diagram: trajectories and parameters
Deterministic queuing model representing one signal cycle
Flow profile diagram representing arrival and departure flows
Cumulative vehicle diagram
Queue accumulation polygon
*Adjusting flow and passenger car equivalents

Representing Signal Control

Types of signal control
Phases: Sequencing and controlling movements
Left turn operational modes
Pretimed control timing parameters

Capacity

Saturation flow rate
Flow ratio
Capacity
Volume-capacity ratio
Sufficiency of capacity

Delay

Uniform delay
Incremental delay

3. THE BASIC METHOD

Introduction

The basic method can be used to predict the performance of a signalized intersection. The method is appropriate when the analyst desires to conduct a quick analysis of existing or proposed intersection conditions, has limited information on the conditions at an intersection, or when the focus is on future conditions. It helps the analyst determine the adequacy of lane geometry, the signal cycle length, and the distribution of green times among the signal phases. The method can be applied using the worksheets provided in this section or by using a software application that implements the method.

Consider using the advanced method…
If any of the following conditions exist, the analyst should instead consider using the advanced method, described in section 5 of this chapter: • The analyst has detailed information on intersection conditions, • The focus is on current or near term conditions, • The analyst desires to make decisions about operating conditions such as lane configurations, signal timing, and signal phasing, • Traffic demand exceeds capacity, and oversaturation, queue spillback, or demand starvation conditions result, or • Detailed analysis of actuated and/or coordinated signal systems is need.

Overview of the basic method…
The basic method predicts values for three performance measures: • Intersection v/c ratio. • The control delay for each movement, for each approach, and for the intersection. • The level of service for each movement, for each approach, and for the intersection. The method can be applied when the following conditions are true or can be assumed: • The intersection has pretimed control, or when the intersection has actuated control but its operation can be modeled by pretimed control. • The intersection has level grade, standard lane widths, and no bus activity. • The demand is less than capacity. The method accounts for: • Pedestrian activity. • Parking activity. • Heavy vehicles. The method requires that the analyst specify: • Lane geometry (number of lanes and allowable movements for each lane), and • Volumes for each turning movement.

Where to go from here	
If you want to…	**Go to page…**
Read an overview of the method…	6
Apply the method…	7
See example calculation to illustrate application of the method…	19

Overview of the Basic Method

The basic method uses the concept of critical phases to determine the adequacy of intersection capacity and to predict the delay that motorists would experience. To use this method, the analyst must understand the concept of sequencing of signal phases described in section 2 of this chapter. The analyst determines the sequence of phases, called the critical phases, that require the maximum amount of green time, based on the movement volumes served by each phase. The movement volumes are adjusted for conditions such as the presence of heavy vehicles, peaking characteristics, pedestrian and parking activity, and other factors.

The method includes seven steps. To use the method, the analyst:	Exhibits
1. Gathers the required data and/or accepts suggested default values	Exhibit 4 Exhibit 5 Exhibit 6
2. Identifies desired left turn operation, or determines left turn operation using three checks	Exhibit 7 Exhibit 8
3. Converts movement volumes to through passenger car equivalent flow rates based on equivalency factors that account for heavy vehicles, peaking, pedestrians, parking, and lane utilization	Exhibit 9 Exhibit 10 Exhibit 11 Exhibit 12 Exhibit 13 Exhibit 14
4. Determines critical lane groups by calculating which sequence of phases requires the maximum amount of green time based on the volumes of the movements that they serve	Exhibit 15 Exhibit 16
5. Assesses whether the capacity of the intersection is sufficient to serve the given volumes	Exhibit 17
6. Determines the capacity and the volume/capacity ratio for each movement	Exhibit 18
7. Determines the delay and level of service for each movement, each approach, and for the intersection.	Exhibit 19 Exhibit 20 Exhibit 21 Exhibit 22 Exhibit 23 Exhibit 24 Exhibit 25 Exhibit 26

Application of the Basic Method

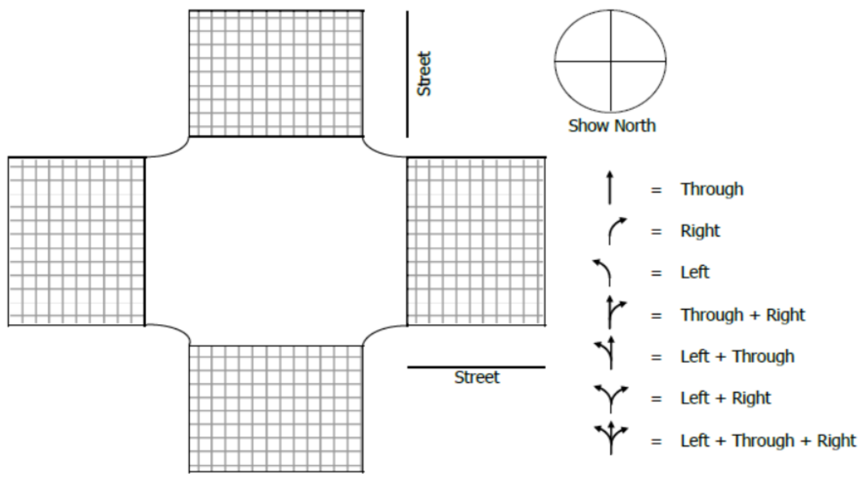
The analyst can apply the method either using a software application or by completing the steps described below and on the following pages, in Exhibit 4 through Exhibit 26.

Step 1a. Gather required data and/or accept default values for the intersection.

- Enter the general and site information.
- Prepare a sketch of the intersection showing lanes and movements.
- Enter the intersection data for peak hour factor, cycle length, and base saturation flow rate.

General Information		Site Information	
Analyst	______	Intersection	______
Agency or company	______		______
Date performed	______	Jurisdiction	______
Analysis time period		Analysis year	

Intersection Geometry



Data Item	Required or Suggested Default Values	Intersection Data
Enter peak hour factor, PHF	Use default value of 0.92 if not known	
Enter cycle length (s), C	Can be estimated using guidance provided in step 5	
Enter base saturation flow rate (veh/h), s	Use default value of 1900 if not known	

Exhibit 4. Data requirements for basic method

Step 1b. Gather required data and/or accept default values for the intersection approaches.

- Enter the following data for each approach:
  - Level of parking activity
  - Level of pedestrian activity
  - Left turn operation

Data Item	Approach Data			
	EB	WB	NB	SB
Specify the level of parking activity • None (default) • Low – 5 parking maneuvers per hour • Medium – 10 parking maneuvers per hour • High – 15 parking maneuvers per hour				
Specify the level of pedestrian activity • None (default) • Low – 50 pedestrians per hour • Medium – 200 pedestrians per hour • High – 400 pedestrians per hour • Extreme – 800 pedestrians per hour				
Specify the left-turn operation (Can be determined using guidance provided in step 2) • Protected left turn operation • Permitted left turn operation • Split phasing • Protected-permitted left turn operation				

Exhibit 5. Data requirements for basic method

Step 1c. Gather required data and/or accept default values for each movement.

- Enter the following data for each movement:
  - Volume
  - Number of lanes
  - Lane use (exclusive or shared)
  - Percent heavy vehicles
- Enter the effective green time if known. Alternatively, it can be calculated in step 6.
- Enter the progression quality if known.

Data Item	Movement Data											
	EB			WB			NB			SB		
	LT	TH	RT	LT	TH	RT	LT	TH	RT	LT	TH	RT
Enter volume (veh/h), V												
Enter number of lanes, N												
Specify lane use, exclusive (E) or shared (S)												
Enter percent heavy vehicles (%), P_{HV}												
Enter effective green time (s), g_{eff} (Can be calculated using guidance provided in step 6)												
Specify progression quality • Good progression, G • Random arrivals (default), R • Poor progression, P												

Exhibit 6. Data requirements for basic method

Step 2. Determine left turn operations.

EITHER select one of the following left turn operational modes by placing an X in the appropriate box for the EB-WB and NB-SB approaches…

	EB-WB Approaches	NB-SB Approaches
Protected LT operation		
Permitted LT operation		
Split phasing		
Protected-permitted LT operation		

OR determine the LT phasing using the following three checks.

Check #1. Left turn lane check. If the number of LT lanes on an approach exceeds 1, then it is recommended that the left turns on that approach be protected.

Approach	EB	WB	NB	SB
Enter number of LT lanes from step 1 (Exhibit 6)				
Select protected LT, Y or N?				

Check #2. Minimum volume check. If the LT volume on any approach exceeds 240 veh/hr, then it is recommended that the left turns on that approach be protected.

Approach	EB	WB	NB	SB
Enter LT volume (veh/h) from step 1 (Exhibit 6)				
Select protected LT, Y or N?				

Check #3. Minimum cross-product check. If the cross product of the left turn volume and the opposing TH volume exceeds the criterion in Exhibit 8, **then it is recommended that left turns on that approach be protected.**

Approach	EB	WB	NB	SB
Enter LT volume (veh/h), V_L from step 1 (Exhibit 6)				
Enter opposing TH volume (veh/h), V_O from step 1 (Exhibit 6)				
Calculate cross product: $V_L \times V_O$				
Enter number of opposing TH lanes from step 1				
Select protected LT, Y or N, based on Exhibit 8				

	EB/WB Approaches	NB/SB Approaches
Enter selected LT mode, protected or permitted.		

