

HCM2010

HIGHWAY CAPACITY MANUAL



CHAPTER 31

SIGNALIZED INTERSECTIONS: SUPPLEMENTAL



TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

WASHINGTON, DC | WWW.TRB.ORG

HCM2010

HIGHWAY CAPACITY MANUAL

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

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



The HCM 2010 consists of four volumes:

Volume 1: Concepts;
Volume 2: Uninterrupted Flow;
Volume 3: Interrupted Flow; and
Volume 4: Applications Guide (electronic only).

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

Volumes 1, 2, and 3 are issued as a boxed set. Volume 4 is electronic only, accessible to registered HCM users via the Internet, and includes four types of content: supplemental chapters on methodological details and emerging issues; interpretations, clarifications, and corrections; comprehensive case studies; and a technical reference library.

To order HCM 2010, go to <http://books.trbbookstore.org/hcm10.aspx>.

For more information about HCM 2010 and TRB publications, contact the Transportation Research Board Business Office, 500 Fifth Street, NW, Washington, DC 20001 (telephone 202-334-3213; fax 202-334-2519; e-mail TRBsales@nas.edu; or through the Internet, www.trb.org).

CHAPTER 31

SIGNALIZED INTERSECTIONS: SUPPLEMENTAL

CONTENTS

1. TRAFFIC SIGNAL CONCEPTS.....	31-1
Types of Traffic Signal Control.....	31-1
Intersection Traffic Movements.....	31-2
Signal Phase Sequence	31-2
Operational Modes.....	31-4
Left-Turn Phase Sequence	31-5
Traffic Flow Characteristics.....	31-6
2. CAPACITY AND PHASE DURATION.....	31-10
Actuated Phase Duration	31-10
Lane Group Flow Rate on Multiple-Lane Approaches	31-30
Pretimed Phase Duration	31-37
Pedestrian and Bicycle Adjustment Factors.....	31-42
3. QUEUE ACCUMULATION POLYGON.....	31-48
Introduction.....	31-48
Concepts	31-48
General Procedure	31-49
Procedure for Selected Lane Groups	31-51
4. QUEUE STORAGE RATIO.....	31-68
Introduction.....	31-68
Concepts	31-68
Procedure for Selected Lane Groups	31-75
5. QUICK ESTIMATION METHOD.....	31-83
Introduction.....	31-83
Input Requirements.....	31-83
Methodology	31-84
6. FIELD MEASUREMENT TECHNIQUES.....	31-97
Field Measurement of Intersection Control Delay	31-97
Field Measurement of Saturation Flow Rate	31-103

7. COMPUTATIONAL ENGINE DOCUMENTATION.....	31-109
Flowcharts.....	31-109
Linkage Lists.....	31-111
8. SIMULATION EXAMPLES	31-117
Introduction.....	31-117
Effect of Storage Bay Overflow	31-117
Effect of Right-Turn-on-Red Operation.....	31-119
Effect of Short Through Lanes	31-122
Effect of Closely Spaced Intersections	31-123
9. REFERENCES	31-125

LIST OF EXHIBITS

Exhibit 31-1 Intersection Traffic Movements and Numbering Scheme	31-2
Exhibit 31-2 Dual-Ring Structure with Illustrative Movement Assignments....	31-3
Exhibit 31-3 Illustrative Protected Lag–Lag and Permitted-Only Phasing.....	31-5
Exhibit 31-4 Illustrative Protected Lead–Lag and Split Phasing	31-6
Exhibit 31-5 Fundamental Attributes of Traffic Flow at Signalized Intersections	31-7
Exhibit 31-6 Fundamental Variables of Traffic Flow at Signalized Intersections	31-8
Exhibit 31-7 Time Elements Influencing Actuated Phase Duration	31-11
Exhibit 31-8 Detection Design and Maximum Allowable Headway	31-16
Exhibit 31-9 Force-Off Points, Yield Point, and Phase Splits	31-21
Exhibit 31-10 Example Equivalent Maximum Green for Fixed Force Mode ...	31-23
Exhibit 31-11 Probability of a Lane Change	31-31
Exhibit 31-12 Input Variables for Lane Group Flow Rate Procedure	31-33
Exhibit 31-13 Example Intersection	31-39
Exhibit 31-14 Conflict Zone Locations	31-42
Exhibit 31-15 Queue Accumulation Polygon for Protected Movements	31-49
Exhibit 31-16 Unblocked Permitted Green Time	31-52
Exhibit 31-17 QAP for Permitted Left-Turn Operation in an Exclusive Lane .	31-60
Exhibit 31-18 QAP for Permitted Left-Turn Operation in a Shared Lane	31-61
Exhibit 31-19 QAP for Leading, Protected-Permitted Left-Turn Operation in an Exclusive Lane	31-61
Exhibit 31-20 QAP for Lagging, Protected-Permitted Left-Turn Operation in an Exclusive Lane	31-61
Exhibit 31-21 QAP for Leading, Protected-Permitted Left-Turn Operation in a Shared Lane	31-62
Exhibit 31-22 QAP for Lagging, Protected-Permitted Left-Turn Operation in a Shared Lane	31-62
Exhibit 31-23 Polygon for Uniform Delay Calculation	31-63
Exhibit 31-24 Time–Space Diagram of Vehicle Trajectory on an Intersection Approach	31-69
Exhibit 31-25 Cumulative Arrivals and Departures During an Oversaturated Analysis Period	31-70
Exhibit 31-26 Third-Term Back-of-Queue Size with Increasing Queue	31-71
Exhibit 31-27 Third-Term Back-of-Queue Size with Decreasing Queue	31-71
Exhibit 31-28 Third-Term Back-of-Queue Size with Queue Clearing	31-71
Exhibit 31-29 Arrival–Departure Polygon.....	31-74

Exhibit 31-30 ADP for Permitted Left-Turn Operation in an Exclusive Lane .	31-77
Exhibit 31-31 ADP for Permitted Left-Turn Operation in a Shared Lane	31-77
Exhibit 31-32 ADP for Leading, Protected-Permitted Left-Turn Operation in an Exclusive Lane	31-77
Exhibit 31-33 ADP for Lagging, Protected-Permitted Left-Turn Operation in an Exclusive Lane	31-78
Exhibit 31-34 ADP for Leading, Protected-Permitted Left-Turn Operation in a Shared Lane	31-78
Exhibit 31-35 ADP for Lagging, Protected-Permitted Left-Turn Operation in a Shared Lane	31-78
Exhibit 31-36 Input Data Requirements for Quick Estimation Method	31-83
Exhibit 31-37 Quick Estimation Input Worksheet	31-84
Exhibit 31-38 Quick Estimation Left-Turn Treatment Worksheet.....	31-86
Exhibit 31-39 Quick Estimation Lane Volume Worksheet	31-87
Exhibit 31-40 Through-Car Equivalents for Permitted Left Turns.....	31-89
Exhibit 31-41 Shared-Lane Left-Turn Adjustment Factor	31-90
Exhibit 31-42 Quick Estimation Control Delay and Level-of-Service Worksheet.....	31-91
Exhibit 31-43 Phase Plans for Quick Estimation Method	31-92
Exhibit 31-44 Phase Plan Summary for Quick Estimation Method	31-92
Exhibit 31-45 Intersection Status Criteria for Quick Estimation Method	31-94
Exhibit 31-46 Progression Adjustment Factor.....	31-95
Exhibit 31-47 Control Delay Field Study Worksheet	31-99
Exhibit 31-48 Acceleration–Deceleration Correction Factor	31-101
Exhibit 31-49 Example Control Delay Field Study Worksheet.....	31-102
Exhibit 31-50 Example Worksheet with Residual Queue at End	31-103
Exhibit 31-51 Saturation Flow Rate Field Study Worksheet	31-105
Exhibit 31-52 Methodology Flowchart.....	31-109
Exhibit 31-53 Setup Module	31-110
Exhibit 31-54 Signalized Intersection Module	31-110
Exhibit 31-55 Initial Queue Delay Module	31-111
Exhibit 31-56 Performance Measures Module	31-111
Exhibit 31-57 Setup Module Routines.....	31-112
Exhibit 31-58 Signalized Intersection Module: Main Routines.....	31-113
Exhibit 31-59 Signalized Intersection Module: Main Routines (continued) ..	31-114
Exhibit 31-60 Signalized Intersection Module: ComputeQAPolygon Routines	31-115
Exhibit 31-61 Performance Measures Module Routines.....	31-116

Exhibit 31-62 Effect of Storage Bay Length on Throughput and Delay	31-118
Exhibit 31-63 Effect of Storage Bay Length on Capacity	31-119
Exhibit 31-64 Effect of Right-Turn-on-Red and Lane Allocation on Delay....	31-120
Exhibit 31-65 Effect of Right-Turn-on-Red and Right-Turn Volume on Delay	31-121
Exhibit 31-66 Effect of Right-Turn-on-Red and Right-Turn Protection on Delay	31-122
Exhibit 31-67 Closely Spaced Intersections	31-123
Exhibit 31-68 Effect of Closely Spaced Intersections on Capacity and Delay	31-123

1. TRAFFIC SIGNAL CONCEPTS

TYPES OF TRAFFIC SIGNAL CONTROL

In general, two types of traffic signal controller unit are in use today. They are broadly categorized as pretimed or actuated according to the type of control they provide. These two types of control are described as follows:

- *Pretimed control* consists of a fixed sequence of phases that are displayed in repetitive order. The duration of each phase is fixed. However, the green interval duration can be changed by time of day or week to accommodate traffic variations. The combination of a fixed phase sequence and duration produces a constant cycle length.
- *Actuated control* consists of a defined phase sequence in which the presentation of each phase depends on whether the phase is on recall or the associated traffic movement has submitted a call for service through a detector. The green interval duration is determined by the traffic demand information obtained from the detector, subject to preset minimum and maximum limits. The termination of an actuated phase requires a call for service from a conflicting traffic movement. An actuated phase may be skipped if no demand is detected.

Most modern controller units have solid-state components that are sufficiently flexible to provide either actuated control or an equivalent pretimed control (through selection of specific settings).

The operation of a pretimed controller can be described as coordinated or not coordinated. In contrast, the operation of an actuated controller can be described as fully actuated, semiactuated, or coordinated-actuated. These actuated control variations are described as follows:

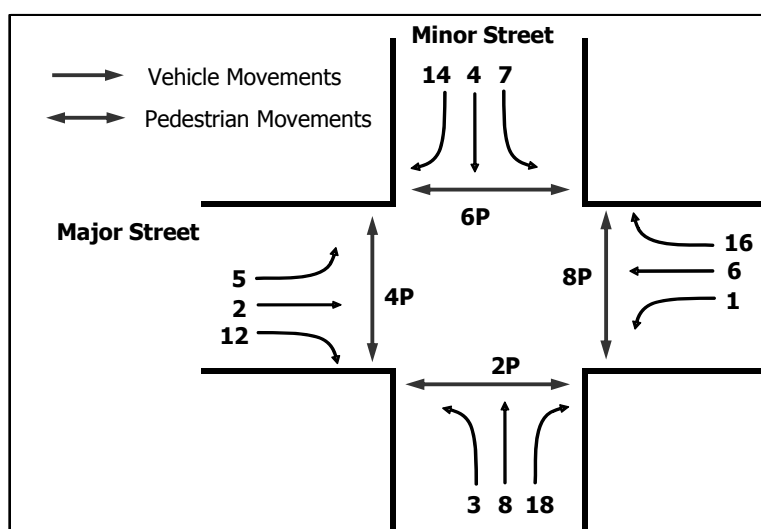
- *Fully actuated control* implies that all phases are actuated and all intersection traffic movements are detected. The sequence and duration of each phase are determined by traffic demand. Hence, this type of control is *not* associated with a constant cycle length.
- *Semiactuated control* uses actuated phases to serve the minor movements at an intersection. Only these minor movements have detection. The phases associated with the major movements are operated as “nonactuated.” The controller is programmed to dwell with the nonactuated phases displaying green for at least a specified minimum duration. The sequence and duration of each actuated phase are determined by traffic demand. Hence, this type of control is *not* associated with a constant cycle length.
- *Coordinated-actuated control* is a variation of semiactuated operation. It uses the controller’s force-off settings to constrain the noncoordinated phases associated with the minor movements so that the coordinated phases are served at the appropriate time during the signal cycle and progression for the major movements is maintained. This type of control *is* associated with a constant cycle length.

Signalized intersections that are close to one another on the same street are often operated as a coordinated signal system, in which specific phases at each intersection are operated on a common time schedule to permit the continuous flow of the associated movements at a planned speed. The signals in a coordinated system typically operate by using pretimed or coordinated-actuated control, and the coordinated phases typically serve the major-street through movements. Signalized intersections that are not part of a coordinated system are characterized as “isolated” and typically operate by using fully actuated or semiactuated control.

INTERSECTION TRAFFIC MOVEMENTS

Exhibit 31-1 illustrates typical vehicle and pedestrian traffic movements at a four-leg intersection. Three vehicular traffic movements and one pedestrian traffic movement are shown for each intersection approach. Each movement is assigned a unique number or a number and letter combination. The letter P denotes a pedestrian movement. The number assigned to each left-turn and through movement is the same as the number typically assigned to each phase by National Electrical Manufacturers Association specification.

Exhibit 31-1
Intersection Traffic
Movements and
Numbering Scheme



Intersection traffic movements are assigned the right-of-way by the signal controller. Each movement is assigned to one or more signal phases. A phase is defined as the green, yellow change, and red clearance intervals in a cycle that are assigned to a specified traffic movement (or movements) (1). The assignment of movements to phases varies in practice, depending on the desired phase sequence and the movements present at the intersection.

SIGNAL PHASE SEQUENCE

Modern actuated controllers implement signal phasing by using a dual-ring structure that allows for the concurrent presentation of a green indication to two phases. Each phase serves one or more movements that do not conflict with each other. Early controllers used a single-ring structure in which all nonconflicting movements were assigned to a common phase, and its duration was dictated by

the movement needing the most time. Of the two structures, the dual-ring structure is more efficient because it allows the controller to adapt phase duration and sequence to the needs of the individual movements. The dual-ring structure is typically used with eight phases; however, more phases are available for complex signal phasing. The eight-phase dual-ring structure is shown in Exhibit 31-2. The symbol Φ represents the word “phase,” and the number following the symbol represents the phase number.

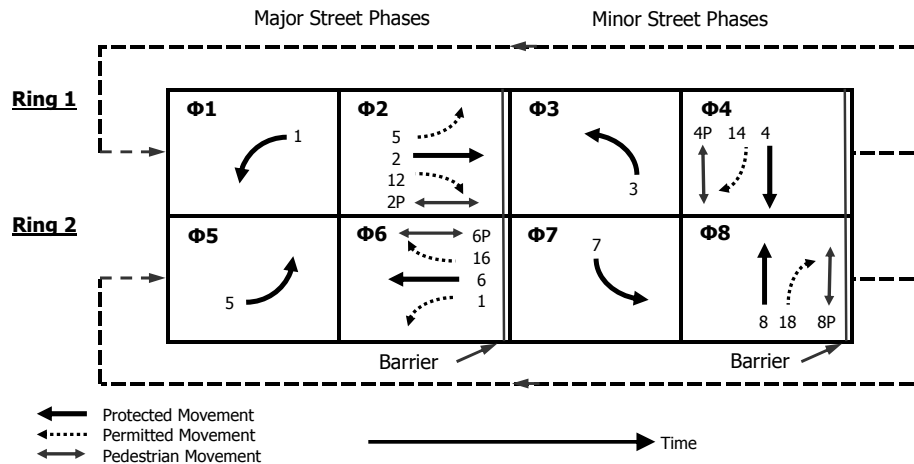


Exhibit 31-2
Dual-Ring Structure with
Illustrative Movement Assignments

Exhibit 31-2 shows one way that traffic movements can be assigned to each of the eight phases. These assignments are illustrative, but they are not uncommon. Each left-turn movement is assigned to an exclusive phase. During this phase, the left-turn movement is “protected” so that it receives a green arrow indication. Each through, right-turn, and pedestrian movement combination is also assigned to an exclusive phase. The dashed arrows indicate turn movements that are served in a “permitted” manner so that the turn can be completed only after yielding the right-of-way to conflicting movements.

Two rings and two barriers are identified in Exhibit 31-2. A ring consists of two or more sequentially timed conflicting phases. Ring 1 consists of Phases 1, 2, 3, and 4. Ring 2 consists of Phases 5, 6, 7, and 8. A barrier is used when there are two or more rings. It represents a reference point in the cycle where one phase in each ring must reach a common point of termination. In Exhibit 31-2, a barrier is shown following Phases 2 and 6. A second barrier is shown following Phases 4 and 8. Between barriers, only one phase can be active at a time in each ring.

The ring structure dictates the sequence of phase presentation. Some common rules are provided in the following list:

- Phase Pairs 1–2, 3–4, 5–6, and 7–8 typically occur in sequence. Thus, Phase Pair 1–2 begins with Phase 1 and ends with Phase 2. Within each phase pair, it is possible to reverse the order of the pair. Thus, the Pair 1–2 could be set to begin with Phase 2 and end with Phase 1 if it is desired to have the left-turn Phase 1 lag through Phase 2.
- Phase Pair 1–2 can operate concurrently with Phase Pair 5–6. That is, Phase 1 or 2 can time with Phase 5 or 6. Similarly, Phase Pair 3–4 can

operate concurrently with Phase Pair 7–8. These phase pairs are also known as concurrency groups.

- For a given concurrency group, the last phase to occur in one phase pair must end at the same time as the last phase to occur in the other pair (i.e., end together at the barrier).
- Phases between two barriers are typically assigned to the movements on a common street.

OPERATIONAL MODES

There are three operational modes for the turn movements at an intersection. The names used to describe these modes refer to the way the turn movement is served by the controller. The three modes are as follows:

- Permitted,
- Protected, and
- Protected-permitted.

The *permitted mode* requires turning drivers to yield to conflicting traffic streams before completing the turn. Permitted left-turning drivers yield to oncoming vehicles and conflicting pedestrians. Permitted right-turning drivers yield to pedestrians. The efficiency of this mode depends on the availability of gaps in the conflicting streams. An exclusive turn lane may be provided, but it is not required. The permitted turn movement is typically presented with a circular green indication (although some agencies use other indications, such as a flashing yellow arrow). The right-turn movements in Exhibit 31-2 are operating in the permitted mode.

The *protected mode* allows turning drivers to travel through the intersection while all conflicting movements are required to yield. This mode provides for efficient turn-movement service; however, the additional turn phase typically results in increased delay to the other movements. An exclusive turn lane is typically provided with this mode. The turn phase is indicated by a green arrow signal indication. Left-turn Movements 3 and 7 in Exhibit 31-2 are operating in the protected mode.

The *protected-permitted mode* represents a combination of the permitted and protected modes. Turning drivers have the right-of-way during the associated left-turn phase. They can also complete the turn “permissively” when the adjacent through movement receives its circular green (or flashing yellow arrow) indication. This mode provides for efficient turn-movement service, often without causing a significant increase in the delay to other movements. Left-turn Movements 1 and 5 in Exhibit 31-2 are operating in the protected-permitted mode.

In general, the operational mode used for one left-turn movement is also used for the opposing left-turn movement. For example, if one left-turn movement is permitted, then so is the opposing left-turn movement. However, this agreement is not required.

LEFT-TURN PHASE SEQUENCE

This subsection describes the sequence of service provided to left-turn movements, relative to the other intersection movements. The typical options include the following:

- No left-turn phase (i.e., permitted only),
- Leading left-turn phase,
- Lagging left-turn phase, or
- Split phasing.

The permitted-only option is used when the left-turn movement operates in the permitted mode. A left-turn phase is not provided with this option. An illustrative implementation of permitted-only phasing for left- and right-turning traffic is shown in Exhibit 31-3 for the minor street.

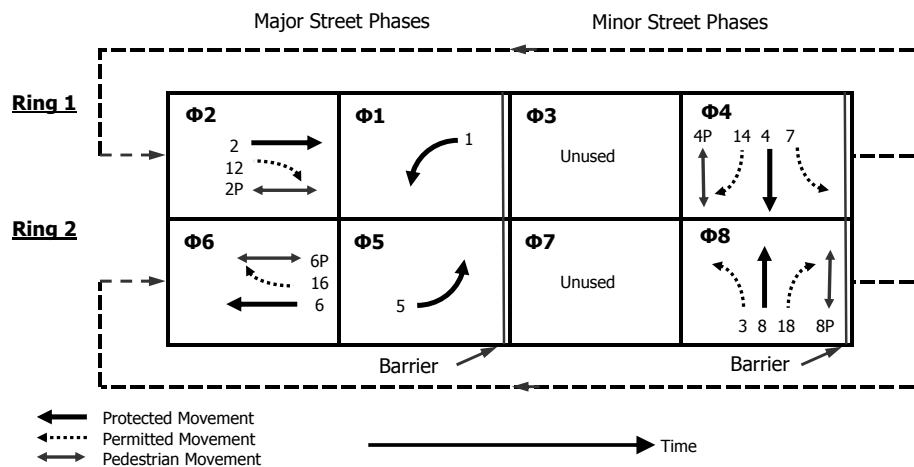
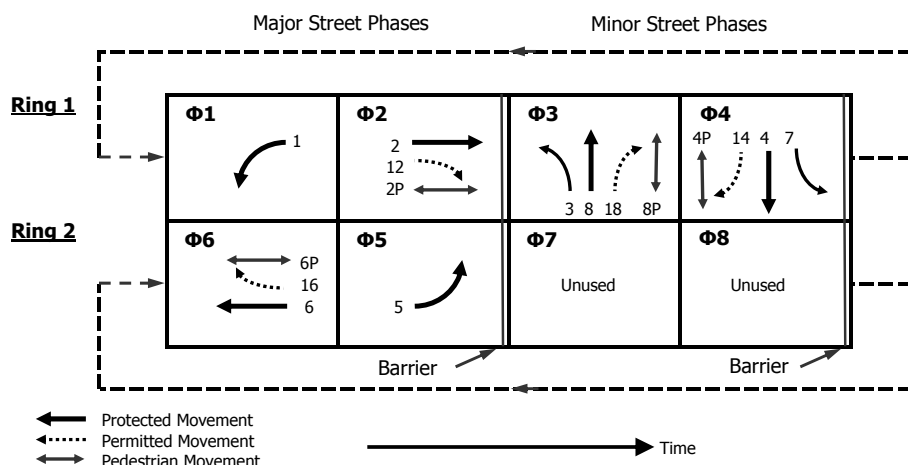


Exhibit 31-3
Illustrative Protected Lag-Lag and
Permitted-Only Phasing

A leading, lagging, or split phase sequence is used when the left turn operates in the protected mode or the protected-permitted mode. The terms “leading” and “lagging” indicate the order in which the left-turn phase is presented, relative to the conflicting through movement. The leading left-turn sequence is shown in Exhibit 31-2 for the left-turn movements on the major and minor streets. The lagging left-turn sequence is shown in Exhibit 31-3 for the left-turn movements on the major street. A mix of leading and lagging phasing (called lead-lag) is shown in Exhibit 31-4 for the left-turn movements on the major street.

Split phasing describes a phase sequence in which one phase serves all movements on one approach and a second phase serves all movements on the opposing approach. Split phasing requires that all approach movements simultaneously receive a green indication. Split phasing is shown in Exhibit 31-4 for the minor street. Other variations of split phasing exist and depend on the treatment of the pedestrian movements. The left-turn movement in a split phase typically operates in the protected mode (as shown), provided that there are no conflicting pedestrian movements.

Exhibit 31-4
Illustrative Protected Lead-
Lag and Split Phasing



TRAFFIC FLOW CHARACTERISTICS

This subsection describes several fundamental attributes of flow at signalized intersections. Exhibit 31-5 provides a reference for much of the discussion. The diagram represents a simple situation of vehicles on one approach to a signalized intersection during one signal cycle. The red clearance interval is not used with the phase serving the subject movement.

Exhibit 31-5 is divided into three parts. The top part shows the time-space trajectories of each vehicle on the approach as it travels "up" the page. The horizontal bar being crossed by the vehicles represents the location of the stop line. The bar's shading variations indicate the signal indication during the cycle. The middle part labels the timing intervals of interest with the symbols used throughout this chapter and Chapter 18, Signalized Intersections. The bottom part is an idealized representation of flow rate (measured at the stop line) as a function of time.

The trajectories in Exhibit 31-5 are a simplified representation of the actual vehicle position as a function of time. The trajectories shown imply that arrival and departure headways are fairly uniform during the cycle. Chapter 7, Interpreting HCM and Alternative Tool Results, provides additional discussion on the topic of vehicle trajectories, without restriction on the uniformity of headways. It also describes a procedure for using trajectory analysis to determine performance measures.

The automobile methodology described in Chapter 18 disaggregates the signal cycle into an effective green time and an effective red time for each phase to facilitate the evaluation of intersection operation. Effective green time is the time that can be used by vehicles to proceed effectively at the saturation flow rate. Effective red time for a phase is equal to the cycle length minus the effective green time. Further definitions of these variables and other basic terms are provided in Exhibit 31-6.

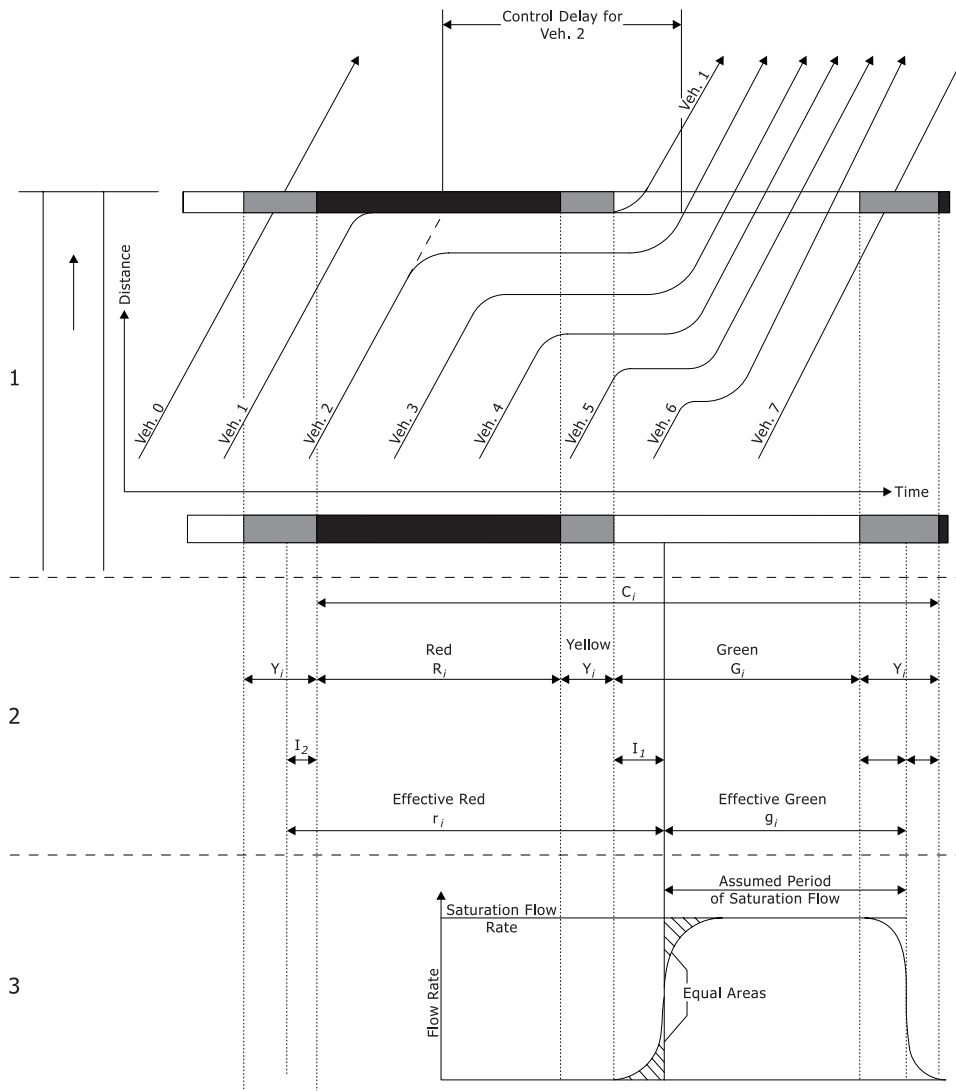


Exhibit 31-5
Fundamental Attributes of Traffic
Flow at Signalized Intersections

Lost Time

Two increments of lost time are associated with a phase. At the beginning of the phase, the first few vehicles in the queue depart at headways that exceed the saturation headway. The longer headway reflects the additional time the first few drivers require to respond to the change in signal indication and accelerate to the running speed. The start-up losses are called start-up lost time l_1 .

At the end of the phase, driver compliance with the yellow indication results in the latter portion of the change period (i.e., the yellow change interval and red clearance interval) not being available for vehicular service. The initial portion of the change period that is consistently used by drivers is referred to as the extension of effective green e . The remainder of the change period is considered to be clearance lost time l_2 . Phase lost time l_i equals the sum of the start-up and clearance lost times.

Exhibit 31-6
Fundamental Variables of
Traffic Flow at Signalized
Intersections

Variable Name	Symbol	Definition
Control delay (s/veh)	d	The component of delay that results when a traffic control device causes a traffic movement to reduce speed or to stop. It represents the increase in travel time relative to the uncontrolled condition.
Clearance lost time (s)	l_c	The time at the end of a phase during which the associated traffic movements can no longer proceed effectively at the saturation flow rate.
Cycle		The time to complete one sequence of signal indications.
Cycle length (s)	C	The total time for a signal to complete one cycle.
Effective green time (s)	g	The time during which a combination of traffic movements is considered to proceed effectively at the saturation flow rate.
Effective red time (s)	r	The time during which a combination of traffic movements is not considered to proceed effectively at the saturation flow rate. It is equal to the cycle length minus the effective green time.
Extension of effective green (s)	e	The initial portion of the yellow change interval during which a combination of traffic movements is considered to proceed effectively at the saturation flow rate.
Green interval duration (s)	G	The duration of the green interval associated with a phase.
Interval		A period of time during which all signal indications remain constant.
Phase lost time (s)	l_t	The sum of the clearance lost time and start-up lost time.
Phase		The green, yellow change, and red clearance intervals assigned to a specified movement (or movements).
Red clearance interval (s)	R_c	This interval follows the yellow change interval and is optionally used to provide additional time before conflicting movements receive a green indication.
Red time (s)	R	The time in the signal cycle during which the signal indication is red for a given phase.
Adjusted saturation flow rate (veh/h/ln)	s	The equivalent hourly rate at which previously queued vehicles can traverse an intersection approach under prevailing conditions, assuming that the green signal is available at all times and no lost times are experienced.
Start-up lost time (s)	l_1	The additional time consumed by the first few vehicles in a queue whose headway exceeds the saturation headway because of the need to react to the initiation of the green interval and accelerate.
Cycle lost time (s)	L	The time lost during the cycle. It represents the sum of the lost time for each critical phase.
Yellow change interval (s)	Y	This interval follows the green interval. It is used to warn drivers of the impending red indication.

The relationship between phase lost time and signal timing is shown in Equation 31-1. Research (2) has shown that start-up lost time is about 2 s and the extension of effective green is about 2 s (longer values may be appropriate for congested conditions or higher speeds). If start-up lost time equals the extension of effective green, then phase lost time is equal to the change period (i.e., $l_t = Y + R_c$).

Equation 31-1

$$l_t = l_1 + l_2 = l_1 + Y + R_c - e$$

where

l_t = phase lost time (s),

l_1 = start-up lost time = 2.0 (s),

l_2 = clearance lost time = $Y + R_c - e$ (s),

e = extension of effective green = 2.0 (s),

Y = yellow change interval (s), and

R_c = red clearance interval (s).

Saturation Flow Rate

Saturation flow rate is a basic parameter used to derive capacity. It is defined in Exhibit 31-6. Saturation flow rate is expressed as an hourly rate, with units of vehicles per hour per lane (veh/h/ln).

A saturation flow rate for prevailing conditions can be determined directly from field measurement. A technique for measuring this rate is described in Section 6.

A procedure for estimating the adjusted saturation flow rate for a lane group is provided in the automobile methodology described in Chapter 18. The procedure consists of a base saturation flow rate and a series of adjustment factors. The factors are used to adjust the base rate to reflect the geometric, traffic, and environmental conditions that may influence the departure headway of vehicles in the subject lane group.

Capacity

The automobile methodology is based on the calculation of lane group capacity and its relationship to demand flow rate. Capacity is computed as the product of adjusted saturation flow rate and effective-green-to-cycle-length ratio. Capacity is defined as the maximum number of vehicles that can reasonably be expected to pass through the intersection under prevailing traffic, roadway, and signalization conditions during a 15-min period. Capacity is expressed as an hourly rate, with units of vehicles per hour.

2. CAPACITY AND PHASE DURATION

This section describes four procedures related to the calculation of capacity and phase duration. The first procedure is used to calculate the average duration of an actuated phase. The second procedure is used to calculate the lane volume distribution on multilane intersection approaches. The third procedure focuses on the calculation of phase duration for pretimed intersection operation. The fourth procedure is used to compute the pedestrian and bicycle saturation flow rate adjustment factors. Each procedure is described in a separate subsection.

ACTUATED PHASE DURATION

This subsection describes a procedure for estimating the average phase duration for an intersection that is operating with actuated control. Where appropriate, the description is extended to include techniques for estimating the duration of noncoordinated and coordinated phases. Unless stated otherwise, a noncoordinated phase is modeled as an actuated phase in this methodology.

This subsection consists of the following seven parts:

- Concepts,
- Volume computations,
- Queue accumulation polygon,
- Maximum allowable headway,
- Equivalent maximum green,
- Average phase duration, and
- Probability of max out.

The last six parts in this list describe a series of calculations that are completed in the sequence shown to obtain estimates of average phase duration and the probability of phase termination by extension to its maximum green limit (i.e., max out).

Concepts

The duration of an actuated phase is composed of five time periods, as shown in Equation 31-2. The first period represents the time lost while the queue reacts to the signal indication changing to green. The second interval represents the effective green time associated with queue clearance. The third period represents the time the green indication is extended by randomly arriving vehicles. It ends when there is a gap in traffic (i.e., gap out) or a max out. The fourth period represents the yellow change interval, and the last period represents the red clearance interval.

Equation 31-2

$$D_p = l_1 + g_s + g_e + Y + R_c$$

where

- D_p = phase duration (s),
 g_s = queue service time (s), and

g_e = green extension time (s).

Other variables are as previously defined.

The relationship between the variables in Equation 31-2 is shown in Exhibit 31-7 with a queue accumulation polygon. Key variables shown in the exhibit are defined in the following list:

q_r = arrival flow rate during the effective red time = $(1 - P)qC/r$ (veh/s),

P = proportion of vehicles arriving during the green indication (decimal),

r = effective red time = $C - g$ (s),

g = effective green time (s),

q_g = arrival flow rate during the effective green time = PqC/g (veh/s),

q = arrival flow rate (veh/s), and

Q_r = queue size at the end of the effective red time = $q_r r$ (veh).

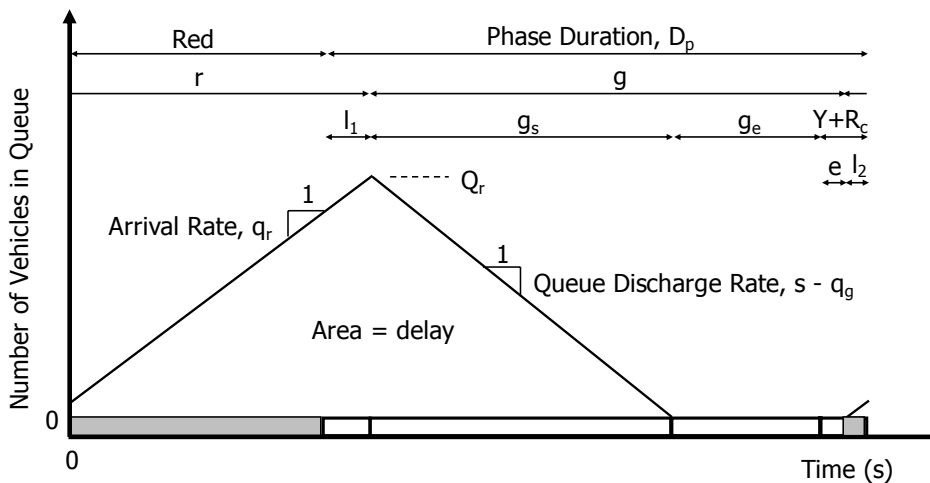


Exhibit 31-7
Time Elements Influencing
Actuated Phase Duration

Exhibit 31-7 shows the relationship between phase duration and queue size for the average signal cycle. During the red interval, vehicles arrive at a rate of q_r and form a queue. The queue reaches its maximum size l_1 seconds after the green interval starts. At this time, the queue begins to discharge at a rate equal to the saturation flow rate s less the arrival rate during green q_g . The queue clears g_s seconds after it first begins to discharge. Thereafter, random vehicle arrivals are detected and cause the green interval to be extended. Eventually, a gap occurs in traffic (or the maximum green limit is reached) and the green interval ends. The end of the green interval coincides with the end of the extension time g_e .

The effective green time for the phase is computed with the following equation:

$$g = D_p - l_1 - l_2 = g_s + g_e + e$$

Equation 31-3

Coordinated Phase Duration

The duration of a coordinated phase is dictated by the cycle length and the force-off settings for the noncoordinated phases. These settings define the points in the signal cycle where each noncoordinated phase must end. The force-off settings are used to ensure that the coordinated phases receive a green indication at a specific time in the cycle. Presumably, this time is synchronized with the coordinated phase time at the adjacent intersections so that traffic progresses along the street segment. In general, the duration of a coordinated phase is equal to the cycle length less the time allocated to the conflicting phase in the same ring and less the time allocated to the minor-street phases. Detectors are not typically assigned to the coordinated phase, and this phase is not typically extended by the vehicles it serves.