Exhibit 7. Determining left turn operations

Number of TH lanes	Minimum Cross-Product
1	50,000
2	90,000
3	110,000

Exhibit 8. Minimum Cross-Product Values for Recommending LT Protection

Step 3a. Convert movement volumes to flow rates in through passenger car equivalents for the EB and WB approaches.

- Enter the movement volumes, percent heavy vehicles, pedestrian activity, opposing volume, parking activity, and number of lanes in lane group.
- Calculate the equivalency factors using Exhibit 11 through Exhibit 14.
- Calculate the equivalent through passenger car flow rate.

	EB			WB		
	LT	TH	RT	LT	TH	RT
Enter movement volume (veh/h), V, from step 1						
Enter percent heavy vehicle (%), P_{HV}, from step 1						
Calculate equivalency factor for heavy vehicles $E_{hv} = 1 + 0.01\, P_{HV}(E_T - 1)$; default E_T = 2						
Enter peak hour factor for intersection, PHF, from step 1						
Calculate equivalency factor for peaking characteristics $E_{PHF} = \frac{1}{PHF}$						
Enter pedestrian activity from step 1						
Enter equivalency factor for right turns, E_{RT}, from Exhibit 11						
Enter total opposing volume (veh/h), V_o, from step 1						
Enter equivalency factor for left turns, E_{LT}, from Exhibit 12						
Enter level of parking activity from step 1						
Enter number of lanes from step 1						
Enter equivalency factor for parking activity, E_p, from Exhibit 13						
Enter number of lanes from step 1						
Enter equivalency factor for lane utilization, E_{LU}, from Exhibit 14						
Enter equivalency factor for other conditions, E_{other} (see note)						
Calculate equivalent through movement flow rate (tpc/h) $v_{adj} = VE_{HV}E_{PHF}E_{LT}E_{RT}E_PE_{LU}E_{other}$						
Enter the number of lanes, N, from step 1						
Calculate the lane flow rate (tpc/h/ln) $v = \frac{v_{adj}}{N}$						

Note: The analyst can use an adjustment factor to account for other conditions, E_{other}, if known.

Exhibit 9. Converting movement volumes to though passenger car equivalents

Step 3b. Convert movement volumes to flow rates in through passenger car equivalents for the NB and SB approaches.

- Enter the movement volumes, percent heavy vehicles, pedestrian activity, opposing volume, parking activity, and number of lanes in lane group.
- Calculate the equivalency factors using Exhibit 11 through Exhibit 14.
- Calculate the equivalent through passenger car flow rate.

	NB			SB		
	LT	TH	RT	LT	TH	RT
Enter movement volume (veh/h), V, from step 1						
Enter percent heavy vehicle (%), P_{HV}, from step 1						
Calculate equivalency factor for heavy vehicles $E_{hv} = 1 + 0.01\,P_{HV}(E_T - 1)$; default $E_T = 2$						
Enter peak hour factor for intersection, PHF, from step 1						
Calculate equivalency factor for peaking characteristics $E_{PHF} = \frac{1}{PHF}$						
Enter pedestrian activity from step 1						
Enter equivalency factor for right turns, E_{RT}, from Exhibit 11						
Enter total opposing volume (veh/h), V_o, from step 1						
Enter equivalency factor for left turns, E_{LT}, from Exhibit 12						
Enter level of parking activity from step 1						
Enter number of lanes from step 1						
Enter equivalency factor for parking activity, E_p, from Exhibit 13						
Enter number of lanes from step 1						
Enter equivalency factor for lane utilization, E_{LU}, from Exhibit 14						
Enter equivalency factor for other conditions, E_{other} (see note)						
Calculate equivalent through movement flow rate (tpc/h) $v_{adj} = VE_{HV}E_{PHF}E_{LT}E_{RT}E_PE_{LU}E_{other}$						
Enter the number of lanes, N, from step 1						
Calculate the lane flow rate (tpc/h/ln) $v = \frac{v_{adj}}{N}$						

Note: The analyst can use an adjustment factor to account for other conditions, E_{other}, if known.

Exhibit 10. Converting movement volumes to though passenger car equivalents

Pedestrian Activity	Pedestrian Volume (p/h)	E_{RT}
None or low	0 – 199	1.2
Moderate	200 – 399	1.3
High	400 – 799	1.5
Extreme	≥ 800	2.1

Exhibit 11. Equivalency factors for right turns

Parking Activity	Number of Lanes	E_P
None	All	1.00
Adjacent parking allowed	1	1.20
	2	1.10
	3	1.05

Exhibit 13. Equivalency factors for parking activity

LT Operation	Total Opposing Volume, V_o, veh/h	E_{LT}
Protected	Any	1.05
Permitted	< 200	1.1
	200 – 599	2.0
	600 – 799	3.0
	800 – 999	4.0
	≥ 1000	5.0
For protected/permitted operation, see xxx.		

Exhibit 12. Equivalency factors for left turns

Lane Movements	Number of Lanes	E_{LU}
Through	1	1.00
	2	1.05
	≥ 3	1.10
Exclusive left turn	1	1.00
	≥ 2	1.03
Exclusive right turn	1	1.00
	≥ 2	1.13

Exhibit 14. Equivalency factors for lane utilization

Step 4a. Determine critical lane groups.

- For the left turn operation previously selected, determine the critical lane groups using either the table for protected LT operation or permitted LT operation. Consult Exhibit 16 for standard phase numbering.

Protected Left Turn Operation

For approaches with protected left turn operation, enter the lane flow rates for each movement. Then calculate the summations noted below.

East-West Approaches						North-South Approaches				
Φ1 Enter: V_{WBLT}		+	Φ2 Enter: $V_{EBTH} + V_{EBRT}$			Φ3 Enter: V_{NBLT}		+	Φ4 Enter: $V_{SBTH} + V_{SBRT}$	
Calculate: $V_{WBLT} + V_{EBTH} + V_{EBRT}$						Calculate: $V_{NBLT} + V_{SBTH} + V_{SBRT}$				
OR					+	OR				
Φ5 Enter: V_{EBLT}		+	Φ6 Enter: $V_{WBTH} + V_{WBRT}$			Φ7 Enter: V_{SBLT}		+	Φ8 Enter: $V_{NBTH} + V_{NBRT}$	
Calculate: $V_{EBLT} + V_{WBTH} + V_{WBRT}$						Calculate: $V_{SBLT} + V_{NBTH} + V_{NBRT}$				
Determine: Max ($V_{WBLT} + V_{EBTH} + V_{EBRT}, V_{EBLT} + V_{WBTH} + V_{WBRT}$)						Determine: Max ($V_{NBLT} + V_{SBTH} + V_{SBRT}, V_{LTSB} + V_{NBTH} + V_{NBRT}$)				

Permitted Left Turn Operation

For approaches with permitted left turn operation, enter the lane flow rates for each movement. Then calculate the summations noted below.

East-West Approaches Φ2/Φ6			North-South Approaches Φ4/Φ8	
Enter: V_{WBLT} Enter: $V_{EBTH} + V_{EBRT}$ Enter: V_{EBLT} Enter: $V_{WBTH} + V_{WBRT}$			Enter: V_{NBLT} Enter: $V_{SBTH} + V_{SBRT}$ Enter: V_{SBLT} Enter: $V_{NBTH} + V_{NBRT}$	
Determine: Max (V_{WBLT}, $V_{EBTH} + V_{EBRT}$, V_{EBLT}, $V_{WBTH} + V_{WBRT}$)			Determine: Max (V_{NBLT}, $V_{SBTH} + V_{SBRT}$, V_{SBLT}, $V_{NBTH} + V_{NBRT}$)	

Step 4b. Determine critical lane flow rates.

The sum of the critical lane flow rates is the sum of the flow rates for the critical lane or lanes, either the lane group pair with the maximum volume for each set of approaches (for protected left turns) or the lane group with the maximum volume for each set of approaches (for permitted left turns).

- Enter the sum of critical lane flow rates and the critical movement(s) for each set of approaches.

East-West Approaches			North-South Approaches	
Enter sum of critical lane flow rates, $v_{crit\text{-}EW}$: Protected LT: Max ($V_{WBLT}+V_{EBTH}+V_{EBRT}, V_{EBLT}+V_{WBTH}+V_{WBRT}$) OR Permitted LT: Max ($V_{WBLT}$, $V_{EBTH}+V_{EBRT}$, V_{EBLT}, $V_{WBTH}+V_{WBRT}$)			Enter sum of critical lane flow rates, $v_{crit\text{-}NS}$: Protected LT: Max ($V_{NBLT}+V_{SBTH}+V_{SBRT}, V_{SBLT}+V_{NBTH}+V_{NBRT}$) OR Permitted LT: Max ($V_{SBLT}$, $V_{NBTH}+V_{NBRT}, V_{NBLT}$, $V_{SBTH}+V_{SBRT}$)	
Identify critical movement(s)			Identify critical movement(s)	
Enter the number of critical phases, $n_{CP,\ EW}$ (1 if permitted LT or 2 if protected LT)			Enter the number of critical phases, $n_{CP,NS}$ (1 if permitted LT or 2 if protected LT)	

Exhibit 15. Determining critical lane groups

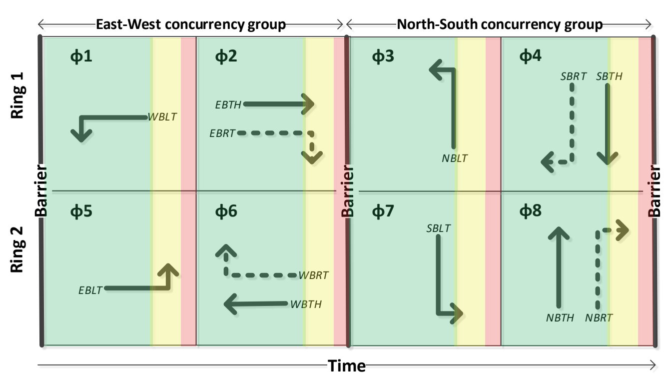


Exhibit 16. Ring barrier diagram

Step 5. Assess Intersection Sufficiency

- Enter the number of critical phases.
- Calculate the sum of the critical lane flows.
- Calculate the intersection capacity.
- Calculate the intersection volume-capacity ratio.
- Determine the intersection status.

Calculate the number of critical phases from step 4 $n_{CP} = n_{CP,EW} + n_{CP,NS}$	
Enter critical lane flow rate, east-west approaches, $v_{crit\text{-}EW}$, from step 4	
Enter critical lane flow rate, north-south approaches, $v_{crit\text{-}NS}$, from step 4	
Calculate sum of critical lane flow rates (tpc/h/ln) $v_{crit} = v_{crit-EW} + v_{crit-NS}$	
Enter base saturation flow rate (veh/h/ln), s, from step 1	
Enter cycle length, C (sec), from step 1, or calculate $C = 30n_{CP}$	
Calculate intersection capacity (tpc/h/ln) $c_I = s_o \frac{[C - (4n_{CP})]}{C}$	
Enter sum of critical lane flow rates, V_{crit}, from above	
Enter intersection capacity (veh/h), c_I, from above	
Calculate intersection volume-to-capacity ratio $X_c = \frac{V_C}{c_I}$	
Determine intersection status from table below:	

X_C	Description	Capacity Assessment
< 0.85	• All demand is accommodated • Delays are low to moderate	Under
0.85 – 0.98	• Demand for critical lane groups near capacity • Some lane groups require more than one cycle to clear intersection • All demand is processed within analysis period • Delays are moderate to high	Near
> 0.98	• Demand for critical lane groups is usually accommodated within cycle • Often requires multiple cycles to clear the intersection • Delays a high • Queues are long	Over

Exhibit 17. Assessing Intersection Sufficiency

Step 6. Calculate Green Times.

- Enter the cycle length, number of phases.
- Calculate the total effective green time.
- Enter the critical lane group movements and the critical lane flow rates.
- Identify the phases controlling the critical movements.
- Calculate the effective green time for each phase.

Enter cycle length (s), C, from step 5	
Enter number of phases, n_{cp}, from step 4	
Calculate total effective green time $g_{TOT} = C - (4n_{cp})$	
Enter sum of critical lane flow rates (tpc/h/ln), V_{crit}, from step 5	

	EB/WB Approaches			
Enter critical lane movements (e.g., EBLT, WBTH) from step 4				
Enter critical lane flow rate (veh/h/ln), $v_{c,i}$, from step 4				
Enter phase number controlling critical lane movements from step 4				
Calculate effective green time for critical lane (s), g_{eff} $g_{eff} = g_{tot}\left(\frac{v_c}{v_{crit,EW} + v_{crit,NS}}\right)$				

	NB-SB Approaches			
Enter critical lane movements (e.g., NBLT, SBTH) from step 4				
Enter critical lane flow rate (veh/h/ln), v_c, from step 4				
Enter phase number controlling critical lane movements from step 4				
Calculate effective green time for critical lane group (s), g_{eff} $g_{eff} = g_{tot}\left(\frac{v_c}{v_{crit,EW} + v_{crit,NS}}\right)$				

Exhibit 18. Calculating green times

Step 7a. Calculate Delay and Determine LOS for Movements for EB/WB Approaches.

- Enter the effective green time and green-to-cycle length ratio for each lane group.
- Calculate the lane group capacity.
- Enter the lane group flow rate.
- Calculate the volume-to-capacity ratio for each lane group.
- Enter the progression factor.
- Calculate the uniform delay, the incremental delay, and the control delay for each lane group.
- Determine the level of service for each lane group.

	EB/WB Approaches					
Enter movements for approach						
Enter effective green time for lane (s), g_{eff} from step 6						
Enter cycle length (s), C, from step 5						
Calculate green-to-cycle length ratio, g_{eff}/C						
Calculate lane capacity (veh/h/ln) $c = 1900\left({g_{eff}}/{C}\right)$						
Enter lane flow rate (tpc/h/ln), v, from step 3a						
Calculate volume-to-capacity ratio $X = \frac{v}{c}$						
Enter progression factor, PF, from Exhibit 21						
Calculate uniform delay (s/veh) $d_1 = PF\left(\frac{0.5C\left(1-{g}/{C}\right)^2}{1-\left[\min\left(1,X\right){g}/{C}\right]}\right)$						
Calculate incremental delay (s/veh) $d_2 = 225\left[(X-1)+\sqrt{(x-1)^2+\frac{16X}{c}}\right]$						
Calculate control delay (s/veh), $d = d_1 + d_2$						
Enter level of service from Exhibit 20						

Exhibit 19. Calculating delay and determining LOS for movements

Control Delay (s/veh)	LOS by Volume-to-Capacity Ratio	
	≤ 1.0	> 1.0
≤10	A	F
> 10 – 20	B	F
> 10 – 20	C	F
> 10 – 20	D	F
> 10 – 20	E	F
>80	F	F

Exhibit 20. Level of service

Quality of Progression	Conditions that Describe Arrivals Associated with Subject Lane Group	Progression Factor, PF
Good progression	Vehicles arrive in platoons during the green interval, or most vehicles arrive during the green interval.	0.70
Random arrivals (default)	The phase serving the subject lane group is not coordinated with the upstream signal, or the intersection is sufficiently distant from other signalized intersections as to be considered isolated.	1.00
Poor progression	Vehicles arrive in platoons during the red interval, or most vehicles arrive during the red indication.	1.25

Exhibit 21. Progression factors

Step 7b. Calculate Delay and Determine LOS for Movements for NB/SB Approaches.

- Enter the effective green time and green-to-cycle length ratio for each lane group.
- Calculate the lane group capacity.
- Enter the lane group flow rate.
- Calculate the volume-to-capacity ratio for each lane group.
- Enter the progression factor.
- Calculate the uniform delay, the incremental delay, and the control delay for each lane group.
- Determine the level of service for each lane group.

	NB/SB Approaches					
Enter movements for approach						
Enter effective green time for lane (s), g_{eff} from step 6						
Enter cycle length (s), C, from step 5						
Calculate green-to-cycle length ratio, g_{eff}/C						
Calculate lane capacity (veh/h/ln) $c = 1900\left({g_{eff}}/{C}\right)$						
Enter lane flow rate (tpc/h/ln), v, from step 3b						
Calculate volume-to-capacity ratio $X = \frac{v}{c}$						
Enter progression factor, PF, from Exhibit 24						
Calculate uniform delay (s/veh) $d_1 = PF\left(\frac{0.5C\left(1-{g}/{C}\right)^2}{1-\left[\min\left(1,X\right){g}/{C}\right]}\right)$						
Calculate incremental delay (s/veh) $d_2 = 225\left[(X-1)+\sqrt{(x-1)^2+\frac{16X}{c}}\right]$						
Calculate control delay (s/veh) $d = d_1 + d_2$						
Determine level of service from Exhibit 23						

Exhibit 22. Calculating delay and determining LOS for movements

Control Delay (s/veh)	LOS by Volume-to-Capacity Ratio	
	≤ 1.0	> 1.0
≤10	A	F
> 10 – 20	B	F
> 20 – 35	C	F
> 35 – 55	D	F
> 55 – 80	E	F
>80	F	F

Exhibit 23. Level of service

Quality of Progression	Conditions that Describe Arrivals Associated with Subject Lane Group	Progression Factor, PF
Good progression	Vehicles arrive in platoons during the green interval, or most vehicles arrive during the green interval.	0.70
Random arrivals (default)	The phase serving the subject lane group is not coordinated with the upstream signal, or the intersection is sufficiently distant from other signalized intersections as to be considered isolated.	1.00
Poor progression	Vehicles arrive in platoons during the red interval, or most vehicles arrive during the red indication.	1.25

Exhibit 24. Progression factors

Step 7c. Calculate Delay and Determine LOS for Approaches and Intersection.