Noncoordinated Phase Duration

The duration of a noncoordinated phase is dictated by traffic demand in much the same manner as is an actuated phase. However, the noncoordinated phase duration is typically constrained by its force-off setting (rather than a maximum green setting). A noncoordinated phase is referred to here and modeled as an “actuated” phase.

Volume Computations

This part describes the calculations needed to quantify the time rate of calls submitted to the controller by the detectors. Two call rates are computed for each signal phase. The first rate represents the flow rate of calls for green extension that arrive during the green interval. The second call rate represents the flow rate of calls for phase activation that arrive during the red indication.

A. Call Rate to Extend Green

The call rate to extend the green indication for a given phase is based on the flow rate of the lane groups served by the phase. If the subject phase ends at a barrier and simultaneous gap out is enabled, then the phase’s call rate is based on the lane groups it serves *plus* those groups served by the phase in the other ring that also ends at the barrier. The call rate is represented in the analysis by the flow rate parameter. This parameter represents an adjusted flow rate that accounts for the natural tendency for vehicles to form “bunches” (i.e., randomly formed platoons). The flow rate parameter for the phase is computed as follows:

Equation 31-4

$$\lambda^* = \sum_{i=1}^m \lambda_i$$

with

Equation 31-5

$$\lambda_i = \frac{\varphi_i q_i}{1 - \Delta_i q_i}$$

Equation 31-6

$$\varphi_i = e^{-b_i \Delta_i q_i}$$

where

- λ^* = flow rate parameter for the phase (veh/s);
- λ_i = flow rate parameter for lane group i ($i = 1, 2, \dots, m$) (veh/s);
- φ_i = proportion of free (unbunched) vehicles in lane group i (decimal);
- q_i = arrival flow rate for lane group $i = v_i/3,600$ (veh/s);
- v_i = demand flow rate for lane group i (veh/h);
- Δ_i = headway of bunched vehicle stream in lane group i ; = 1.5 s for single-lane lane group, 0.5 s otherwise (s/veh);
- m = number of lane groups served during the phase; and
- b_i = bunching factor for lane group i (0.6, 0.5, and 0.8 for lane groups with 1, 2, and 3 or more lanes, respectively).

It is also useful to compute the following three variables for each phase. These variables are used in a later step to compute green extension time.

$$\varphi^* = e^{-\sum_{i=1}^m b_i \Delta_i q_i}$$

Equation 31-7

$$\Delta^* = \frac{\sum_{i=1}^m \lambda_i \Delta_i}{\lambda^*}$$

Equation 31-8

$$q^* = \sum_{i=1}^m q_i$$

Equation 31-9

where

- φ^* = combined proportion of free (unbunched) vehicles for the phase (decimal),
- Δ^* = equivalent headway of bunched vehicle stream served by the phase (s/veh), and
- q^* = arrival flow rate for the phase (veh/s).

The call rate for green extension for a phase that does not end at a barrier is equal to the flow rate parameter λ^* . If two phases terminate at the barrier and simultaneous gap out is enabled, then the lane group parameters for each phase are combined to estimate the call rate for green extension. Specifically, the variable m in the preceding six equations is modified to represent the combined number of lane groups served by both phases.

The following rules are evaluated to determine the number of lane groups served m if simultaneous gap out is enabled. They are described for the case in which Phases 2, 6, 4, and 8 end at the barrier (as shown in Exhibit 31-2). The rules should be modified if other phase pairs end at the barrier:

1. If Phases 2 and 6 have simultaneous gap out enabled, then the lane groups associated with Phase 2 are combined with those associated with Phase 6 in evaluating Equation 31-4 to Equation 31-9 for Phase 6.

Similarly, the lane groups associated with Phase 6 are combined with those associated with Phase 2 in evaluating these equations for Phase 2.

2. If Phases 4 and 8 have simultaneous gap out enabled, then the lane groups associated with Phase 4 are combined with those associated with Phase 8 in evaluating Phase 8. Similarly, the lane groups associated with Phase 8 are combined with those associated with Phase 4 in evaluating Phase 4.

B. Call Rate to Activate a Phase

The call rate to activate a phase is used to determine the probability that the phase is activated in the forthcoming cycle sequence. This rate is based on the arrival flow rate of the traffic movements served by the phase and whether the phase is associated with dual entry. Vehicles or pedestrians can call a phase, so a separate call rate is computed for each traffic movement.

i. Determine Phase Vehicular Flow Rate. The vehicular flow rate associated with a phase depends on the type of movements it serves as well as the approach lane allocation. The following rules apply in determining the phase vehicular flow rate:

1. If the phase exclusively serves a left-turn movement, then the phase vehicular flow rate is equal to the left-turn movement flow rate.
2. If the phase serves a through or right-turn movement and there is no exclusive left-turn phase for the adjacent left-turn movement, then the phase vehicular flow rate equals the approach flow rate.
3. If the phase serves a through or right-turn movement and there is an exclusive left-turn phase for the adjacent left-turn movement then:
 - a. If there is a left-turn bay, then the phase vehicular flow rate equals the sum of the through and right-turn movement flow rates.
 - b. If there is no left-turn bay, then the phase vehicular flow rate equals the approach flow rate.
 - c. If split phasing is used, then the phase vehicular flow rate equals the approach flow rate.

ii. Determine Activating Vehicular Call Rate. The activating vehicular call rate q_v^* is equal to the phase vehicular flow rate divided by 3,600 to convert it to units of vehicles per second. If dual entry is activated for a phase, then the activation call rate must be modified by adding its original rate to that of both concurrent phases. For example, if Phase 2 is set for dual entry, then the modified Phase 2 activation call rate equals the original Phase 2 activation call rate plus the activation rate of Phase 5 and the activation rate of Phase 6. In this manner, Phase 2 is activated when demand is present for Phase 2, 5, or 6.

iii. Determine Activating Pedestrian Call Rate. The activating pedestrian call rate q_p^* is equal to the pedestrian flow rate associated with the subject approach divided by 3,600 to convert it to units of pedestrians per second. If dual entry is activated for a phase, then the activation call rate must be modified by adding its original rate to that of the opposing through phase. For example, if Phase 2 is set for dual entry, then the modified Phase 2 activation call rate equals the original

Phase 2 activation call rate plus the activation rate of Phase 6. In this manner, Phase 2 is activated when pedestrian demand is present for Phase 2 or 6.

Queue Accumulation Polygon

This part summarizes the procedure used to construct the queue accumulation polygon associated with a lane group. This polygon defines the queue size for a traffic movement as a function of time during the cycle. It is discussed at this point in Section 2 to illustrate its use in calculating queue service time. The procedure is described more fully in Section 3.

For polygon construction, all flow rate variables are converted to common units of vehicles per second per lane. The presentation in this part is based on these units for q and s . If the flow rate q exceeds the lane capacity, then it is set to equal this capacity.

A polygon is shown in Exhibit 31-7 for a through movement in an exclusive lane. At the start of the effective red, vehicles arrive at a rate of q_r and accumulate to a length of Q_r vehicles at the time the effective green begins. Thereafter, the queue begins to discharge at a rate of $s - q_g$ until it clears after g_s seconds. The queue service time g_s represents the time required to serve the queue present at the end of effective red Q_r plus any additional arrivals that join the queue before it fully clears. Queue service time is computed as $Q_r/[s - q_g]$. Substituting the variable relationships in the previous variable list into this equation yields the following equation for estimating queue service time:

$$g_s = \frac{qC(1 - P)}{s / 3,600 - qC(P / g)}$$

Equation 31-10

The polygon in Exhibit 31-7 applies to some types of lane group. Other polygon shapes are possible. A detailed procedure for constructing polygons is described in Section 3.

Maximum Allowable Headway

This part describes a procedure for calculating the maximum allowable headway (*MAH*) for the detection associated with a phase. It consists of two steps. Step A computes the *MAH* for each lane group served by the subject phase. Step B combines the *MAH* into an equivalent *MAH* for the phase. The latter step is used when a phase serves two or more lane groups or when simultaneous gap out is enabled.

The procedure addresses the situation in which there is one zone of detection per lane. This type of detection is referred to here as "stop-line detection" because the detection zone is typically located at the stop line. However, some agencies prefer to locate the detection zone at a specified distance upstream from the stop line. This procedure can be used to evaluate any single-detector-per-lane design, provided that the detector is located so that only the subject traffic movement travels over this detector during normal operation.

The detector length and detection mode input data are specified by movement group. When these data describe a through movement group, it is reasonable to assume that they also describe the detection in any shared-lane

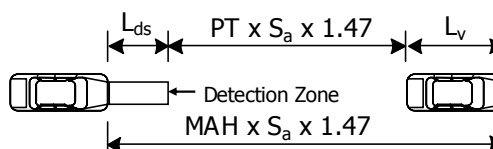
lane groups that serve the through movement. This assumption allows the movement group inputs to describe the associated lane group values, and the analysis can proceed on a lane-group basis. However, if this assumption is not valid or if information about the detection design for each lane is known, then the procedure can be extended to the calculation of *MAH* for each lane. The lane-specific *MAH*s would then be combined for the phase that serves these lanes.

Concepts

The *MAH* represents the maximum time that can elapse between successive calls for service without terminating the phase by gap out. It is useful for describing the detection design and signal settings associated with a phase. The *MAH* depends on the number of detectors serving the lane group, the length of these detectors, and the average vehicle speed in the lane group.

The relationship between passage time *PT*, detection zone length L_{ds} , vehicle length L_v , average speed S_a , and *MAH* is shown in Exhibit 31-8. The two vehicles shown are traveling from left to right and have a headway equal to the *MAH* so that the second vehicle arrives at the detector the instant the passage time is set to time out.

Exhibit 31-8
Detection Design and
Maximum Allowable
Headway



According to Exhibit 31-8, Equation 31-11 can be derived for estimating the *MAH* for stop-line detection operating in the presence mode.

Equation 31-11

$$MAH = PT + \frac{L_{ds} + L_v}{1.47 S_a}$$

with

Equation 31-12

$$L_v = L_{pc} (1 - 0.01 P_{HV}) + 0.01 L_{HV} P_{HV} - D_{sv}$$

where

MAH = maximum allowable headway (s/veh),

PT = passage time setting (s),

L_{ds} = length of the stop-line detection zone (ft),

L_v = detected length of the vehicle (ft),

S_a = average speed on the intersection approach (mi/h),

L_{pc} = stored passenger car lane length = 25 (ft),

P_{HV} = percent heavy vehicles in the corresponding movement group (%),

L_{HV} = stored heavy-vehicle lane length = 45 (ft), and

D_{sv} = distance between stored vehicles = 8 (ft).

The average speed on the intersection approach can be estimated with Equation 31-13.

$$S_a = 0.90 (25.6 + 0.47 S_{pl})$$

where S_{pl} is the posted speed limit (mi/h).

Equation 31-11 is derived for the typical case in which the detection unit is operating in the presence mode. If it is operating in the pulse mode, then the *MAH* equals the passage time setting *PT*.

A. Determine Maximum Allowable Headway

Equation 31-11 has been modified to adapt it to various combinations of lane use and left-turn operation. A family of equations is presented in this step. The appropriate equation is selected for the subject lane group and then used to compute the corresponding *MAH*.

The equations presented in this step are derived for the typical case in which the detection unit is operating in the presence mode. If a detector is operating in the pulse mode, then the *MAH* equals the passage time setting *PT*.

The *MAH* for lane groups serving through vehicles is calculated with Equation 31-14.

$$MAH_{th} = PT_{th} + \frac{L_{ds,th} + L_v}{1.47 S_a}$$

where

MAH_{th} = maximum allowable headway for through vehicles (s/veh),

PT_{th} = passage time setting for phase serving through vehicles (s), and

$L_{ds,th}$ = length of the stop-line detection zone in the through lanes (ft).

The *MAH* for a left-turn movement served in exclusive lanes with the protected mode (or protected-permitted mode) is based on Equation 31-14, but it is adjusted to account for the slower speed of the left-turn movement. The adjusted equation is shown as Equation 31-15.

$$MAH_{lt,e,p} = PT_{lt} + \frac{L_{ds,lt} + L_v}{1.47 S_a} + \frac{E_L - 1}{s_o / 3,600}$$

where

$MAH_{lt,e,p}$ = maximum allowable headway for protected left-turning vehicles in exclusive lane (s/veh),

PT_{lt} = passage time setting for phase serving the left-turning vehicles (s),

$L_{ds,lt}$ = length of the stop-line detection zone in the left-turn lanes (ft),

E_L = equivalent number of through cars for a protected left-turning vehicle = 1.05, and

s_o = base saturation flow rate (pc/h/ln).

The *MAH* value for left-turning vehicles served in a shared lane with the protected-permitted mode is shown as Equation 31-16:

Equation 31-13

Equation 31-14

Equation 31-15

Equation 31-16

$$MAH_{lt,s,p} = MAH_{th} + \frac{E_L - 1}{s_o / 3,600}$$

where $MAH_{lt,s,p}$ is the maximum allowable headway for protected left-turning vehicles in a shared lane (s/veh).

The MAH value for left-turning vehicles served in an exclusive lane with the permitted mode is adjusted to account for the longer headway of the turning vehicle. In this case, the longer headway includes the time spent waiting for an acceptable gap in the opposing traffic stream. Equation 31-17 addresses these adjustments.

Equation 31-17

$$MAH_{lt,e} = PT_{th} + \frac{L_{ds,lt} + L_v}{1.47 S_a} + \frac{3,600}{s_l} - t_{fh}$$

where

$MAH_{lt,e}$ = maximum allowable headway for permitted left-turning vehicles in exclusive lane (s/veh);

s_l = saturation flow rate in exclusive left-turn lane group with permitted operation (veh/h/ln); and

t_{fh} = follow-up headway (4.5 if the subject left turn is served in a shared lane, 2.5 if the subject left turn is served in an exclusive lane) (s).

The MAH value for right-turning vehicles served in an exclusive lane with the protected mode is computed with Equation 31-18.

Equation 31-18

$$MAH_{rt,e,p} = PT_{rt} + \frac{L_{ds,rt} + L_v}{1.47 S_a} + \frac{E_R - 1}{s_o / 3,600}$$

where

$MAH_{rt,e,p}$ = maximum allowable headway for protected right-turning vehicles in exclusive lane (s/veh),

PT_{rt} = passage time setting for phase serving right-turning vehicles (s),

E_R = equivalent number of through cars for a protected right-turning vehicle = 1.18, and

$L_{ds,rt}$ = length of the stop-line detection zone in the right-turn lanes (ft).

If the variable E_R in Equation 31-18 is divided by the pedestrian-bicycle saturation flow rate adjustment factor f_{Rpb} and PT_{th} is substituted for PT_{rt} , then the equation can be used to estimate $MAH_{rt,e}$ for permitted right-turning vehicles in an exclusive lane.

The following equations are used to estimate the MAH for left- and right-turning vehicles that are served in a shared lane with the permitted mode:

Equation 31-19

$$MAH_{lt,s} = MAH_{th} + \frac{3,600}{s_l} - t_{fh}$$

Equation 31-20

$$MAH_{rt,s} = MAH_{th} + \frac{(E_R / f_{Rpb}) - 1}{s_o / 3,600}$$

where $MAH_{lt,s}$ is the maximum allowable headway for permitted left-turning vehicles in a shared lane (s/veh) and $MAH_{rt,s}$ is the maximum allowable headway for permitted right-turning vehicles in a shared lane (s/veh).

B. Determine Equivalent Maximum Allowable Headway

The equivalent MAH (i.e., MAH^*) is calculated for cases in which more than one lane group is served by a phase. It is also calculated for phases that end at a barrier and that are specified in the controller as needing to gap out at the same time as a phase in the other ring. The following rules are used to compute the equivalent MAH .

1. If simultaneous gap out is not enabled, or the phase does not end at the barrier, then:
 - a. If the phase serves only one movement, then the MAH^* for the phase equals the MAH computed for the corresponding lane group.
 - b. This rule subset applies when the phase serves all movements and there is no exclusive left-turn phase for the approach (i.e., it operates with the permitted mode). The equations shown apply to the most general case in which a left-turn, through, and right-turn movement exist and a through lane group exists. If any of these movements or lane groups does not exist, then their corresponding flow rate parameter equals 0.0 veh/s.
 - i. If there is no left-turn lane group or right-turn lane group (i.e., shared lanes), then the MAH^* for the phase is computed from Equation 31-21.

$$MAH^* = \frac{P_L \lambda_{sl} MAH_{lt,s} + [(1 - P_L) \lambda_{sl} + \lambda_t + (1 - P_R) \lambda_{sr}] MAH_{th} + P_R \lambda_{sr} MAH_{rt,s}}{\lambda_{sl} + \lambda_t + \lambda_{sr}}$$

Equation 31-21

where

- λ_{sl} = flow rate parameter for shared left-turn and through lane group (veh/s),
 - λ_t = flow rate parameter for exclusive through lane group (veh/s),
 - λ_{sr} = flow rate parameter for shared right-turn and through lane group (veh/s),
 - P_L = proportion of left-turning vehicles in the shared lane (decimal), and
 - P_R = proportion of right-turning vehicles in the shared lane (decimal).
- ii. If there is a right-turn lane group but no left-turn lane group, then Equation 31-22 is applicable.

$$MAH^* = \frac{P_L \lambda_{sl} MAH_{lt,s} + [(1 - P_L) \lambda_{sl} + \lambda_t] MAH_{th} + \lambda_r MAH_{rt,e}}{\lambda_{sl} + \lambda_t + \lambda_r}$$

Equation 31-22

where λ_r is the flow rate parameter for the exclusive right-turn lane group (veh/s).

- iii. If there is a left-turn lane group but no right-turn lane group, then the MAH^* for the phase is computed with Equation 31-23.

Equation 31-23

$$MAH^* = \frac{\lambda_l MAH_{lt,e} + [\lambda_t + (1 - P_R) \lambda_{sr}] MAH_{th} + P_R \lambda_{sr} MAH_{rt,s}}{\lambda_l + \lambda_t + \lambda_{sr}}$$

where λ_l is the flow rate parameter for the exclusive left-turn lane group (veh/s).

- iv. If there is a left-turn lane group and a right-turn lane group, then the MAH^* for the phase is computed with Equation 31-24.

Equation 31-24

$$MAH^* = \frac{\lambda_l MAH_{lt,e} + \lambda_t MAH_{th} + \lambda_r MAH_{rt,e}}{\lambda_l + \lambda_t + \lambda_r}$$

- c. If the phase serves only a through lane group, right-turn lane group, or both, then:

- i. If there is a right-turn lane group and a through lane group, then the MAH^* for the phase is computed with Equation 31-25.

Equation 31-25

$$MAH^* = \frac{\lambda_t MAH_{th} + \lambda_r MAH_{rt,e}}{\lambda_t + \lambda_r}$$

- ii. If there is a shared right-turn-and-through lane group, then the MAH^* for the phase is computed with Equation 31-26.

Equation 31-26

$$MAH^* = \frac{[\lambda_t + (1 - P_R) \lambda_{sr}] MAH_{th} + P_R \lambda_{sr} MAH_{rt,s}}{\lambda_t + \lambda_{sr}}$$

- d. If the phase serves all approach movements using split phasing, then:

- i. If there is one lane group (i.e., a shared lane), then the MAH^* for the phase equals the MAH computed for the lane group.
- ii. If there is more than one lane group, then the MAH^* is computed with the equations in previous Rule 1.b but $MAH_{lt,e,p}$ is substituted for $MAH_{lt,e}$ and $MAH_{lt,s,p}$ is substituted for $MAH_{lt,s}$.

- e. If the phase has protected-permitted operation with a shared left-turn and through lane, then the equations in previous Rule 1.b (i.e., 1.b.i and 1.b.ii) apply. The detection for this phasing does not influence the duration of the left-turn phase. The left-turn phase will be set to minimum recall and extend to its minimum value before terminating.

- 2. If simultaneous gap out is enabled and the phase ends at the barrier, then the MAH^* for the phase is computed with Equation 31-27, where the summations shown are for all lane groups served by the subject (or concurrent) phase.

Equation 31-27

$$MAH^* = \frac{MAH \sum \lambda_i + MAH_c \sum \lambda_{c,i}}{\sum \lambda_i + \sum \lambda_{c,i}}$$

where

MAH^* = equivalent maximum allowable headway for the phase (s/veh),

MAH_c = maximum allowable headway for the concurrent phase that also ends at the barrier (s/veh), and

$\lambda_{c,i}$ = flow rate parameter for lane group i served in the concurrent phase that also ends at the barrier (veh/s).

When there is split phasing, there are no concurrent phases and Equation 31-27 does not apply.

Equivalent Maximum Green

In coordinated-actuated operation, the force-off points are used to constrain the duration of the noncoordinated phases. The maximum green setting is also available to provide additional constraint; however, it is not commonly used. In fact, the default mode in most modern controllers is to inhibit the maximum green timer when the controller is used in a coordinated signal system.

The relationship between the force-off points, yield point, and phase splits is shown in Exhibit 31-9. The yield point is associated with the coordinated phases (i.e., Phases 2 and 6). It coincides with the start of the yellow change interval. If a call for service by one of the noncoordinated phases arrives after the yield point is reached, then the coordinated phases begin the termination process by presenting the yellow indication. Calls that arrive before the yield point are not served until the yield point is reached.

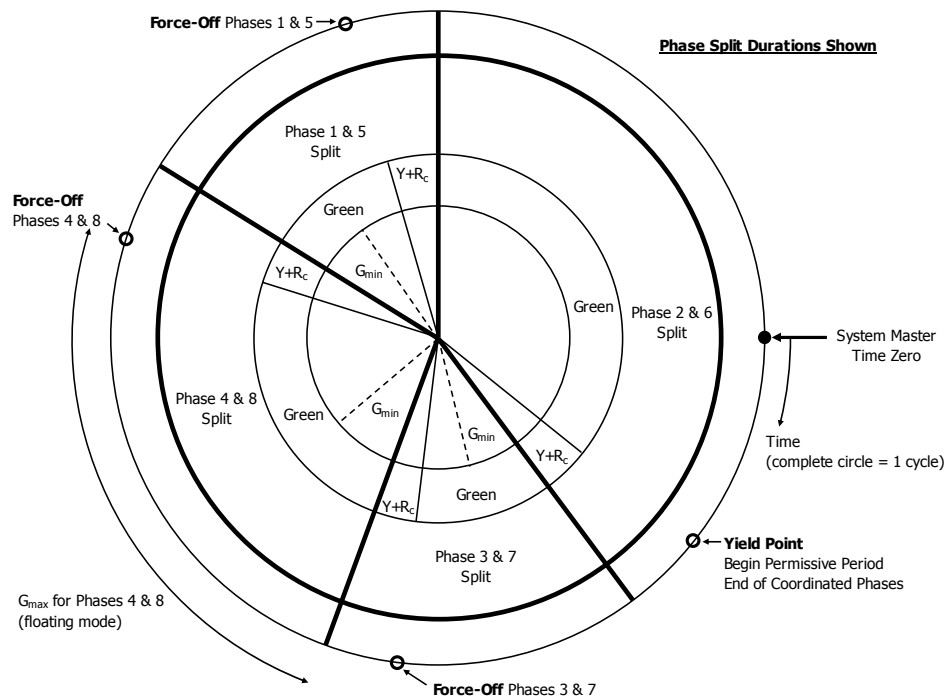


Exhibit 31-9
Force-Off Points, Yield Point, and
Phase Splits

The force-off and yield points for common phase pairs are shown in Exhibit 31-9 to occur at the same time. This approach is shown for convenience of

illustration. In practice, the two phases may have different force-off or yield points.

A permissive period typically follows the yield point. If a conflicting call arrives during the permissive period, then the phase termination process begins immediately and all phases associated with conflicting calls are served in sequence. Permissive periods are typically long enough to ensure that all calls for service are met during the signal cycle. This methodology does not explicitly model permissive periods. It is assumed that the permissive period begins at the yield point and is sufficiently long that all conflicting calls are served in sequence each cycle.

One force-off point is associated with each of Phases 1, 3, 4, 5, 7, and 8. If a phase is extended to its force-off point, the phase begins the termination process by presenting the yellow indication (phases that terminate at a barrier must be in agreement to terminate before the yellow indication will be presented). Modern controllers compute the force-off points and yield point by using the entered phase splits and change periods based on the relationships shown in Exhibit 31-9.

The concept of “equivalent” maximum green is useful for modeling noncoordinated phase operation. This maximum green replicates the effect of a force-off or yield point on phase duration. The procedure described in this part is used to compute the equivalent maximum green for coordinated-actuated operation. Separate procedures are described for the “fixed” force mode and the “floating” force mode.

A. Determine Equivalent Maximum Green for Floating Force Mode

This step is applicable if the controller is set to operate in the floating force mode. With this mode, each noncoordinated phase has its force-off point set at the split time after the phase first becomes active. The force-off point for a phase is established when the phase is first activated. Thus, the force-off point “floats,” or changes, each time the phase is activated. This operation allows unused split time to revert to the coordinated phase via an early return to green. The equivalent maximum green for this mode is computed as being equal to the phase split less the change period. This relationship is shown in Exhibit 31-9 for Phases 4 and 8.

B. Determine Equivalent Maximum Green for Fixed Force Mode

This step is applicable if the controller is set to operate in the fixed force mode. With this mode, each noncoordinated phase has its force-off point set at a fixed time in the cycle, relative to time zero on the system master. The force-off points are established whenever a new timing plan is selected (e.g., by time of day) and remains “fixed” until a new plan is selected. This operation allows unused split time to revert to the following phase.

The equivalent maximum green for this mode is computed for each phase. It is computed by first establishing the fixed force-off points (as shown in Exhibit 31-9) and then computing the average duration of each noncoordinated phase. The calculation process is iterative. For the first calculation of average

phase duration, the maximum green is equal to the phase split less the change period. Thereafter, the maximum green for a specific phase is computed as the difference between its force-off point and the sum of the previous phases, starting with the first noncoordinated phase. Equation 31-28 illustrates this computation for Phase 4, using the ring structure shown in Exhibit 31-2. A similar calculation is performed for the other phases.

$$G_{max,4} = FO_4 - (YP_2 + CP_2 + G_3 + CP_3)$$

Equation 31-28

where

$G_{max,4}$ = equivalent maximum green for Phase 4 (s),

FO_4 = force-off point for Phase 4 (s),

YP_2 = yield point for Phase 2 (s),

G_3 = green interval duration for Phase 3 (s), and

CP_i = change period (yellow change interval plus red clearance interval) for phase i (s).

The maximum green obtained from this equation is shown in Exhibit 31-10 for the ring that serves Phases 1, 2, 3, and 4. Unlike Exhibit 31-9, Exhibit 31-10 illustrates the *actual* average phase durations for a given cycle. In this example, Phase 3 timed to its minimum green and terminated. It never reached its force-off point. The unused time from Phase 3 was made available to Phase 4, which resulted in a larger maximum green than was obtained with the floating mode (see Exhibit 31-9). If every noncoordinated phase extends to its force-off point, then the maximum green from the fixed force mode equals that obtained from the floating force mode.

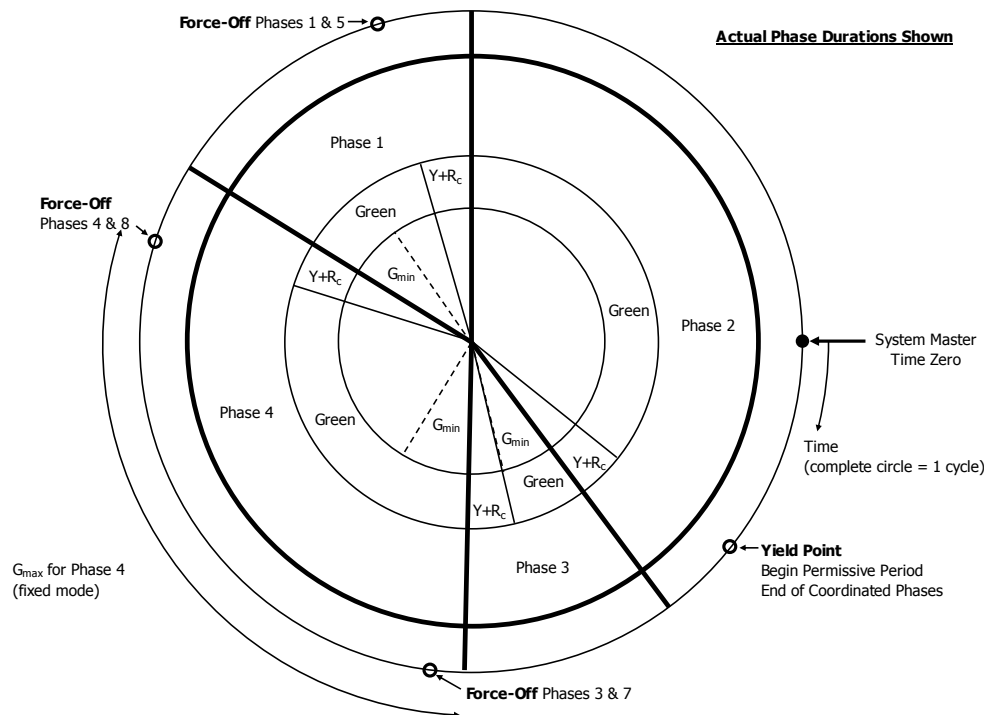


Exhibit 31-10
Example Equivalent Maximum
Green for Fixed Force Mode

Average Phase Duration

This part describes the sequence of calculations needed to estimate the average duration of a phase. In fact, the process requires the combined calculation of the duration of all phases together because of the constraints imposed by the controller ring structure and associated barriers.

The calculation process is iterative because several intermediate equations require knowledge of the green interval duration. Specifically, the green interval duration is required in calculating lane group flow rate, queue service time, permitted green time, left-turn volume served during the permitted portion of a protected-permitted mode, and equivalent maximum green. To overcome this circular dependency, the green interval for each phase is initially estimated and then the procedure is implemented by using this estimate. When completed, the procedure provides a new initial estimate of the green interval duration. The calculations are repeated until the initial estimate and computed green interval duration are effectively equal.

The calculation steps that compose the procedure are described in the following paragraphs.

A. Compute Effective Change Period

The change period is computed for each phase. It is equal to the sum of the yellow change interval and the red clearance interval (i.e., $Y + R_c$). For phases that end at a barrier, the longer change period of the two phases that terminate at a barrier is used to define the effective change period for both phases.

B. Estimate Green Interval

An initial estimate of the green interval duration is provided for each phase. For the first iteration with fully actuated control, the initial estimate is equal to the maximum green setting. For the first iteration with coordinated-actuated control, the initial estimate is equal to the input phase split less the change period.

C. Compute Equivalent Maximum Green (Coordinated-Actuated)

If the controller is operating as coordinated-actuated, then the equivalent maximum green is computed for each phase. It is based on the estimated green interval duration, phase splits, and change periods. The previous part titled Equivalent Maximum Green described how to compute this value.

D. Construct Queue Accumulation Polygon

The queue accumulation polygon is constructed for each lane group and corresponding phase by using the known flow rates and signal timing. The procedure for constructing this polygon was summarized in the previous part titled Queue Accumulation Polygon. It is described in more detail in Section 3.

E. Compute Queue Service Time

The queue service time g_s is computed for each queue accumulation polygon constructed in the previous step. For through movements, or left-turn movements served during a left-turn phase, the polygon in Exhibit 31-7 applies

and Equation 31-10 can be used. The procedure described in Section 3 is applicable to more complicated polygon shapes.

F. Compute Call Rate to Extend Green

The extending call rate is represented as the flow rate parameter λ . This parameter is computed for each lane group served by an actuated phase and then aggregated to a phase-specific value. The procedure for computing this parameter is described in the previous part titled Volume Computations.

G. Compute Equivalent Maximum Allowable Headway

The equivalent maximum allowable headway MAH^* is computed for each actuated phase. The procedure for computing the MAH^* is described in the previous part titled Maximum Allowable Headway.

H. Compute Number of Extensions Before Max Out

The average number of extensions before the phase terminates by max out is computed for each actuated phase with the following equation:

$$n = q^* [G_{max} - (g_s + l_1)] \geq 0.0$$

Equation 31-29

where n is the number of extensions before the green interval reaches its maximum limit, G_{max} is the maximum green setting (s), and other variables are as previously defined.

I. Compute Probability of Green Extension

The probability of the green interval being extended by randomly arriving vehicles is computed for each actuated phase with the following equation:

$$p = 1 - \phi^* e^{-\lambda^* (MAH^* - \Delta^*)}$$

Equation 31-30

where p is the probability of a call headway being less than the maximum allowable headway and other variables are as previously defined.

J. Compute Green Extension Time

The average green extension time is computed for each actuated phase with the following equation:

$$g_e = \frac{p^2(1-p^n)}{q^*(1-p)}$$

Equation 31-31

K. Compute Activating Call Rate

The call rate to activate a phase is computed for each actuated phase. A separate rate is computed for vehicular traffic and for pedestrian traffic. The rate for each travel mode is based on its flow rate and the use of dual entry. The procedure for computing this rate is described in the previous part titled Volume Computations.

L. Compute Probability of Phase Call

The probability that an actuated phase is called depends on whether it is set on recall in the controller. If it is on recall, then the probability that the phase is called equals 1.0. If the phase is not on recall, then the probability that it is called can be estimated with Equation 31-32 to Equation 31-34.

Equation 31-32

$$p_c = p_v(1 - p_p) + p_p(1 - p_v) + p_v p_p$$

with

Equation 31-33

$$p_v = 1 - e^{-q_v^* C}$$

Equation 31-34

$$p_p = 1 - e^{-q_p^* P_p C}$$

where

p_c = probability that the subject phase is called,

p_v = probability that the subject phase is called by a vehicle detection,

p_p = probability that the subject phase is called by a pedestrian detection,

q_v^* = activating vehicular call rate for the phase (veh/s),

q_p^* = activating pedestrian call rate for the phase (p/s), and

P_p = probability of a pedestrian pressing the detector button = 0.51.

Other variables are as previously defined.

The probability of a pedestrian pressing the detector button reflects the tendency of some pedestrians to decline from using the detector button before crossing a street. Research indicates that about 51% of all crossing pedestrians will push the button to place a call for pedestrian service (3).

M. Compute Unbalanced Green Duration

The unbalanced average green interval duration is computed for each actuated phase with Equation 31-35 to Equation 31-37.

Equation 31-35

$$G_u = G_{veh,call} p_v(1 - p_p) + G_{ped,call} p_p(1 - p_v) + \max[G_{veh,call}, G_{ped,call}] p_v p_p \leq G_{max}$$

with

Equation 31-36

$$G_{veh,call} = \max \left[\begin{array}{c} l_1 + g_s + g_e \\ G_{min} \end{array} \right]$$

Equation 31-37

$$G_{ped,call} = Walk + PC$$

where

G_u = unbalanced green interval duration for a phase (s),

$G_{veh,call}$ = average green interval given that the phase is called by a vehicle detection (s),

G_{min} = minimum green setting (s),

$G_{ped,call}$ = average green interval given that the phase is called by a pedestrian detection (s),

$Walk$ = pedestrian walk setting (s), and

PC = pedestrian clear setting (s).

If maximum recall is set for the phase, then G_u is equal to G_{max} . If the phase serves a left-turn movement that operates in the protected mode, then the probability that it is called by pedestrian detection p_p is equal to 0.0.

If the phase serves a left-turn movement that operates in the protected-permitted mode and the left-turn movement shares a lane with through vehicles, then the green interval duration is equal to the phase's minimum green setting.

The green interval duration obtained from this step is "unbalanced" because it does not reflect the constraints imposed by the controller ring structure and associated barriers. These constraints are imposed in Step O or Step P, depending on the type of control used at the intersection.

It is assumed that the rest-in-walk mode is not enabled.

N. Compute Unbalanced Phase Duration

The unbalanced average phase duration is computed for each actuated phase by adding the unbalanced green interval duration and the corresponding change period components. This calculation is completed with Equation 31-38.

$$D_{up} = G_u + Y + R_c$$

Equation 31-38

where D_{up} is the unbalanced phase duration (s).

If simultaneous gap out is enabled, the phase ends at a barrier, and the subject phase experiences green extension when the concurrent phase has reached its maximum green limit, then both phases are extended but only due to the call flow rate of the subject phase. Hence, the green extension time computed in Step J is too long. The effect is accounted for in the current step by multiplying the green extension time from Step J by a "flow rate ratio." This ratio represents the sum of the flow rate parameter for each lane group served by the subject phase divided by the sum of the flow rate parameter for each group served by the subject phase and served by the concurrent phase (the latter sum equals the call rate from Step F).

O. Compute Average Phase Duration—Fully Actuated Control

For this discussion, it is assumed that Phases 2 and 6 are serving Movements 2 and 6, respectively, on the major street (see Exhibit 31-2). If the left-turn movements on the major street operate in the protected mode or the protected-permitted mode, then Movements 1 and 5 are served during Phases 1 and 5, respectively. Similarly, Phases 4 and 8 are serving Movements 4 and 8, respectively, on the minor street. If the left-turn movements on the minor street are protected or protected-permitted, then Phases 3 and 7 are serving Movements 3 and 7, respectively. If a through movement phase occurs first in a phase pair, then the other phase (i.e., the one serving the opposing left-turn movement) is a "lagging" left-turn phase.

The following rules are used to estimate the average duration of each phase:

1. Given two phases that occur in sequence between barriers (i.e., phase a followed by phase b), the duration of $D_{p,a}$ is equal to the unbalanced

Equation 31-39

phase duration of the first phase to occur (i.e., $D_{p,a} = D_{up,a}$). The duration of $D_{p,b}$ is based on Equation 31-39 for the major-street phases.

$$D_{p,b} = \max[D_{up,1} + D_{up,2}, D_{up,5} + D_{up,6}] - D_{p,a}$$

where

$D_{p,b}$ = phase duration for phase b , which occurs just after phase a (s);

$D_{p,a}$ = phase duration for phase a , which occurs just before phase b (s); and

$D_{up,i}$ = unbalanced phase duration for phase i ; $i = 1, 2, 5$, and 6 for major street and $i = 3, 4, 7$, and 8 for minor street (s).

Equation 31-40 applies for the minor street phases:

Equation 31-40

$$D_{p,b} = \max[D_{up,3} + D_{up,4}, D_{up,7} + D_{up,8}] - D_{p,a}$$

For example, if the phase pair consists of Phase 3 followed by Phase 4 (i.e., a leading left-turn arrangement), then $D_{p,3}$ is set to equal $D_{up,3}$ and $D_{p,4}$ is computed from Equation 31-40. In contrast, if the pair consists of Phase 8 followed by Phase 7 (i.e., a lagging left-turn arrangement), then $D_{p,8}$ is set to equal $D_{up,8}$, and $D_{p,7}$ is computed from Equation 31-40.

2. If an approach is served with one phase operating in the permitted mode (but not split phasing), then $D_{p,a}$ equals 0.0 and the equations above are used to estimate the duration of the phase (i.e., $D_{p,b}$).
3. If split phasing is used, then $D_{p,a}$ equals the unbalanced phase duration for one approach and $D_{p,b}$ equals the unbalanced phase duration for the other approach.

P. Compute Average Phase Duration—Coordinated-Actuated Control

For this discussion, it is assumed that Phases 2 and 6 are the coordinated phases serving Movements 2 and 6, respectively (see Exhibit 31-2). If the left-turn movements operate in the protected mode or the protected-permitted mode, then the opposing left-turn movements are served during Phases 1 and 5. If a coordinated phase occurs first in the phase pair, then the other phase (i.e., the one serving the opposing left-turn movement) is a “lagging” left-turn phase.

The following rules are used to estimate the average duration of each phase:

1. If the phase is associated with the street serving the coordinated movements, then:
 - a. If a left-turn phase exists for the subject approach, then its duration $D_{p,l}$ equals $D_{up,l}$ and the opposing through phase has a duration $D_{p,t}$ based on Equation 31-41.

Equation 31-41

$$D_{p,t} = C - \max[D_{up,3} + D_{up,4}, D_{up,7} + D_{up,8}] - D_{p,l}$$

where $D_{p,t}$ is the phase duration for coordinated phase t ($t = 2$ or 6) (s), $D_{p,l}$ is the phase duration for left-turn phase l ($l = 1$ or 5) (s), and other variables are as previously defined.

If Equation 31-41 is applied to Phase 2, then t equals 2 and l equals 1. If it is applied to Phase 6, then t equals 6 and l equals 5.

- b. If a left-turn phase does not exist for the subject approach, then $D_{p,l}$ equals 0.0 and Equation 31-41 is used to estimate the duration of the coordinated phase.

This procedure for determining average phase duration accommodates split phasing only on the street that does not serve the coordinated movements.

If $D_{p,t}$ obtained from Equation 31-41 is less than the minimum phase duration ($= G_{min} + Y + R_c$), then the phase splits are too generous and do not leave adequate time for the coordinated phases.

2. If the phase is associated with the street serving the noncoordinated movements, then the rules described in Step O are used to determine the phase's average duration.

Q. Compute Green Interval Duration

The average green interval duration is computed for each phase by subtracting the yellow change and red clearance intervals from the average phase duration, as shown in Equation 31-42.

$$G = D_p - Y - R_c$$

Equation 31-42

where G is the green interval duration (s), and other variables are as previously defined.

R. Compare Computed and Estimated Green Interval Durations

The green interval duration from the previous step is compared with the value estimated in Step B. If the two values differ by 0.1 s or more, then the computed green interval becomes the "new" initial estimate and the sequence of calculations is repeated starting with Step C. This process is repeated until the two green intervals differ by less than 0.1 s.

If the intersection is semiactuated or fully actuated, the equilibrium cycle length is computed with Equation 31-43:

$$C_e = \sum_{i=1}^4 D_{p,i}$$

Equation 31-43

where C_e is the equilibrium cycle length (s), i is the phase number, and other variables are as previously defined. The sum in this equation includes all phases in Ring 1. The equilibrium cycle length is used in all subsequent calculations where cycle length C is an input variable.

Probability of Max Out

When the green indication is extended to its maximum green limit, the associated phase is considered to have terminated by max out. The probability of max out can be equated to the joint probability of there being a sequence of calls to the phase in service, each call having a headway that is shorter than the equivalent maximum allowable headway for the phase. This probability can be stated mathematically with Equation 31-44.

Equation 31-44

$$p_x = p^{n_x}$$

with

Equation 31-45

$$n_x = \frac{G_{max} - MAH^* - (g_s + l_1)}{h} \geq 0.0$$

Equation 31-46

$$h = \frac{\Delta^* + \varphi^* / \lambda^* - (MAH^* + 1 / \lambda^*) \varphi^* e^{-\lambda^* (MAH^* - \Delta^*)}}{1 - \varphi^* e^{-\lambda^* (MAH^* - \Delta^*)}}$$

where

p_x = probability of phase termination by extension to the maximum green limit,

n_x = number of calls necessary to extend the green to max out, and

h = average call headway for all calls with headways less than MAH^* (s).

Other variables are as previously defined.

LANE GROUP FLOW RATE ON MULTIPLE-LANE APPROACHES

Introduction

When drivers approach an intersection, their primary criterion for lane choice is movement accommodation (i.e., left, through, or right). If multiple exclusive lanes are available to accommodate their movement, they tend to choose the lane that minimizes their service time (i.e., the time required to reach the stop line, as influenced by the number and type of vehicles between them and the stop line). This criterion tends to result in relatively equal lane use under most circumstances.

If one of the lanes being considered is a shared lane, then service time is influenced by the distribution of turning vehicles in the shared lane. Turning vehicles tend to have a longer service time because of the turn maneuver. Moreover, when turning vehicles operate in the permitted mode, their service time can be lengthy because of the gap search process.

Observation of driver lane-choice behavior indicates that there is an equilibrium lane flow rate that characterizes the collective choices of the population of drivers. Research indicates that the equilibrium flow rate can be estimated from the lane volume distribution that yields the minimum service time for the population of drivers having a choice of lanes (4).

A model for predicting the equilibrium lane flow rate on an intersection approach is described in this subsection. The model is based on the principle that through drivers will choose the lane that minimizes their perceived service time. As a result of this lane selection process, each lane will have the same minimum service time. The principle is represented mathematically by (a) defining service time for each lane as the product of lane flow rate and saturation headway, (b) representing this product as the lane demand-to-saturation-flow-rate ratio (i.e.,

v/s ratio), and (c) making the v/s ratios equal among alternative approach lanes. Equation 31-47 is derived from this representation.

$$\frac{v_i}{s_i} = \frac{\sum_{i=1}^{N_{th}} v_i}{\sum_{i=1}^{N_{th}} s_i}$$

Equation 31-47

where

- v_i = demand flow rate in lane i (veh/h/ln),
- s_i = saturation flow rate in lane i (veh/h/ln), and
- N_{th} = number of through lanes (shared or exclusive) (ln).

The “equalization of flow ratios” principle has been embodied in the HCM since the 1985 edition. Specifically, it has been used to derive the equation for estimating the proportion of left-turning vehicles in a shared lane P_L .

During field observations of various intersection approaches, it was noted that the principle overestimated the effect of turning vehicles in shared lanes for very low and for very high approach flow rate conditions (5). Under low flow rate conditions, it was rationalized that through drivers are not motivated to change lanes because the frequency of turns is very low and the threat of delay is negligible. Under high-flow-rate conditions, it was rationalized that through drivers do not have an opportunity to change lanes because of the lack of adequate gaps in the outside lane. The field observations also indicated that most lane choice decisions (and related lane changes) for through drivers tended to occur upstream of the intersection, before deceleration occurs.

As a result of the aforementioned field observations, the model was extended to include the probability of a lane change. The probability of a lane change represents the joint probability of there being motivation (i.e., moderate to high flow rates) and opportunity (i.e., adequate lane change gaps). A variable that is common to each probability distribution is the ratio of the approach flow rate to the maximum flow rate that would allow any lane changes. This maximum flow rate is the rate corresponding to the minimum headway considered acceptable for a lane change (i.e., about 3.7 s) (6). Exhibit 31-11 illustrates the modeled relationship between lane change probability and the flow ratio in the traffic lanes upstream of the intersection, before deceleration occurs (5).

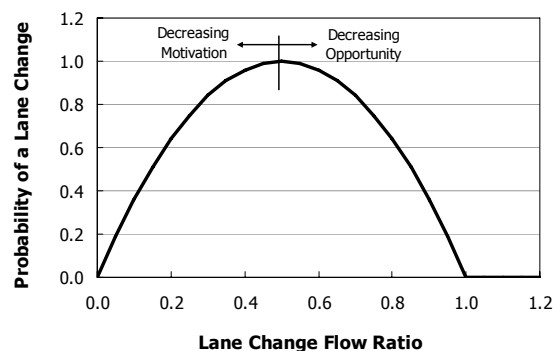


Exhibit 31-11
Probability of a Lane Change

Procedure

The procedure described in this part is generalized so that it can be applied to any signalized intersection approach with any combination of exclusive turn lanes, shared lanes, and exclusive through lanes. At least one shared lane must be present, and the approach must have two or more lanes (or bays) serving two or more traffic movements. This type of generalized formulation is attractive because of its flexibility; however, the trade-off is that the calculation process is iterative. If a closed-form solution is desired, then one would likely have to be uniquely derived for each lane assignment combination.

The procedure is described in the following steps. Input variables used in the procedure are identified in the following list and are shown in Exhibit 31-12:

- N_l = number of lanes in exclusive left-turn lane group (ln),
- N_{sl} = number of lanes in shared left-turn and through lane group (ln),
- N_t = number of lanes in exclusive through lane group (ln),
- N_{sr} = number of lanes in shared right-turn and through lane group (ln),
- N_r = number of lanes in exclusive right-turn lane group (ln),
- N_{lr} = number of lanes in shared left- and right-turn lane group (ln),
- v_{lt} = left-turn demand flow rate (veh/h),
- v_{th} = through demand flow rate (veh/h),
- v_{rt} = right-turn demand flow rate (veh/h),
- v_l = demand flow rate in exclusive left-turn lane group (veh/h/ln),
- v_{sl} = demand flow rate in shared left-turn and through lane group (veh/h),
- v_t = demand flow rate in exclusive through lane group (veh/h/ln),
- v_{sr} = demand flow rate in shared right-turn and through lane group (veh/h),
- v_r = demand flow rate in exclusive right-turn lane group (veh/h/ln),
- v_{lr} = demand flow rate in shared left- and right-turn lane group (veh/h),
- $v_{sl,lt}$ = left-turn flow rate in shared lane group (veh/h/ln),
- $v_{sr,rt}$ = right-turn flow rate in shared lane group (veh/h/ln),
- s_l = saturation flow rate in exclusive left-turn lane group with permitted operation (veh/h/ln),
- s_{sl} = saturation flow rate in shared left-turn and through lane group with permitted operation (veh/h/ln),
- s_t = saturation flow rate in exclusive through lane group (veh/h/ln),
- s_{sr} = saturation flow rate in shared right-turn and through lane group with permitted operation (veh/h/ln),
- s_r = saturation flow rate in exclusive right-turn lane group with permitted operation (veh/h/ln),

s_{lr} = saturation flow rate in shared left- and right-turn lane group (veh/h/ln),

s_{th} = saturation flow rate of an exclusive through lane (= base saturation flow rate adjusted for lane width, heavy vehicles, grade, parking, buses, and area type) (veh/h/ln),

g_p = effective green time for permitted left-turn operation (s),

g_f = time before the first left-turning vehicle arrives and blocks the shared lane (s), and

g_u = duration of permitted left-turn green time that is not blocked by an opposing queue (s).

Each shared-lane lane group has one lane (i.e., $N_{sl} = 1$, $N_{sr} = 1$, and $N_{lr} = 1$). Procedures for calculating g_p , g_f , and g_u are provided in Section 3.

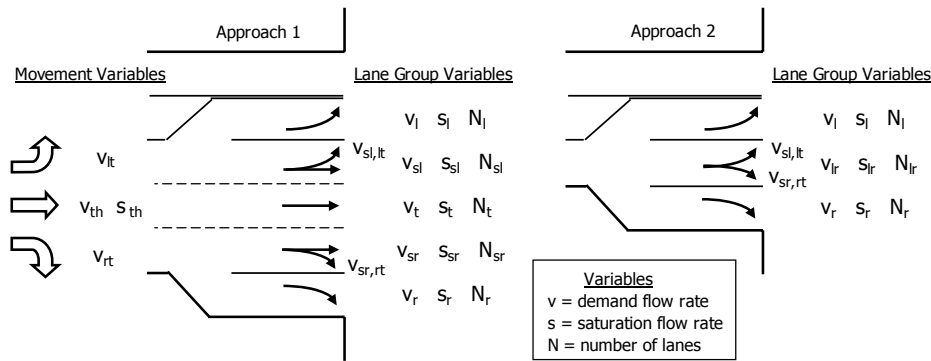


Exhibit 31-12
Input Variables for Lane Group Flow Rate Procedure

A. Compute Modified Through-Car Equivalent

Three modified through-car equivalent factors are computed for the left-turn movement. These factors are computed with Equation 31-48 through Equation 31-52.

$$E_{L,m} = (E_L - 1)P_{lc} + 1$$

Equation 31-48

$$E_{L1,m} = \left(\frac{E_{L1}}{f_{Lpb}} - 1 \right) P_{lc} + 1$$

Equation 31-49

$$E_{L2,m} = \left(\frac{E_{L2}}{f_{Lpb}} - 1 \right) P_{lc} + 1$$

Equation 31-50

with

$$P_{lc} = 1 - \left(\left[2 \frac{v_{app}}{s_{lc}} \right] - 1 \right)^2 \geq 0.0$$

Equation 31-51

$$v_{app} = \frac{v_{lt} + v_{th} + v_{rt}}{N_{sl} + N_t + N_{sr}}$$

Equation 31-52

where

- $E_{L,m}$ = modified through-car equivalent for a protected left-turning vehicle,
- $E_{L1,m}$ = modified through-car equivalent for a permitted left-turning vehicle,
- E_{L1} = equivalent number of through cars for a permitted left-turning vehicle,
- $E_{L2,m}$ = modified through-car equivalent for a permitted left-turning vehicle when opposed by a queue on a single-lane approach,
- E_{L2} = equivalent number of through cars for a permitted left-turning vehicle when opposed by a queue on a single-lane approach,
- f_{Lpb} = pedestrian adjustment factor for left-turn groups,
- P_{lc} = probability of a lane change among the approach through lanes,
- v_{app} = average demand flow rate per through lane (upstream of any turn bays on the approach) (veh/h/ln),
- s_{lc} = maximum flow rate at which a lane change can occur = $3,600/t_{lc}$ (veh/h/ln), and
- t_{lc} = critical merge headway = 3.7 (s).

The factor obtained from Equation 31-50 is applicable when permitted left-turning vehicles are opposed by a queue on a single-lane approach. Equations for calculating E_{L1} and E_{L2} are provided in Section 3. A procedure for calculating f_{Lpb} is provided later in this section.

If the approach has a shared left- and right-turn lane on the approach (as shown in Approach 2 in Exhibit 31-12), then Equation 31-53 is used to compute the average demand flow rate per lane (with $N_{lr} = 1.0$).

Equation 31-53

$$v_{app} = (v_{lt} + v_{rt}) / N_{lr}$$

The modified through-car equivalent for permitted right-turning vehicles is computed with Equation 31-54.

Equation 31-54

$$E_{R,m} = \left(\frac{E_R}{f_{Rpb}} - 1 \right) P_{lc} + 1$$

where $E_{R,m}$ is the modified through-car equivalent for a protected right-turning vehicle, f_{Rpb} is the pedestrian-bicycle adjustment factor for right-turn groups, and other variables are as previously defined.

A procedure for calculating f_{Rpb} is provided later in this section.

B. Estimate Shared-Lane Lane Group Flow Rate

The procedure requires an initial estimate of the demand flow rate for each traffic movement in each shared-lane lane group on the subject approach. For the shared lane serving left-turn and through vehicles, the left-turn flow rate in the shared lane $v_{sl,lt}$ is initially estimated as 0.0 veh/h and the total lane group flow rate v_{sl} is estimated as equal to the average flow rate per through lane v_{app} . For the shared lane serving right-turn vehicles, the right-turn flow rate in the shared lane $v_{sr,rt}$ is estimated as 0.0 veh/h and the total lane group flow rate v_{sr} is estimated as

equal to the average flow rate per through lane v_{app} . These estimates will be updated in a subsequent step.

C. Compute Exclusive Lane Group Flow Rate

The demand flow rate in the exclusive left-turn lane group v_l is computed with Equation 31-55, where all variables are as previously defined.

$$v_l = \frac{v_{lt} - v_{sl,lt}}{N_l} \geq 0.0$$

Equation 31-55

A similar calculation is completed to estimate the demand flow rate in the exclusive right-turn lane group v_r . Then, the flow rate in the exclusive through lane group is computed with Equation 31-56.

$$v_t = \frac{v_{th} - v_{sl,lt} - v_{sr,rt}}{N_t} \geq 0.0$$

Equation 31-56

D. Compute Proportion of Turns in Shared-Lane Lane Groups

The proportion of left-turning vehicles in the shared left-turn and through lane is computed with Equation 31-57.

$$P_L = \frac{v_{sl,lt}}{v_{sl}} \leq 1.0$$

Equation 31-57

where P_L is the proportion of left-turning vehicles in the shared lane. Substitution of $v_{sr,rt}$ for $v_{sl,lt}$ and v_{sr} for v_{sl} in Equation 31-57 yields an estimate of the proportion of right-turning vehicles in the shared lane P_R .

The proportion of left-turning vehicles in the shared left- and right-turn lane is computed with Equation 31-58.

$$P_L = \frac{v_{sl,lt}}{v_{lr}} \leq 1.0$$

Equation 31-58

Substituting $v_{sr,rt}$ for $v_{sl,lt}$ in Equation 31-58 yields an estimate of the proportion of right-turning vehicles in the shared lane P_R .

E. Compute Lane Group Saturation Flow Rate

The saturation flow rate for the lane group shared by the left-turn and through movements is computed with Equation 31-59.

$$s_{sl} = \frac{s_{th}}{g_p} \left(g_f + \frac{g_{diff}}{1 + P_L (E_{L2,m} - 1)} + \frac{\min(g_p - g_f, g_u)}{1 + P_L (E_{L1,m} - 1)} \right) \geq s_{sl,min}$$

Equation 31-59

with

$$s_{sl,min} = (1 + P_L) \frac{3,600}{g_p}$$

Equation 31-60

where g_{diff} is the supplemental service time for shared single-lane approaches (s), $s_{sl,min}$ is the minimum saturation flow rate in shared left-turn and through lane

group with permitted operation (veh/h/ln), and other variables are as previously defined.

An equation for calculating g_{diff} is provided in Section 3 (Equation 31-103).

Equation 31-61 is used to compute the saturation flow rate in a shared right-turn and through lane group s_{sr} .

Equation 31-61

$$s_{sr} = \frac{s_{th}}{1 + P_R (E_{R,m} - 1)}$$

where P_R is the proportion of right-turning vehicles in the shared lane (decimal).

The saturation flow rate for the lane group serving left-turning vehicles in an exclusive lane s_l is computed with Equation 31-59, with $P_L = 1.0$, $g_{diff} = 0.0$, $g_f = 0.0$, and s_{th} replaced by s_{lt} (see Equation 31-106). Similarly, the saturation flow rate in an exclusive right-turn lane group s_r is computed with Equation 31-61, with $P_R = 1.0$.

The saturation flow rate for the lane group serving through vehicles in an exclusive lane is computed with Equation 31-62.

Equation 31-62

$$s_t = s_{th} f_s$$

where f_s is the adjustment factor for all lanes serving through vehicles on an approach with a shared left-turn and through lane group (= 1.0 if $N_{sl} = 0$; 0.91 otherwise).

The saturation flow rate for the shared left- and right-turn lane is computed with Equation 31-63.

Equation 31-63

$$s_{lr} = \frac{s_{th}}{1 + P_L (E_{L,m} - 1) + P_R (E_{R,m} - 1)}$$

F. Compute Flow Ratio

The flow ratio for the subject intersection approach is computed with Equation 31-64.

Equation 31-64

$$y^* = \frac{v_l N_l + v_{sl} N_{sl} + v_t N_t + v_{sr} N_{sr} + v_r N_r + v_{lr} N_{lr}}{s_l N_l + s_{sl} N_{sl} + s_t N_t + s_{sr} N_{sr} + s_r N_r + s_{lr} N_{lr}}$$

where y^* is the flow ratio for the approach. If a shared left- and right-turn lane exists on the subject approach, then $N_{sl} = 0$, $N_t = 0$, $N_{sr} = 0$, and $N_{lr} = 1$; otherwise, $N_{sl} = 1$, $N_t \geq 0$, $N_{sr} = 1$, and $N_{lr} = 0$.

G. Compute Revised Lane Group Flow Rate

The flow ratio from Step F is used to compute the demand flow rate in the exclusive left-turn lane group with Equation 31-65.

Equation 31-65

$$v_l = s_l y^*$$

In a similar manner, the demand flow rate for the other lane groups is estimated by multiplying the flow ratio y^* by the corresponding lane group saturation flow rate.

H. Compute Turn-Movement Flow Rate in Shared-Lane Lane Groups

The left-turn demand flow rate in the shared lane group is computed with Equation 31-66.

$$v_{sl,lt} = v_{lt} - v_l \geq 0.0$$

Equation 31-66

Equation 31-66 can be used to compute the right-turn demand flow rate in the shared lane group by substituting $v_{sr,rt}$ for $v_{sl,lt}$, v_{rt} for v_{lt} , and v_r for v_l .

The demand flow rate in each shared-lane lane group is now compared with the rate estimated in Step B. If they differ by less than 0.1 veh/h, then the procedure is complete and the flow rates estimated in Steps G and H represent the best estimate of the flow rate for each lane group.

If there is disagreement between the lane group demand flow rates, then the calculations are repeated, starting with Step C. However, for this iteration, the flow rates computed in Steps G and H are used in the new calculation sequence. The calculations are complete when the flow rates used at the start of Step C differ from those obtained in Step H by less than 0.1 veh/h.

PRETIMED PHASE DURATION

The design of a pretimed timing plan can be a complex and iterative process that is generally carried out with the assistance of software. Several software products are available for this purpose. This subsection describes various strategies for pretimed signal timing design and provides a procedure for implementing one of these strategies.

Design Strategies

Several aspects of signal timing design are beyond the scope of this manual. One such aspect is the choice of the timing strategy. Three basic strategies are commonly used for pretimed signals.

One strategy is to equalize the volume-to-capacity ratios for critical lane groups. It is the simplest strategy and the only one that may be calculated without excessive iteration. Under this strategy, the green time is allocated among the various signal phases in proportion to the flow ratio of the critical lane group for each phase. It is described briefly in the next part. It is also used in the quick estimation method described in Section 5.

A second strategy is to minimize the total delay to all vehicles. This strategy is generally proposed as the optimal solution to the signal-timing problem. Variations of this strategy often combine other performance measures (e.g., stop rate, fuel consumption) in the optimization function. Many signal-timing software products offer this optimization feature. Some products use a delay estimation procedure identical to the methodology in Chapter 18, whereas others use minor departures from it.

A third strategy is to equalize the level of service for all critical lane groups. This strategy promotes a level of service on all approaches that is consistent with the overall intersection level of service. It improves on the first and second strategies because they tend to produce a higher delay per vehicle for the minor movements at the intersection (and therefore a less favorable level of service).

Determining Phase Duration on the Basis of Vehicle Demand

Signal timing based on equalization of the volume-to-capacity ratio is described in this part. It uses Equation 31-67, Equation 31-68, and Equation 31-69. These equations are used to estimate the cycle length and effective green time for each critical phase. Conversion to green interval duration follows by applying the appropriate lost-time increments.

Equation 31-67

$$X_c = \left(\frac{C}{C - L} \right) \sum_{i \in ci} y_{c,i}$$

Equation 31-68

$$C = \frac{L X_c}{X_c - \sum_{i \in ci} y_{c,i}}$$

Equation 31-69

$$g_i = \frac{v_i C}{N_i s_i X_i} = \left(\frac{v}{N s} \right)_i \left(\frac{C}{X_i} \right)$$

where

C = cycle length (s),

L = cycle lost time (s),

X_c = critical intersection volume-to-capacity ratio,

$y_{c,i}$ = critical flow ratio for phase $i = v_i / (N s_i)$,

ci = set of critical phases on the critical path,

X_i = volume-to-capacity ratio for lane group i ,

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

N_i = number of lanes in lane group i (ln),

s_i = saturation flow rate for lane group i (veh/h/ln), and

g_i = effective green time for lane group i (s).

The summation term in each of these equations represents the summation of a specific variable for the set of critical phases. A critical phase is one phase of a set of phases that occur in sequence whose combined flow ratio is the largest for the signal cycle.

Procedure

The following steps summarize the procedure for estimating the cycle length and effective green time for the critical phases:

1. Compute the flow ratio $[= v_i / (N s_i)]$ for each lane group and identify the critical flow ratio for each phase. When there are several lane groups on the approach and they are served during a common phase, the lane group with the largest flow ratio represents the critical flow ratio for the phase. A procedure for identifying the critical phases and associated flow ratios is described in Chapter 18, Signalized Intersections.
2. If signal-system constraints do not dictate the cycle length, then estimate the minimum cycle length with Equation 31-68 by setting X_c equal to 1.0.

3. If signal-system constraints do not dictate the cycle length, then estimate the desired cycle length with Equation 31-68 by substituting a target volume-to-capacity ratio X_t for the critical ratio X_c . A value of X_t in the range of 0.80 to 0.90 is recommended for this purpose.
4. If signal-system constraints do not dictate the cycle length, then use the results of Steps 2 and 3 to select an appropriate cycle length for the signal. Otherwise, the cycle length is that dictated by the signal system.
5. Estimate the effective green time for each phase with Equation 31-69 and the target volume-to-capacity ratio.
6. Check the timing to ensure that the effective green time and the lost time for each phase in a common ring sum to the cycle length.

Example Application

The procedure is illustrated by a sample calculation. Consider the intersection shown in Exhibit 31-13.

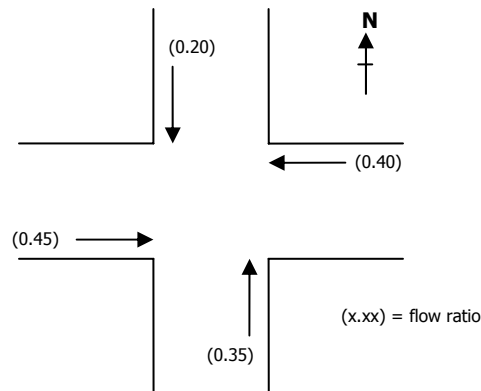


Exhibit 31-13
Example Intersection

Phases 2 and 6 serve the eastbound and westbound approaches, respectively. Phases 4 and 8 serve the southbound and northbound approaches, respectively. One phase from each pair will represent the critical phase and dictate the duration of both phases. It is assumed that the lost time for each phase equals the change period (i.e., the yellow change interval plus the red clearance interval). Thus, the lost time for each critical phase is 4 s, or 8 s for the cycle.

In this simple example, only one lane group is served on each approach, so the critical flow ratios can be identified by inspection of Exhibit 31-13. Specifically, the critical flow ratio for the east–west phases is that associated with the eastbound approach (i.e., Phase 2) at a value of 0.45. Similarly, the critical flow ratio for the north–south phases is that associated with the northbound approach (i.e., Phase 8).

The minimum cycle length that will avoid oversaturation is computed by Equation 31-68 with $X_c = 1.00$.

$$C(\text{minimum}) = \frac{8(1.0)}{1.0 - (0.45 + 0.35)} = \frac{8}{0.2} = 40 \text{ s}$$

A target volume-to-capacity ratio of 0.80 is used to estimate the target cycle length.

$$C = \frac{8(0.8)}{0.8 - (0.45 + 0.35)} = \frac{6.4}{0} = \text{infinity}$$

This computation indicates that a critical volume-to-capacity ratio of 0.8 cannot be provided with the present demand levels at the intersection.

As a second trial estimate, a target volume-to-capacity ratio of 0.92 is selected and used to estimate the target cycle length.

$$C = \frac{8(0.92)}{0.92 - (0.45 + 0.35)} = 61 \text{ s}$$

The estimate is rounded to 60 s for practical application. Equation 31-67 is then used to estimate the critical volume-to-capacity ratio of 0.923 for the selected cycle length of 60 s.

With Equation 31-69, the effective green time is allocated so that the volume-to-capacity ratio for each critical lane group is equal to the target volume-to-capacity ratio. Thus, for the example problem, the target volume-to-capacity ratio for each phase is 0.923. The effective green times are computed with Equation 31-69. The results of the calculations are listed below:

$$g_2 = 0.45(60 / 0.923) = 29.3 \text{ s}$$

$$g_8 = 0.35(60 / 0.923) = 22.7 \text{ s}$$

$$g_2 + g_8 + L = 29.3 + 22.7 + 8.0 = 60.0 \text{ s}$$

The duration of the effective green interval for Phase 6 is the same as for Phase 2, given that they have the same phase lost time. Similarly, the effective green interval for Phase 4 is the same as for Phase 8.

Determining Phase Duration on the Basis of Pedestrian Considerations

Two pedestrian considerations are addressed in this part, as they relate to pretimed phase duration. One consideration addresses the time a pedestrian needs to perceive the signal indication and traverse the crosswalk. A second consideration addresses the time needed to serve cyclic pedestrian demand. When available, local guidelines or practice should be used to establish phase duration on the basis of pedestrian considerations.

A minimum green interval duration that allows a pedestrian to perceive the indication and traverse the crosswalk can be computed with Equation 31-70.

Equation 31-70

$$G_{p,min} = t_{pr} + \frac{L_{cc}}{S_p} - Y - R_c$$

where

$G_{p,min}$ = minimum green interval duration based on pedestrian crossing time (s),

t_{pr} = pedestrian perception of signal indication and curb departure time = 7.0 (s),

L_{cc} = curb-to-curb crossing distance (ft),
 S_p = pedestrian walking speed = 3.5 (ft/s),
 Y = yellow change interval (s), and
 R_c = red clearance interval (s).

The variable t_{pr} in this equation represents the time pedestrians need to perceive the start of the phase and depart from the curb. A value of 7.0 s represents a conservatively long value that is adequate for most pedestrian crossing conditions. The variable S_p represents the pedestrian walking speed in a crosswalk. A value of 3.5 ft/s represents a conservatively slow value that most pedestrians will exceed.

If a permitted or protected-permitted left-turn operation is used for the left-turn movement that crosses the subject crosswalk, then the subtraction of the yellow change interval and the red clearance interval in Equation 31-70 may cause some conflict between pedestrians and left-turning vehicles. If this conflict can occur, then the minimum green interval duration should be computed as $G_{p,min} = t_{pr} + (L_{cc}/S_p)$.

The second pedestrian consideration in timing design is the time required to serve pedestrian demand. The green interval duration should equal or exceed this time to ensure pedestrian demand is served each cycle. The time needed to serve this demand is computed with either Equation 31-71 or Equation 31-72, along with Equation 31-73.

If the crosswalk width W is greater than 10 ft, then:

$$t_{ps} = 3.2 + \frac{L_{cc}}{S_p} + 2.7 \frac{N_{ped}}{W}$$

Equation 31-71

If the crosswalk width W is less than or equal to 10 ft, then:

$$t_{ps} = 3.2 + \frac{L_{cc}}{S_p} + 0.27 N_{ped}$$

Equation 31-72

with

$$N_{ped} = \frac{v_{ped,i}}{3,600} C$$

Equation 31-73

where

t_{ps} = pedestrian service time (s),
 W = effective width of crosswalk (ft),
 N_{ped} = number of pedestrians crossing during an interval (p), and
 $v_{ped,i}$ = pedestrian flow rate in the subject crossing for travel direction i (p/h).

Other variables are as previously defined.

Equation 31-73 assumes that pedestrians always cross at the start of the phase. Thus, it yields a conservatively large estimate of N_{ped} because some pedestrians arrive and cross during the green indication.

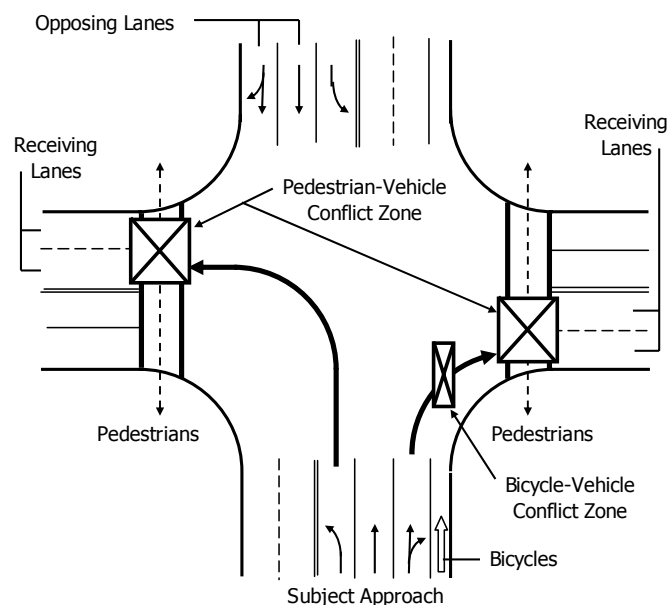
Equation 31-73 is specific to the pedestrian flow rate in one direction of travel along the subject crosswalk. If pedestrian flow rate varies significantly during the analysis period for the crosswalk's two travel directions, then t_{ps} should be calculated for both travel directions and the larger value should be used to estimate the green interval duration needed to serve pedestrian demand.

PEDESTRIAN AND BICYCLE ADJUSTMENT FACTORS

Exhibit 31-14 shows sample conflict zones where intersection users compete for space. This competition reduces the saturation flow rate of the turning automobiles. Its effect is quantified in the pedestrian and bicycle adjustment factors. This subsection describes a procedure for calculating the pedestrian and bicycle adjustment factors. These factors are used in the procedure for calculating the adjusted saturation flow rate that is described in Chapter 18.

This subsection consists of two parts. The first part describes the procedure for computing (a) the pedestrian-bicycle adjustment factor for right-turn lane groups and (b) the pedestrian adjustment factor for left-turn lane groups from a one-way street. The second part describes the procedure for computing the pedestrian adjustment factor for left-turn groups served by permitted or protected-permitted operation.

Exhibit 31-14
Conflict Zone Locations



The following guidance is used to determine the pedestrian adjustment factor for lane groups serving left-turn movements f_{Lpb} :

- If there are no conflicting pedestrians, then f_{Lpb} is equal to 1.0.
- If the lane group is on a two-way street and the protected mode or split phasing is used, then f_{Lpb} is equal to 1.0.
- If the lane group is on a two-way street and either the permitted mode or the protected-permitted mode is used, then the procedure described in the second part to follow is used to calculate f_{Lpb} .

- If the lane group is on a one-way street, then the procedure described in the first part to follow is used to compute f_{Lpb} .

The following guidance is used to determine the pedestrian–bicycle adjustment factor for lane groups serving right-turn movements f_{Rpb} :

- If there are no conflicting pedestrians or bicycles, then f_{Rpb} is equal to 1.0.
- If the protected mode is used, then f_{Rpb} is equal to 1.0.
- If the permitted mode or the protected-permitted mode is used, then the procedure described in the first part to follow is used to compute f_{Rpb} .

Right-Turn Movements and Left-Turn Movements from One-Way Street

A. Determine Pedestrian Flow Rate During Service

This procedure requires knowledge of the phase duration and cycle length. If these variables are not known and the intersection is pretimed, then they can be estimated by the quick estimation method described in Section 5. If the intersection is actuated, then the average phase duration and cycle length are computed by the procedure described previously in this section.

The pedestrian flow rate during the pedestrian service time is computed with Equation 31-74.

$$v_{pedg} = v_{ped} \frac{C}{g_{ped}} \leq 5,000$$

Equation 31-74

where

v_{pedg} = pedestrian flow rate during the pedestrian service time (p/h),

v_{ped} = pedestrian flow rate in the subject crossing (walking in both directions) (p/h),

C = cycle length (s), and

g_{ped} = pedestrian service time (s).

If the phase providing service to pedestrians is actuated, has a pedestrian signal head, and rest-in-walk is not enabled, then the pedestrian service time is equal to the smaller of (a) the effective green time for the phase or (b) the sum of the walk and pedestrian clear settings [i.e., $g_{ped} = \min(g, Walk + PC)$]. Otherwise, the pedestrian service time can be assumed to equal the effective green time for the phase (i.e., $g_{ped} = g$).

B. Determine Average Pedestrian Occupancy

If the pedestrian flow rate during the pedestrian service time is 1,000 p/h or less, then the pedestrian occupancy is computed with Equation 31-75.

$$OCC_{pedg} = \frac{v_{pedg}}{2,000}$$

Equation 31-75

where OCC_{pedg} is the pedestrian occupancy.

Alternatively, if this flow rate exceeds 1,000 p/h, then Equation 31-76 is used.

Equation 31-76

$$OCC_{pedg} = 0.4 + \frac{v_{pedg}}{10,000} \leq 0.90$$

A practical upper limit on v_{pedg} of 5,000 p/h should be maintained when Equation 31-76 is used.

C. Determine Bicycle Flow Rate During Green

The bicycle flow rate during the green indication is computed with Equation 31-77.