- Enter the equivalent through flow rate for each movement.
- Enter the control delay for each movement
- Calculate the delay for each approach and for the intersection.
- Determine the intersection LOS.

	EB			WB			NB			SB		
	LT	TH	RT	LT	TH	RT	LT	TH	RT	LT	TH	RT
Enter lane flow rate for each movement from steps 3a and 3b (tpc/h/ln), v												
Enter control delay for each movement, (s/veh), d, from steps 7a and 7b												
Calculate approach delay (s/veh) $d_A = \frac{\sum dv}{\sum v}$												
Calculate approach flow rate (veh/h) $V_A = v_{adj,LT} + v_{adj,TH} + v_{adj,RT}$												
Calculate intersection delay (s/veh) $d_I = \frac{\sum d_A V_A}{\sum V_A}$												
Enter the critical intersection volume-to-capacity ratio from step 5												
Determine intersection LOS from Exhibit 26												

Exhibit 25. Calculating delay and determining LOS for approaches and intersection

Control Delay (s/veh)	LOS by Volume-to-Capacity Ratio	
	≤ 1.0	> 1.0
≤10	A	F
> 10 – 20	B	F
> 10 – 20	C	F
> 10 – 20	D	F
> 10 – 20	E	F
>80	F	F

Exhibit 26. Level of service

4. EXAMPLE CALCULATION FOR BASIC METHOD

The following example illustrates the application of the basic method. Explanations are provided so that the analyst can better understand and be able to apply each step to the conditions of a given problem.

Example Calculation. Complete Application of Basic Method

The facts: A standard 4-approach intersection has the geometric and volume characteristics given in Exhibit 27. Exhibit 28 shows the phasing plan for this intersection, based on leading protected left turns. The cycle length is 90 sec and the lost time is 4 sec/phase. The saturation flow rate is 1900 veh/hr/ln for through movements and protected left turn movements.

To do: Determine the sufficiency of intersection capacity, the delay, and the level of service for the intersection and its approaches using the basic method.

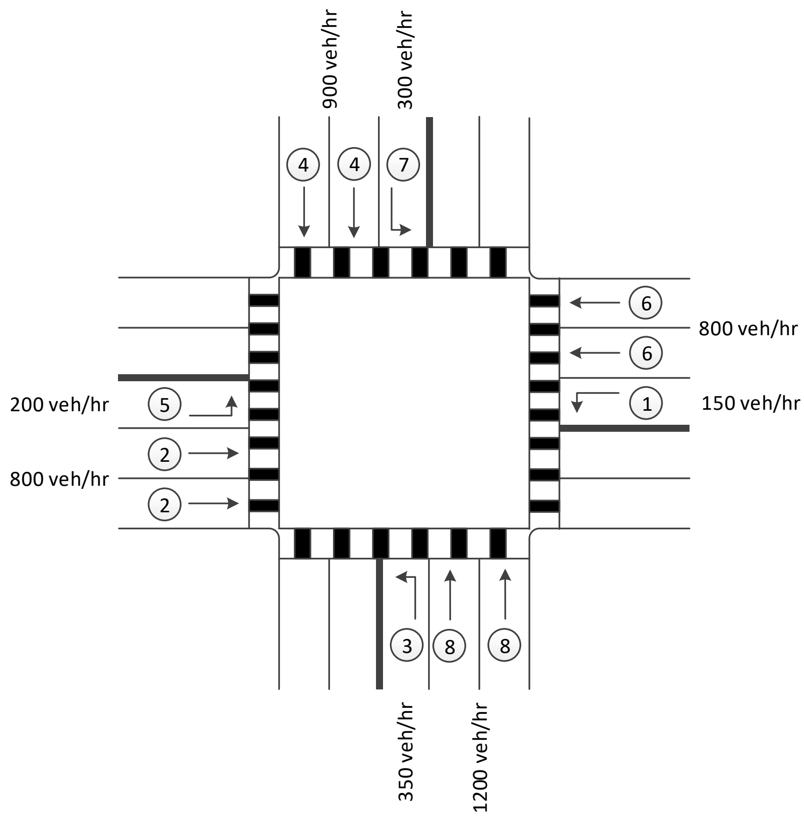


Exhibit 27. Volume and lane information for Example Calculation 1

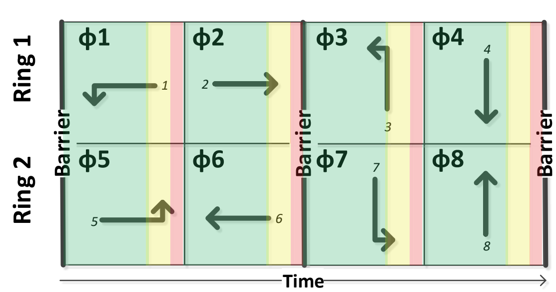


Exhibit 28. Phasing and movement information for Example Calculation 1

In Step 1, data are gathered or default values are accepted for the intersection, the intersection approaches, and for each movement. Some points of interest:

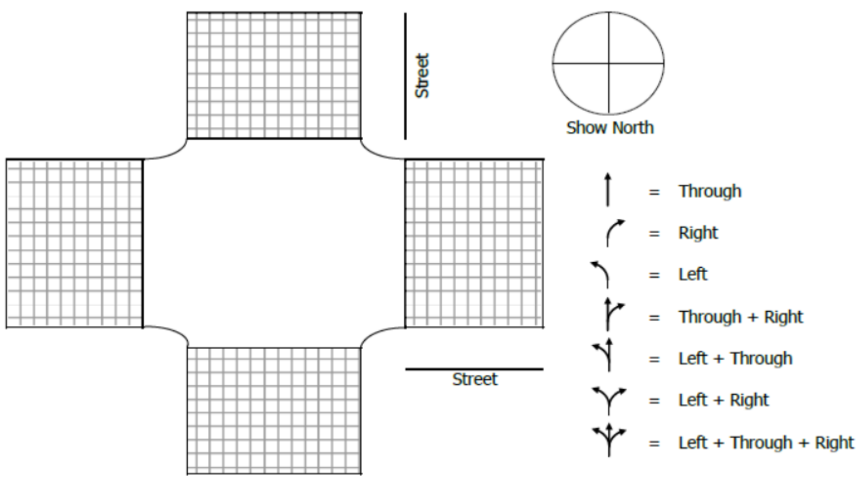
- The left turn operation will be determined in step 2 based on the three left turn checks described there.
- The cycle length will be calculated in step 5.
- The effective green times will be calculated in step 6.
- If known, the peak hour factor and the base saturation flow rate can be specified by the analyst. The default values of 0.92 and 1900 are used here.

Step 1a. Gather required data and/or accept default values for the intersection.

- Enter the general and site information
- Prepare a sketch of the intersection showing lanes and movements
- Enter the intersection data for peak hour factor, cycle length, and base saturation flow rate

General Information		Site Information	
Analyst	Joe Vandal	Intersection	A Street and First Street
Agency or company	City of Bosworth		
Date performed	2015.11.27	Jurisdiction	City of Bosworth
Analysis time period	PM Peak Period	Analysis year	2020

Intersection Geometry



Data Item	Required or Suggested Default Values	Intersection Data
Enter peak hour factor, PHF	Use default value of 0.92 if not known	0.92
Enter cycle length (s), C	Can be estimated using guidance provided in step 5	Will be estimated in step 5
Enter base saturation flow rate (veh/h), s	Use default value of 1900 if not known	1900

Exhibit 29. Data requirements for basic method

Step 1b. Gather required data and/or accept default values for the intersection approaches.

- Enter the following data for each approach:
  - Level of parking activity
  - Level of pedestrian activity
  - Left turn operation

Data Item	Approach Data			
	EB	WB	NB	SB
Specify the level of parking activity • None (default) • Low – 5 parking maneuvers per hour • Medium – 10 parking maneuvers per hour • High – 15 parking maneuvers per hour	None	None	None	None
Specify the level of pedestrian activity • None (default) • Low – 50 pedestrians per hour • Medium – 200 pedestrians per hour • High – 400 pedestrians per hour • Extreme – 800 pedestrians per hour	None	None	None	None
Specify the left-turn operation (Can be determined using guidance provided in step 2) • Protected left turn operation • Permitted left turn operation • Split phasing • Protected-permitted left turn operation	To be determined in step 2		To be determined in step 2	

Exhibit 30. Data requirements for basic method

Step 1c. Gather required data and/or accept default values for each movement.

- Enter the following data for each movement:
  - Volume
  - Number of lanes
  - Lane use (exclusive or shared)
  - Percent heavy vehicles
- Enter the effective green time if known. Alternatively, it can be calculated in step 6.
- Enter the progression quality if known.

Data Item	Movement Data											
	EB			WB			NB			SB		
	LT	TH	RT	LT	TH	RT	LT	TH	RT	LT	TH	RT
Enter volume (veh/h), V	200	800	0	150	800	0	350	1200	0	300	900	0
Enter number of lanes, N	1	2	0	1	2	0	1	2	0	1	2	0
Specify lane use, exclusive (E) or shared (S)	E	E		E	E		E	E		E	E	
Enter percent heavy vehicles (%), P_{HV}	0	0		0	0		0	0		0	0	
Enter effective green time (s), g_{eff} (Can be calculated using guidance provided in step 6)												
Specify progression quality • Good progression, G • Random arrivals (default), R • Poor progression, P	R	R		R	R		R	R		R	R	

Exhibit 31. Data requirements for basic method

The analyst can either specify the left turn operation for each approach in step 1b or determine it using the three checks provided in step 2. In this example the analyst uses the checks to determine the left turn operation.