Equation 31-77

$$v_{bicg} = v_{bic} \frac{C}{g} \leq 1,900$$

where

v_{bicg} = bicycle flow rate during the green indication (bicycles/h),

v_{bic} = bicycle flow rate (bicycles/h),

C = cycle length (s), and

g = effective green time (s).

D. Determine Average Bicycle Occupancy

The average bicycle occupancy is computed with Equation 31-78.

Equation 31-78

$$OCC_{bicg} = 0.02 + \frac{v_{bicg}}{2,700}$$

where OCC_{bicg} is the bicycle occupancy and v_{bicg} is the bicycle flow rate during the green indication (bicycles/h).

A practical upper limit on v_{bicg} of 1,900 bicycles/h should be maintained when Equation 31-78 is used.

E. Determine Relevant Conflict Zone Occupancy

Equation 31-79 is used for right-turn movements with no bicycle interference or for left-turn movements from a one-way street. This equation is based on the assumptions that (a) pedestrian crossing activity takes place during the time period associated with g_{ped} and (b) no crossing occurs during the green time period $g - g_{ped}$, when this time period exists.

Equation 31-79

$$OCC_r = \frac{g_{ped}}{g} OCC_{pedg}$$

where OCC_r is the relevant conflict-zone occupancy and other variables are as previously defined.

Alternatively, Equation 31-80 is used for right-turn movements with pedestrian and bicycle interference, with all variables previously defined:

Equation 31-80

$$OCC_r = \left(\frac{g_{ped}}{g} OCC_{pedg} \right) + OCC_{bicg} - \left(\frac{g_{ped}}{g} OCC_{pedg} OCC_{bicg} \right)$$

F. Determine Unoccupied Time

If the number of cross-street receiving lanes is equal to the number of turn lanes, then turning vehicles will not be able to maneuver around pedestrians or bicycles. In this situation, the time the conflict zone is unoccupied is computed with Equation 31-81.

$$A_{pbT} = 1 - OCC_r$$

Equation 31-81

where A_{pbT} is the unoccupied time and OCC_r is the relevant conflict-zone occupancy.

Alternatively, if the number of cross-street receiving lanes exceeds the number of turn lanes, turning vehicles will more likely maneuver around pedestrians or bicycles. In this situation, the effect of pedestrians and bicycles on saturation flow is lower and the time the conflict zone is unoccupied is computed with Equation 31-82, with all variables as previously defined.

$$A_{pbT} = 1 - 0.6 OCC_r$$

Equation 31-82

Either Equation 31-81 or Equation 31-82 is used to compute A_{pbT} . The choice of which equation to use should be based on careful consideration of the number of turn lanes and the number of receiving lanes. At some intersections, drivers may consistently and deliberately make illegal turns from an exclusive through lane. At other intersections, proper turning cannot be executed because the receiving lane is blocked by double-parked vehicles. For these reasons, the number of turn lanes and receiving lanes should be determined from field observation.

G. Determine Saturation Flow Rate Adjustment Factor

For permitted right-turn operation in an exclusive lane, Equation 31-83 is used to compute the pedestrian–bicycle adjustment factor.

$$f_{Rpb} = A_{pbT}$$

Equation 31-83

where f_{Rpb} is the pedestrian–bicycle adjustment factor for right-turn groups and A_{pbT} is the unoccupied time.

For protected-permitted operation in an exclusive lane, the factor from Equation 31-83 is used to compute the adjusted saturation flow rate during the permitted period. The factor has a value of 1.0 when used to compute the adjusted saturation flow rate for the protected period.

For left-turn movements from a one-way street, Equation 31-84 is used to compute the pedestrian adjustment factor.

$$f_{Lpb} = A_{pbT}$$

Equation 31-84

where f_{Lpb} is the pedestrian adjustment factor for left-turn groups and A_{pbT} is the unoccupied time.

Permitted and Protected-Permitted Left-Turn Movements

This part describes a procedure for computing the adjustment factor for left-turn movements on a two-way street that are operating in either the permitted

mode or the protected-permitted mode. The calculations in this part supplement the procedure described in the previous part. The calculations described in Steps A and B in the previous part must be completed first (substitute the effective permitted green time g_p for g in Step A). Then, the calculations described in this part are completed.

This procedure does not account for vehicle–bicycle conflict during the left-turn maneuver.

A. Compute Pedestrian Occupancy After Queue Clears

The pedestrian occupancy after the opposing queue clears is computed with Equation 31-85 or Equation 31-86. The opposing-queue service time g_q is computed as the effective permitted green time g_p less the duration of permitted left-turn green time that is not blocked by an opposing queue g_u (i.e., $g_q = g_p - g_u$).

If $g_q < g_{ped}$ then:

Equation 31-85

$$OCC_{pedu} = OCC_{pedg} (1 - 0.5 g_q / g_{ped})$$

otherwise:

Equation 31-86

$$OCC_{pedu} = 0.0$$

where OCC_{pedu} is the pedestrian occupancy after the opposing queue clears, g_q is the opposing queue service time ($= g_s$ for the opposing movement) (s), and other variables are as previously defined.

If the opposing-queue service time g_q equals or exceeds the pedestrian service time g_{ped} , then the opposing queue consumes the entire pedestrian service time.

B. Determine Relevant Conflict Zone Occupancy

After the opposing queue clears, left-turning vehicles complete their maneuvers on the basis of accepted gap availability in the opposing traffic stream. Relevant conflict-zone occupancy is a function of the probability of accepted gap availability and pedestrian occupancy. It is computed with Equation 31-87.

Equation 31-87

$$OCC_r = \frac{g_{ped} - g_q}{g_p - g_q} (OCC_{pedu}) e^{-5.00 v_o / 3,600}$$

where v_o is the opposing demand flow rate (veh/h), g_p is the effective green time for permitted left-turn operation (s), and other variables are as previously defined.

C. Determine Unoccupied Time

Either Equation 31-81 or Equation 31-82 from the previous part (i.e., Step F) is used to compute A_{pbT} . The choice of which equation to use should be based on consideration of the number of left-turn lanes and the number of receiving lanes.

D. Determine Saturation Flow Rate Adjustment Factor

Equation 31-88 is used to compute the pedestrian adjustment factor f_{Lpb} from A_{pbT} , the unoccupied time.

$$f_{Lpb} = A_{pbT}$$

Equation 31-88

3. QUEUE ACCUMULATION POLYGON

INTRODUCTION

This section describes a procedure for using the queue accumulation polygon (QAP) concept. It consists of three main subsections. The first subsection provides a review of concepts related to the QAP. The second subsection describes a general procedure for developing the QAP. The third subsection extends the general procedure to the evaluation of left-turn lane groups.

The discussion in this section describes basic principles for developing polygons for selected types of lane assignment, lane grouping, left-turn operation, and phase sequence. The analyst is referred to the computational engine (see Section 7) for specific calculation details, especially as they relate to assignments, groupings, left-turn operations, and phase sequences not addressed in this section.

CONCEPTS

The QAP is a graphic tool for describing the deterministic relationship between vehicle arrivals, departures, queue service time, and delay. The QAP defines the queue size for a traffic movement as a function of time during the cycle. The shape of the polygon is defined by the following factors: arrival flow rate during the effective red and green intervals, saturation flow rate associated with each movement in the lane group, signal indication status, left-turn operation mode, and phase sequence. Once constructed, the polygon can be used to compute the queue service time and uniform delay for the corresponding lane group.

A QAP is shown in Exhibit 31-15. The variables shown in the exhibit are defined in the following list:

- r = effective red time = $C - g$ (s),
- g = effective green time (s),
- C = cycle length (s),
- g_s = queue service time = $Q_r / (s - q_g)$ (s),
- g_e = green extension time (s),
- q = arrival flow rate = $v / 3,600$ (veh/s),
- v = demand flow rate (veh/h),
- q_r = arrival flow rate during the effective red time = $(1 - P)qC / r$ (veh/s),
- q_g = arrival flow rate during the effective green time = PqC / g (veh/s),
- Q_r = queue size at the end of the effective red time = $q_r r$ (veh),
- P = proportion of vehicles arriving during the green indication (decimal), and
- s = adjusted saturation flow rate (veh/h/ln).

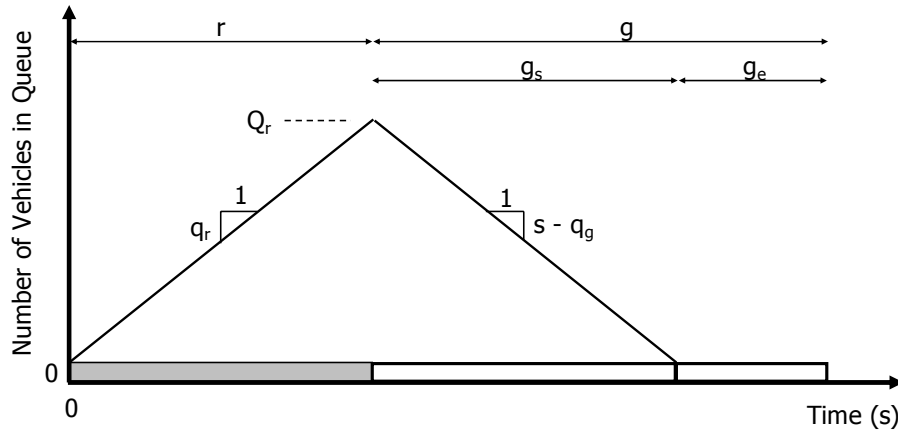


Exhibit 31-15
Queue Accumulation Polygon for
Protected Movements

In application, all flow rate variables are converted to common units of vehicles per second per lane. The presentation in this section is based on these units for q and s .

The polygon in Exhibit 31-15 applies to either a through lane group or a left- or right-turn lane group with exclusive lanes operating with the protected mode. Other polygon shapes are possible, depending on whether the lane group includes a shared lane and whether the lane group serves a permitted (or protected-permitted) left-turn movement. In general, a unique polygon shape will be dictated by each combination of left-turn operational mode (i.e., permitted, protected, protected-permitted) and phase sequence (i.e., lead, lag, split). A general procedure for constructing these polygons is described in the next subsection.

GENERAL PROCEDURE

This subsection describes a general procedure for constructing the QAP for a lane group at a signalized intersection. It is directly applicable to left-turn lane groups that have exclusive lanes and protected phasing, through lane groups with exclusive lanes, and right-turn lane groups with exclusive lanes. Variations of this procedure that extend it to turn lane groups with shared lanes, permitted operation, or protected-permitted operation are described in the next subsection.

The construction of a QAP is based on identification of flow rates and service times during the average signal cycle. These rates and times define periods of queue growth, queue service, and service upon arrival. As shown in Exhibit 31-15, the rates and times define queue size as it varies during the cycle. The resulting polygon formed by the queue size profile can be decomposed into a series of trapezoid or triangle shapes, with each shape having a known time interval. Collectively, the areas of the individual shapes can be added to equal the area of the polygon and the time intervals added to equal the cycle length.

The QAP calculation sequence follows the order of interval occurrence over time, and the results can be recorded graphically (e.g., Exhibit 31-15) or in a tabular manner (i.e., row by row, where each row represents one time interval). A time interval is defined to begin and end at points where either the departure rate or the arrival rate changes. For the duration of the interval, these rates are assumed to be constant.

The following text outlines the calculation sequence used to construct a QAP for a specified lane group. The sequence is repeated for each lane group at the intersection, with the through lane groups evaluated first so that the saturation flow rate of permitted left-turn lane groups can be based on the known queue service time for the opposing traffic movements.

1. The QAP calculations for a given lane group start with the end of the effective green period for the phase serving the subject lane group in a protected manner. The initial queue Q_i is assumed to equal 0.0 veh.
2. Determine the points in the cycle where the arrival flow rate or the discharge rate changes. The arrival rate may change because of platoons formed by an upstream signal, so it is expressed in terms of the arrival rate during green q_g and during red q_r . The discharge rate may change because of the start or end of effective green, a change in the saturation flow rate, the depletion of the subject queue, the depletion of the opposing queue, or the departure of left-turn vehicles as sneakers.
3. For the time interval between the points identified in Step 2, number each interval and compute its duration. Also, identify the arrival rate and discharge rate associated with the interval. Finally, confirm that the sum of all interval durations equals the cycle length.
4. Calculate the capacity of each interval for which there is some discharge, including sneakers when applicable. The sum of these capacities equals the total lane group capacity. Calculate the demand volume for each interval for which there are some arrivals. The sum of these volumes equals the total lane group volume.
5. Calculate the volume-to-capacity ratio X for the lane group by dividing the lane group's total volume by its total capacity. If the volume-to-capacity ratio exceeds 1.0, then calculate the adjusted arrival flow rate q' for each interval by dividing the original flow rate q by X (i.e., $q' = q/X$).
6. Calculate the queue at the end of interval i with Equation 31-89.

Equation 31-89

$$Q_i = Q_{i-1} - (s/3,600 - q/N) t_{d,i} \geq 0.0$$

where Q_i is the queue size at the end of interval i (veh), $t_{d,i}$ is the duration of time interval i during which the arrival flow rate and saturation flow rate are constant (s), and other variables are as previously defined.

7. If the queue at the end of interval i equals 0.0 veh, then compute the duration of the trapezoid or triangle with Equation 31-90. The subject interval should be divided into two intervals, with the first interval having a duration of $t_{t,i}$ and the second interval having a duration of $t_{d,i} - t_{t,i}$. The second interval has starting and ending queues equal to 0.0 veh.

Equation 31-90

$$t_{t,i} = \min(t_{d,i}, Q_{i-1} / w_q)$$

where $t_{t,i}$ is the duration of trapezoid or triangle in interval i (s), w_q is the queue change rate (= discharge rate minus arrival rate) (veh/s), and other variables are as previously defined.

8. Steps 6 and 7 are repeated for each interval in the cycle.

9. When all intervals are completed, the assumption of a zero starting queue (made in Step 1) is checked. The queue size computed for the last interval should always equal the initially assumed value. If this is not the case, then Steps 6 through 8 are repeated by using the ending queue size of the last interval as the starting queue size for the first interval.
10. When all intervals have been evaluated and the starting and ending queue sizes are equal, then the uniform delay can be calculated. This calculation starts with computing the area of each trapezoid or triangle. Then, these areas are added to determine the total delay. Finally, the total delay is divided by the number of arrivals per cycle to produce uniform delay. Equations for calculating uniform delay by using the QAP are described in Step 7 of the next subsection.

PROCEDURE FOR SELECTED LANE GROUPS

This subsection describes a seven-step procedure for constructing the QAP for selected lane groups. The focus is on left-turn movements in lane groups with shared lanes, permitted operation, or protected-permitted operation. However, there is some discussion of other lane groups, lane assignments, and operation. The procedure described in this subsection represents an extension of the general procedure described in the previous subsection.

Step 1. Determine Permitted Green Time

This step applies when the subject left-turn movement is served by using the permitted mode or the protected-permitted mode. Two effective green times are computed. One is the effective green time for permitted left-turn operation g_p . This green time occurs during the period when the adjacent and opposing through movements both have a green ball indication (after adjustment for lost time).

The other effective green time represents the duration of permitted left-turn green time that is not blocked by an opposing queue g_u . This green time represents the time during the effective green time for permitted left-turn operation g_p that is not used to serve the opposing queue. This time is available to the subject left-turn movement to filter through the conflicting traffic stream.

Exhibit 31-16 provides equations for computing the unblocked permitted green time for left-turn Movement 1 (see Exhibit 31-1) when Dallas left-turn phasing is not used. Similar equations can be derived for the other left-turn movements or when Dallas phasing is used. The variables defined in this exhibit are provided in the following list:

- g_u = duration of permitted left-turn green time that is not blocked by an opposing queue (s),
- G_U = displayed green interval corresponding to g_u (s),
- e = extension of effective green = 2.0 (s),
- l_1 = start-up lost time = 2.0 (s),
- G_q = displayed green interval corresponding to g_q (s),
- D_p = phase duration (s),

Exhibit 31-16
Unblocked Permitted Green
Time

R_c = red clearance interval (s),
 Y = yellow change interval (s), and
 g_q = opposing queue service time ($= g_s$ for the opposing movement) (s).

Phase Sequence (phase numbers shown in boxes)			Displayed Unblocked Permitted Green Time $G_U(s)^a$	Permitted Start-Up Lost Time $l_{1,p}(s)^b$	Permitted Extension Time $e_p(s)^c$			
Lead- Lead	<table><tr><td>1</td><td>2</td></tr><tr><td>5</td><td>6</td></tr></table>	1	2	5	6	$G_{U1} = \min[D_{p1} + D_{p2} - D_{p5} - Y_6 - R_{c5},$ $G_{U1}^*]$ with $G_{U1}^* = D_{p2} - Y_6 - R_{c5} - G_{q2}$	$l_{1,1}^*$	e_1
	1	2						
	5	6						
<table><tr><td>1</td><td>2</td></tr><tr><td>5</td><td>6</td></tr></table>	1	2	5	6	$G_{U1} = D_{p2} - Y_6 - R_{c5} - G_{q2}$	$l_{1,1}^*$	e_1	
1	2							
5	6							
Lead- Lag or Lead- Perm	<table><tr><td>1</td><td>2</td></tr><tr><td>6</td><td>5</td></tr></table>	1	2	6	5	$G_{U1} = D_{p5} - Y_6 - R_{c5} - D_{p1} - G_{q2}$	0.0	e_1
	1	2						
	6	5						
	<table><tr><td>1</td><td>2</td></tr><tr><td>6</td><td>5</td></tr></table>	1	2	6	5	No permitted period	Not applicable	Not applicable
1	2							
6	5							
<table><tr><td>1</td><td>2</td></tr><tr><td colspan="2">6</td></tr></table>	1	2	6		$G_{U1} = D_{p5} - Y_6 - R_{c5} - D_{p1} - G_{q2}$	0.0	e_1	
1	2							
6								
Lag- Lead or Lag- Perm	<table><tr><td>2</td><td>1</td></tr><tr><td>5</td><td>6</td></tr></table>	2	1	5	6	No permitted period	Not applicable	Not applicable
	2	1						
	5	6						
	<table><tr><td>2</td><td>1</td></tr><tr><td>5</td><td>6</td></tr></table>	2	1	5	6	$G_{U1} = D_{p2} - Y_2 - R_{c2} - \max[D_{p5}, G_{q2}]$	$l_{1,1}$	0.0
2	1							
5	6							
<table><tr><td>2</td><td>1</td></tr><tr><td colspan="2">6</td></tr></table>	2	1	6		$G_{U1} = \min[D_{p2} - Y_2 - R_{c2}, D_{p5} - Y_6 - R_{c5}]$ $- G_{q2}$	$l_{1,1}$	0.0	
2	1							
6								
Perm- Lead	<table><tr><td colspan="2">2</td></tr><tr><td>5</td><td>6</td></tr></table>	2		5	6	$G_{U1} = D_{p2} - Y_2 - R_{c2} - \max[D_{p5}, G_{q2}]$	$l_{1,1}$	e_1
	2							
5	6							
Perm- Lag	<table><tr><td colspan="2">2</td></tr><tr><td>6</td><td>5</td></tr></table>	2		6	5	$G_{U1} = \min[D_{p2} - Y_2 - R_{c2}, D_{p5} - Y_6 - R_{c5}]$ $- G_{q2}$	$l_{1,1}$	e_1
	2							
6	5							
Perm- Perm	<table><tr><td colspan="2">2</td></tr><tr><td colspan="2">6</td></tr></table>	2		6		$G_{U1} = D_{p2} - Y_6 - R_{c5} - G_{q2}$	$l_{1,1}$	e_1
2								
6								
Lag- Lag	<table><tr><td>2</td><td>1</td></tr><tr><td>6</td><td>5</td></tr></table>	2	1	6	5	$G_{U1} = \min[D_{p2} - Y_2 - R_{c2}, D_{p5} - Y_6 - R_{c5}]$ $- G_{q2}$	$l_{1,1}$	e_1^*
	2	1						
	6	5						
<table><tr><td>2</td><td>1</td></tr><tr><td>6</td><td>5</td></tr></table>	2	1	6	5	$G_{U1} = \min[D_{p2} - Y_2 - R_{c2}, D_{p5} - Y_6 - R_{c5}]$ $- G_{q2}$	$l_{1,1}$	e_1^*	
2	1							
6	5							

Notes: ^a G_{q2} is computed for each opposing lane and the value used corresponds to the lane requiring the longest time to clear. In general, if the opposing lanes serve through movements exclusively, then $G_{q2} = g_q + l_1$. If an opposing lane is shared, then $G_{q2} = g_p - g_e + l_1$, where g_p is the effective green time for permitted operation (s), g_e is the green extension time (s), and l_1 is the start-up lost time (s).
^b If $D_{p5} > (D_{p1} - Y_1 - R_{c1})$ then, $l_{1,1}^* = D_{p5} - (D_{p1} - Y_1 - R_{c1}) + l_1 - e_1$; otherwise, $l_{1,1}^* = 0.0$. Regardless, the result should not be less than 0.0 or more than l_1 .
^c $e_1^* = D_{p2} - (D_{p5} - Y_6 - R_{c5})$, provided that the result is not less than 0.0 or more than e_1 .
 Perm = permitted.

For the first four variables in the preceding list, the subscript "1" is added to the variable when used in Exhibit 31-16. This subscript denotes Movement 1. For the next four variables in the list, a numeric subscript is added to the variable when used in the exhibit. This subscript denotes the phase number associated with the variable. Exhibit 31-16 applies only to left-turn Movement 1. The subscripts need to be changed to apply the equations to other left-turn movements.

The equations shown in Exhibit 31-16 indicate that the effective green time for the permitted operation of Phase 1 depends on the duration of Phase 2 and

sometimes the duration of Phase 5. In all instances, Movement 1 has permitted operation during all, or a portion of, Phase 6.

For a given left-turn lane group, one of the equations in the second column of Exhibit 31-16 will apply. It is used to compute the displayed green interval corresponding to g_u (i.e., G_u). The computed G_u is required to have a nonnegative value. If the calculation yields a negative value, then G_u is set to 0.0.

The same equation can be used to compute the displayed green interval corresponding to g_p (i.e., G_p) by substituting G_p for G_u and 0.0 for G_q . Again, the computed G_p is required to have a nonnegative value. If the calculation yields a negative value, then G_p is set to 0.0.

Equation 31-91 is used to compute the effective green time for permitted left-turn operation.

$$g_p = G_p - l_{1,p} + e_p \geq 0.0$$

Equation 31-91

where

g_p = effective green time for permitted left-turn operation (s),

G_p = displayed green interval corresponding to g_p (s),

$l_{1,p}$ = permitted start-up lost time (s), and

e_p = permitted extension of effective green (s).

The values of $l_{1,p}$ and e_p used in Equation 31-91 are obtained from columns three and four, respectively, of Exhibit 31-16.

The start-up lost time for g_u is considered to occur coincident with the start-up lost time associated with g_p . Hence, if the opposing queue service time consumes an initial portion of g_p , then there is no start-up lost time associated with g_u . The rationale for this approach is that left-turn drivers waiting for the opposing queue to clear will be anticipating queue clearance and may be moving forward slowly (perhaps already beyond the stop line) so that there is negligible start-up lost time at this point. This approach also accommodates the consideration of multiple effective green time terms when there is a shared lane (e.g., g_j) and it avoids inclusion of multiple start-up lost times during g_p . In accordance with this rationale, Equation 31-92 is used to compute the permitted left-turn green time that is not blocked by an opposing queue g_u , where other variables are as previously defined.

$$g_u = G_u + e_p \leq g_p$$

Equation 31-92

If protected-permitted operation exists and Dallas phasing is used, then the displayed green interval corresponding to g_u (i.e., G_u) is equal to the opposing through phase duration minus the queue service time and change period of the opposing through phase (i.e., $G_{u1} = D_{p2} - Y_2 - R_{c2} - G_{q2}$). The permitted start-up lost time $l_{1,p}$ and permitted extension of effective green e_p are equal to l_1 and e , respectively. Otherwise, all the calculations described previously apply.

Step 2. Determine Time Before First Left-Turn Vehicle Arrives

This step applies when the left-turn movement is served by using the permitted mode on a shared-lane approach. The variable of interest represents

the time that elapses from the start of the permitted green to the arrival of the first left-turning vehicle at the stop line. During this time, through vehicles in the shared lane are served at the saturation flow rate of an exclusive through lane.

Considerations of vehicle distribution impose an upper limit on the time before the first left-turn vehicle arrives when it is used to define a period of saturation flow. This limit is computed with Equation 31-93.

Equation 31-93

$$g_{f,\max} = \frac{(1 - P_L)}{0.5 P_L} (1 - [1 - P_L]^{0.5 g_p}) - l_{1,p} \geq 0.0$$

where $g_{f,\max}$ is the maximum time before the first left-turning vehicle arrives and within which there are sufficient through vehicles to depart at saturation (s), P_L is the proportion of left-turning vehicles in the shared lane (decimal), and other variables are as previously defined.

The value of 0.5 in two locations in Equation 31-93 represents the approximate saturation flow rate (in veh/s) of through vehicles in an exclusive lane. This approximation simplifies the calculation and provides sufficient accuracy in the estimate of $g_{f,\max}$.

The time before the first left-turning vehicle arrives and blocks the shared lane is computed with Equation 31-94 or Equation 31-95, along with Equation 31-96.

If the approach has one lane, then:

Equation 31-94

$$g_f = \max(G_p e^{-0.860 LTC^{0.629}} - l_{1,p}, 0.0) \leq g_{f,\max}$$

otherwise:

Equation 31-95

$$g_f = \max(G_p e^{-0.882 LTC^{0.717}} - l_{1,p}, 0.0) \leq g_{f,\max}$$

with

Equation 31-96

$$LTC = \frac{v_{lt} C}{3,600}$$

where

g_f = time before the first left-turning vehicle arrives and blocks the shared lane (s),

LTC = left-turn flow rate per cycle (veh/cycle), and

v_{lt} = left-turn demand flow rate (veh/h).

Other variables are as previously defined.

Step 3. Determine Permitted Left-Turn Saturation Flow Rate

This step applies when left-turning vehicles are served by using the permitted mode or the protected-permitted mode from an exclusive lane. The saturation flow rate for permitted left-turn operation is calculated with Equation 31-97.

$$s_p = \frac{v_o e^{-v_o t_{cg}/3,600}}{1 - e^{-v_o t_{fh}/3,600}}$$

Equation 31-97

where

s_p = saturation flow rate of a permitted left-turn movement (veh/h/ln);

v_o = opposing demand flow rate (veh/h);

t_{cg} = critical headway = 4.5 (s); and

t_{fh} = follow-up headway (4.5 if the subject left turn is served in a shared lane, 2.5 if the subject left turn is served in an exclusive lane) (s).

In those instances in which the opposing volume equals 0.0 veh/h during the analysis period, the opposing volume is set to a value of 0.1 veh/h.

The opposing demand flow rate is not adjusted for unequal lane use in this equation. Increasing this flow rate to account for unequal lane use would misrepresent the frequency and size of headways in the opposing traffic stream. Thus, this adjustment would result in the left-turn saturation flow rate being underestimated.

Step 4. Determine Through-Car Equivalent

This step applies when left-turning vehicles are served by using the permitted mode or the protected-permitted mode. Two variables are computed to quantify the relationship between left-turn saturation flow rate and the base saturation flow rate. The first variable represents the more common case in which left-turning vehicles filter through an oncoming traffic stream. It is computed from Equation 31-98.

$$E_{L1} = \frac{s_o}{s_p}$$

Equation 31-98

where

E_{L1} = equivalent number of through cars for a permitted left-turning vehicle,

s_o = base saturation flow rate (pc/h/ln), and

s_p = saturation flow rate of a permitted left-turn movement (veh/h/ln).

The second variable to be computed represents the case in which the opposing approach has one lane. It describes the saturation flow rate during the time interval coincident with the queue service time of the opposing queue. For this case, the saturation flow rate during the period after the arrival of the first blocking left-turning vehicle and before the end of the opposing queue service time is influenced by the proportion of left-turning vehicles in the opposing traffic stream. These vehicles create artificial gaps in the opposing traffic stream through which the blocking left-turning vehicles on the subject approach can turn. This effect is considered through calculation of the following through-car equivalency factor with Equation 31-99 and Equation 31-100.

Equation 31-99

$$E_{L2} = \frac{1 - (1 - P_{lto})^{n_q}}{P_{lto}} \geq 1.0$$

with

Equation 31-100

$$n_q = 0.5 (g_p - g_u - g_f) \geq 0.0$$

where

E_{L2} = equivalent number of through cars for a permitted left-turning vehicle when opposed by a queue on a single-lane approach,

P_{lto} = proportion of left-turning vehicles in the opposing traffic stream (decimal), and

n_q = maximum number of opposing vehicles that could arrive after g_f and before g_u (veh).

Other variables are as previously defined.

Step 5. Determine Proportion of Turns in a Shared Lane

This step applies when turning vehicles share a lane with through vehicles and the approach has two or more lanes. The proportion of turning vehicles in the shared lane is used in the next step to determine the saturation flow rate for the shared lane.

The proportion of left-turning vehicles in the shared lane P_L is computed if the shared lane includes left-turning vehicles. The proportion of right-turning vehicles in the shared lane P_R is computed if the shared lane includes right-turning vehicles. Guidance for computing these two variables is provided in Section 2.

If the approach has one traffic lane, then P_L equals the proportion of left-turning vehicles on the subject approach P_{lt} and P_R equals the proportion of right-turning vehicles on the subject approach P_{rt} .

Step 6. Determine Lane Group Saturation Flow Rate

The saturation flow rate for the lane group is computed during this step. When the lane group consists of an exclusive lane operating in the protected mode, then it has one saturation flow rate. This rate equals the adjusted saturation flow rate computed by the procedure described in the automobile methodology in Chapter 18.

The focus of discussion in this step is the calculation of saturation flow rate for shared-lane lane groups and for lane groups for which the permitted or protected-permitted mode is used. As the discussion indicates, these lane groups often have two or more saturation flow rates, depending on the phase sequence and operational mode of the turn movements.

Permitted Right-Turn Operation in Shared Lane

The saturation flow rate for permitted right-turn operation in a shared lane is computed with Equation 31-101.

$$s_{sr} = \frac{s_{th}}{1 + P_R \left(\frac{E_R}{f_{Rpb}} - 1 \right)}$$

Equation 31-101

where

s_{sr} = saturation flow rate in shared right-turn and through lane group with permitted operation (veh/h/ln),

s_{th} = saturation flow rate of an exclusive through lane (= base saturation flow rate adjusted for lane width, heavy vehicles, grade, parking, buses, and area type) (veh/h/ln),

P_R = proportion of right-turning vehicles in the shared lane (decimal),

E_R = equivalent number of through cars for a protected right-turning vehicle = 1.18, and

f_{Rpb} = pedestrian–bicycle adjustment factor for right-turn groups.

The value of f_{Rpb} is obtained by the procedure described in Section 2.

The saturation flow rate for the permitted period of a protected-permitted operation in a shared lane is equal to that obtained from Equation 31-101. The saturation flow rate for the protected period is equal to that obtained from the equation when f_{Rpb} is equal to 1.0.

Permitted Left-Turn Operation in Exclusive Lane

The saturation flow rate for a permitted left-turn operation in an exclusive lane is computed with Equation 31-102.

$$s_l = s_p f_w f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{Lpb}$$

Equation 31-102

where s_l is the saturation flow rate in an exclusive left-turn lane group with permitted operation (veh/h/ln) and the other variables are defined following Equation 18-5 in Chapter 18.

Permitted Left-Turn Operation in Shared Lane

There are three possible saturation flow periods during the effective green time associated with permitted left-turn operation. The first period occurs before arrival of the first left-turning vehicle in the shared lane. This left-turning vehicle will block the shared lane until the opposing queue clears and a gap is available in the opposing traffic stream. The duration of this flow period is g_f . The saturation flow during this period is equal to s_{th} .

The second period of flow begins after g_f and ends with clearance of the opposing queue. It is computed with the following equation:

$$g_{diff} = g_p - g_u - g_f \geq 0.0$$

Equation 31-103

where g_{diff} is the supplemental service time for shared single-lane approaches (s) and other variables are as previously defined. This period may or may not exist, depending on the values of g_u and g_f .

If there are two or more opposing traffic lanes, then the saturation flow during the second period s_{sl2} equals 0.0 veh/h/ln. However, if the opposing approach has only one traffic lane, then the flow during this period occurs at a reduced rate that reflects the blocking effect of left-turning vehicles as they await an opposing left-turning vehicle. Left-turning vehicles during this period are assigned a through-car equivalent E_{L2} . The saturation flow rate for the shared lane is computed with Equation 31-104.

Equation 31-104

$$s_{sl2} = \frac{s_{th}}{1 + P_L \left(\frac{E_{L2}}{f_{Lpb}} - 1 \right)}$$

where s_{sl2} is the saturation flow rate in the shared left-turn and through lane group during Period 2 (veh/h/ln) and P_L is the proportion of left-turning vehicles in the shared lane (decimal).

The third period of flow begins after clearance of the opposing queue or arrival of the first blocking left-turn vehicle, whichever occurs last. Its duration equals the smaller of $g_p - g_f$ or g_u . The saturation flow rate for this period is computed with Equation 31-105.

Equation 31-105

$$s_{sl3} = \frac{s_{th}}{1 + P_L \left(\frac{E_{L1}}{f_{Lpb}} - 1 \right)}$$

where s_{sl3} is the saturation flow rate in the shared left-turn and through lane group during Period 3 (veh/h/ln).

For multiple-lane approaches, the impact of the shared lane is extended to include the adjacent through traffic lanes. Specifically, queued drivers are observed to maneuver from lane to lane on the approach to avoid delay associated with the left-turning vehicles in the shared lane. The effect of this impact is accounted for by multiplying the saturation flow rate of the adjacent lanes by a factor of 0.91.

Protected-Permitted Left-Turn Operation in Exclusive Lane

Two saturation flow rates are associated with protected-permitted operation. The saturation flow rate during the protected period s_{lt} is computed with Equation 31-106.

Equation 31-106

$$s_{lt} = s_o f_w f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT}$$

where s_{lt} is the saturation flow rate of an exclusive left-turn lane with protected operation (veh/h/ln) and the other variables are defined following Equation 18-5 in Chapter 18.

The saturation flow rate during the permitted period is computed with Equation 31-102. The duration of the permitted period is equal to g_u .

Protected-Permitted Left-Turn Operation in Shared Lane

The use of a protected-permitted operation in a shared lane has some special requirements to ensure safe and efficient operation. This operational mode requires display of the green ball when the left-turn green arrow is displayed (i.e., the green arrow is not displayed without also displaying the green ball). The following conditions are applied for actuated, protected-permitted operation in a shared lane:

- The left-turn phase is set to minimum recall.
- The maximum green setting for the left-turn phase must be less than or equal to the minimum green for the adjacent through phase.
- If both opposing approaches have protected-permitted operation in a shared lane, then the phase sequence must be lead-lag.
- No vehicle detection is assigned to the left-turn phase.
- Vehicle detection in the shared lane is assigned to the adjacent through movement phase.

There are four possible saturation flow periods during the effective green time associated with protected-permitted left-turn operation in a shared lane. The first three periods are the same as those for permitted left-turn operation in a shared lane (as described previously).

The fourth period of flow coincides with the left-turn phase (i.e., the protected period). Its duration is equal to the effective green time for the left-turn phase g_L . The flow rate during this period is computed with Equation 31-107.

$$s_{sl4} = \frac{s_{th}}{1 + P_L (E_L - 1)}$$

Equation 31-107

where s_{sl4} is the saturation flow rate in the shared left-turn and through lane group during Period 4 (veh/h/ln) and other variables are as previously defined.

For multiple-lane approaches, the impact of the shared lane is extended to include the adjacent through lanes. This impact is accounted for by multiplying the saturation flow rate of the adjacent lanes by a factor of 0.91.

Protected Left- and Right-Turn Operation in a Shared Lane

The saturation flow rate in a shared left- and right-turn lane group with protected operation is computed with Equation 31-108.

$$s_{lr} = \frac{s_{th}}{1 + P_L (E_L - 1) + P_R (E_R - 1)}$$

Equation 31-108

where s_{lr} is the saturation flow rate in the shared left- and right-turn lane group (veh/h/ln).

Step 7. Define Queue Accumulation Polygon

During this step, the green times and saturation flow rates are used to construct the QAP associated with each lane group. The polygon is then used to estimate uniform delay and queue service time. With regard to the latter item,

the lane group with the longest queue service time dictates the queue service time for the phase.

The QAP in Exhibit 31-15 applies to either a through lane group or a left- or right-turn lane group with exclusive lanes operating with the protected mode. This polygon also applies to split phasing and to shared lane groups serving through and right-turning vehicles operating with the permitted mode. For split phasing, each approach is evaluated separately to determine its queue service time and uniform delay. If the approach has left- or right-turn lanes, then a separate polygon is constructed for each turn lane group.

More complicated combinations of lane assignment, phase sequence, and left-turn operational mode dictate more complicated polygons. A polygon (or its tabular equivalent) must be derived for each combination. The most common combinations are illustrated in Exhibit 31-17 to Exhibit 31-20.

The concept is extended to shared left-turn and through lane groups with protected-permitted operation in Exhibit 31-21 and Exhibit 31-22. Other polygon shapes exist, depending on traffic flow rates, phase sequence, lane use, and left-turn operational mode. The concept of polygon construction must be extended to these other combinations to accurately estimate queue service time and uniform delay.