- Based on check #1, protected left turns are not required; permitted left turns are acceptable.
- Check #2, however, the minimum volume check, shows that protected left turns are required for the NB/SB approaches.
- Check #3, based on the left turn volume and the opposing through volume, requires protected left turns for all approaches.

If any of the checks are exceeded, protected left turn operation is selected for those approaches. Thus, in this case, protected left turns are selected for all four intersection approaches.

Step 2. Determine left turn operations. **EITHER** select one of the following left turn operational modes by placing an X in the appropriate box for the EB-WB and NB-SB approaches…				
	EB-WB Approaches		**NB-SB Approaches**	
Protected LT operation				
Permitted LT operation				
Split phasing				
Protected-permitted LT operation				
OR determine the LT phasing using the following three checks.				
Check #1. Left turn lane check. If the number of LT lanes on an approach exceeds 1, then it is recommended that the left turns on that approach be protected.				
Approach	**EB**	**WB**	**NB**	**SB**
Enter number of LT lanes from step 1 (Exhibit 31)	1	1	1	1
Select protected LT, Y or N?	N		N	
Check #2. Minimum volume check. If the LT volume on any approach exceeds 240 veh/hr, then it is recommended that the left turns on that approach be protected.				
Approach	**EB**	**WB**	**NB**	**SB**
Enter LT volume (veh/h) from step 1 (Exhibit 31)	200	150	350	300
Select protected LT, Y or N?	N		Y	
Check #3. Minimum cross-product check. If the cross product of the left turn volume and the opposing TH volume exceeds the criterion in Exhibit 33 **then it is recommended that left turns on that approach be protected.**				
Approach	**EB**	**WB**	**NB**	**SB**
Enter LT volume (veh/h), V_L from step 1 (Exhibit 31)	200	150	350	300
Enter opposing TH volume (veh/h), V_O from step 1 (Exhibit 31)	800	800	900	1200
Calculate cross product: $V_L \times V_O$	160,000	120,000	315,000	360,000
Enter number of opposing TH lanes from step 1	2	2	2	2
Select protected LT, Y or N, based on Exhibit 33	Y		Y	
	EB/WB Approaches		**NB/SB Approaches**	
Enter selected LT mode, protected or permitted	Protected LT		Protected LT	

Exhibit 32. Determining left turn operations

Number of TH lanes	Minimum Cross-Product
1	50,000
2	90,000
3	110,000

Exhibit 33. Minimum Cross-Product Values for Recommending LT Protection

Factors such as lane utilization produce a larger effect on traffic operations than represented by the measured traffic volume. Often traffic naturally gravitates more to one lane than to the others and the effect produces a higher effective or equivalent volume. In this example, the EBTH volume is 800 veh/h, over two lanes. Studies have shown that for a two lane approach, the effective flow rate as measured in through passenger car equivalents (TPCE) is five percent higher than the measured traffic volume in veh/h. The equivalency factor for lane utilization is 1.05, reflecting this effect. The resulting flow rate is 840 tpc/h.

Similarly, the default peak hour factor of 0.92 results in an equivalency factor accounting for peaking characteristics of 1.087. This means that the concentration of traffic flow during the hour produces an equivalent flow rate for the EB TH approach of 870 tpc/h.

Exhibit 34 and Exhibit 35 show the calculations for TPCE considering the effects of peaking characteristics, pedestrian activity, left turns, and lane utilization. The cumulative effect of these two factors produces a flow rate of 917 tpc/h for the EBTH movement.

Step 3a. Convert movement volumes to flow rates in through passenger car equivalents for the EB and WB approaches.

- Enter the movement volumes, percent heavy vehicles, pedestrian activity, opposing volume, parking activity, and number of lanes in lane group.
- Calculate the equivalency factors using Exhibit 36 through Exhibit 39.
- Calculate the equivalent through passenger car equivalent flow rate.

	EB			WB		
	LT	TH	RT	LT	TH	RT
Enter movement volume (veh/h), V, from step 1	200	800	0	150	800	0
Enter percent heavy vehicle (%), P_{HV}, from step 1	0	0		0	0	
Calculate equivalency factor for heavy vehicles $E_{hv} = 1 + 0.01\, P_{HV}(E_T - 1)$; default E_T = 2	1.00	1.00		1.00	1.00	
Enter peak hour factor for intersection, PHF, from step 1	0.92					
Calculate equivalency factor for peaking characteristics $E_{PHF} = \frac{1}{PHF}$	1.087					
Enter pedestrian activity from step 1			None			None
Enter equivalency factor for right turns, E_{RT}, from Exhibit 36			1.2			1.2
Enter total opposing volume (veh/h), V_o, from step 1	800			800		
Enter equivalency factor for left turns, E_{LT}, from Exhibit 37	1.05			1.05		
Enter level of parking activity from step 1	None	None		None	None	
Enter number of lanes from step 1	1	2		1	2	
Enter equivalency factor for parking activity, E_p, from Exhibit 38	1.00	1.00		1.00	1.00	
Enter number of lanes from step 1	1	2		1	2	
Enter equivalency factor for lane utilization, E_{LU}, from Exhibit 39	1.00	1.05		1.00	1.05	
Enter equivalency factor for other conditions, E_{other} (see note)						
Calculate equivalent through movement flow rate (tpc/h) $v_{adj} = VE_{HV}E_{PHF}E_{LT}E_{RT}E_PE_{LU}E_{other}$	228	913		171	913	
Enter the number of lanes, N, from step 1	1	2		1	2	
Calculate the lane flow rate (tpc/h/ln) $v = \frac{v_{adj}}{N}$	228	457		171	457	

Exhibit 34. Converting movement volumes to though passenger car equivalents

The effect of another equivalency factor, this time for left turn movements, is shown here. The given volume for the NBLT movement is 550 veh/h. While the movement is controlled by a protected left turn phase, vehicles depart from the stop line more slowly than the through movements as they negotiate the left turn maneuver. Studies have shown that the resulting through passenger car equivalent is five percent higher for these left turning vehicles. Thus, for the NBLT movement the resulting equivalent flow rate is 368 tpc/h.

Including the equivalency factor for peaking characteristics of 1.087, the resulting flow rate for the NBLT movement is 399 tpc/h.

Note that in the last line of Exhibit 35, the equivalent through movement flow rate is divided by the number of lanes to produce the lane flow rates for each movement. Since the EBLT movement is served in one lane, the lane flow rate (399 tpc/h/ln) is the same as the equivalent movement flow rate.

Step 3b. Convert movement volumes to flow rates in through passenger car equivalents for the NB and SB approaches.

- Enter the movement volumes, percent heavy vehicles, pedestrian activity, opposing volume, parking activity, and number of lanes in lane group.
- Calculate the equivalency factors using Exhibit 36 through Exhibit 39.
- Calculate the equivalent through passenger car equivalent flow rate.

	NB			SB		
	LT	TH	RT	LT	TH	RT
Enter movement volume (veh/h), V, from step 1	350	1200	0	300	900	0
Enter percent heavy vehicle (%), P_{HV}, from step 1	0	0		0	0	
Calculate equivalency factor for heavy vehicles $E_{hv} = 1 + 0.01\, P_{HV}(E_T - 1)$; default E_T = 2	1.00	1.00		1.00	1.00	
Enter peak hour factor for intersection, PHF, from step 1	0.92					
Calculate equivalency factor for peaking characteristics $E_{PHF} = \frac{1}{PHF}$	1.087					
Enter pedestrian activity from step 1			None			None
Enter equivalency factor for right turns, E_{RT}, from Exhibit 36			1.2			1.2
Enter total opposing volume (veh/h), V_o, from step 1	900			1200		
Enter equivalency factor for left turns, E_{LT}, from Exhibit 37	1.05			1.05		
Enter level of parking activity from step 1	None	None		None	None	
Enter number of lanes from step 1	1	2		1	2	
Enter equivalency factor for parking activity, E_p, from Exhibit 38	1.00	1.00		1.00	1.00	
Enter number of lanes from step 1	1	2		1	2	
Enter equivalency factor for lane utilization, E_{LU}, from Exhibit 39	1.00	1.05		1.00	1.05	
Enter equivalency factor for other conditions, E_{other} (see note)						
Calculate equivalent through movement flow rate (tpc/h) $v_{adj} = V E_{HV} E_{PHF} E_{LT} E_{RT} E_P E_{LU} E_{other}$	399	1370		342	1027	
Enter the number of lanes, N, from step 1	1	2		1	2	
Calculate the lane flow rate (tpc/h/ln) $v = \frac{v_{adj}}{N}$	399	685		342	514	

Exhibit 35. Converting movement volumes to though passenger car equivalents

Pedestrian Activity	Pedestrian Volume (p/h)	E_{RT}
None or low	0 – 199	1.2
Moderate	200 – 399	1.3
High	400 – 799	1.5
Extreme	≥ 800	2.1

Exhibit 36. Equivalency factors for right turns

Parking Activity	Number of Lanes in Lane Group	E_P
None	All	1.00
Adjacent parking allowed	1	1.20
	2	1.10
	3	1.05

Exhibit 38. Equivalency factors for parking activity

LT Operation	Total Opposing Volume, V_o, veh/h	E_{LT}
Protected	Any	1.05
Permitted	< 200	1.1
	200 – 599	2.0
	600 – 799	3.0
	800 – 999	4.0
	≥ 1000	5.0
For protected/permitted operation, see xxx.		

Exhibit 37. Equivalency factors for left turns

Lane Group Movements	Number of Lanes in Lane Group	E_{LU}
Through	1	1.00
	2	1.05
	≥ 3	1.10
Exclusive left turn	1	1.00
	≥ 2	1.03
Exclusive right turn	1	1.00
	≥ 2	1.13

Exhibit 39. Equivalency factors for lane utilization

Step 4 determines the critical lanes and the critical lane flow rates. The concept of the critical lane is based on the ring barrier diagram, which describes the sequencing of phases and the movements that they control. In this example, there are leading protected left turns for each of the four approaches. The ring barrier diagram for this operation is shown in Exhibit 40. Exhibit 41 shows the calculation process for protected left turn operation.

For the east-west approaches, phases 1 and 2 must time sequentially, with phase 2 following phase 1. Phases 5 and 6 must also time sequentially. The sequence with the maximum sum of critical lane flow rates is the critical sequence. It is the sequence that requires the maximum green time of the two possible sequences, either phases 1 and 2 or phases 5 and 6. In this example, the flow rate sum for the movements controlled by phases 1 and 2 is 628 tpc/h, while the sum for the movements controlled by phases 5 and 6 is 685 tpc/h. Thus the phases from ring 2, phases 5 and 6, are the critical phases. The critical movements are the EBLT and the WBTH movements.

Similarly for the NB/SB approaches, phases 7 and 8 are the critical phases since the movements controlled by phases 7 and 8 have a greater critical lane flow rate sum than the movements controlled by phases 3 and 4. The critical movements are the SBLT and the NBTH movements since the sum of the critical lane flow rates for these movements are greater than the sum for the NBLT and SBTH movements.

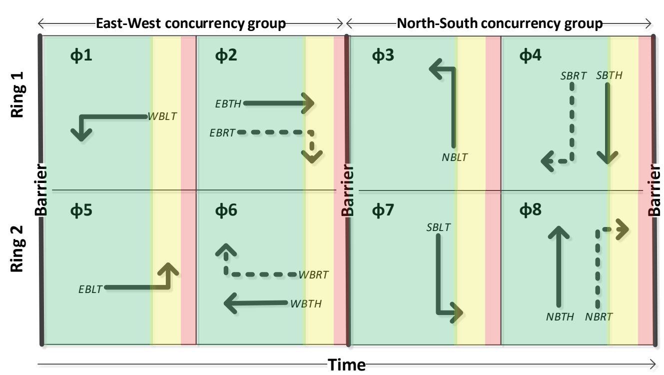


Exhibit 40. Ring barrier diagram

Step 4a. Determine critical lane groups.

- For the left turn operation previously selected, determine the critical lanes using either the table for protected LT operation or permitted LT operation. Consult Exhibit 40 for standard phase numbering.

Protected Left Turn Operation

For the approaches with protected left turn operation, enter the lane flow rates for each movement. Then calculate the summations noted below.

East-West Approaches						North-South Approaches				
Φ1 Enter: V_{WBLT}	171	+	Φ2 Enter: $V_{EBTH} + V_{EBRT}$	457		Φ3 Enter: V_{NBLT}	399	+	Φ4 Enter: $V_{SBTH} + V_{SBRT}$	514
Calculate: $V_{WBLT} + V_{EBTH} + V_{EBRT}$			628			Calculate: $V_{NBLT} + V_{SBTH} + V_{SBRT}$			913	
		OR			+			OR		
Φ5 Enter: V_{EBLT}	228	+	Φ6 Enter: $V_{WBTH} + V_{WBRT}$	457		Φ7 Enter: V_{SBLT}	342	+	Φ8 Enter: $V_{NBTH} + V_{NBRT}$	685
Calculate: $V_{EBLT} + V_{WBTH} + V_{WBRT}$			685			Calculate: $V_{SB} + V_{NBTH} + V_{NBRT}$			1027	
Determine: Max ($V_{WBLT} + V_{EBTH} + V_{EBRT}, V_{EBLT} + V_{WBTH} + V_{WBRT}$)				685		Determine: Max ($V_{NBLT} + V_{SBTH} + V_{SBRT}, V_{SBLT} + V_{NBTH} + V_{NBRT}$)				1027

Permitted Left Turn Operation

For the approaches with permitted left turn operation, enter the lane flow rates for each movement. Then calculate the summations noted below.

East-West Approaches Φ2/Φ6			North-South Approaches Φ4/Φ8	
Enter: V_{WBLT} Enter: $V_{EBTH} + V_{EBRT}$ Enter: V_{EBLT} Enter: $V_{WBTH} + V_{WBRT}$			Enter: V_{NBLT} Enter: $V_{SBTH} + V_{SBRT}$ Enter: V_{SBLT} Enter: $V_{NBTH} + V_{NBRT}$	
Determine: Max (V_{WBLT}, $V_{EBTH} + V_{EBRT}$, V_{EBLT}, $V_{WBTH} + V_{WBRT}$)			Determine: Max (V_{NBLT}, $V_{SBTH} + V_{SBRT}$, V_{SBLT}, $V_{NBTH} + V_{NBRT}$)	

Step 4b. Determine critical lane flow rates.

The sum of the critical lane flow rates is the sum of the flow rates for the critical lane or lanes, either the lane group pair with the maximum volume for each set of approaches (for protected left turns) or the lane group with the maximum volume for each set of approaches (for permitted left turns).

- Enter sum of the critical lane flow rate and the critical movement(s) for each set of approaches.

East-West Approaches			North-South Approaches	
Enter sum of critical lane flow rates, $v_{crit\text{-}EW}$: Protected LT: Max ($V_{WBLT}+V_{EBTH}+V_{EBRT}, V_{EBLT}+V_{WBTH}+V_{WBRT}$) OR Permitted LT: Max ($V_{WBLT}$, $V_{EBTH}+V_{EBRT}$, V_{EBLT}, $V_{WBTH}+V_{WBRT}$)	685		Enter sum of critical lane flow rates, $v_{crit\text{-}NS}$: Protected LT: Max ($V_{NBLT}+V_{SBTH}+V_{SBRT}, V_{SBLT}+V_{NBTH}+V_{NBRT}$) OR Permitted LT: Max ($V_{SBLT}$, $V_{NBTH}+V_{NBRT}$, V_{NBLT}, $V_{SBTH}+V_{SBRT}$)	1027
Identify critical movement(s)	EBLT WBTH		Identify critical movement(s)	SBLT NBTH
Enter the number of critical phases, $n_{CP,EW}$ (1 if permitted LT or 2 if protected LT)	2		Enter the number of critical phases, $n_{CP,NS}$ (1 if permitted LT or 2 if protected LT)	2

Exhibit 41. Determining critical lane groups

In step 5, the analyst determines whether there is sufficient capacity to accommodate the given volumes. The capacity could be insufficient if either there are not enough lanes or if the green times have not been properly allocated. The determination is made by comparing the sum of the critical lane flow rates with the intersection capacity.

In this example, the sum of the critical lane flow rates is 1712 tpc/h/ln, based on the sum of the critical lane flows for the EB/WB and the NB/SB approaches. The base saturation flow rate (1900 veh/h/ln) is adjusted to account for lost time. With four critical phases, the lost time is 16 sec per cycle, based on 4 sec per critical phase. The effective green time available is thus 104 sec per cycle. The resulting intersection capacity is 1647 tpc/h/ln.

The analyst concludes that since the sum of the critical lane flow rates exceeds the intersection capacity, there is not sufficient capacity to accommodate the given volumes. This is also shown by the intersection volume-to-capacity ratio, which exceeds 1. The intersection status is "over capacity".

Step 5. Assess Intersection Sufficiency.

- Enter the number of critical phases.
- Calculate the sum of the critical lane flows.
- Calculate the intersection capacity.
- Calculate the intersection volume-capacity ratio.
- Determine the intersection status.