Most of the variables shown in the following exhibits were defined in a previous subsection. The following variables are also defined at this time:

g_l = effective green time for left-turn phase (s);

g_{vs} = queue service time during permitted left-turn operation (s);

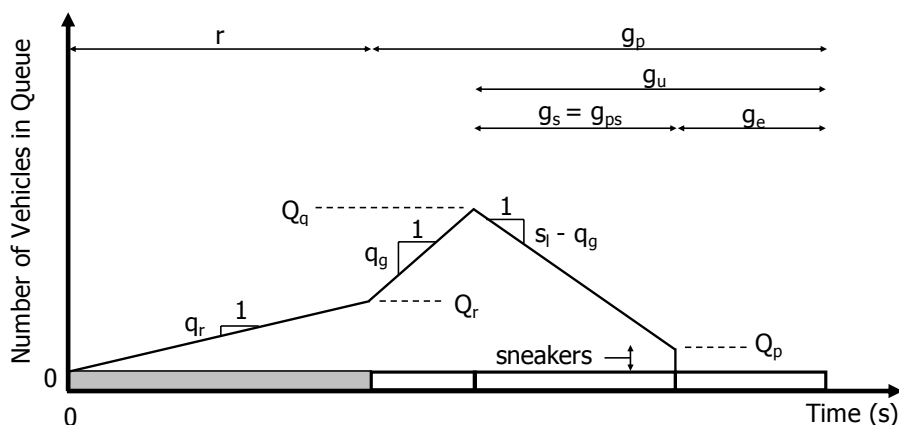
Q_g = queue size at the start of g_u (veh);

Q_v = queue size at the end of permitted service time (veh);

Q_p' = queue size at the end of permitted service time, adjusted for sneakers (veh); and

$$Q_f = \text{queue size at the end of } g_f \text{ (veh).}$$

Exhibit 31-17
QAP for Permitted Left-Turn
Operation in an Exclusive
Lane



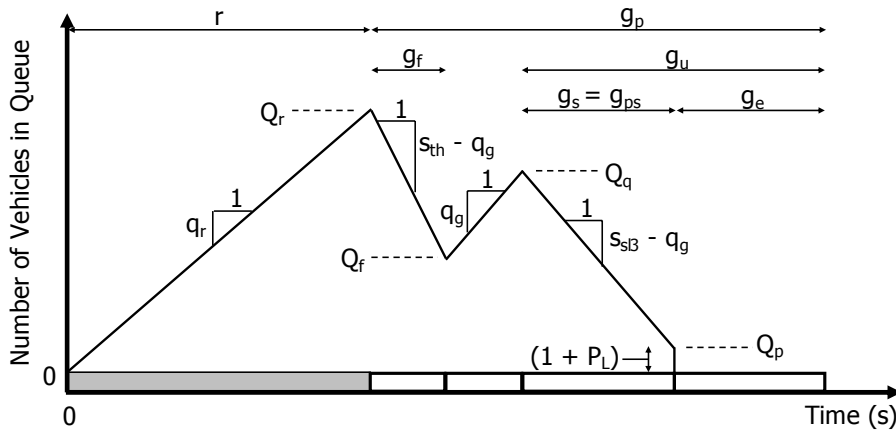


Exhibit 31-18
QAP for Permitted Left-Turn
Operation in a Shared Lane

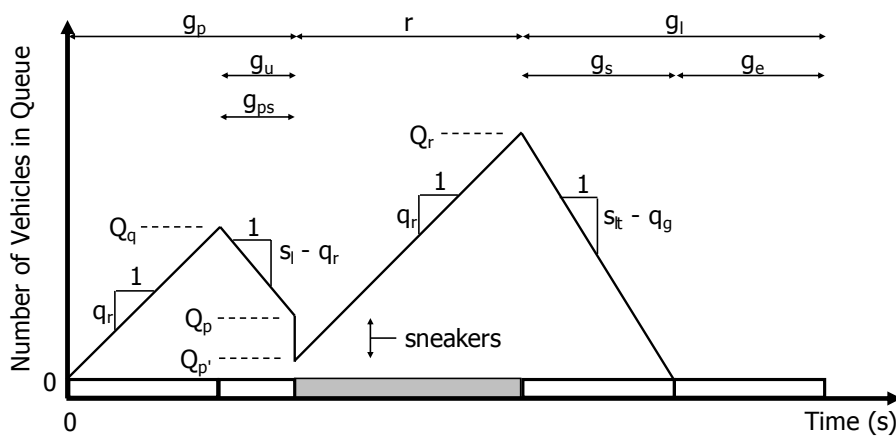


Exhibit 31-19
QAP for Leading, Protected-
Permitted Left-Turn Operation in
an Exclusive Lane

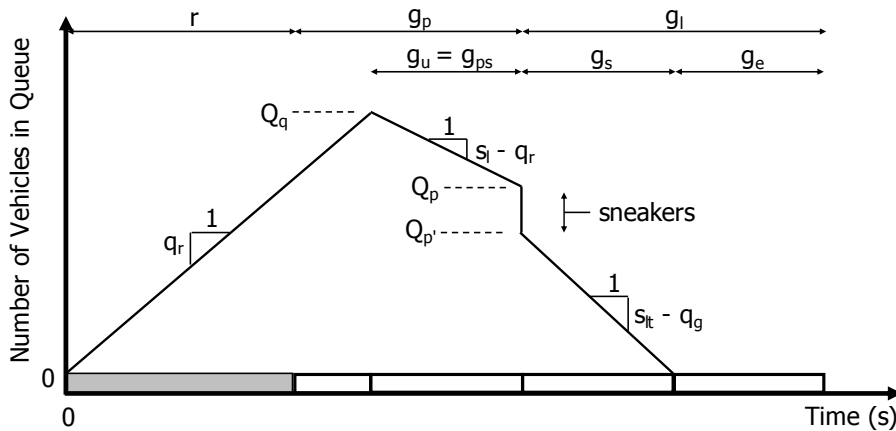


Exhibit 31-20
QAP for Lagging, Protected-
Permitted Left-Turn Operation in
an Exclusive Lane

Exhibit 31-21

QAP for Leading, Protected-Permitted Left-Turn Operation in a Shared Lane

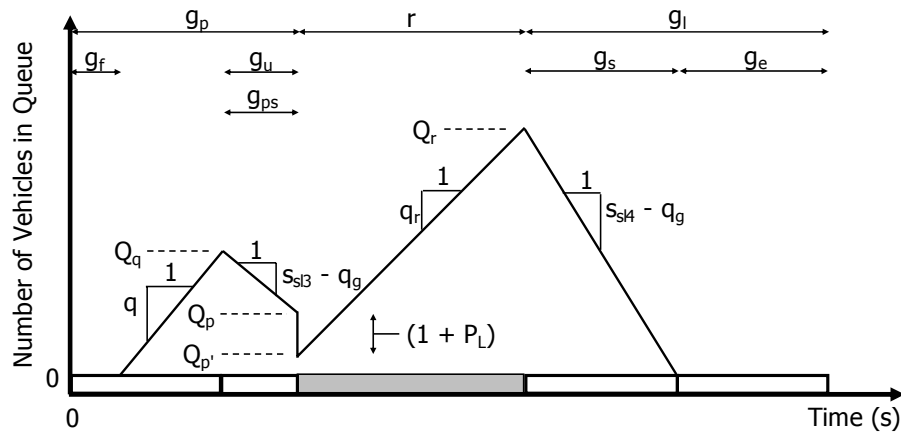
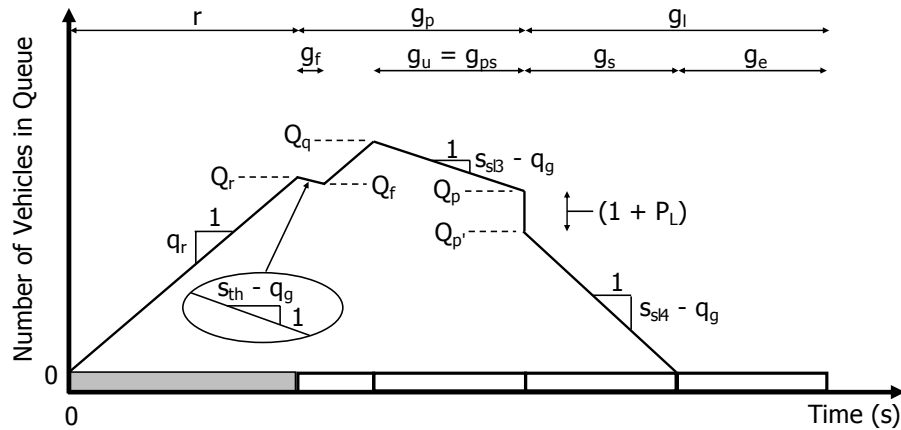


Exhibit 31-22

QAP for Lagging, Protected-Permitted Left-Turn Operation in a Shared Lane



The polygon in Exhibit 31-17 applies to the left-turn lane group with an exclusive lane that operates in the permitted mode during the adjacent through phase. If the phase extends to max out, then some left-turning vehicles will be served as sneakers.

The polygon in Exhibit 31-18 applies to the left-turn and through lane group on a shared lane approach with permitted operation. If the phase extends to max out, then some left-turning vehicles will be served as sneakers. The expected number of sneakers served is computed as $1 + P_L$, where P_L is the proportion of left-turning vehicles in the shared lane.

The polygon in Exhibit 31-19 applies to left-turn movements that have protected-permitted operation with a leading left-turn phase and an exclusive lane. The polygon in Exhibit 31-20 applies to left-turn movements that have protected-permitted operation with a lagging left-turn phase and an exclusive lane. If a queue exists at the end of the permitted period for either polygon, then the queue is reduced by the number of sneakers.

The polygon in Exhibit 31-21 applies to left-turn movements that have protected-permitted operation with a leading left-turn phase and a shared left-turn and through lane group. The polygon in Exhibit 31-22 applies to the same movements and operation but with a lagging left-turn phase. If a queue exists at the end of the permitted period for either polygon, then the queue is reduced by the expected number of sneakers served (which is computed as $1 + P_L$).

As noted previously, all polygons are based on the requirement that lane volume cannot exceed lane capacity for the purpose of estimating the queue service time. This requirement is met in the polygons shown because the queue size equals 0.0 veh at some point during the cycle.

Exhibit 31-18 through Exhibit 31-22 are shown to indicate that queue size equals 0.0 veh at the start of the cycle (i.e., time = 0.0 s). In fact, the queue may not equal 0.0 veh at the start of the cycle for these polygons. Rather, there may be a nonzero queue at the start of the cycle and a queue of 0.0 veh may not be reached until a different time in the cycle. Thus, in modeling any one of the polygons in Exhibit 31-18 through Exhibit 31-22, an iterative process is required. For the first iteration, the queue is assumed to equal 0.0 veh at the start of the cycle. The polygon is then constructed and the queue status is checked at the end of the cycle. If the queue at the end of the cycle is not 0.0 veh, then this value is used as a starting point in a second polygon construction. The second polygon will result in a queue at the end of the cycle that equals the queue used at the start of the cycle. Moreover, a queue value of 0.0 veh will occur at some point in the cycle.

A. Compute Uniform Delay and Queue Service Time

The procedure for calculating uniform delay and queue service time is described in this step. Exhibit 31-23 is used for this purpose.

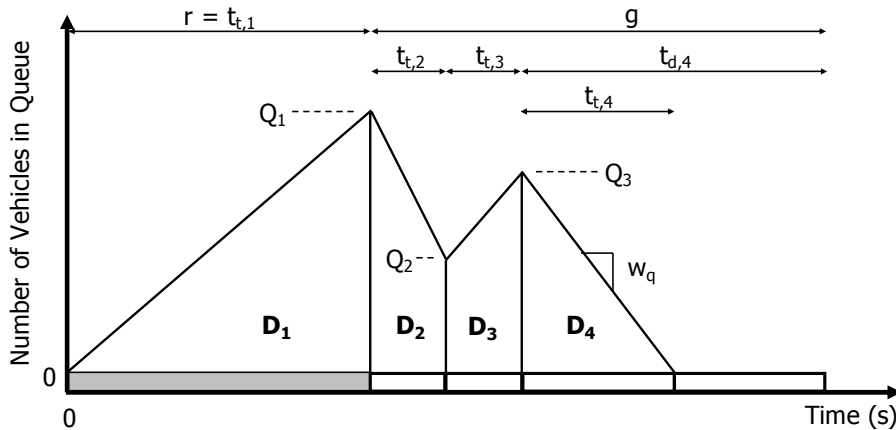


Exhibit 31-23
Polygon for Uniform Delay
Calculation

The area bounded by the polygon represents the total delay incurred during the average cycle. The total delay is then divided by the number of arrivals per cycle to estimate the average uniform delay. These calculations are summarized in Equation 31-109 with Equation 31-110.

$$d_1 = \frac{0.5 \sum_{i=1} (Q_{i-1} + Q_i) t_{t,i}}{qC}$$

Equation 31-109

with

$$t_{t,i} = \min(t_{d,i}, Q_{i-1} / w_q)$$

Equation 31-110

where d_1 is the uniform delay (s/veh) and other variables are as previously defined.

The summation term in Equation 31-109 includes all intervals for which there is a nonzero queue. In general, $t_{i,i}$ will equal the duration of the corresponding interval. However, during some intervals, the queue will decrease to 0.0 veh and $t_{i,i}$ will be only as long as the time required for the queue to dissipate ($= Q_{i-1}/w_q$). This condition is shown to occur during Time Interval 4 in Exhibit 31-23.

The time required for the queue to dissipate represents the queue service time. The queue can dissipate during one or more intervals for turn movements that operate in the protected-permitted mode and for shared-lane lane groups.

For lane groups with exclusive lanes and protected operation, there is one queue service time. It is followed by the green extension time.

For permitted left-turn operation in an exclusive lane, there is one queue service time. It is followed by the green extension time.

For permitted left-turn operation in a shared lane, there can be two queue service times. The green extension time follows the last service time to occur.

For protected-permitted left-turn operation in an exclusive lane, there can be two queue service times. The service time that ends during the protected period is followed by the green extension time.

For protected-permitted left-turn operation in a shared lane, there can be three queue service times. The green extension time can follow the service time that ends during the protected period, but it is more likely to follow the last service time to occur during the permitted period.

For phases serving through or right-turning vehicles in two or more lane groups, the queue service time is measured from the start of the phase to the time when the queue in each lane group has been serviced (i.e., the longest queue service time controls). This consideration is extended to lane groups with shared through and left-turning vehicles.

B. Calculate Lane Group Capacity

This step describes the procedure used to calculate lane group capacity. It is based on the QAP and considers all opportunities for service during the cycle. The equations vary, depending on the left-turn operational mode, phase sequence, and lane assignments for the subject lane group.

Protected Left-Turn Operation in Exclusive Lane

The capacity for a protected left-turn operation in an exclusive-lane lane group is computed with Equation 31-111.

Equation 31-111

$$c_{l,e,p} = \frac{g s_{lt}}{C} N_l$$

where $c_{l,e,p}$ is the capacity of an exclusive-lane lane group with protected left-turn operation (veh/h), N_l is the number of lanes in exclusive left-turn lane group (ln), and other variables are as previously defined.

The available capacity for the lane group is computed with Equation 31-112.

$$c_{a,l,e,p} = \frac{G_{max} s_{lt}}{C} N_l$$

Equation 31-112

where $c_{a,l,e,p}$ is the available capacity of an exclusive-lane lane group with protected left-turn operation (veh/h), G_{max} is the maximum green setting (s), and other variables are as previously defined.

Equation 31-111 and Equation 31-112 can be used to calculate the capacity of lane groups composed of through lanes and those composed of right-turn lanes with proper substitution of saturation flow rate, number of lanes, and maximum green variables.

Permitted Left-Turn Operation in Exclusive Lane

The capacity for a permitted left-turn operation in an exclusive-lane lane group is computed with Equation 31-113.

$$c_{l,e} = \frac{\min(g_p - g_f, g_u) s_l + 3,600 n_s}{C} N_l$$

Equation 31-113

where $c_{l,e}$ is the capacity of an exclusive-lane lane group with permitted left-turn operation (veh/h), n_s is the number of sneakers per cycle = 2.0 (veh), and other variables are as previously defined.

The available capacity for the lane group is computed with Equation 31-114.

$$c_{a,l,e} = c_{l,e} + \frac{(G_{max} - g) s_l}{C} N_l$$

Equation 31-114

where $c_{a,l,e}$ is the available capacity of an exclusive-lane lane group with permitted left-turn operation (veh/h) and other variables are as previously defined.

In the previous equation, the saturation flow rate s_l is specifically included in the term with the maximum green setting G_{max} because this rate represents the saturation flow rate present at the end of the green interval. This is the saturation flow rate that would occur when the green is extended to its maximum green limit as a result of cycle-by-cycle fluctuations in the demand flow rate.

Permitted Left-Turn Operation in Shared Lane

The capacity for a permitted left-turn operation in a shared-lane lane group is computed with Equation 31-115.

$$c_{sl} = \frac{g_p s_{sl} + 3,600 (1 + P_L)}{C}$$

Equation 31-115

where c_{sl} is the capacity of a shared-lane lane group with permitted left-turn operation (veh/h), s_{sl} is the saturation flow rate in shared left-turn and through lane group with permitted operation (veh/h/ln), and other variables are as previously defined.

The saturation flow rate in Equation 31-115 is computed with Equation 31-116 (all variables were previously defined).

Equation 31-116

$$s_{sl} = \frac{s_{th}}{g_p} \left(g_f + \frac{g_{diff}}{1 + P_L \left(\frac{E_{L2}}{f_{Lpb}} - 1 \right)} + \frac{\min(g_p - g_f, g_u)}{1 + P_L \left(\frac{E_{L1}}{f_{Lpb}} - 1 \right)} \right)$$

The available capacity for the lane group is computed with Equation 31-117.

Equation 31-117

$$c_{a,sl} = c_{sl} + \frac{(G_{max} - g_p) s_{sl3}}{C}$$

where $c_{a,sl}$ is the available capacity of a shared-lane lane group with permitted left-turn operation (veh/h) and other variables were previously defined.

In the previous equation, the saturation flow rate s_{sl3} is specifically included in the term with the maximum green setting G_{max} because this rate represents the saturation flow rate present at the end of the green interval.

Protected-Permitted Left-Turn Operation in Exclusive Lane

The capacity for a protected-permitted left-turn operation in an exclusive-lane lane group is computed with Equation 31-118.

Equation 31-118

$$c_{l,e,pp} = \left(\frac{g_l s_{lt}}{C} + \frac{\min(g_p - g_f, g_u) s_l + 3,600 n_s}{C} \right) N_l$$

where $c_{l,e,pp}$ is the capacity of an exclusive-lane lane group with protected-permitted left-turn operation (veh/h) and other variables were previously defined.

The available capacity for the lane group is computed with Equation 31-119.

Equation 31-119

$$c_{a,l,e,pp} = \left(\frac{G_{max} s_{lt}}{C} + \frac{\min(g_p - g_f, g_u) s_l + 3,600 n_s}{C} \right) N_l$$

where $c_{a,l,e,pp}$ is the available capacity of an exclusive-lane lane group with protected-permitted left-turn operation (veh/h) and other variables were previously defined.

In the previous equation, the saturation flow rate s_{lt} is specifically included in the term with the maximum green setting G_{max} because this rate represents the saturation flow rate present at the end of the protected green period.

Protected-Permitted Left-Turn Operation in Shared Lane

The capacity for a protected-permitted left-turn operation in a shared-lane lane group is computed with Equation 31-120.

Equation 31-120

$$c_{sl,pp} = \frac{g_l s_{sl4}}{C} + \frac{g_p s_{sl} + 3,600 (1 + P_L)}{C}$$

where $c_{sl,pp}$ is the capacity of a shared-lane lane group with protected-permitted left-turn operation (veh/h) and other variables are as previously defined.

If the lane group is associated with a leading left-turn phase, then the available capacity for the lane group is computed with Equation 31-121.

$$c_{a,sl,pp} = c_{sl,pp} + \frac{(G_{max} - g_p) s_{sl3}}{C}$$

Equation 31-121

where $c_{a,sl,pp}$ is the available capacity of a shared-lane lane group with protected-permitted left-turn operation (veh/h) and other variables are as previously defined.

When the lane group is associated with a lagging left-turn phase, then the variable s_{sl3} in the previous equation is replaced by s_{sl4} .

4. QUEUE STORAGE RATIO

INTRODUCTION

This section discusses queue storage ratio as a performance measure at a signalized intersection. This measure represents the ratio of the back-of-queue size to the available vehicle storage length. The first subsection reviews concepts related to back-of-queue estimation. The second subsection describes a procedure for estimating the back-of-queue size and queue storage ratio.

The discussion in this section describes basic principles for quantifying the back of queue for selected types of lane assignment, lane grouping, left-turn operation, and phase sequence. The analyst is referred to the computational engine (see Section 7) for specific calculation details, especially as they relate to assignments, groupings, left-turn operation, and phase sequences not addressed in this section.

CONCEPTS

The *back of queue* represents the maximum backward extent of queued vehicles during a typical cycle, as measured from the stop line to the last queued vehicle. The back-of-queue size is typically reached after the onset of the green indication. The point when it is reached occurs just before the most distant queued vehicle begins forward motion as a consequence of the green indication and in response to the forward motion of the vehicle ahead.

A queued vehicle is defined to be a vehicle that is fully stopped as a consequence of the signal. A *full stop* is defined to occur when a vehicle slows to zero (or a crawl speed, if in queue) as a consequence of the change in signal indication from green to red, but not necessarily in direct response to an observed red indication.

The back-of-queue size that is estimated by the equations described here represents an overall average for the analysis period. It is represented in units of vehicles.

Background

Queue size is defined here to include only fully stopped vehicles. Vehicles that slow as they approach the back of the queue are considered to incur a *partial stop* but are not considered to be part of the queue. The distinction between a full and a partial stop is shown in Exhibit 31-24. This exhibit illustrates the trajectory of several vehicles as they traverse an intersection approach during one signal cycle. There is no residual queue at the end of the cycle.

Each thin line in Exhibit 31-24 that slopes upward from left to right represents the trajectory of one vehicle. The average time between trajectories represents the headway between vehicles (i.e., the inverse of flow rate q). The slope of the trajectory represents the vehicle's speed. The curved portion of a trajectory indicates deceleration or acceleration. The horizontal portion of a trajectory indicates a stopped condition. The effective red r and effective green g

times are shown at the top of the exhibit. The other variables shown are defined in the discussion below.

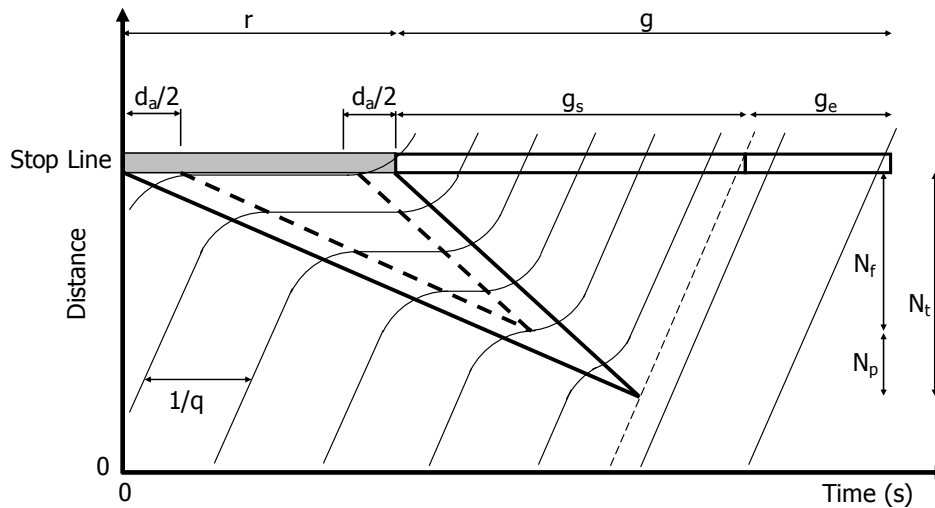


Exhibit 31-24
Time-Space Diagram of Vehicle
Trajectory on an Intersection
Approach

Exhibit 31-24 shows the trajectories of eight vehicles. The first five trajectories (counting from left to right) have a horizontal component to their trajectory that indicates they have reached a full stop as a result of the red indication. The sixth trajectory has some deceleration and acceleration but the vehicle does not stop. This trajectory indicates that a partial stop was incurred for the associated vehicle. The last two trajectories do not incur deceleration or acceleration, and the associated vehicles do not slow or stop. Thus, the number of full stops N_f is 5 and the number of partial stops N_p is 1. The total number of stops N_t is 6. The back-of-queue size is equal to the number of full stops.

The back-of-queue size (computed by the procedure described in the next subsection) represents the average back-of-queue for the analysis period. It is based only on those vehicles that arrive during the analysis period and join the queue. It includes the vehicles that are still in queue after the analysis period ends. The back-of-queue size for a given lane group is computed with Equation 31-122.

$$Q = Q_1 + Q_2 + Q_3$$

Equation 31-122

where

- Q = back-of-queue size (veh/ln),
- Q_1 = first-term back-of-queue size (veh/ln),
- Q_2 = second-term back-of-queue size (veh/ln), and
- Q_3 = third-term back-of-queue size (veh/ln).

The first-term back-of-queue estimate quantifies the queue size described in Exhibit 31-24. It represents the queue caused by the signal cycling through its phase sequence.

The second-term back-of-queue estimate consists of two queue components. One component accounts for the effect of random, cycle-by-cycle fluctuations in

Exhibit 31-25
Cumulative Arrivals and
Departures During an
Oversaturated Analysis
Period

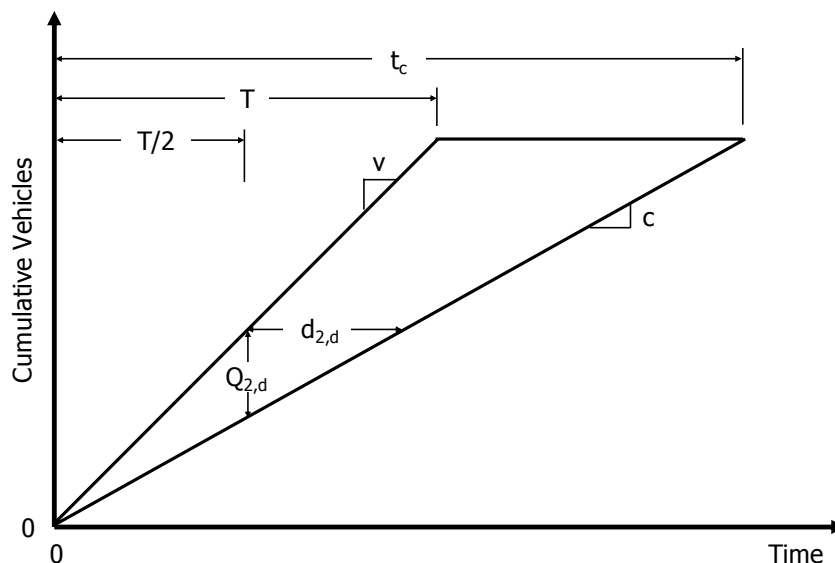


Exhibit 31-25 illustrates the queue growth that occurs as vehicles arrive at a demand flow rate v during the analysis period T , which has capacity c . The deterministic delay component is represented by the triangular area bounded by the thick line and is associated with an average delay per vehicle represented by the variable $d_{2,d}$. The average queue size associated with this delay is shown in the exhibit as $Q_{2,d}$. The queue present at the end of the analysis period $[= T(v - c)]$ is referred to as the *residual queue*.

The equation used to estimate the second-term queue is based on the assumption that no initial queue is present at the start of the analysis period. The third-term back-of-queue estimate is used to account for the additional queuing that occurs during the analysis period because of an initial queue. This queue is a result of unmet demand in the previous time period. It does *not* include any vehicles that may be in queue due to random, cycle-by-cycle fluctuations in demand that occasionally exceed capacity. When a multiple-period analysis is undertaken, the initial queue for the second and subsequent analysis periods is equal to the residual queue from the previous analysis period.

Exhibit 31-26 illustrates the queue due to an initial queue as a trapezoid shape bounded by thick lines. The average queue is represented by the variable Q_3 . The initial queue size is shown as consisting of Q_b vehicles. The duration of time during the analysis period for which the effect of the initial queue is still present is represented by the variable t . This duration is shown to equal the analysis period in Exhibit 31-26. However, it can be less than the analysis period duration for some lower-volume conditions.

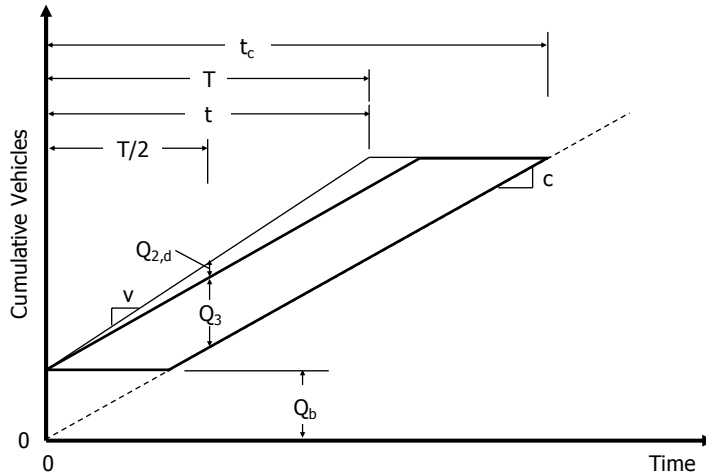


Exhibit 31-26
Third-Term Back-of-Queue Size
with Increasing Queue

Exhibit 31-26 illustrates the case in which the demand flow rate v exceeds the capacity c during the analysis period. In contrast, Exhibit 31-27 and Exhibit 31-28 illustrate alternative cases in which the demand flow rate is less than the capacity.

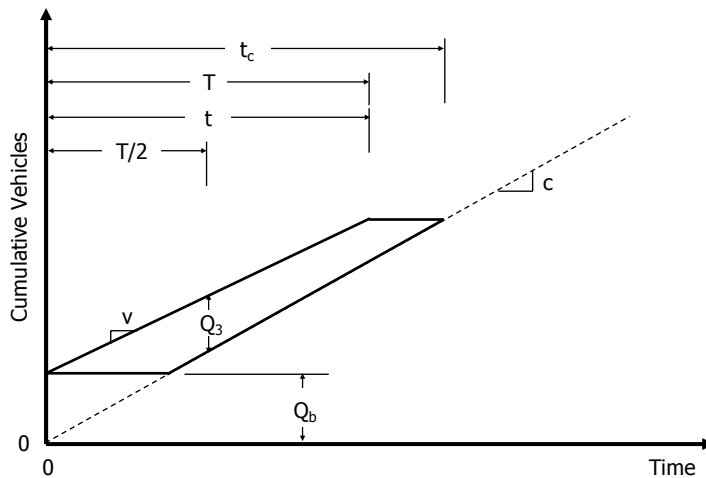


Exhibit 31-27
Third-Term Back-of-Queue Size
with Decreasing Queue

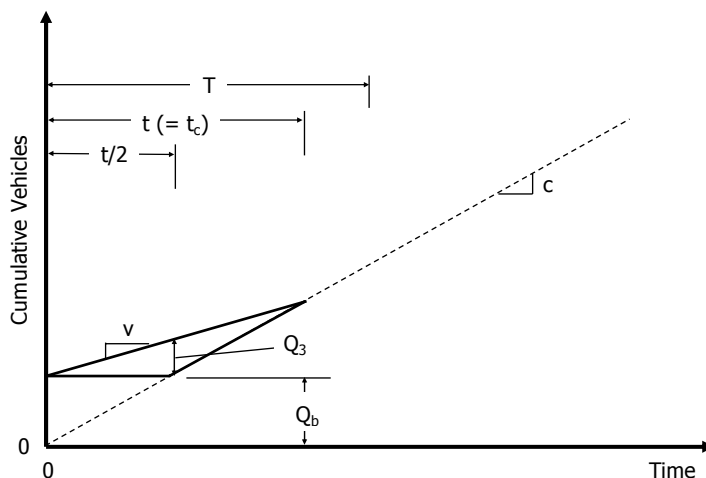


Exhibit 31-28
Third-Term Back-of-Queue Size
with Queue Clearing

In this chapter, the phrase *initial queue* is always used in reference to the initial queue due to unmet demand in the previous time period. It *never* refers to vehicles in queue due to random, cycle-by-cycle fluctuations in demand.

Acceleration–Deceleration Delay

The acceleration–deceleration delay d_a term shown in Exhibit 31-24 is used to distinguish between a fully and a partially stopped vehicle. This delay term represents the time required to decelerate to a stop and then accelerate back to the initial speed, less the time it would have taken to traverse the equivalent distance at the initial speed.

Various definitions are used to describe when a vehicle is “stopped” for the purpose of field measurement. These definitions typically allow the observed vehicle to be called “stopped” even if it has a slow speed (e.g., 2 to 5 mi/h) while moving up in the queue. Many stochastic simulation programs also have a similar allowance. These practical considerations in the count of stopped vehicles require the specification of a threshold speed that can be used to identify when a vehicle is effectively stopped. The acceleration–deceleration delay for a specified threshold speed is estimated with Equation 31-123.

Equation 31-123

$$d_a = \frac{[1.47(S_a - S_s)]^2}{2(1.47 S_a)} \left(\frac{1}{r_a} + \frac{1}{r_d} \right)$$

where

d_a = acceleration–deceleration delay (s),

S_a = average speed on the intersection approach (mi/h),

S_s = threshold speed defining a stopped vehicle = 5.0 (mi/h),

r_a = acceleration rate = 3.5 (ft/s²), and

r_d = deceleration rate = 4.0 (ft/s²).

The average speed on the intersection approach S_a is representative of vehicles that would pass unimpeded through the intersection if the signal were green for an extended period. It can be estimated with the following equation:

Equation 31-124

$$S_a = 0.90(25.6 + 0.47S_{pl})$$

where S_{pl} is the posted speed limit (mi/h).

The threshold speed S_s represents the speed at or below which a vehicle is said to be effectively stopped while in queue or when joining a queue. The strictest definition of this speed is 0.0 mi/h, which coincides with a complete stop. However, vehicles sometimes move up in the queue while drivers wait for the green indication. A vehicle that moves up in the queue and then stops again does not incur an additional full stop. The threshold speed that is judged to differentiate between vehicles that truly stop and those that are just moving up in the queue is 5 mi/h.

Acceleration–deceleration delay values from Equation 31-123 typically range from 8 to 14 s, with larger values in this range corresponding to higher speeds.

Arrival–Departure Polygon

The arrival–departure polygon (ADP) associated with a lane is a graphic tool for computing the number of full stops N_f . The number of full stops has been shown to be equivalent to the first-term back-of-queue (7).

The ADP separately portrays the cumulative number of arrivals and departures associated with a traffic movement as a function of time during the average cycle. It is related but not identical to the QAP. The main difference is that the polygon sides in the ADP represent an arrival rate or a discharge rate but not both. In contrast, the polygon sides in the QAP represent the combined arrival and discharge rates that may occur during a common time interval.

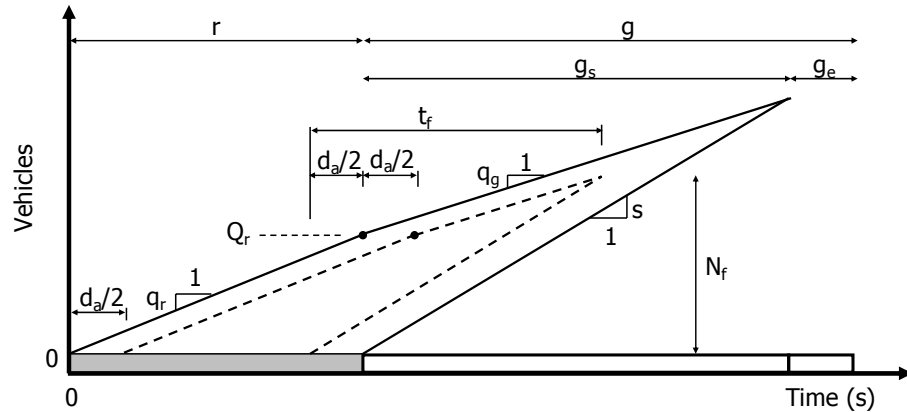
The ADP is useful for estimating the stop rate and back-of-queue size, while the QAP is useful for estimating delay and queue service time.

The ADP for a through movement is presented in Exhibit 31-29. It shows the polygon for a typical cycle. The red and green intervals are ordered from left to right in the sequence of presentation so that the last two time periods correspond to the queue service time g_s and green extension time g_e of the subject phase. The variables shown in the exhibit are defined in the following list:

- t_f = service time for fully stopped vehicles (s),
- N_f = number of fully stopped vehicles (veh/ln),
- g_s = queue service time (s),
- g_e = green extension time (s),
- q_r = arrival flow rate during the effective red time = $(1 - P)qC/r$ (veh/s),
- P = proportion of vehicles arriving during the green indication (decimal),
- q = arrival flow rate = $v/3,600$ (veh/s),
- v = demand flow rate (veh/h),
- r = effective red time = $C - g$ (s),
- g = effective green time (s),
- C = cycle length (s),
- q_g = arrival flow rate during the effective green time = PqC/g (veh/s), and
- Q_r = queue size at the end of the effective red time = $q_r t_f$ (veh).

In application, all flow rate variables are converted to common units of vehicles per second per lane. The presentation in this section is based on these units for q and s . If the flow rate q exceeds the lane capacity, then it is set to equal this capacity.

Exhibit 31-29
Arrival-Departure Polygon



The higher solid trend line in Exhibit 31-29 corresponds to vehicles arriving at the intersection. The lower solid trend line corresponds to queued vehicles departing the stop line. The lower trend line is horizontal during the effective red, denoting no departures. The vertical distance between these two lines at any instant in time represents the number of vehicles in the queue.

At the start of the effective red, vehicles begin to queue at a rate of q_r and accumulate to a length of Q_r vehicles at the time the effective green begins. Thereafter, the rate of arrival is q_g until the end of the effective green period. The queue service time g_s represents the time required to serve the queue present at the end of the effective red Q_r plus any additional arrivals that join the queue before it fully clears. The dashed line in this exhibit represents only those vehicles that complete a full stop. The dashed line lags behind the solid arrival line by one-half of the value of d_a (i.e., $d_a/2$). In contrast, the dashed line corresponding to initiation of the departure process leads the solid departure line by $d_a/2$.