Calculate the number of critical phases from step 4 $n_{CP} = n_{CP,EW} + n_{CP,NS}$	4
Enter critical lane flow rate, east-west approaches, $v_{crit\text{-}EW}$, from step 4	685
Enter critical lane flow rate, north-south approaches, $v_{crit\text{-}NS}$, from step 4	1027
Calculate sum of critical lane flow rates (tpc/h/ln) $v_{crit} = v_{crit-EW} + v_{crit-NS}$	1712
Enter base saturation flow rate (veh/h/ln), s, from step 1	1900
Enter cycle length, C (sec), from step 1, or calculate $C = 30n_{CP}$	120
Calculate intersection capacity (tpc/h/ln) $c_I = s_o \frac{[C - (4n_{CP})]}{C}$	1647
Enter sum of critical lane flow rates, V_{crit}, from above	1712
Enter intersection capacity (veh/h), c_I, from above	1647
Calculate intersection volume-to-capacity ratio $X_c = \frac{V_C}{c_I}$	1.04
Determine intersection status from table below:	Over

X_C	Description	Capacity Assessment
< 0.85	• All demand is accommodated • Delays are low to moderate	Under
0.85 – 0.98	• Demand for critical lane groups near capacity • Some lane groups require more than one cycle to clear intersection • All demand is processed within analysis period • Delays are moderate to high	Near
> 0.98	• Demand for critical lane groups is usually accommodated within cycle • Often requires multiple cycles to clear the intersection • Delays a high • Queues are long	Over

Exhibit 42. Assessing Intersection Sufficiency

The green time for each critical phase is calculated in step 6. The green time is based on the ratio of the critical lane flow rate to the sum of the critical lane flow rates. For example, for the WBTH movement, the critical lane flow rate is 457 veh/h/ln. The ratio of this flow rate to the sum of the critical lane flow rates is 0.267.

$$\frac{v_{WBTH}}{\sum v_{crit}} = \frac{457}{1712} = 0.267$$

The total effective green time is split between the four critical phases, based on this ratio for each movement. For the phase controlling the WBTH movement, the resulting effective green time is 27.7 sec.

$$(0.267)(104 \text{ sec}) = 27.7\ sec$$

This process is repeated for the other three critical phases and the movements that they serve: EBLT, NBLT, and SBTH.

Step 6. Calculate Green Times.

- Enter the cycle length, number of phases.
- Calculate the total effective green time.
- Enter the critical lane movements and the critical lane flow rates.
- Identify the phases controlling the critical movements.
- Calculate the effective green time for each phase.

Enter cycle length (s), C, from step 5	120
Enter number of phases, n_{cp}, from step 4	4
Calculate total effective green time $g_{TOT} = C - (4n_{cp})$	104
Enter sum of critical lane flow rates (tpc/h/ln), V_{crit}, from step 5	1712

	EB/WB Approaches			
Enter critical lane movements (e.g., EBLT, WBTH) from step 4	EBLT	WBTH		
Enter critical lane flow rate (veh/h/ln), v_c, from step 4	228	457		
Enter phase number controlling critical lane movements from step 4	5	6		
Calculate effective green time for critical lane (s), g_{eff} $g_{eff} = g_{tot}\left(\frac{v_c}{v_{crit,EW} + v_{crit,NS}}\right)$	13.8	27.7		

	NB-SB Approaches			
Enter critical lane movements (e.g., NBLT, SBTH) from step 4	NBLT	SBTH		
Enter critical lane flow rate (veh/h/ln), v_c, from step 4	342	685		
Enter phase number controlling critical lane movements from step 4	3	4		
Calculate effective green time for critical lane (s), g_{eff} $g_{eff} = g_{tot}\left(\frac{v_c}{v_{crit,EW} + v_{crit,NS}}\right)$	20.8	41.6		

Exhibit 43. Calculating green times

The delay and LOS for the movements on the EB and WB approaches are calculated using step 7a. The effective green time for each non-critical phase is set equal to the effective green time for its concurrent critical phase. For example, the effective green time for the phase controlling the WBLT movement is set equal to the effective green time for the phase controlling the WBLT movement. The duration of each phase (1 and 5) is calculated to be 13.8 sec.

Continuing with the LT movements in this example, the lane group capacity is calculated to be 220 veh/h/ln, while the volume-to-capacity ratio is 1.04 for the EBLT movement and 0.78 for the WBLT movement. The control delay for the EBLT movement, the sum of the uniform delay term and the incremental delay turn, is 124.8 sec/veh. The level of service for the EBLT movement is determined to be F regardless of the control delay because the volume-to-capacity ratio exceeds 1.

The control delay for the WBLT movement is 87.5 sec/veh. The level of service for the WBLT movement is E since the control delay is greater than 55 sec/veh but less than 80 sec/veh. The volume-to-capacity ratio LOS standard is not applied since the ratio for the WBLT movement is less than one.

Step 7a. Calculate Delay and Determine LOS for Movements for EB/WB Approaches.

- Enter the effective green time and green-to-cycle length ratio for each lane group.
- Calculate the lane group capacity.
- Enter the lane group flow rate.
- Calculate the volume-to-capacity ratio for each lane group.
- Enter the progression factor.
- Calculate the uniform delay, the incremental delay, and the control delay for each lane group.
- Determine the level of service for each lane group.

	EB/WB Approaches					
Enter movements on approach	EBLT	EBTH	WBLT	WBTH		
Enter effective green time (s), g_{eff} from step 6	13.8	27.7	13.8	27.7		
Enter cycle length (s), C, from step 5	120					
Calculate green-to-cycle length ratio, g_{eff}/C	0.115	0.231	0.115	0.231		
Calculate lane capacity (veh/h/ln) $c = 1900\left({}^{g_{eff}}/_{C}\right)$	220	439	220	439		
Enter lane flow rate (tpc/h/ln), v, from step 3a	228	457	171	457		
Calculate volume-to-capacity ratio $X = \frac{v}{c}$	1.04	1.04	0.78	1.04		
Enter progression factor, PF, from Exhibit 24	1.00	1.00	1.00	1.00		
Calculate uniform delay (s/veh) $d_1 = PF\left(\frac{0.5C\left(1-{}^{g}/_{C}\right)^2}{1-\left[\min(1,X)\,{}^{g}/_{C}\right]}\right)$	53.1	46.1	51.6	46.1		
Calculate incremental delay (s/veh) $d_2 = 225\left[(X-1)+\sqrt{(x-1)^2+\frac{16X}{c}}\right]$	71.5	41.1	23.5	41.1		
Calculate control delay (s/veh), $d = d_1 + d_2$	124.6	87.3	75.0	87.3		
Enter level of service from Exhibit 47	F	F	E	F		

Exhibit 44. Calculating delay and determining LOS for movements

The delay and LOS for the movements on the NB and SB approaches are calculated using step 7b. As in step 7a, the effective green time for each non-critical phase is set equal to the effective green time for its concurrent critical phase. For example, the effective green time for the phase controlling the SBTH movement is set equal to the effective green time for the phase controlling the NBTH movement. Each phase (4 and 8) is calculated to be 41.6 sec.

Continuing with the TH movements in this example, the lane capacity is calculated to be 659 veh/h/ln, while the volume-to-capacity ratio is 1.04 for the NBTH movement and 0.78 for the SBTH movement. The control delay for the NBTH movement, the sum of the uniform delay term and the incremental delay turn, is 124.8 sec/veh. The level of service for the EBLT movement is determined to be F regardless of the control delay because the volume-to-capacity ratio exceeds 1.

The control delay for the WBLT movement is 87.5 sec/veh. The level of service for the WBLT movement is E since the control delay is greater than 55 sec/veh but less than 80 sec/veh. The volume-to-capacity ratio LOS standard is not applied since the ratio for the WBLT movement is less than one.

Step 7b. Calculate Delay and Determine LOS for Movements for NB/SB Approaches.

- Enter the effective green time and green-to-cycle length ratio for each lane group.
- Calculate the lane group capacity.
- Enter the lane group flow rate.
- Calculate the volume-to-capacity ratio for each lane group.
- Enter the progression factor.
- Calculate the uniform delay, the incremental delay, and the control delay for each lane group.
- Determine the level of service for each lane group.

	NB/SB Approaches					
Enter movements on approach	NBLT	NBTH	SBLT	SBTH		
Enter effective green time (s), g_{eff} from step 6	20.8	41.6	20.8	41.6		
Enter cycle length (s), C, from step 5	120					
Calculate green-to-cycle length ratio, g_{eff}/C	0.173	0.347	0.173	0.347		
Calculate lane capacity (veh/h/ln) $c = 1900\left({}^{g_{eff}}/_{C}\right)$	329	659	329	659		
Enter effective green time for lane group (s), g_{eff} from step 6	399	685	342	514		
Calculate volume-to-capacity ratio $X = \frac{v}{c}$	1.21	1.04	1.04	0.78		
Enter progression factor, PF, from Exhibit 24	1.00	1.00	1.00	1.00		
Calculate uniform delay (s/veh) $d_1 = PF\left(\frac{0.5C\left(1-{}^{g}/_{C}\right)^2}{1-\left[\min(1,X)\,{}^{g}/_{C}\right]}\right)$	49.6	39.2	49.6	35.1		
Calculate incremental delay (s/veh) $d_2 = 225\left[(X-1)+\sqrt{(x-1)^2+\frac{16X}{c}}\right]$	120.6	35.7	60.3	4.6		
Calculate control delay (s/veh) $d = d_1 + d_2$	170.2	74.9	109.9	39.7		
Determine level of service from Exhibit 47	F	F	F	E		

Exhibit 45. Calculating delay and determining LOS for movements

The delay and LOS for the approaches and the intersection are determined based on the movement delays and volume-to-capacity ratios, weighted by the flow rates on each approach. For example, the delay for the WB approach, 99.7 sec/veh, is calculated based on the delays and flow rates for the EBLT and EBTH movements:

$$d_A = \frac{d_{EBLT}v_{EBLT} + d_{EBTH}v_{EBTH}}{v_{EBLT} + v_{EBTH}} = \frac{(238)(124.6) + (913)(87.3)}{228 + 913} = 99.7\ sec/veh$$

Since the delay for this approach exceeds 80 sec, the LOS is F.

Similarly, the intersection delay and LOS are determined based on a weighted average of the delay for each of the approaches. Here the average delay is 91.8 sec/veh and the LOS is F.

Step 7c. Calculate Delay and Determine LOS for Approaches and Intersection.

- Enter the equivalent through flow rate for each movement.
- Enter the control delay for each movement
- Calculate the delay for each approach and for the intersection.
- Determine the intersection LOS.

	EB			WB			NB			SB		
	LT	TH	RT	LT	TH	RT	LT	TH	RT	LT	TH	RT
Enter lane flow rate for each movement from steps 3a and 3b (tpc/h/ln), v	228	913	0	171	913	0	399	1370	0	342	1027	0
Enter control delay for each movement, (s/veh), d, from steps 7a and 7b	124.6	87.3		75.0	87.3		170.2	74.9		109.9	39.7	
Calculate approach delay (s/veh) $d_A = \frac{\sum dv}{\sum v}$	99.7			83.9			110.0			67.8		
Calculate approach flow rate (veh/h) $V_A = v_{adj,LT} + v_{adj,TH} + v_{adj,RT}$	1141			1084			1769			1370		
Calculate intersection delay (s/veh) $d_I = \frac{\sum d_A V_A}{\sum V_A}$	91.8											
Enter the critical intersection volume-to-capacity ratio from step 5	1.04											
Determine intersection LOS from Exhibit 47	F											

Exhibit 46. Calculating delay and determining LOS for approaches and intersection

Control Delay (s/veh)	LOS by Volume-to-Capacity Ratio	
	≤ 1.0	> 1.0
≤10	A	F
> 10 – 20	B	F
> 10 – 20	C	F
> 10 – 20	D	F
> 10 – 20	E	F
>80	F	F

Exhibit 47. Level of service

5. GUIDANCE FOR ADVANCED APPLICATIONS

Note

There are two ways of thinking about and presenting the advanced method:

- The first option is to specify the method as completely as possible so that software developers can write a faithful implementation of the method, or
- The second option is to specify the method as completely as possible but with the understanding that software developers will implement the method based on their own interpretation of the method and their own professional judgement.

The following text is based on the second option.

Introduction

The advanced method can be used to predict the performance of a signalized intersection. The method is appropriate when the analyst has detailed information on intersection conditions and when the focus is on current or near term conditions. A detailed description of the components of the method is provided in chapter 31. The method must be applied using a software application. Different software applications may implement the method in different ways and may not completely or fully implement the method described here, and in chapter 31. The analyst must be familiar with the specific software application that he or she intends to use, the data that it requires, and the performance measures that it produces. This section provides the analyst with information needed to use such a software application.

The advanced method helps the analyst make decisions about operating conditions such as lane configurations, signal timing, and signal phasing. The method predicts values for five performance measures:

- The capacity for each movement and approach
- The v/c ratio for each movement and approach and the intersection
- The control delay for each movement, for each approach, and for the intersection.
- The level of service for each movement, for each approach, and for the intersection.
- The queue storage ratio for each movement, for each approach, and for the intersection.

The advanced method can be applied when the following conditions are true:

- The intersection has pretimed or actuated control.
- There is no turn bay overflow, no demand starvation for any movement, and there is no queue spillback from a downstream intersection.
- There are no lanes added just upstream or downstream of the intersection.
- There is no storage of shared left turn vehicles within the intersection to permit bypass of through vehicles in some lanes.
- There are no multiple advance detections in the same lane.
- There is no premature phase termination due to short passage times or detection zone lengths, or both.
- There is no delay to movements not under signal control
- There is no rest-in-walk, signal preemption, signal priority, phase overlap, or gap reduction or variable initial timing parameters.

However, when the analyst confronts conditions that exceed the capability of the advanced method, the analyst should consider using a simulation model. While a description of simulation methods is beyond the scope of this manual, the analyst can consult the Simulation Handbook [xx] and other references [xx-xx] to determine if these methods are appropriate for the problem under consideration. Some common conditions that warrant the use of a simulation model include:

- When demand exceeds capacity resulting in oversaturated conditions.
- When a study of signal timing conditions for actuated or actuated-coordinated control is required.
- When queues interact between movements or intersections.
- When demand starvation results for one or more movements.

Overview of the Method

The advanced method is implemented in software applications that are available to the analyst. More details of the method are given in chapter 31. An overview of the method is provided here. The method is based on a deterministic queuing model of average traffic flow and signal timing conditions during one signal cycle. The analyst can read more about the relevant queuing model in section 2 of this chapter.

The advanced method predicts the capacity of each lane group as well as the average delay experienced by travelers that are a part of each lane group. A lane group, the most fundamental unit of analysis, is a lane or group of lanes that exclusively serve one movement or a lane that is shared by two or more movements. The predicted capacity is the product of the green ratio (the ratio of the effective green time for the lane group and the intersection's cycle length) and the saturation flow rate. The delay is determined using a queue accumulation polygon, and is based on the arrival flow rate, the arrival pattern, the saturation flow rate, and the effective green time for a lane group, and the cycle length for the intersection.

The method:

- Determines the adjusted saturation flow rate based on the ideal saturation flow rate and the conditions of a given situation such as the lane width, the proportion of heavy vehicles in the traffic stream, the level of parking activity, the level of bus activity, the lane utilization, the proportion of turning vehicles in the lane group, and other factors.
- Predicts the arrival flow pattern based on flow conditions at an upstream signalized intersection or predicts the proportion of vehicles arriving during each green interval.
- Predicts the phase durations for actuated control or uses known phase times for pretimed control.
- Predicts the capacity for each movement based on the saturation flow rate, the effective green, and the cycle length.
- Predicts the delay using the queue accumulation polygon.
- Determines the level of service based on the delay and the volume-to-capacity ratio.
- Predicts the queue storage ratio.

Data Requirements

The advanced method requires that the analyst specify details about traffic flow characteristics, geometric design data, signal control data, and other data. The data requirements depend on the type of problem under consideration and the software application that will be used. Data most commonly used in the advanced method are listed and discussed in Exhibit 48 through Exhibit 51.

Input Data Element	Basis	Discussion
Demand flow rate	Movement	x
Right-turn-on-red flow rate	Approach	x
Percent heavy vehicles	Movement group	x
Intersection peak hour factor	Intersection	x
Platoon ratio	Movement group	x
Upstream filtering adjustment factor	Movement group	x
Initial queue	Movement group	x
Base saturation flow rate	Movement group	x
Lane utilization adjustment factor	Movement group	x
Pedestrian flow rate	Approach	x
Bicycle flow rate	Approach	x
On-street parking maneuver rate	Movement group	x
Local bus stopping rate	Approach	x
Unsignalized movement delay		x

Exhibit 48. Traffic characteristics data

Input Data Element	Basis	Discussion
Number of lanes	Movement group	x
Average lane width	Movement group	x
Number of receiving lanes	Approach	x
Turn bay length	Movement group	x
Presence of on-street parking	Movement group	x
Approach grade	Approach	x

Exhibit 49. Geometric design data

Input Data Element	Basis	Discussion		
Type of signal control	Intersection	Pretimed	Actuated	Actuated-Coordinated
Phase sequence	Intersection	x	x	x
Left-turn operational mode	Approach	x	x	x
Green duration	Phase	x		
Passage time	Phase		x	x
Maximum green	Phase		x	x
Minimum green	Phase		x	x
Yellow change	Phase	x	x	x
Red clearance	Phase	x	x	x
Walk	Phase	x	x	x
Pedestrian clear	Phase	x	x	x
Phase recall	Phase		x	x
Dual entry	Phase		x	x
Simultaneous gap-out	Approach		x	x
Cycle length	Intersection	x		x
Phase splits	Phase			x
Offset	Intersection			x
Offset reference point	Intersection			x
Force mode	Intersection			x

Exhibit 50. Signal control data

Input Data Element	Basis	Discussion		
Type of signal control		Pretimed	Actuated	Actuated-Coordinated
Analysis period duration	Intersection	x	x	x
Speed limit	Approach	x	x	x
Stop-line detector length and detection mode	Movement group		x	x
Area type	Intersection	x	x	x

Exhibit 51. Other data

Performance Measures

The following outputs are predicted by the advanced method.

- The capacity for each movement and approach
- The v/c ratio for each movement and approach and the intersection
- The control delay for each movement, for each approach, and for the intersection.
- The level of service for each movement, for each approach, and for the intersection.
- The queue storage ratio for each movement, for each approach, and for the intersection.