One-half of the acceleration-deceleration delay d_a (i.e., $d_a/2$) occurs at both the end of the arrival process and the start of the discharge process. This assumption is made for convenience in developing the polygon. The derivation of the stop rate and queue length equations indicates that the two components are always combined as d_a . Thus, the assumed distribution of this delay to each of the two occurrences does not influence the accuracy of the estimated back-of-queue size.

The number of fully stopped vehicles N_f represents the number of vehicles that arrive before the queue of stopped vehicles has departed. Equation 31-125 is derived for computing this variable (all other variables previously defined).

Equation 31-125

$$N_f = q_r r + q_g (t_f - d_a)$$

Equation 31-126 can also be derived for estimating N_f .

Equation 31-126

$$N_f = \frac{s t_f}{3,600}$$

Combining Equation 31-125 and Equation 31-126 to eliminate N_f and solve for t_f yields Equation 31-127.

$$t_f = \frac{q_r r - q_g d_a}{s - q_g}$$

Equation 31-127

Equation 31-127 can be used with Equation 31-125 to obtain an estimate of N_f . The first-term back-of-queue size is then computed with the following equation:

$$Q_1 = N_f$$

Equation 31-128

The polygon in Exhibit 31-29 applies to either a through lane group or a left- or right-turn lane group with exclusive lanes operating with the protected mode. Other shapes are possible, depending on whether the lane group includes a shared lane and whether the lane group serves a permitted (or protected-permitted) left-turn movement. In general, a unique shape is dictated by each combination of left-turn operational mode (i.e., permitted, protected, protected-permitted) and phase sequence (i.e., lead, lag, split). A general procedure for constructing these polygons is described in the next subsection.

PROCEDURE FOR SELECTED LANE GROUPS

This subsection describes a procedure for estimating the back-of-queue size for a lane group at a signalized intersection. The procedure is described in a narrative format and does not define every equation needed to develop a polygon for every combination of lane allocation, left-turn operational mode, and phase sequence. This approach is taken because of the large number of equations required to address the full range of combinations found at intersections in most cities. Nevertheless, all these equations have been developed and are automated in the computational engine that is described in Section 7. Some of the equations presented in the previous section are repeated in this subsection for reader convenience.

The procedure requires the previous construction of the QAP. The construction of the QAP is described in Section 3.

Step 1. Determine Acceleration–Deceleration Delay

The acceleration–deceleration delay term is used to distinguish between fully and partially stopped vehicles. It is computed with Equation 31-129 and Equation 31-130, where all variables were previously defined.

$$d_a = \frac{[1.47(S_a - S_s)]^2}{2(1.47 S_a)} \left(\frac{1}{r_a} + \frac{1}{r_d} \right)$$

Equation 31-129

with

$$S_a = 0.90(25.6 + 0.47 S_{pl})$$

Equation 31-130

Step 2. Define Arrival–Departure Polygon

During this step, the green times and flow rates used previously to construct the QAP are now used to construct the ADP associated with each lane group served during a phase.

The ADP in Exhibit 31-29 applies to either a through lane group or a left- or right-turn lane group with exclusive lanes operating with the protected mode. This polygon is also applicable to split phasing and to shared lane groups serving through and right-turning vehicles operating with the permitted mode. For split phasing, each approach is evaluated separately to determine its overall stop rate. If the approach has a turn lane, then a separate polygon is constructed for both the turn and the through lane groups.

More complicated combinations of phase sequence and left-turn operational mode dictate more complicated polygons. A polygon must be derived for each combination. The most common combinations are illustrated in Exhibit 31-30 to Exhibit 31-33.

The concept is extended to shared left-turn and through lane groups with protected-permitted operation in Exhibit 31-34 and Exhibit 31-35. Other polygon shapes exist, depending on traffic flow rates, phase sequence, lane use, and left-turn operational mode. The concept of construction must be extended to these other shapes to estimate accurately the back-of-queue size.

Most variables shown in these exhibits were defined in previous subsections and parts. The following variables are also defined:

- g_p = effective green time for permitted left-turn operation (s),
- g_u = duration of permitted left-turn green time that is not blocked by an opposing queue (s),
- g_f = time before the first left-turning vehicle arrives and blocks the shared lane (s),
- g_l = effective green time for left-turn phase (s),
- g_{ps} = queue service time during permitted left-turn operation (s),
- s_p = saturation flow rate of a permitted left-turn movement (veh/h/lane),
- s_{lt} = saturation flow rate of an exclusive left-turn lane with protected operation = s_{th}/E_L (veh/h/lane),
- E_L = equivalent number of through cars for a protected left-turning vehicle = 1.05,
- s_{th} = saturation flow rate of an exclusive through lane (= base saturation flow rate adjusted for lane width, heavy vehicles, grade, parking, buses, and area type) (veh/h/lane), and
- P_L = proportion of left-turning vehicles in the shared lane (decimal).

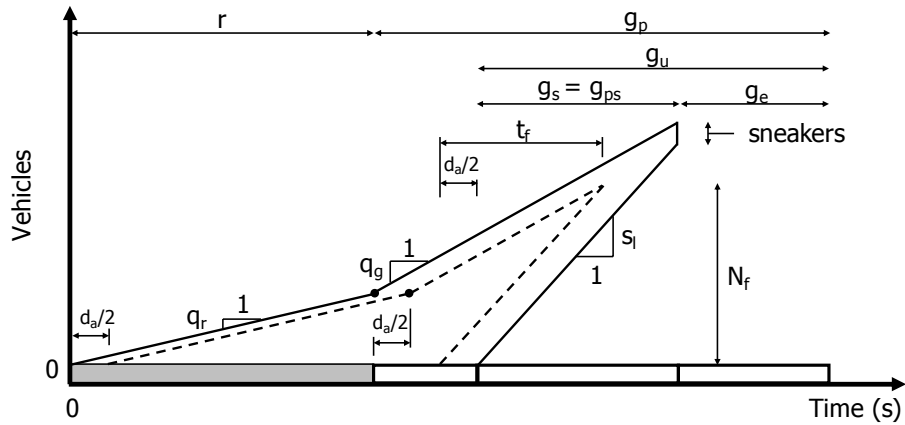


Exhibit 31-30
ADP for Permitted Left-Turn
Operation in an Exclusive Lane

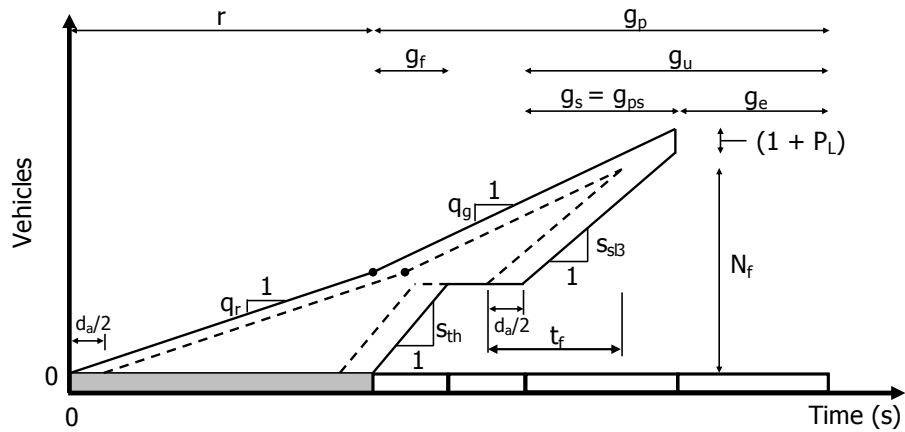


Exhibit 31-31
ADP for Permitted Left-Turn
Operation in a Shared Lane

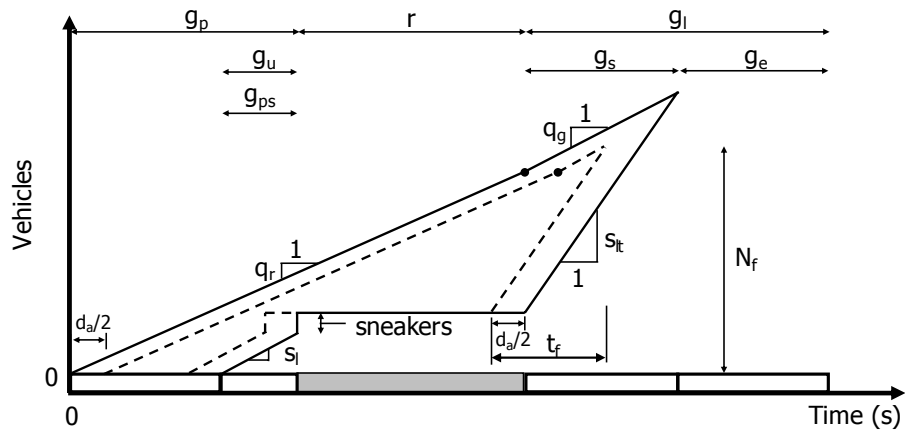
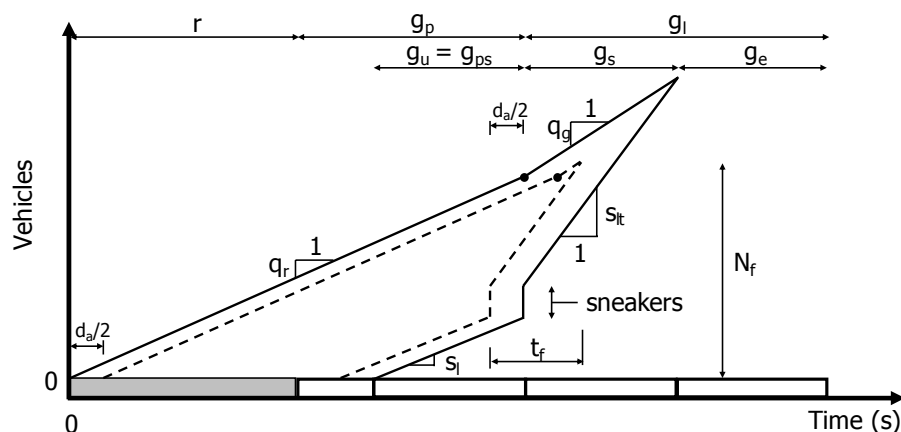


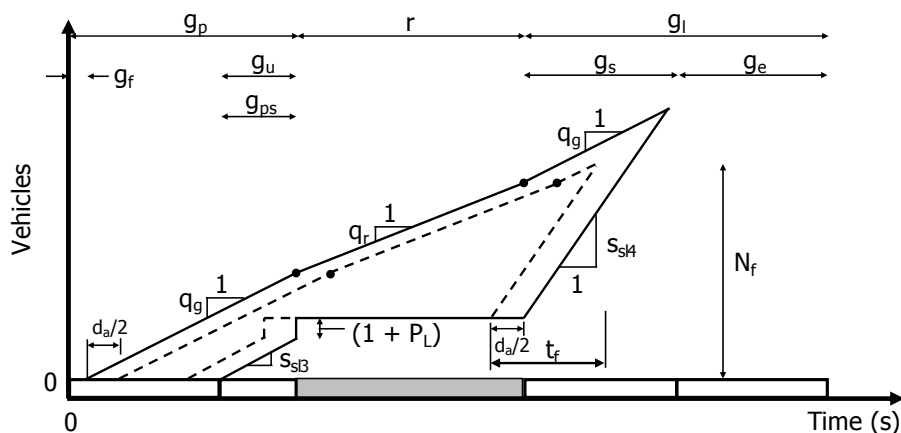
Exhibit 31-32
ADP for Leading, Protected-
Permitted Left-Turn Operation in
an Exclusive Lane

Exhibit 31-33

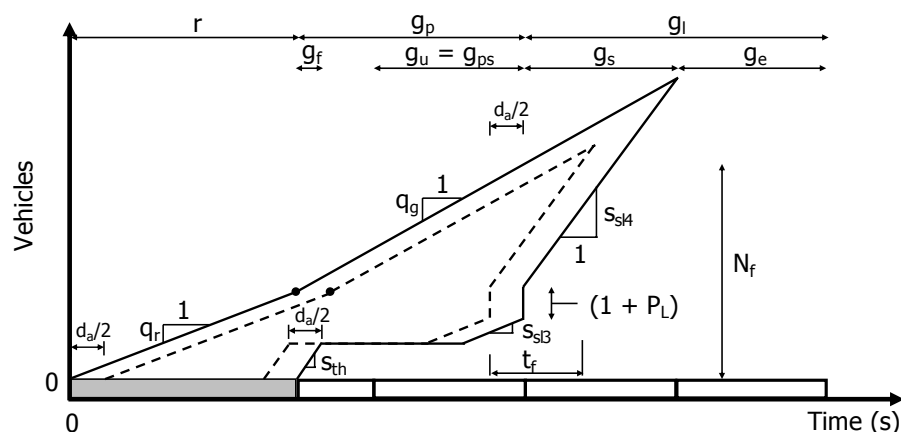
ADP for Lagging, Protected-Permitted Left-Turn Operation in an Exclusive Lane

**Exhibit 31-34**

ADP for Leading, Protected-Permitted Left-Turn Operation in a Shared Lane

**Exhibit 31-35**

ADP for Lagging, Protected-Permitted Left-Turn Operation in a Shared Lane



The polygon in Exhibit 31-30 applies to the left-turn lane group served by an exclusive lane that operates in the permitted mode during the adjacent through phase. If the phase extends to max out, then some left-turning vehicles will be served as sneakers.

The polygon in Exhibit 31-31 applies to the left-turn and through lane group on a shared lane approach with permitted operation. If the phase extends to max out, then some left-turning vehicles will be served as sneakers. The expected

number of sneakers served is computed as $(1 + P_L)$, where P_L is the proportion of left-turning vehicles in the shared lane.

The polygon in Exhibit 31-32 applies to left-turn movements that have protected-permitted operation with a leading left-turn phase and an exclusive left-turn lane. The polygon in Exhibit 31-33 applies to the same movements and operation but with a lagging left-turn phase. If a queue exists at the end of the permitted period for either polygon, then the queue is reduced by the number of sneakers.

The polygon in Exhibit 31-34 applies to left-turn movements that have protected-permitted operation with a leading left-turn phase and a shared left-turn-and-through lane group. The polygon in Exhibit 31-35 applies to the same movements and operation but with a lagging left-turn phase. If a queue exists at the end of the permitted period for either polygon, then the queue is reduced by the expected number of sneakers served (computed as $1 + P_L$).

As noted previously, all polygons are based on the requirement that lane volume cannot exceed lane capacity for the purpose of estimating the queue service time. This requirement is met in the polygons shown because the queue size equals 0.0 veh at some point during the cycle.

Step 3. Define Arrival–Departure Polygon for Stopped Vehicles

During this step, the polygon defined in the previous step is enhanced to include the polygon shape for the fully stopped vehicles. The fully stopped vehicle polygon is defined by dashed lines in Exhibit 31-29 to Exhibit 31-35.

Two rules guide the development of this polygon feature. First, the dashed line that corresponds to arrivals at the stopped queue *lags* behind the solid arrival line by $d_a/2$ s. Second, the dashed line that corresponds to initiation of the departure process *leads* the solid departure line by $d_d/2$ s.

Step 4. Compute Service Time for Fully Stopped Vehicles

The service time t_f is computed for each polygon constructed in the previous step. When the polygon in Exhibit 31-29 applies, then either Equation 31-131 or Equation 31-132 can be used to compute this time.

If $d_a \leq (1 - P)gX$, then:

$$t_f = \frac{q C (1 - P - P d_a / g)}{s (1 - \min(1, X) P)}$$

Equation 31-131

otherwise:

$$t_f = \frac{q C (1 - P) (r - d_a)}{s (r - \min(1, X) [1 - P] g)}$$

Equation 31-132

where X is the volume-to-capacity ratio and other variables are as previously defined.

The saturation flow rate s used in Equation 31-131 and Equation 31-132 represents the adjusted saturation flow rate that is computed by the procedure described in Chapter 18, Signalized Intersections.

Step 5. Compute the Number of Fully Stopped Vehicles

The number of fully stopped vehicles N_f is computed for each polygon constructed in Step 3. When the polygon in Exhibit 31-29 applies, then Equation 31-133 or Equation 31-134 can be used to compute the number of stops (all variables are as previously defined).

If $d_a \leq (1 - P)gX$, then:

Equation 31-133

$$N_f = q_r r + q_g (t_f - d_a)$$

otherwise:

Equation 31-134

$$N_f = q_r (r - d_a + t_f)$$

Step 6. Compute the First-Term Back-of-Queue Size

The first-term back-of-queue estimate Q_1 (in vehicles per lane) is computed by using the number of fully stopped vehicles from the previous step. It is computed with Equation 31-135, where N_f is the number of fully stopped vehicles.

Equation 31-135

$$Q_1 = N_f$$

For some of the more complex ADPs that include left-turn movements operating with the permitted mode, the queue may dissipate at two or more points during the cycle. If this occurs, then N_{fi} is computed for each of the i periods between queue dissipation points. The first-term back-of-queue estimate is then equal to the largest of the N_{fi} values computed in this manner.

Step 7. Compute the Second-Term Back-of-Queue Size

Equation 31-136 is used to compute the second-term back-of-queue estimate Q_2 for lane groups served by an actuated phase.

Equation 31-136

$$Q_2 = \frac{c_A}{3,600 N} d_2$$

where

Q_2 = second-term back-of-queue size (veh/ln),

c_A = average capacity (veh/h),

d_2 = incremental delay (s/veh), and

N = number of lanes in lane group (ln).

The procedure for calculating the average capacity c_A for the subject lane group is described in Chapter 18. If there is no initial queue, then the average capacity is equal to the lane group capacity c .

Step 8. Compute the Third-Term Back-of-Queue Size

The third-term back-of-queue estimate Q_3 is calculated with Equation 31-137 through Equation 31-142.

$$Q_3 = \frac{1}{N T} \left(t_A \frac{Q_b + Q_e - Q_{eo}}{2} \right)$$

Equation 31-137

with

$$Q_e = Q_b + t_A (v - c_A)$$

Equation 31-138

 If $v \geq c_A$ then:

$$Q_{eo} = T(v - c_A)$$

Equation 31-139

$$t_A = T$$

Equation 31-140

 If $v < c_A$ then:

$$Q_{eo} = 0.0 \text{ veh}$$

Equation 31-141

$$t_A = Q_b / (c_A - v) \leq T$$

Equation 31-142

where

 Q_3 = third-term back-of-queue size (veh/ln),

 t_A = adjusted duration of unmet demand in the analysis period (h),

 T = analysis period duration (h),

 Q_b = initial queue at the start of the analysis period (veh),

 Q_e = queue at the end of the analysis period (veh), and

 Q_{eo} = queue at the end of the analysis period when $v \geq c_A$ and $Q_b = 0.0$ (veh).

Other variables are as previously defined.

Step 9. Compute the Back-of-Queue Size

 The average back-of-queue estimate Q for a lane group, in vehicles per lane, is computed with Equation 31-143 (all other variables previously defined).

$$Q = Q_1 + Q_2 + Q_3$$

Equation 31-143

 If desired, a percentile back-of-queue estimate $Q_{\%}$ can be computed with Equation 31-144.

$$Q_{\%} = (Q_1 + Q_2) f_{B\%} + Q_3$$

Equation 31-144

with

 If $v \geq c_A$ then:

$$f_{B\%} = \min \left(1.8, 1.0 + z \sqrt{\frac{I}{Q_1 + Q_2}} + 0.60 z^{0.24} \left(\frac{g}{C} \right)^{0.33} (1 - e^{-2 X_A}) \right)$$

Equation 31-145

$$X_A = v / c_A$$

Equation 31-146

 If $v < c_A$ then:

$$f_{B\%} = \min \left(1.8, 1.0 + z \sqrt{\frac{I}{Q_1 + Q_2}} \right)$$

Equation 31-147

where

$Q_{\%}$ = percentile back-of-queue size (veh/ln);

$f_{B\%}$ = percentile back-of-queue factor;

z = percentile parameter = 1.04 for 85th percentile queue, 1.28 for 90th percentile queue, 1.64 for 95th percentile queue;

I = upstream filtering adjustment factor; and

X_A = average volume-to-capacity ratio.

Other variables are as previously defined.

Step 10. Compute Queue Storage Ratio

If the lane group is served by a bay or lane of limited storage length, then the queue storage ratio can be computed with Equation 31-148.

Equation 31-148

$$R_Q = \frac{L_h Q}{L_a}$$

with

Equation 31-149

$$L_h = L_{pc} (1 - 0.01 P_{HV}) + 0.01 L_{HV} P_{HV}$$

where

R_Q = queue storage ratio,

L_a = available queue storage distance (ft/ln),

L_h = average vehicle spacing in stationary queue (ft/veh),

L_{pc} = stored passenger car lane length = 25 (ft),

L_{HV} = stored heavy-vehicle lane length = 45 (ft), and

P_{HV} = percent heavy vehicles in the corresponding movement group (%).

Average vehicle spacing is the average length between the front bumpers of two successive vehicles in a stationary queue. The available queue storage distance is equal to the turn bay (or lane) length.

The queue storage ratio is useful for quantifying the potential blockage of the available queue storage distance. If the queue storage ratio is less than 1.0, then blockage will not occur during the analysis period. Blockage will occur if the queue storage ratio is equal to or greater than 1.0.

If desired, a percentile queue storage ratio can be computed with Equation 31-150.

Equation 31-150

$$R_{Q\%} = \frac{L_h Q_{\%}}{L_a}$$

where $R_{Q\%}$ is the percentile queue storage ratio and other variables are as previously defined.

5. QUICK ESTIMATION METHOD

INTRODUCTION

This section describes a simplified method for determining the critical intersection volume-to-capacity ratio X_c , signal timing, and delay for a signalized intersection. This method can be used when minimal data are available for the analysis and only approximate results are desired.

X_c is the measure of effectiveness for quick estimation methods.

INPUT REQUIREMENTS

The overall data requirements are summarized in Exhibit 31-36. The input worksheet is shown in Exhibit 31-37. Some of the input requirements may be met by assumed values or default values. Other data items are site-specific and must be obtained in the field.

Data Item	Comments
Volumes	By movement as projected.
Lanes	Left, through, or right; exclusive or shared.
Adjusted saturation flow rate	Includes all adjustments for PHF, CBD, grades, etc.
Left-turn phasing treatment (phasing plan)	Use actual treatment, if known. See discussion of phasing plan development.
Cycle length (minimum and maximum)	Use actual value, if known. May be estimated by using control delay and LOS worksheet.
Lost time	May be estimated by using control delay and LOS worksheet
Green times	Use actual values, if known. May be estimated by using control delay and LOS worksheet.
Coordination	Isolated intersection versus intersection influenced by upstream signals.
Peak hour factor	Use default value of 0.90 if not known.
Parking	On-street parking is or is not present.
Area type	Signal is or is not in CBD.

Note: PHF = peak hour factor, CBD = central business district, LOS = level of service.

As a minimum, the analyst must provide traffic volumes and the approach lane configuration for the subject intersection. Default values for several variables are specifically identified in the methodology and integrated into the method. These values have been selected to be generally representative of typical conditions. Additional default values are identified in Section 3 of Chapter 18, Signalized Intersections.

Exhibit 31-36

Input Data Requirements for Quick Estimation Method

Exhibit 31-37
Quick Estimation Input
Worksheet

QUICK ESTIMATION INPUT WORKSHEET															
General Information						Site Information									
Analyst _____						Intersection _____									
Agency or Company _____						Area Type ☐ CBD ☐ Other									
Date Performed _____						Jurisdiction _____									
Analysis Time Period _____						Analysis Year _____									
Intersection Geometry															
Volume and Signal Input															
				EB			WB			NB			SB		
				LT	TH	RT ¹	LT	TH	RT ¹	LT	TH	RT ¹	LT	TH	RT ¹
Volume, V (veh/h)															
Proportion of LT or RT (P_{LT} or P_{RT}) ²					-			-			-			-	
Parking (Yes/No)															
Left-turn treatment (permitted, protected, not opposed) (if known)															
Peak-hour factor, PHF _____															
Cycle length				Minimum, C_{min} _____ s		Maximum, C_{max} _____ s		or		Given, C _____ s					
Lost time/phase _____ s															
Notes															
1. RT volumes, as shown, exclude RTOR. 2. $P_{LT} = 1.000$ for exclusive left-turn lanes, and $P_{RT} = 1.000$ for exclusive right-turn lanes. Otherwise, they are equal to the proportions of turning volumes in the lane group.															

METHODOLOGY

The quick estimation method consists of the five steps identified below:

1. Determine left-turn treatment,
2. Determine lane volume,
3. Determine signal timing,
4. Determine critical intersection volume-to-capacity ratio, and
5. Determine control delay.

Step 1: Determine Left-Turn Treatment

The signal timing needs of permitted left-turn movements are not considered in synthesis of the traffic signal timing plan in the quick estimation method. Therefore, failure to assume protected left-turn phases for heavy left-turn flow rates will generally produce an overly optimistic assessment of the critical volume-to-capacity ratio and intersection operations.

Exhibit 31-38 describes a procedure for determining the left-turn treatment for each intersection approach. Treatment alternatives are specific to the left-turn phase sequence and include no left-turn phase (i.e., permitted only), left-turn phase (i.e., protected), and split phasing (i.e., not opposed). The left-turn treatment checks should not be used as the sole determinant of the need for a left-turn phase.

Even if the analyst already knows that the permitted left-turn mode will be implemented, this left-turn treatment check must still be used to verify that the left-turn treatment does not conflict with the assumptions on which this quick estimation method are based. The automobile methodology presented in Chapter 18, Signalized Intersections, should be used to analyze an intersection with permitted left-turn movements that fail the left-turn treatment checks in Exhibit 31-38.

The determination of the left-turn treatment is accomplished through four checks. Once it is determined that a left-turn phase is recommended for a given intersection approach, additional checks for that approach are unnecessary.

The first check recommends use of a left-turn phase if there is more than one left-turn lane on the approach.

The second check recommends use of a left-turn phase if the unadjusted left-turn volume exceeds 240 veh/h.

The third check recommends use of a left-turn phase if the cross-product of the unadjusted left-turn and opposing mainline volumes exceeds the minimum values shown in Exhibit 31-38. The opposing mainline volume used in this step is usually the summation of the opposing through and right-turning volumes. If the opposing approach geometry is such that the subject left-turning drivers can safely ignore the opposing right-turning vehicles, then the opposing right-turn volume can be excluded from the summation. Right-turn vehicles can sometimes be ignored when there is an exclusive right-turn lane on the opposing approach and the right-turning vehicles have their own lane to turn into on the cross street (i.e., there are two or more receiving lanes on the cross street).

The fourth check compares the left-turn volume with the “sneaker” capacity and the equivalence factor (computed in the next step). The sneaker capacity represents the average number of left-turning vehicles that can complete their turn after the green interval. This check recommends the use of a left-turn phase if either the unadjusted left-turn volume exceeds the sneaker capacity or the equivalence factor exceeds 3.5.

Do not use the quick estimation method as the sole basis for determining the need for a left-turn phase.

Exhibit 31-38
Quick Estimation Left-Turn
Treatment Worksheet

QUICK ESTIMATION LEFT-TURN TREATMENT WORKSHEET														
General Information														
Description _____														
Check # 1. Left-Turn Lane Check														
Approach	EB	WB	NB	SB										
Number of left-turn lanes														
Protect left turn (Y or N)?														
If the number of left-turn lanes on any approach exceeds 1, then it is recommended that the left turns on that approach be protected. Those approaches with protected left turns need not be evaluated in subsequent checks.														
Check # 2. Minimum Volume Check														
Approach	EB	WB	NB	SB										
Left-turn volume														
Protect left turn (Y or N)?														
If left-turn volume on any approach exceeds 240 veh/h, then it is recommended that the left turns on that approach be protected. Those approaches with protected left turns need not be evaluated in subsequent checks.														
Check # 3. Minimum Cross-Product Check														
Approach	EB	WB	NB	SB										
Left-turn volume, V_L (veh/h)														
Opposing mainline volume, V_o (veh/h)														
Cross-product ($V_L * V_o$)														
Opposing through lanes														
Protected left turn (Y or N)?														
<table border="0"> <tr> <td colspan="2">Minimum Cross-Product Values for Recommending Left-Turn Protection</td> </tr> <tr> <td>Number of Through Lanes</td> <td>Minimum Cross-Product</td> </tr> <tr> <td>1</td> <td>50,000</td> </tr> <tr> <td>2</td> <td>90,000</td> </tr> <tr> <td>3</td> <td>110,000</td> </tr> </table>					Minimum Cross-Product Values for Recommending Left-Turn Protection		Number of Through Lanes	Minimum Cross-Product	1	50,000	2	90,000	3	110,000
Minimum Cross-Product Values for Recommending Left-Turn Protection														
Number of Through Lanes	Minimum Cross-Product													
1	50,000													
2	90,000													
3	110,000													
If the cross-product on any approach exceeds the above values, then it is recommended that the left turns on that approach be protected. Those approaches with protected left turns need not be evaluated in subsequent checks.														
Check # 4. Sneaker Check														
Approach	EB	WB	NB	SB										
Left-turn volume, V_L (veh/h)														
Sneaker capacity, c_s (veh/h) $c_s = 7200/C$														
Equivalence factor, E_{LT}														
Protected left turn (Y or N)?														
If the equivalence factor is 3.5 or higher (computed in the Quick Estimation Lane Volume Worksheet) and the unadjusted left turn is greater than the sneaker capacity, then it is recommended that the left turns on that approach be protected.														
Notes														
1. If any approach is recommended for left-turn protection but the analyst evaluates it as having permitted operation, then this quick estimation method may give overly optimistic results. The analyst should instead use the methodology described in Chapter 18, Signalized Intersections. 2. All volumes used in this worksheet are unadjusted hourly volumes.														

Step 2: Determine Lane Volume

The lane volume worksheet is shown in Exhibit 31-39. Its purpose is to establish the individual lane flow rate (in veh/h/ln) on each intersection approach. This information is then used in the control delay and level-of-service worksheet to synthesize the signal-timing plan. The directional designations (e.g., RT = right turn, LT = left turn) refer to the traffic movements as they approach the intersection.

Exhibit 31-39

Quick Estimation Lane Volume Worksheet

QUICK ESTIMATION LANE VOLUME WORKSHEET			
General Information			
Description/Approach _____			
Right-Turn Movement			
	Exclusive RT Lane	Shared RT Lane	
RT volume, V_R (veh/h)			
Number of exclusive RT lanes, N_{RT}		use 1	
RT adjustment factor, ¹ f_{RT}			
RT volume per lane, V_{RT} (veh/h/ln)			
$V_{RT} = \frac{V_R}{(N_{RT} \times f_{RT})}$			
Left-Turn Movement			
LT volume, V_L (veh/h)			
Opposing mainline volume, V_O (veh/h)			
Number of exclusive LT lanes, N_{LT}			
LT adjustment factor, ² f_{LT}			
LT volume per lane, ³ V_{LT} (veh/h/ln)			
$V_{LT} = \frac{V_L}{(N_{LT} \times f_{LT})}$	Permitted LT, use 0 _____	Protected LT _____	Not Opposed LT _____
Through Movement			
	Permitted LT	Protected LT	Not Opposed LT
Through volume, V_T (veh/h)			
Parking adjustment factor, f_p			
Number of through lanes, N_{TH}			
Total approach volume, ⁴ V_{tot} (veh/h)			
$V_{tot} = \frac{V_{RT}(\text{shared}) + V_T + V_{LT}(\text{not opp.})}{f_p}$			
Through Movement with Exclusive LT Lane			
Through volume per lane, V_{TH} (veh/h/ln)			
$V_{TH} = \frac{V_{tot}}{N_{TH}}$			
Critical lane volume, ⁵ V_{CL} (veh/h)			
Max[V_{LT} , V_{RT} (exclusive), V_{TH}]			
Through Movement with Shared LT Lane			
Proportion of left turns, P_{LT}		Does not apply	Does not apply
Equivalence factor, E_{L1}		Does not apply	Does not apply
Shared lane LT adjustment factor, f_{DL}			use 1.0
Through volume per lane, V_{TH} (veh/h/ln)			
$V_{TH} = \frac{V_{tot}}{(N_{TH} \times f_{DL})}$			
Critical lane volume, ⁵ V_{CL} (veh/h)			
Max[V_{RT} (exclusive), V_{TH}]			
Notes			
1. For RT shared or single lanes, use 0.85. For RT double lanes, use 0.75. 2. For LT single lanes, use 0.95. For LT double lanes, use 0.92. For a one-way street or T-intersection, use 0.85 for one lane and 0.75 for two lanes. 3. For unopposed LT shared lanes, $N_{LT} = 1$. 4. For exclusive RT lanes, V_{RT} (shared) = 0. If not opposed, add V_{LT} to V_T and set $V_{LT}(\text{not opp.}) = 0$. 5. V_{LT} is included only if LT is unopposed. V_{RT} (exclusive) is included only if RT is exclusive.			

Each of the three left-turn treatments (i.e., permitted, protected, and not opposed) must be processed differently in computing the lane volume. Therefore, the lane volume worksheet contains three columns, each representing one of the treatment alternatives. Only one of the three columns should be used for each approach. The following instructions address the procedure for completing the lane volume worksheet.

A. Compute Lane Volume for Right-Turn Movement

As a first step, remove the right-turn-on-red volume from the right-turn traffic count to obtain the right-turn volume V_R .

The right-turn adjustment factor f_{RT} is 0.85 for a single lane or a shared lane and 0.75 for two lanes.

The right-turn lane volume V_{RT} is computed by dividing the right-turn volume by the product of the number of exclusive right-turn lanes and the right-turn adjustment factor.

B. Compute Lane Volume for Left-Turn Movement

The next computation involves the left-turn volume V_L . If the left-turn movement operates in the protected-permitted mode with an exclusive left-turn lane, then two vehicles per cycle should be removed from the left-turn volume to account for the effect of sneakers. If the cycle length has not been established, then the maximum allowable cycle length should be used. To prevent unreasonably short protected left-turn phases, this volume adjustment step should not reduce the left-turn volume to a value below four vehicles per cycle.

The opposing mainline volume V_o is the total approach volume minus the left-turn volume from exclusive lanes or from a single-lane approach. The number of exclusive left-turn lanes is the number of lanes exclusively designated to accommodate the left-turn movement.

The left-turn adjustment factor f_{LT} applies to either a left-turn movement served by a left-turn phase with an exclusive left-turn lane (or lanes) or an unopposed left-turn movement. This factor is 0.95 for single lanes and 0.92 for double lanes. If the left-turn movement is not opposed because of a one-way street or T-intersection, then pedestrian interference must be considered. The corresponding value of 0.85 for one lane and 0.75 for two lanes is used.

The left-turn lane volume V_{LT} is computed by dividing the left-turn volume by the product of the number of exclusive left-turn lanes and the left-turn adjustment factor. The left-turn volume is entered directly if there is no exclusive left-turn lane. Zero should always be entered if the left turn operates in the permitted mode.

C. Compute Through-Movement Volume

The through volume V_T for the approach, excluding the left- and right-turn volumes, is placed in the appropriate row to correspond to the applicable left-turn treatment (i.e., permitted, protected, or not opposed).

The parking adjustment factor f_p is computed with Equation 31-151.

Equation 31-151

$$f_p = \frac{N_{TH} - 0.1 - \frac{18N_m}{3,600}}{N_{TH}} \geq 0.050$$

where N_m is the parking maneuver rate adjacent to lane group (maneuvers/h) and N_{TH} is the number of through lanes (shared or exclusive) (ln).

The number of through lanes N_{TH} includes any lane that serves through vehicles. Exclusive turn lanes should be excluded.

For an unopposed shared lane, the total approach volume V_{tot} is the sum of the shared-lane right-turn volume, through volume, and left-turn volume.

D. Compute Lane Volume for Through Movement with Exclusive Turn Lane

For approaches with an exclusive left-turn lane (or lanes), the through-lane volume V_{TH} is computed by dividing total approach volume by the number of through lanes.

The critical lane volume V_{CL} is normally the same as the through-lane volume, unless the right turn has an exclusive lane or the left turn is not opposed and either of these movements is more critical than the through movement. If both conditions apply, the critical lane volume will be the largest of the left-lane volume, exclusive right-lane volume, and through-lane volume.

E. Compute Lane Volume for Through Movement with Shared Lane

The computation of critical lane volume in the case of shared left-turn lanes is more complicated and requires a more detailed computational procedure. The equivalence factor E_{L1} for a permitted left turn is obtained from Exhibit 31-40 or computed with Equation 31-152.

Type of Left-Turn Lane	Through-Car Equivalent E_{L1} as a Function of Opposing Flow Rate (veh/h)						
	1	200	400	600	800	1,000	1,200 ^a
Shared	1.4	1.7	2.1	2.5	3.1	3.7	4.5
Exclusive	1.3	1.6	1.9	2.3	2.8	3.3	4.0

Note: ^a Use Equation 31-152, with Equation 31-153, for opposing flow in excess of 1,200 veh/h; v_o must be ≥ 0.1 veh/h.

Exhibit 31-40

Through-Car Equivalents for Permitted Left Turns

$$E_{L1} = \frac{S_o}{S_p} - I_{sh}$$

Equation 31-152

with

$$S_p = \frac{v_o e^{-v_o t_{cg}/3,600}}{1 - e^{-v_o t_{fh}/3,600}}$$

Equation 31-153

where

E_{L1} = equivalent number of through cars for a permitted left-turning vehicle,

s_o = base saturation flow rate (pc/h/ln),

s_p = saturation flow rate of a permitted left-turn movement (veh/h/ln),

I_{sh} = indicator variable for shared lane (= 1.0 if the subject left turn is served in a shared lane, 0 if the subject left turn is served in an exclusive lane),

v_o = opposing demand flow rate (veh/h),

t_{cg} = critical headway = 4.5 (s), and

Exhibit 31-41
Shared-Lane Left-Turn
Adjustment Factor

t_{fh} = follow-up headway (= 4.5 if the subject left turn is served in a shared lane, 2.5 if the subject left turn is served in an exclusive lane) (s).

An equivalence factor that exceeds 3.5 implies that left-turn capacity is derived substantially from sneakers. Therefore, if the equivalence factor is greater than 3.5 and the left-turn volume is greater than two vehicles per cycle, it is likely that the subject left turn will not have adequate capacity without a left-turn phase (with either the protected or the protected-permitted left-turn mode).

The shared-lane left-turn adjustment factor f_{DL} is computed according to Exhibit 31-41. This reduction factor is applied to the through volumes to account for the effect of left-turning vehicles waiting to turn through a gap in the opposing traffic stream. For lanes that are not opposed, this factor is 1.0 because these vehicles will have gaps through which to turn.

Permitted Left Turn	
Lane groups with two or more lanes:	Subject to a minimum value that applies at very low left-turning volumes when some cycles will have no left-turn arrivals:
$f_{DL} = \frac{(N_{TH} - 1) + e^{-(N_{TH} V_L E_{L1})/600}}{N_{TH}}$	$f_{DL(\min)} = \frac{(N_{TH} - 1) + e^{-(V_L C_{\max})/3,600}}{N_{TH}}$
Lane groups with only one lane for all movements:	
$f_{DL} = e^{-0.02 (E_{L1} + 10 P_{LT}) V_L C_{\max} / 3,600}$	
Protected-Plus-Permitted Left Turn (one direction only)	
If $V_o < 1,220$ veh/h, then:	If $V_o \geq 1,220$ veh/h, then:
$f_{DL} = \frac{1}{1 + \left(\frac{P_{LT}(235 + 0.435 V_o)}{1,400 - V_o} \right)}$	$f_{DL} = \frac{1}{1 + 4.525 P_{LT}}$

The through-lane volume V_{TH} is then computed by dividing the total approach volume by the product of the number of through lanes and the shared-lane left-turn adjustment factor.

The critical lane volume V_{CL} is the maximum of either the through-lane volume or the right-turn volume from an exclusive right-turn lane. If one or more left-turn movements operate in the permitted mode, the need for a left-turn phase should be reexamined at this point.

Step 3: Determine Signal Timing

The purpose of this step is to estimate a feasible signal timing plan for the intersection. The signal timing plan is required to estimate delay. Note that the signal timing plan estimated by the method described in this step is not necessarily the optimal timing plan.

The timing plan is estimated in the following five component steps:

1. Develop phasing plan,
2. Compute critical phase volume and lost time,
3. Compute critical sum and cycle lost time,

4. Compute cycle length, and
5. Compute green time.

The information determined during these component steps is recorded in Exhibit 31-42.

QUICK ESTIMATION CONTROL DELAY AND LOS WORKSHEET				
General Information				
Description _____				
East-West Phasing Plan				
Selected plan _____	Phase No. 1	Phase No. 2	Phase No. 3	
Movement codes _____				
Critical phase volume, CV (veh/h)				
Lost time/phase, t_L (s)				
North-South Phasing Plan				
Selected plan _____	Phase No. 1	Phase No. 2	Phase No. 3	
Movement codes _____				
Critical phase volume, CV (veh/h)				
Lost time/phase, t_L (s)				
Intersection Status Computation				
Critical sum, CS (veh/h) $CS = \sum CV$				
Lost time/cycle, L (s) $L = \sum t_L$				
Reference sum flow rate RS (veh/h) ¹				
Cycle length, C (s) $C_{min} \leq C \leq C_{max}$ $C = C_{max}$ when $CS \geq RS$	$C = \frac{L}{1 - \frac{CS}{RS}}$			
Critical v/c ratio, X_c $X_c = \frac{CS}{1700 PHF f_a \left(1 - \frac{L}{C}\right)}$				
Intersection status (relationship to capacity)	Under ____ Near ____ At ____ Over ____			
Green Time Calculation				
East-West Phasing	Phase No. 1	Phase No. 2	Phase No. 3	
Green time, g (s) $g = (C - L) \left(\frac{CV}{CS} \right) + t_L$				
North-South Phasing	Phase No. 1	Phase No. 2	Phase No. 3	
Green time, g (s) $g = (C - L) \left(\frac{CV}{CS} \right) + t_L$				
Control Delay and LOS				
	EB	WB	NB	SB
Lane group _____				
Lane group adjusted volume from Lane Volume worksheet, V (veh/h)				
Green ratio, g/C				
Lane group saturation flow rate, s (veh/h) $s = RS \times \text{number of lanes in lane group}$				
v/c ratio, X $X = \frac{V/s}{g/C}$				
Lane group capacity, c (veh/h) $c = \frac{V}{X}$				
Progression adjustment factor, PF				
Uniform delay, d_1 (s/veh)				
Incremental delay, d_2 (s/veh)				
Control delay, $d = d_1(PF) + d_2$ (s/veh)				
Delay by approach, d_A (s/veh) $\frac{\sum(d)(V)}{\sum V}$				
Approach flow rate, V_A (veh/h)				
Intersection delay, d_I (s/veh) $d_I = \frac{\sum(d_A)(V_A)}{\sum V_A}$		Intersection LOS (Exhibit 18-4)		
Notes				
1. $RS = 1530 \times PHF \times f_a$, where f_a is area adjustment factor (= 0.90 for CBD and 1.0 for all other area types).				

Exhibit 31-42

Quick Estimation Control Delay and Level-of-Service Worksheet

A. Develop Phasing Plan

The phase plan is selected from the alternatives presented in Exhibit 31-43. If the phasing plan is not known, the selection is made on the basis of the user-

Exhibit 31-43
Phase Plans for Quick
Estimation Method

specified left-turn treatment and the dominant left-turn movements identified from the left-turn treatment worksheet.

Phase Plan	Eastbound	Westbound	Northbound	Southbound
1a	Permitted	Permitted	Permitted	Permitted
1b	Permitted	Not opposed	Permitted	Not opposed
1c	Not opposed	Permitted	Not opposed	Permitted
2a	Permitted	Protected	Permitted	Protected
2b	Protected	Permitted	Protected	Permitted
3a	Protected ^a	Protected	Protected ^a	Protected
3b	Protected	Protected ^a	Protected	Protected ^a
4	Not opposed	Not opposed	Not opposed	Not opposed

Note: ^a Dominant left turn for each opposing movement.

When the phase plan has been selected, the movement codes are entered in the first two sections of the control delay and level-of-service worksheet.

B. Compute Critical Phase Volume and Lost Time

The critical phase volume CV is the volume for the movement that requires the longest green time during the phase. If two opposing lefts are moving during the same phase, the critical phase volume is the higher-volume left turn. The appropriate choice for critical lane volume is given in the phase plan summary shown in Exhibit 31-44, along with a code that identifies the movements that are allowed to proceed in each phase. For example, NBSBTH indicates that the northbound and southbound through movements have the right-of-way on the specified phase.

Exhibit 31-44
Phase Plan Summary for
Quick Estimation Method

Phase Plan	Phase No.	Lost Time (s)	East–West		North–South	
			Movement Code	Critical Volume	Movement Code	Critical Volume
1a, 1b, 1c	1	4	EBWBTH	Max(EBTH, WBTH, WBLT)	NBSBTH	Max(NBTH, NBLT, SBTH, SBLT)
2a	1	4	WBTHLT	WBLT	SBTHLT	SBLT
	2	4	EBWBTH	Max(WBTH-WBLT, EBTH)	NBSBTH	Max(SBTH-SBLT, NBTH)
2b	1	4	EBTHLT	EBLT	NBTHLT	NBLT
	2	4	EBWBTH	Max(EBTH-EBLT, WBTH)	NBSBTH	Max(NBTH-NBLT, SBTH)
3a	1	4	EBWBTLT	WBLT	NBSBLT	SBLT
	2	0	EBTHLT	EBLT-WBLT	NBTHLT	NBLT-SBLT
	3	4	EBWBTH	Max(WBTH, EBTH-(EBLT-WBLT))	NBSBTH	Max(SBTH, NBTH-(NBLT-SBLT))
3b	1	4	EBWBTLT	EBLT	NBSBLT	NBLT
	2	0	WBTHLT	WBLT-EBLT	SBTHLT	SBLT-NBLT
	3	4	EBWBTH	Max(EBTH, WBTH-(WBLT-EBLT))	NBSBTH	Max(NBTH, SBTH-(SBLT-NBLT))
4	1	4	EBTHLT	Max(EBTH, EBLT)	NBTHLT	Max(NBTH, NBLT)
	2	4	WBTHLT	Max(WBTH, WBLT)	SBTHLT	Max(SBTH, SBLT)

Exhibit 31-44 also indicates the lost time assigned to each phase l_i . This time is determined for each phase and entered in the first two sections of the control delay and level-of-service worksheet. Phase lost time is incurred during any phase in which a movement is both started and stopped.

C. Compute Critical Sum and Cycle Lost Time

When all phases have been completed, the critical sum CS of the critical phase volumes is entered in the third section of this worksheet.

The cycle lost time L represents the sum of the phase lost time for each of the critical phases. For example, if Phase Plan 1 were selected for both streets, then there would be a total of 8 s of cycle lost time (4 s for each street).

D. Compute Cycle Length

If the cycle length C is known, then this step is skipped. If the cycle length is unknown, then it is computed by Equation 31-154.

$$C = \frac{L}{1 - \left[\frac{CS}{RS} \right]}$$

Equation 31-154

with

$$C_{min} \leq C \leq C_{max}$$

$$C = C_{max} \quad \text{when } CS \geq RS$$

where

C = cycle length (s),

C_{min} = minimum cycle length (s),

C_{max} = maximum cycle length (s),

L = cycle lost time (s),

CS = critical sum (veh/h),

RS = reference sum flow rate = $1,530 \times PHF \times f_a$ (veh/h),

PHF = peak hour factor, and

f_a = adjustment factor for area type = 0.90 if central business district and 1.00 otherwise.

The reference sum RS of phase flow rates represents the theoretical maximum value that the intersection could accommodate at an infinite cycle length. The recommended value for the reference sum is computed as an adjusted saturation flow rate. The value of 1,530 is about 90 percent of the base saturation flow rate of 1,700 pc/h/ln. The objective is to produce a volume-to-capacity ratio of 0.90 for all critical movements.

The cycle length determined from this equation should be checked against reasonable minimum and maximum values. The cycle length must not exceed a maximum allowable value set by the local jurisdiction (such as 150 s), and it must be long enough to serve pedestrians (use 60 s if local data are not available).

E. Compute Green Time

The effective green time g estimated in this step is based on the principle of dividing the cycle time among the conflicting phases so that the critical movements will have the same volume-to-capacity ratio. The cycle lost time must be subtracted from the cycle length to determine the effective green time per

cycle, which must then be apportioned among all phases. The effective green time per cycle is then allocated to each critical phase in proportion to the contribution of its critical phase volume to the critical sum. The effective green time for a phase is computed with Equation 31-155.

Equation 31-155

$$g = (C - L) \frac{CV}{CS}$$

where g is the effective green time (s), CV is the critical phase flow rate (veh/h), and other variables are as previously defined.

This method for estimating green time will not necessarily minimize the overall delay at the intersection.

Step 4: Determine Critical Intersection Volume-to-Capacity Ratio

The critical intersection volume-to-capacity ratio X_c is an approximate indicator of the overall sufficiency of the intersection geometrics. The computational method involves the summation of conflicting critical lane flow rates for the intersection. The computations depend on traffic signal phasing, which in turn depends on the left-turn treatment. The critical intersection volume-to-capacity ratio is computed with Equation 31-156.

Equation 31-156

$$X_c = \frac{CS}{1,700 PHF f_a \left(1 - \frac{L}{C}\right)}$$

where X_c is the critical intersection volume-to-capacity ratio and other variables are as previously defined.

Although it is not appropriate to assign a level of service to the intersection on the basis of X_c , it is appropriate to evaluate the operational status of the intersection for quick estimation purposes. Exhibit 31-45 expresses the intersection status as over, at, near, or under capacity.

Exhibit 31-45
Intersection Status Criteria
for Quick Estimation Method

Critical Volume-to-Capacity Ratio (X_c)	Relationship to Capacity
≤ 0.85	Under capacity
$> 0.85-0.95$	Near capacity
$> 0.95-1.00$	At capacity
> 1.00	Over capacity

Step 5: Determine Control Delay

First, the lane groups are established for all approaches. Lane grouping is explained in Chapter 18, Signalized Intersections.

Lane group volumes V are computed by summing the adjusted volumes obtained from the lane volume worksheet for each lane group on each approach.

The green ratio g/C is computed by using the effective green time and cycle length values from the top portion of the control delay and level-of-service worksheet.

The lane group saturation flow rate s is equal to the reference sum times the number of lanes in the lane group.

The lane group volume-to-capacity ratio X is calculated by using adjusted lane group volume, lane group saturation flow rate, and green ratio.

Lane group capacity c is calculated by using lane group adjusted volume and lane group volume-to-capacity ratio.

The progression adjustment factor PF is selected from Exhibit 31-46. If the subject lane group is uncoordinated, then Arrival Type 3 is appropriate. If the subject lane group is coordinated, then Arrival Type 4 is appropriate.

Arrival Type	Progression Adjustment Factor PF as a Function of Green Ratio					
	0.2	0.3	0.4	0.5	0.6	0.7
Uncoordinated	1.00	1.00	1.00	1.00	1.00	1.00
Coordinated ^a	0.92	0.86	0.78	0.67	0.50	0.22

Note: ^a $PF = (1 - [1.33 g/C]) / (1 - g/C)$.

Exhibit 31-46
Progression Adjustment Factor

The uniform delay d_1 is computed with Equation 31-157.

$$d_1 = \frac{0.5 C (1 - g/C)^2}{1 - [\min(1, X)g/C]}$$

Equation 31-157

where d_1 is uniform delay (s/veh), X is volume-to-capacity ratio, and other variables are as previously defined. The notation $\min(1, X)$ used in the equation indicates that the smaller of the two values (i.e., 1 and X) is used in the equation.

The incremental delay d_2 is computed with Equation 31-158.

$$d_2 = 900 T \left[(X - 1) + \sqrt{(X - 1)^2 + \frac{4 X}{c T}} \right]$$

Equation 31-158

where

d_2 = incremental delay (s/veh),

c = capacity (veh/h), and

T = analysis period duration (h).

Other variables are as previously defined.

The analysis period is equal to 0.25 h if a peak hour factor is used to estimate peak 15-min flow rates. If a peak hour factor is not used and the input volumes represent forecast hourly traffic demands, then the analysis period is 1.0 h.

The control delay is computed with Equation 31-159.

$$d = d_1(PF) + d_2$$

Equation 31-159

where d is control delay (s/veh), PF is the progression adjustment factor, and other variables are as previously defined.

Approach delay and intersection delay are calculated as a weighted average of the lane group delays. The weight for a lane group is based on the volume of each movement included in the group, as recorded on the input worksheet. The adjusted volumes used to compute capacity should not be used to compute approach delay or intersection delay. Exhibit 18-4 in Chapter 18 can be used to obtain a level-of-service estimate for the intersection, based on the computed intersection delay.

This procedure does not provide sufficient information for the computation of delay for a permitted left-turn movement from an exclusive turn lane. The analyst may ignore this delay in the computations or may use the more detailed methodology provided in Chapter 18. In addition, the quick estimation method does not include the delay associated with sneakers. The sneaker volume was subtracted from the left-turn volume associated with left-turn movements operating in a permitted mode or a protected-permitted mode.

6. FIELD MEASUREMENT TECHNIQUES

This section describes two techniques for estimating key traffic characteristics by using field data. The first subsection describes a technique for estimating control delay. The second subsection describes a technique for estimating saturation flow rate.

FIELD MEASUREMENT OF INTERSECTION CONTROL DELAY

General Notes

Delay can be measured at existing intersections as an alternative to the estimation of delay by using the methodology in Chapter 18, Signalized Intersections. There are a number of techniques for measuring delay, including a test-car survey, vehicle path tracing, input-output analysis, and queue counting. The first three techniques tend to require more time to implement than the last technique but provide more accurate delay estimates. They are often limited to sampling when implemented manually. They may be more appropriate when oversaturated conditions are present. The first two techniques can be used to estimate delay on either a movement basis or a lane group basis. The last two techniques are more amenable to delay measurement on a lane group basis.

The queue-count technique is recommended for control delay measurement. It is based on direct observation of vehicle-in-queue counts for a subject lane group. It normally requires two field personnel for each lane group surveyed. Also needed are (a) a multifunction digital watch that includes a countdown-repeat timer, with the countdown interval in seconds, and (b) a volume-count board with at least two tally counters. Alternatively, a laptop computer can be programmed to emit audio count markers at user-selected intervals, take volume counts, and execute real-time delay computations.

The queue-count technique is applicable to all undersaturated lane groups. Significant queue buildup can make the technique impractical for oversaturated lane groups or lane groups with limited storage length. If queues are lengthy, then the technique should be modified by subdividing the lane group into manageable segments (or zones) and assigning an observer to each zone. Each observer then counts queued vehicles in his or her assigned zone.

If queues are lengthy or the demand volume-to-capacity ratio is near 1.0, then care must be taken to continue the vehicle-in-queue count past the end of the arrival count period, as detailed in subsequent paragraphs. This extended counting period is required for consistency with the analytic delay equation used in the chapter text.

The technique does not directly measure delay during deceleration and during a portion of acceleration. These delay elements are very difficult to measure without sophisticated tracking equipment. Nevertheless, this technique has been shown to yield a reasonable estimate of control delay by application of appropriate adjustment factors (8, 9). One adjustment factor accounts for sampling errors that may occur. Another factor accounts for unmeasured

acceleration–deceleration delay. This adjustment factor is a function of the number of vehicles in queue each cycle and the approach speed.

Approach Speed

Exhibit 31-47 shows a worksheet that can be used for recording observations and computing control delay for the subject lane group. Before starting the survey, observers need to estimate the average approach speed during the study period. Approach speed is the speed at which vehicles would pass unimpeded through the intersection if the signal were green for an extended period and volume was light. This speed may be obtained by driving through the intersection a few times when the signal is green and there is no queue. The approach speed is recorded at an upstream location that is least affected by the operation of the subject signalized intersection as well as that of any other signalized intersection.

Survey Period

The duration of the survey period must be clearly defined in advance so the last arriving vehicle or vehicles that stop in the period can be identified and counted until they exit the intersection. It is logical to define the survey period on the basis of the same considerations used to define an evaluation analysis period (as described in Chapter 18). A typical survey period is 15 min.

Count Interval

The survey technique is based on recording a vehicle-in-queue count at specific points in time. A count interval in the range of 10 to 20 s has been found to provide a good balance between delay estimate precision and observer capability. The actual count interval selected from this range is based on consideration of survey period duration and the type of control used at the intersection.

The count interval *should* be an integral divisor of the survey period duration. This characteristic ensures that a complete count of events is taken for the full survey period. It also allows easier coordination of observer tasks during the field study. For example, if the study period is 15 min, the count interval can be 10, 12, 15, 18, or 20 s.

If the intersection has pretimed or coordinated-actuated control, the count interval *should not* be an integral divisor of the cycle length. This characteristic eliminates potential survey bias due to queue buildup in a cyclical pattern. For example, if the cycle length is 120 s, the count interval can be 11, 13, 14, 16, 17, 18, or 19 s.

If the intersection has actuated control, the count interval may be chosen as the most convenient value for conducting the field survey with consideration of survey period duration.

Measurement Technique

The survey should begin at the start of the red indication associated with the subject lane group and, ideally, when no initial queue is present. If the survey period does start with an initial queue present, then these queued vehicles need

to be excluded from subsequent queue counts. This requirement stems from the need to be consistent with the delay equation in Chapter 18. This equation is derived to estimate the delay to vehicles that arrive during the survey period, not before.

INTERSECTION CONTROL DELAY WORKSHEET											
General Information						Site Information					
Analyst _____						Intersection _____					
Agency or Company _____						Area Type ☐ CBD ☐ Other					
Date Performed _____						Jurisdiction _____					
Analysis Time Period _____						Analysis Year _____					
Input Initial Parameters											
Number of lanes, N _____						Total vehicles arriving, V_{tot} _____					
Approach speed, S_a (mi/h) _____						Stopped-vehicle count, V_{stop} _____					
Survey count interval, I_s (s) _____						Cycle length, C (s) _____					
Input Field Data											
Clock Time	Cycle Number	Number of Vehicles in Queue									
		Count Interval									
		1	2	3	4	5	6	7	8	9	10
Total											
Computations											
Total vehicles in queue, ΣV_{iq} = _____ veh						Number of cycles surveyed, N_c = _____					
Time-in-queue per vehicle, $d_{vq} = \left(I_s \frac{\Sigma V_{iq}}{V_{tot}} \right) 0.9$ _____ s/veh						Fraction of vehicles stopping, $FVS = \frac{V_{stop}}{V_{tot}}$ _____					
No. of vehicles stopping/lane/cycle = $\frac{V_{stop}}{(N_c \times N)}$ _____ veh/ln						Accel-decel correction delay, $d_{ad} = FVS \times CF$ _____ s/veh					
Accel-decel correction factor, CF _____ s/veh						Control delay, $d = d_{vq} + d_{ad}$ _____ s/veh					

Exhibit 31-47
Control Delay Field Study
Worksheet

Observer 1 Tasks

- Observer 1 keeps track of the end of the standing queue in each lane of the subject lane group. For purposes of the survey, a vehicle is considered as having joined the queue when it approaches within one car length of a stopped vehicle and is itself about to stop. This definition is used because of the difficulty of keeping track of the moment when a vehicle comes to a stop.

2. At the start of each count interval, Observer 1 records the number of vehicles in queue in all lanes of the subject lane group. The countdown-repeat timer on a digital watch can be used to signal the count time. This count includes vehicles that arrive when the signal is actually green but stop because queued vehicles ahead have not yet started moving. All vehicles that join a queue are included in the vehicle-in-queue count until they “exit” the intersection. A through vehicle exits the intersection when its rear axle crosses the stop line. A turning vehicle exits the intersection the instant it clears the opposing through traffic (or pedestrians to which it must yield) and begins accelerating back to the approach speed. The vehicle-in-queue count often includes some vehicles that have regained speed but have not yet exited the intersection.
3. Observer 1 records the vehicle-in-queue count in the appropriate count-interval box on the worksheet. Ten boxes are provided for each “count cycle” (note that a count cycle is not the same as a signal cycle). Any number of boxes can be used to define the count cycle; however, as many as possible should be used to ensure best use of worksheet space. The clock time at the start of the count cycle is recorded in the first column. The count cycle number is recorded in the second column of the sheet.
4. At the end of the survey period, Observer 1 continues taking vehicle-in-queue counts for all vehicles that arrived during the survey period until all of them have exited the intersection. This step requires the observer to make a mental note of the last stopping vehicle that arrived during the survey period in each lane of the lane group and continue the vehicle-in-queue counts until the last stopping vehicle or vehicles, plus all vehicles in front of the last stopping vehicles, exit the intersection. Stopping vehicles that arrive after the end of the survey period are not included in the final vehicle-in-queue counts.

Observer 2 Tasks

1. Observer 2 maintains three counts during the survey period. The first is a count of the vehicles that arrive during the survey period. The second is a count of the vehicles that arrive during the survey period and that stop one or more times. A vehicle stopping multiple times is counted only once as a stopping vehicle. The third count is the count of signal cycles, as measured by the number of times the red indication is presented for the subject lane group. For lane groups with a turn movement and protected or protected-permitted operation, the protected red indication is used for this purpose. If the survey period does not start or end at the same time as the presentation of a red indication, then the number of count intervals that occur in the interim can be used to estimate the fraction of the cycle that occurred at the start or end of the survey period.
2. Observer 2 enters all counts in the appropriate boxes on the worksheet.

Data Reduction Tasks

1. Sum each column of vehicle-in-queue counts, then sum the column totals for the entire survey period.

2. A vehicle recorded as part of a vehicle-in-queue count is assumed to be in queue, on average, for the time interval between counts. On this basis, the average time-in-queue per vehicle arriving during the survey period is estimated with Equation 31-160.

$$d_{vq} = \left(I_s \frac{\sum V_{iq}}{V_{tot}} \right) 0.9$$

Equation 31-160

where

d_{vq} = time-in-queue per vehicle (s/veh),

I_s = interval between vehicle-in-queue counts (s),

$\sum V_{iq}$ = sum of vehicle-in-queue counts (veh), and

V_{tot} = total number of vehicles arriving during the survey period (veh).

The 0.9 adjustment factor in Equation 31-160 accounts for the errors that may occur when the queue-count technique is used to estimate delay. Research has shown that the adjustment factor value is fairly constant for a variety of conditions (8).

3. Compute the fraction of vehicles stopping and the average number of vehicles stopping per lane in each signal cycle, as indicated on the worksheet.
4. Use Exhibit 31-48 to look up the correction factor appropriate to the lane group approach speed and the average number of vehicles stopping per lane in each cycle. This factor adjusts for deceleration and acceleration delay, which cannot be measured directly with manual techniques (9).

Approach Speed (mi/h)	Acceleration–Deceleration Correction Factor CF (s/veh) as a Function of the Average Number of Vehicles Stopping		
	≤ 7 veh/ln/cycle	8–19 veh/ln/cycle	20–30 veh/ln/cycle ^a
≤ 37	+5	+2	–1
>37–45	+7	+4	+2
>45	+9	+7	+5

Exhibit 31-48
Acceleration–Deceleration
Correction Factor

Note: ^a Vehicle-in-queue counts in excess of about 30 veh/ln/cycle are typically unreliable.

5. Multiply the correction factor by the fraction of vehicles stopping. Then, add this product to the time-in-queue value from Task 2 to obtain the estimate of control delay for the subject lane group.

Example Application

Exhibit 31-49 presents sample data for a lane group during a 15-min survey period. The intersection has a 115-s cycle. A 15-s count interval is selected because it is not an integral divisor of the cycle length, but it is an integral divisor of the survey period.

Exhibit 31-49
Example Control Delay Field
Study Worksheet

INTERSECTION CONTROL DELAY WORKSHEET											
General Information						Site Information					
Analyst _____						Intersection <u>Cicero & Belmont</u>					
Agency or Company _____						Area Type ☐ CBD ☒ Other					
Date Performed _____						Jurisdiction _____					
Analysis Time Period <u>PM</u>						Analysis Year <u>1999</u>					
Input Initial Parameters											
Number of lanes, N <u>2</u>						Total vehicles arriving, V_{tot} <u>530</u>					
Approach speed, S_a (mi/h) <u>40</u>						Stopped-vehicle count, V_{stop} <u>223</u>					
Survey count interval, I_s (s) <u>15</u>						Cycle length, C (s) _____					
Input Field Data											
Clock Time	Cycle Number	Number of Vehicles in Queue									
		Count Interval									
		1	2	3	4	5	6	7	8	9	10
4:34	1	3	8	11	15	12	2	0	2		
	2	6	12	15	16	6	0	0	2		
	3	7	11	14	14	2	0	0			
	4	5	7	10	13	13	2	0	1		
4:42	5	4	6	10	12	3	0	0	1		
	6	5	7	9	13	4	0	0			
	7	3	6	8	12	12	0	0	0		
4:47	8	4	7	11	16	9	0				
Total		37	64	88	111	61	4	0	6		
Computations											
Total vehicles in queue, $\Sigma V_{iq} =$ <u>371</u> veh						Number of cycles surveyed, $N_c =$ <u>7.8</u>					
Time-in-queue per vehicle, $d_{vq} = \left(I_s \frac{\Sigma V_{iq}}{V_{tot}} \right) 0.9 =$ <u>9.5</u> s/veh						Fraction of vehicles stopping, $FVS = \frac{V_{stop}}{V_{tot}} =$ <u>0.42</u>					
No. of vehicles stopping/lane/cycle = $\frac{V_{stop}}{(N_c \times N)} =$ <u>14</u> veh/ln						Accel-decel correction delay, $d_{ad} = FVS \times CF$ <u>1.7</u> s/veh					
Accel-decel correction factor, CF <u>4</u> s/veh						Control delay, $d = d_{vq} + d_{ad} =$ <u>11.2</u> s/veh					

The exhibit shows that data are recorded for six, seven, or eight intervals during each count cycle. This choice is arbitrary and based solely on best use of worksheet space.

The data reduction results are shown at the bottom of the exhibit. A control delay of 11.2 s/veh is estimated for the subject lane group.

Exhibit 31-50 shows how the study would have been completed if a queue remained at the end of the 15-min survey period. Only the vehicles that arrived during the 15-min period would be counted.

FIELD MEASUREMENT OF SATURATION FLOW RATE

Concepts

The saturation flow rate represents the maximum rate of flow in a traffic lane, as measured at the stop line during the green indication. It is usually

achieved after 10 to 14 s of green, which corresponds to the front axle of the fourth to sixth queued passenger car crossing the stop line.

The base saturation flow rate represents the saturation flow rate for a traffic lane that is 12 ft wide and has no heavy vehicles, a flat grade, no parking, no buses that stop at the intersection, even lane utilization, and no turning vehicles. It is usually stable over a period of time in a given area and normally exhibits a relatively narrow distribution among intersections in that area.

The prevailing saturation flow rate is the rate measured in the field for a specific lane group at a specific intersection. It may vary significantly among intersections with similar lane groups because of differences in lane width, traffic composition (i.e., percent heavy vehicles), grade, parking, bus stops, lane use, and turning vehicle operation. If the intersections are located in different areas, then the prevailing saturation flow rate may also vary because of areawide differences in the base saturation flow rate.

The adjusted saturation flow rate is the rate computed by the procedure described in Chapter 18. It represents an estimate of the prevailing saturation flow rate. It can vary among intersections for the same reasons as stated previously for the prevailing saturation flow rate. Any potential bias in the estimate is minimized by local calibration of the base saturation flow rate.

The prevailing saturation flow rate and the adjusted saturation flow rate are both expressed in units of vehicles. As a result, their value reflects the traffic composition in the subject traffic lane. In contrast, the base saturation flow rate is expressed in units of passenger cars and does not reflect traffic composition.

Measurement Technique

This part describes the technique for measuring the prevailing saturation flow rate for a given traffic lane. In general, vehicles are recorded when their front axles cross the stop line. The measurement period starts at the beginning of the green interval or when the front axle of the first vehicle in the queue passes the stop line. Saturation flow rate is calculated only from the data recorded after the fourth vehicle in the queue passes the stop line.

The vehicle's front axle, the stop line, and the time the fourth queued vehicle crosses the stop line represent three key reference points for saturation flow measurement. Other reference points on the vehicle, on the road, or in time may yield different saturation flow rates. To maintain consistency with the methodology described in Chapter 18 and to facilitate information exchange, the aforementioned three reference points must be maintained.

If the stop line is not visible or if vehicles consistently stop beyond the stop line, then an alternative reference line must be established. This reference line should be established just beyond the typical stopping position of the first queued vehicle. Vehicles should consistently stop behind this line. Observation of several cycles before the start of the study should be sufficient to identify this substitute reference line.

The following paragraphs describe the tasks associated with a single-lane saturation flow survey. A two-person field crew is recommended. However, one

person with a tape recorder, push-button event recorder, or a notebook computer with appropriate software will suffice. The field notes and tasks identified in the following paragraphs must be adjusted according to the type of equipment used. A sample field worksheet for recording observations is included as Exhibit 31-51.

Exhibit 31-51
Saturation Flow Rate Field Study Worksheet

FIELD SATURATION FLOW RATE STUDY WORKSHEET																		
General Information									Site Information									
Analyst _____ Agency or Company _____ Date Performed _____ Analysis Time Period _____									Intersection _____ Area Type ☐ CBD ☐ Other _____ Jurisdiction _____ Analysis Year _____									
Lane Movement Input																		
Identify all lane movements and the lane studied																		
Input Field Measurement																		
Veh. in queue	Cycle 1			Cycle 2			Cycle 3			Cycle 4			Cycle 5			Cycle 6		
	Time	HV	T	Time	HV	T	Time	HV	T	Time	HV	T	Time	HV	T	Time	HV	T
1																		
2																		
3																		
4																		
5																		
6																		
7																		
8																		
9																		
10																		
11																		
12																		
13																		
14																		
15																		
16																		
17																		
18																		
19																		
20																		
End of saturation																		
End of green																		
No. veh. > 20																		
No. veh. on yellow																		
Glossary and Notes																		
HV = Heavy vehicles (vehicles with more than 4 tires on pavement) T = Turning vehicles (L = Left, R = Right) Pedestrians and buses that block vehicles should be noted with the time that they block traffic, for example, P12 = Pedestrians blocked traffic for 12 s B15 = Bus blocked for 15 s																		

General Tasks

Measure and record the area type as well as the width and grade of the lane being studied. Enter these data in the lane movement input section of the field worksheet.

Select an observation point where the roadway reference line (e.g., stop line) for the surveyed lane and the corresponding signal heads are clearly visible. When a vehicle crosses this line unimpeded, it has entered the intersection conflict space for the purpose of saturation flow measurement. Left- or right-turning vehicles yielding to opposing through traffic or yielding to pedestrians are not recorded until they proceed through the opposing traffic.

Recorder Tasks

During the measurement period, note the last vehicle in the stopped queue when the signal turns green. Describe the last vehicle to the timer. Note on the worksheet which vehicles are heavy vehicles and which vehicles turn left or right. Record the time called out by the timer.

Timer Tasks

Start the stopwatch at the beginning of the green indication and notify the recorder. Count aloud each vehicle in the queue as its front axle crosses the stop line and note the time of crossing. Call out the time of the fourth, tenth, and last vehicle in the stopped queue as its front axle is crossing the stop line.

If queued vehicles are still entering the intersection at the end of the green interval, call out (saturation through the end of green—last vehicle was number XX). Note any unusual events that may have influenced the saturation flow rate, such as buses, stalled vehicles, and unloading trucks.

The period of saturation flow begins when the front axle of the fourth vehicle in the queue crosses the roadway reference line (e.g., stop line) and ends when the front axle of the last queued vehicle crosses this line. The last queued vehicle may be a vehicle that joined the queue during the green indication.

Data Reduction

Measurements are taken cycle by cycle. To reduce the data for each cycle, the time recorded for the fourth vehicle is subtracted from the time recorded for the last vehicle in the queue. This value represents the sum of the headways for the fifth through n th vehicle, where n is the number of the last vehicle surveyed (which may not be the last vehicle in the queue). This sum is divided by the number of headways after the fourth vehicle [i.e., divided by $(n - 4)$] to obtain the average headway per vehicle under saturation flow. The saturation flow rate is 3,600 divided by this average headway.

For example, if the time for the fourth vehicle was observed as 10.2 s and the time for the 14th and last vehicle surveyed is 36.5 s, the average saturation headway per vehicle is as follows:

$$\frac{(36.5 - 10.2)}{(14 - 4)} = \frac{26.3}{10} = 2.63 \text{ s/veh}$$

The prevailing saturation flow rate in that cycle is as follows:

$$\frac{3,600}{2.63} = 1,369 \text{ veh/h/ln}$$

To obtain a statistically significant value, a minimum of 15 signal cycles (each with more than eight vehicles in the initial queue) is typically required. The average of the saturation headway per vehicle values from the individual cycles is divided into 3,600 to obtain the prevailing saturation flow rate for the surveyed lane. The percentage of heavy vehicles and turning vehicles in the sample should be determined and noted for reference.

Calibration Technique

This part describes a technique for quantifying the base saturation flow rate at a local level. It consists of three tasks. The first task entails measuring the prevailing saturation flow rate at representative locations in the local area. The second task requires the calculation of an adjusted saturation flow rate for the same locations where a prevailing saturation flow rate was measured. The third task combines the information to compute the local base saturation flow rate.

It is recognized that this technique will require some resource investment by the agency. However, it should need to be completed only once every few years. In fact, it should be repeated only when there is evidence of a change in local driver behavior. The benefit of this calibration activity will be realized by the agency in terms of more accurate estimates of automobile performance, which should translate into more effective decisions related to infrastructure investment and system management.

Task 1. Measure Prevailing Saturation Flow Rate

This task requires the measurement of prevailing saturation flow rate at one or more lane groups at each of several representative intersections in the local area. The minimum number of lane groups needed in the data set is difficult to judge for all situations; however, it should reflect a statistically valid sample. The data set should also provide reasonable geographic and physical representation of the population of signalized intersections in the local area.

The lane groups for which the prevailing saturation flow rate is measured should include a representative mix of left-turn, through, and right-turn lane groups. It should not include left-turn lane groups that operate in the permitted or the protected-permitted mode or right-turn lane groups that have protected-permitted operation. These lane groups are excluded because of the complex nature of permitted and protected-permitted operation. The saturation flow rate for these lane groups tends to have a large amount of random variation that makes it more difficult to quantify the local base saturation flow rate with an acceptable level of precision.

Once the set of lane groups is identified, the technique described in the previous part is used to measure the prevailing saturation flow rate at each location.

Task 2. Compute Adjusted Saturation Flow Rate

For this task, the saturation flow rate calculation procedure in Chapter 18 is used to compute the adjusted saturation flow rate for each lane group in the data set. If a lane group is at an intersection with actuated control for one or more phases, the automobile methodology (as opposed to just the saturation flow rate procedure) will need to be used to compute the adjusted saturation flow rate accurately. Regardless, the base saturation flow rate used with the procedure (or methodology) for this task must be 1,900 pc/h/ln.

Task 3. Compute Local Base Saturation Flow Rate

The local base saturation flow rate is computed with Equation 31-161.

Equation 31-161

$$s_{o,local} = 1,900 \frac{\sum_{i=1}^m s_{prevailing,i}}{\sum_{i=1}^m s_i}$$

where

$s_{o,local}$ = local base saturation flow rate (pc/h/ln),

$s_{prevailing,i}$ = prevailing saturation flow rate for lane group i (veh/h/ln),

s_i = (adjusted) saturation flow rate for lane group i (veh/h/ln), and

m = number of lane groups.

Once the local base saturation flow rate $s_{o,local}$ is quantified by this technique, it is substituted thereafter for s_o in any equation in Chapter 18 that references this variable.

7. COMPUTATIONAL ENGINE DOCUMENTATION

This section uses a series of flowcharts and linkage lists to document the logic flow for the computational engine.

FLOWCHARTS

The methodology flowchart is shown in Exhibit 31-52. The methodology is shown to consist of four main modules:

- Setup module,
- Signalized intersection module,
- Initial queue delay module, and
- Performance measures module.

This subsection provides a separate flowchart for each of these modules.

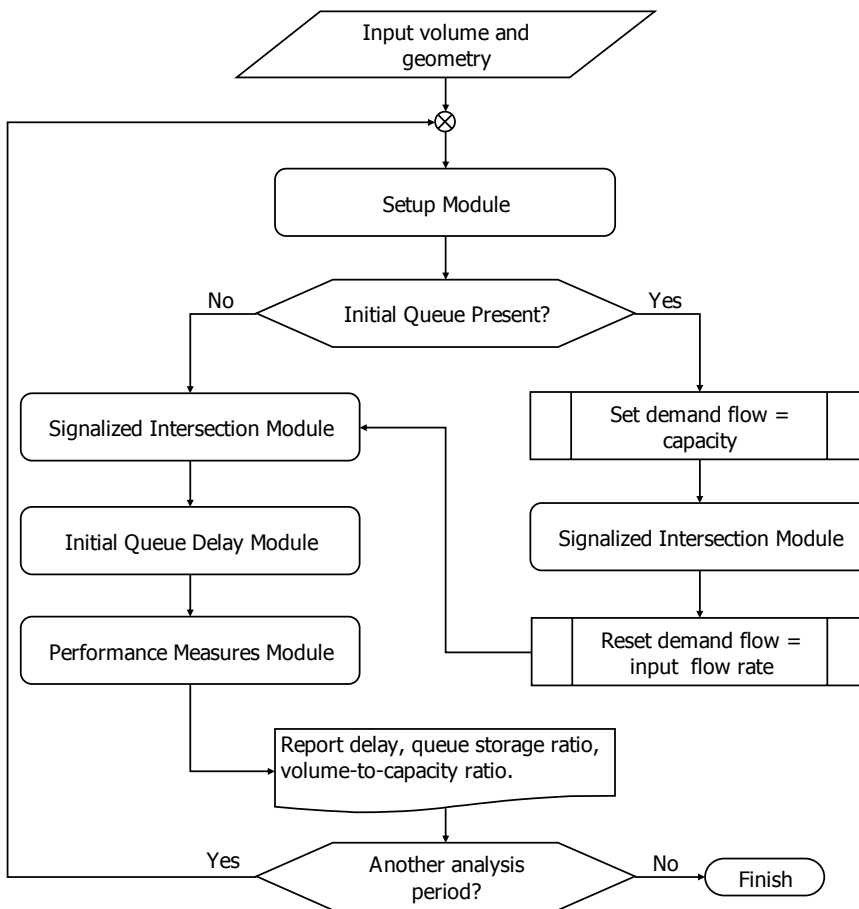
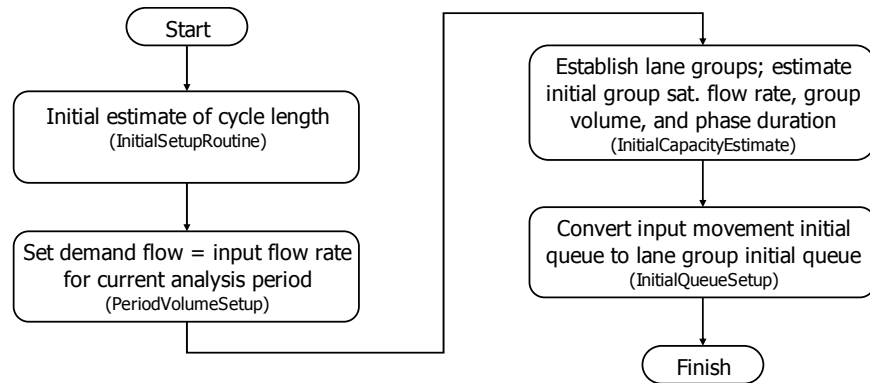


Exhibit 31-52
Methodology Flowchart

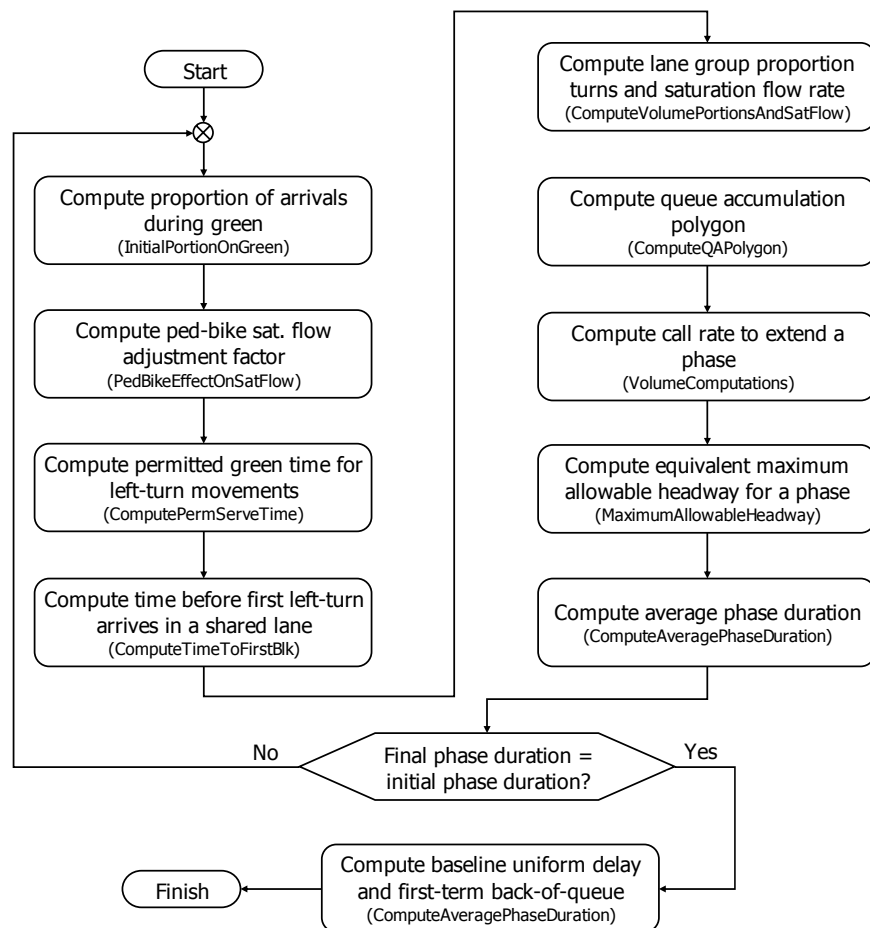
The setup module is shown in Exhibit 31-53. It consists of four main routines, as shown in the large rectangles of the exhibit. The main function of each routine, as well as the name given to it in the computational engine, is also shown in the exhibit. These routines are described further in the next subsection.

Exhibit 31-53
Setup Module



The signalized intersection module is shown in Exhibit 31-54. It consists of nine main routines. The main function of each routine, as well as the name given to it in the computational engine, is also shown in the exhibit. These routines are described further in the next subsection.

Exhibit 31-54
Signalized Intersection
Module



The initial queue delay module is shown in Exhibit 31-55. It consists of four main routines. The main function of each routine is also shown in the exhibit.

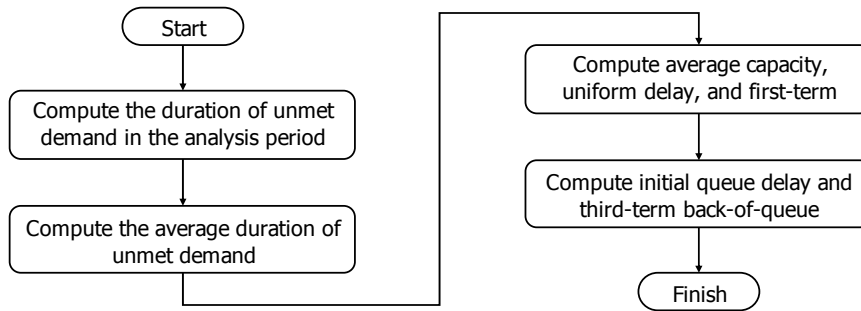


Exhibit 31-55
Initial Queue Delay Module

The performance measures module is shown in Exhibit 31-56. It consists of four main routines. The main function of each routine is also shown in the exhibit. Two of the routines are complicated enough to justify their development as separate entities in the computational engine. The name given to each of these two routines is also shown in the exhibit. These two routines are described further in the next subsection.

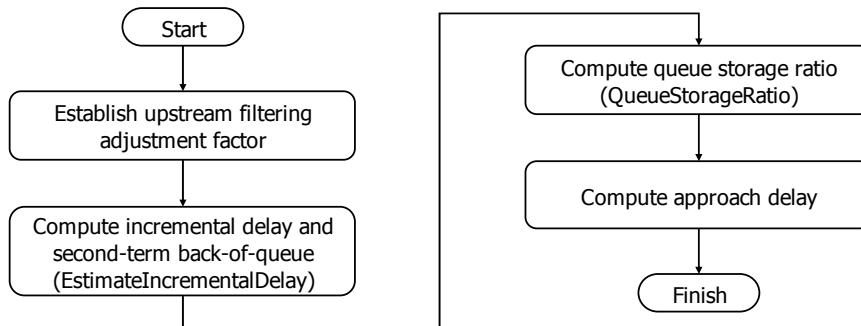


Exhibit 31-56
Performance Measures Module

LINKAGE LISTS

This subsection uses linkage lists to describe the main routines that compose the computational engine. Each list is provided in a table that identifies the routine and the various subroutines that it references. Conditions for which the subroutine is used are also provided.

The lists are organized by module, as described in the previous subsection. Five tables are provided to address the following three modules:

- Setup module (one table),
- Signalized intersection module (three tables), and
- Performance measures module (one table).

The initial queue delay module does not have a linkage list because it does not call any specific routines.

The linkage list for the setup module is provided in Exhibit 31-57. The main routines are listed in Column 1 and were previously identified in Exhibit 31-53.

Exhibit 31-57
Setup Module Routines

Routine	Subroutine	Conditions for Use
InitialSetupRoutine	Compute change period ($Y + R_c$).	None
	Compute initial estimate of cycle length C .	None
PeriodVolumeSetup	a. Compute period volume before initial queue analysis, and b. Restore period volume if initial queue analysis conducted.	Used for multiple-period analysis
	a. Save input volume as it will be overwritten if initial queue is present, and b. Restore input volume if initial queue analysis conducted.	Used for single-period analysis
InitialCapacityEstimate	getPermissiveLeftServiceTime (computes g_{ul} , the duration of the permitted period that is not blocked by an opposing queue)	Used if subject phase serves a left-turn movement with: a. permitted mode, or b. protected-permitted mode
	getPermissiveLeftEffGreen (computes g_{pl} , the duration of the permitted green for permitted left-turn movements)	Used if subject phase serves a left-turn movement with: a. permitted mode, or b. protected-permitted mode
	Define lane groups for each approach.	None
	Establish initial estimate of lane group volume, saturation flow rate, number of lanes capacity.	None
	Establish initial estimate of proportion turns in a shared-lane lane group.	Used for shared-lane lane groups
	PermittedSatFlow (computes permitted left-turn saturation flow rate s_p)	Used if lane group serves a left-turn movement with protected-permitted mode
	getParkBusSatFlowAdj (computes combined parking and bus blockage sat. flow adjustment factors)	Used for each lane "outside" lane group
	Establish initial estimate of queue service time g_s	None
InitialQueueSetup	Distribute input movement initial queue to corresponding lane groups.	Used for first analysis period
	Assign residual queue from last period to initial of current period, and distribute initial queue among affected lane groups.	Used for second and subsequent analysis periods

The linkage list for the signalized intersection module is provided in Exhibit 31-58 and Exhibit 31-59. The main routines are listed in Column 1 of each exhibit and were previously identified in Exhibit 31-54. The ComputeQAPolygon routine is complex enough to justify the presentation of its subroutines in a separate linkage list. This supplemental list is provided in Exhibit 31-60.

Routine	Subroutine	Conditions for Use
InitialPortionOnGreen	Compute portion arriving during green P .	None
PedBikeEffectOnSatFlow	PedBikeEffectOnLefts	Used if subject phase serves a left-turn movement with: a. permitted mode, or b. protected-permitted mode
	PedBikeEffectOnRights	Used if subject phase serves a right-turn movement
	PedBikeEffectOnLeftsUnopposed	Used if subject phase serves a left-turn movement with split phasing
ComputePermServeTime	getPermissiveLeftServiceTime (computes g_u , the duration of the permitted period that is not blocked by an opposing queue)	Used if subject phase serves a left-turn movement with: a. permitted mode, or b. protected-permitted mode
	getPermissiveLeftEffGreen (computes g_p , the duration of the permitted green for permitted left-turn movements)	Used if subject phase serves a left-turn movement with: a. permitted mode, or b. protected-permitted mode
ComputeTimeToFirstBlk	getTimetoFirstBlk (computes g_r , the time before the first left-turning vehicle arrives and blocks the shared lane)	Used if subject phase serves a left-turn movement in a shared lane with: a. permitted mode, or b. protected-permitted mode
ComputeVolumePortions -AndSatFlow	PermittedSatFlow (computes permitted left-turn saturation flow rate s_p)	Used if lane group serves a left-turn movement with protected-permitted mode
	PortionTurnsInSharedTRLane (computes proportion of right-turning vehicles in shared lane P_R)	Used if approach has exclusive left-turn lane and subject lane group is a shared lane serving through and right-turning vehicles
	SatFlowforPermExclLefts	Used if lane group serves a left-turn movement with a permitted mode in an exclusive lane
	PortionTurnsInSharedLTRLane (computes proportion of right-turning vehicles in shared lane P_R and proportion of left-turning vehicles in shared lane P_L)	Used if approach has a shared lane serving left-turn and through vehicles
ComputeQAPolygon	QAP_ProtPermExclLane	Used if lane group serves a left-turn movement in an exclusive lane with the protected-permitted mode
	QAP_ProtMvmtExclLane	Used if lane group's movement has an exclusive lane and is serviced with protected mode
	QAP_ProtSharedLane	Used if lane group has: a. shared lane with through and right-turning movements b. a shared lane with through and left-turning movements served with split phasing
	QAP_PermLeftExclLane	Used if lane group serves a left-turn movement in an exclusive lane with the permitted mode
	QAP_PermSharedLane	Used if lane group serves a left-turn movement in a shared lane with the permitted mode

Exhibit 31-58

Signalized Intersection Module:
Main Routines

Exhibit 31-59
Signalized Intersection
Module: Main Routines
(continued)

Routine	Subroutine	Conditions for Use
Volume Computations	Determine call rate to extend green λ	None
	Determine call rate to activate a phase q_v, q_p	None
MaximumAllowable-Headway	Compute maximum allowable headway for each lane group MAH .	Calculations vary depending on lane group movements, lane assignment, phase sequence, and left-turn operational mode
	Compute equivalent maximum allowable headway for each phase and timer MAH^* .	None
ComputeAverage-PhaseDuration	Compute probability of green extension p .	Computed for all phases except for the timer that serves the protected left-turn movement in a shared lane
	Compute maximum queue service time for all lane groups served during the phase.	None
	Compute probability of phase termination by extension to maximum limit (i.e., max out).	None
	Compute green extension time g_e .	None
	Compute probability of a phase call p_c .	None
	Compute unbalanced green duration G_u .	None
	Compute average phase duration D_p .	None

Routine	Subroutine	Conditions for Use
QAP_ProtPermExclLane	ADP_ProtPermExcl (compute baseline first-term back-of-queue estimate Q_{lb})	Used for lane groups with left-turn movements in exclusive lane and served by protected-permitted mode
	getUniformDelay (compute baseline uniform delay d_{lb})	None
	Compute queue service time g_s .	None
	Compute lane group available capacity.	None
	Compute movement capacity.	None
QAP_ProtMvmtExclLane	ADP_ProtMvmt (compute baseline first-term back-of-queue estimate Q_{lb})	Used for lane groups with one service period
	getUniformDelay (compute baseline uniform delay d_{lb})	None
	Compute queue service time g_s .	None
	Compute lane group available capacity.	None
	Compute movement capacity.	None
QAP_ProtSharedLane	ADP_ProtMvmt (compute baseline first-term back-of-queue estimate Q_{lb})	Used for lane groups with one service period
	getUniformDelay (compute baseline uniform delay d_{lb})	None
	Compute queue service time g_s .	None
	Compute lane group available capacity.	None
	Compute movement capacity.	None
QAP_PermLeftExclLane	ADP_PermLeftExclLane (compute baseline first-term back-of-queue estimate Q_{lb})	Used for lane groups with left-turn movements in exclusive lane and served by permitted mode
	getUniformDelay (compute baseline uniform delay d_{lb})	None
	Compute queue service time g_s .	None
	Compute lane group available capacity.	None
	Compute movement capacity.	None
QAP_PermSharedLane	ADP_PermSharedMvmt (compute baseline first-term back-of-queue estimate Q_{lb})	Used for shared-lane lane groups with a permitted left-turn movement
	ADP_ProtMvmt (compute baseline first-term back-of-queue estimate Q_{lb})	Used for lane groups with one service period
	ADP_ProtPermShared (compute baseline first-term back-of-queue estimate Q_{lb})	Used for lane groups with left-turn movements in shared-lane lane group and served by protected-permitted mode
	getUniformDelay (compute baseline uniform delay d_{lb})	None
	Compute queue service time g_s .	None
	Compute lane group available capacity.	None
	Compute movement capacity.	None

Exhibit 31-60

Signalized Intersection Module:
ComputeQAPolygon Routines

Exhibit 31-61
Performance Measures
Module Routines

The linkage list for the performance measures module is provided in Exhibit 31-61. The main routines are listed in Column 1 and were previously identified in Exhibit 31-56.

Routine	Subroutine	Conditions for Use
EstimateIncrementalDelay	Compute incremental delay d_2 and second-term back-of-queue estimate Q_2 .	None
QueueStorageRatio	Compute queue storage ratio L_q .	None

8. SIMULATION EXAMPLES

INTRODUCTION

This section illustrates the use of alternative evaluation tools to evaluate the operation of a signalized intersection. The intersection described in Example Problem 1 from Chapter 18 is used for this purpose. There are no limitations in this example that would suggest the need for alternative tools. However, it is possible to introduce situations, such as short left-turn bays, in which an alternative tool might provide a more realistic assessment of intersection operation.

The basic intersection layout of the example intersection is shown in Exhibit 18-37. The left-turn movements on the north-south street operate under protected-permitted control and lead the opposing through movements (i.e., a lead-lead phase sequence). The left-turn movements on the east-west street operate as permitted. To simplify the discussion, the pedestrian and parking activity is removed. A pretimed signal operation is used.

EFFECT OF STORAGE BAY OVERFLOW

The effect of left-turn storage bay overflow is described in this subsection as a means of illustrating the use of alternative tools. The automobile methodology in Chapter 18 can be used to compute a queue storage ratio that compares the back-of-queue estimate with the available storage length. This ratio is used to identify bays that have inadequate storage. Overflow from a storage bay can be expected to reduce approach capacity and increase the approach delay. However, these effects of bay overflow are not addressed by the automobile methodology.

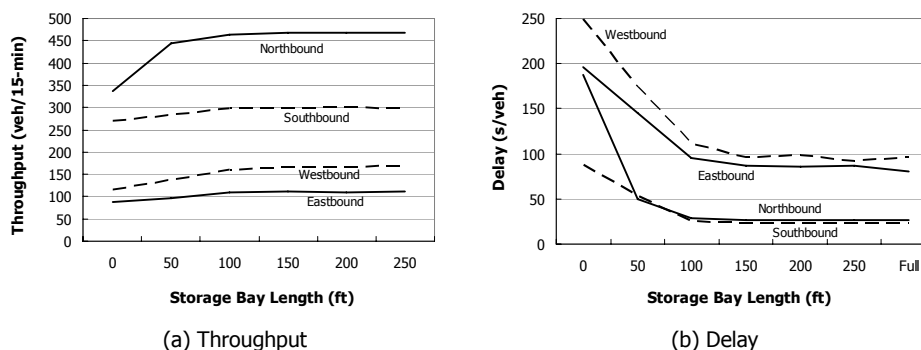
Effect of Overflow on Approach Capacity and Delay

A simulation software product was selected as the alternative tool for this analysis. The intersection was simulated for a range of storage bay lengths from 0 to 250 ft. All other input data remained the same. The results presented here represent the average of 30 simulation runs for each case.

The effect of bay overflow was assessed by examining the relationship between bay length, approach throughput, and approach delay. Exhibit 31-62 shows this effect. The throughput on each approach is equal to the demand volume when storage is adequate but drops off when the bay length is decreased.

A delay comparison is also presented in Exhibit 31-62. The delay on each approach increases as bay length is reduced. The highest delay is associated with a zero-length bay, which is effectively a shared lane. The zero-length case is included here to establish a boundary condition. The delay value becomes excessive when overflow occurs. This situation often degrades into oversaturation, and a proper assessment of delay would require a multiple-period analysis to account for the buildup of long-term queues.

Exhibit 31-62
Effect of Storage Bay Length
on Throughput and Delay



For case-specific applications, parameters that could influence the evaluation of bay overflow include the following:

- Number of lanes for each movement,
- Demand volumes for each movement,
- Impedance of left-turning vehicles by oncoming traffic during permitted periods,
- Signal timing plan (cycle length and phase times),
- Factors that affect the number of left-turn sneakers for left-turn movements that have permitted operation, and
- Other factors that influence the saturation flow rates.

The example intersection described here had two through lanes in all directions. If only one through lane had existed, the blockage effect would have been much more severe.

Effect of Overflow on Through Movement Capacity

This part illustrates how an alternative tool can be used to model congestion due to storage bay overflow. An example was set up involving constant blockage of a through lane by left-turning vehicles. This condition arises only under very severe oversaturation.

The following variables are used for this examination:

- Cycle length is 90 s,
- Effective green time is 41 s, and
- Saturation flow rate is 1,800 veh/h/ln.

The approach has two through lanes. Traffic volumes were sufficient to overload both lanes, so that the number of trips processed by the simulation model was determined to be an indication of through movement capacity. With no storage bay overflow effect, this capacity is computed as 1,640 veh/h ($= 3,600 \times 41/90$). So, in a 15-min period, 410 trips were processed on average when there was no overflow.

Exhibit 31-63 shows the effect of the storage bay length on the through movement capacity. The percentage of the full capacity is plotted as a function of the storage bay length over the range of 0 to 600 ft. As expected, a zero-length bay reduces the capacity to 50% of its full value because one lane would be

constantly blocked. At the other extreme, the “no blockage” condition, achieved by setting the left-turn volume to zero, indicates that the full capacity was available. The loss of capacity is more or less linear for storage lengths up to 600 ft, at which point about 90% of the full capacity is achieved.

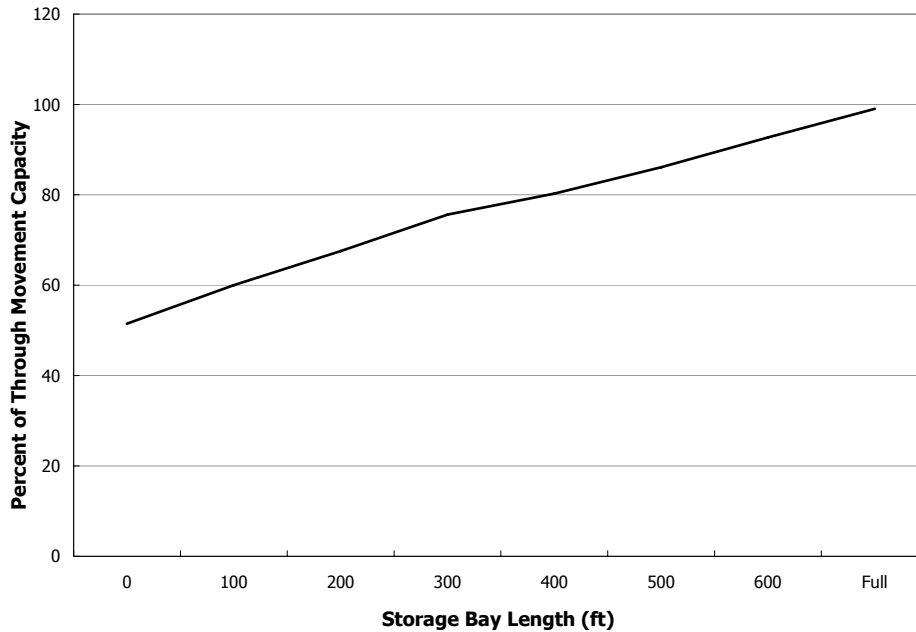


Exhibit 31-63
Effect of Storage Bay Length on Capacity

Bay overflow is a very difficult phenomenon to deal with analytically, and a substantial variation in its treatment is expected among alternative tools. The main issue for modeling is the behavior of left-turning drivers denied access to the left-turn bay because of the overflow. The animated graphics display produced by some tools can often be used to examine this behavior and assess its validity. Typically, selected model parameters can be adjusted so that the resulting behavior is more realistic.

EFFECT OF RIGHT-TURN-ON-RED OPERATION

The treatment of right-turn-on-red (RTOR) operation in the automobile methodology is limited to the removal of RTOR vehicles from the right-turn demand volume. If the right-turn movement is served by an exclusive lane, the methodology offers that the RTOR volume can be estimated as equal to the left-turn demand of the complementary cross street left-turn movement, whenever this movement is provided a left-turn phase. Given the simplicity of this treatment, it may be preferable to use an alternative tool to evaluate explicitly RTOR operation under the following conditions:

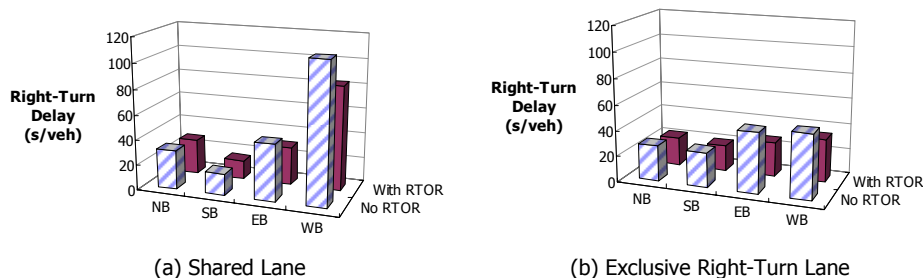
- RTOR operation occurs at the intersection,
- Right turns are a critical element of the operation,
- An acceptable level of service depends on RTOR movements, or
- Detailed phasing alternatives involving RTOR are being considered.

The remainder of this subsection examines the RTOR treatment offered in the automobile methodology. The objective of this discussion is to illustrate when alternative tools should be considered.

Effect of Right-Turn Lane Allocation

This part examines the effect of the lane allocation for the right-turn movement. The lane-allocation scenarios considered include (a) provision of a shared lane for the right-turn movement and (b) provision of an exclusive right-turn lane. Exhibit 31-64 shows the results of the analysis with the intersection in Example Problem 1 of Chapter 18. The intersection was simulated with and without the RTOR volume.

Exhibit 31-64
Effect of Right-Turn-on-Red
and Lane Allocation on Delay



For the most part, there are only minimal differences in delay when RTOR is allowed relative to when it is not allowed. The northbound and southbound approaches had no shadowing opportunities because the eastbound and westbound movements did not have a protected left-turn phase. As a result, the effect of lane allocation and RTOR operation was negligible for the northbound and southbound right-turn movements. In contrast, the eastbound and westbound right-turn movements were shadowed by the protected left-turn phases for the northbound and southbound approaches. As a result, the effect of lane allocation was more notable for the eastbound and the westbound right-turn movements.

Effect of Right-Turn Demand Volume

This part examines the effect of right-turn demand volume on right-turn delay, with and without RTOR allowed. The right-turn volumes varied from 100 to 400 veh/h on all approaches. Exclusive right-turn storage bays were provided on each approach.

The results are shown in Exhibit 31-65. They indicate that delay to the northbound and southbound right-turn movements was fairly insensitive to right-turn volume, with or without RTOR allowed. The available green time on these approaches provided adequate capacity for the right turns. RTOR operation provided about a 25% delay reduction.

The delay to the eastbound and westbound right-turn movements increased rapidly with right-turn volume when RTOR was not allowed. At 300 veh/h and no RTOR, the right-turn delay becomes excessive in both directions. With RTOR, delay is less sensitive to right-turn volume. This trend indicates that the additional capacity provided by RTOR is beneficial for higher right-turn volume levels.

The treatment of RTOR suggested in automobile methodology (i.e., removal of the RTOR vehicles from the right-turn volume) was also examined. The simulation analysis was repeated with the right-turn volumes reduced in this manner to explore the validity of this treatment.

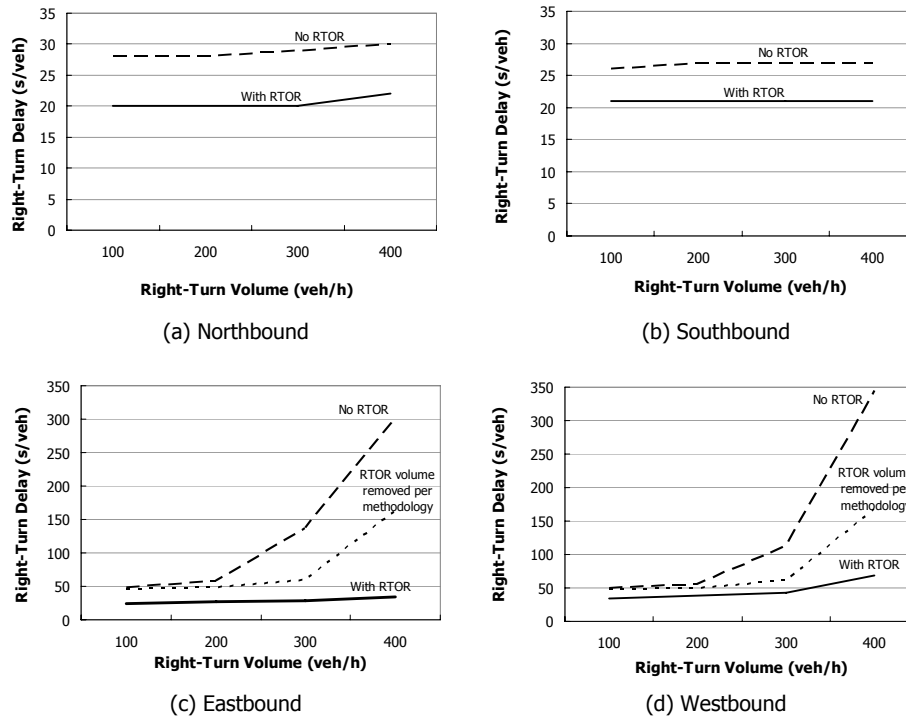


Exhibit 31-65
Effect of Right-Turn-on-Red and
Right-Turn Volume on Delay

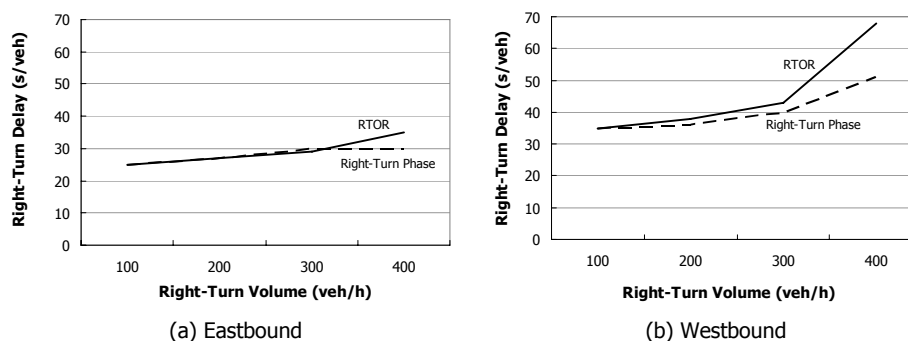
The results of this analysis are shown for the eastbound and westbound approaches in Exhibit 31-65. The trends shown suggest that the treatment yields a result that is closer to the “with RTOR” case, as intended. However, use of the treatment in this case could still lead to erroneous conclusions about right-turn delay at high right-turn volumes.

Effect of a Protected Right-Turn Phase

This part examines the effect of adding a protected right-turn phase (with RTOR not allowed), relative to just allowing RTOR. The example intersection was modified to include an exclusive right-turn storage bay and a protected right-turn phase for both the eastbound and the westbound approaches. Each phase was timed concurrently with the complementary northbound or southbound left-turn phase, as appropriate. The results are shown in Exhibit 31-66. The protected phase does not improve over RTOR operation at low volume levels. However, it does provide some delay reduction at the high end of the volume scale.

Exhibit 31-66

Effect of Right-Turn-on-Red
and Right-Turn Protection on
Delay



Summary

This examination indicates that RTOR operation can have some effect on right-turn delay. The effect is most notable when there are no shadowing opportunities in the phase sequence for right-turn service or the right-turn volume is high. The use of an alternative tool to evaluate RTOR operation may provide a more realistic estimate of delay than simple removal of RTOR vehicles from the right-turn demand volume, as suggested in Chapter 18.

EFFECT OF SHORT THROUGH LANES

One identified limitation of the automobile methodology is its inability to evaluate short through lanes that are added or dropped at the intersection. The intersection described in Example Problem 1 from Chapter 18 is used in this subsection to illustrate the effect of short through lanes.

Several alternative tools can address the effect of short through lanes. Each tool will have its own unique method of representing lane drop or add geometry and models of driver behavior. Some degree of approximation is involved with all evaluation tools.

The question under consideration is, "How much additional through traffic could the northbound approach accommodate if a lane were added both 150 ft upstream and 150 ft downstream of the intersection?" The capacity of the original two northbound lanes was computed as 1,778 veh/h (i.e., 889 veh/h/ln) by using the automobile methodology. Then, the simulation tool's start-up lost time and saturation headway parameters were adjusted so that the simulation tool produced the same capacity. It was found in this case that a 2.3-s headway and 3.9-s start-up lost time produced the desired capacity.

Finally, the additional through lane was added to the simulated intersection and the process of determining capacity was repeated. On the basis of an average of 30 runs, the capacity of the additional lane was computed as 310 veh/h. Theoretically, the addition of a full lane would increase the capacity by another 889 veh/h, for a total of 2,667 veh/h.

The alternative tool indicates that the additional lane contributes only 0.35 equivalent lane ($= 310/889$). This result cannot be stated as a general conclusion that applies to all cases because other parameters (such as the signal timing plan and the proportion of right turns in the lane group) will influence the results. More important, the results are likely to vary among alternative tools given the likely differences in their driver behavior models.

EFFECT OF CLOSELY SPACED INTERSECTIONS

The automobile methodology does not account for the effect of queue spillback from a downstream signal or demand starvation from an upstream signal. It is generally accepted that simulation of these effects is desirable when two closely spaced signalized intersections interact with each other in this manner.

The effect of closely spaced intersections is examined in this part. Consider two intersections separated by 200 ft along the north-south roadway. They operate with the same cycle length and the same northbound and southbound green time. To keep the problem simple, only through movements are allowed at these intersections. The northbound approach is used in this discussion to illustrate the effect of the adjacent intersection. The layout of this system and the resulting lane blockage are illustrated in Exhibit 31-67.

This exhibit illustrates both spillback and demand starvation at one point in the cycle. For the northbound direction, traffic queues have spilled back from the downstream intersection to block the upstream intersection. For the southbound direction, the traffic at the upstream intersection is prevented from reaching the downstream intersection by the red signal at the upstream intersection. Valuable green time was being wasted in both travel directions at the southern intersection.

Exhibit 31-68 illustrates the relationship between signal offset and the performance of the northbound travel direction. In terms of capacity, the exhibit shows that, under the best case condition (i.e., zero offset), the capacity is maintained at a value slightly above the demand volume. Under the worst-case conditions, the capacity is reduced to slightly below 1,000 veh/h. The demand volume-to-capacity ratio under this condition is about 1.7.

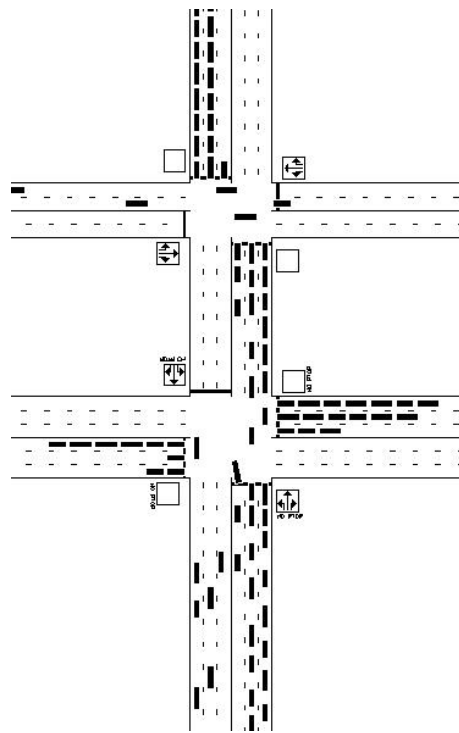
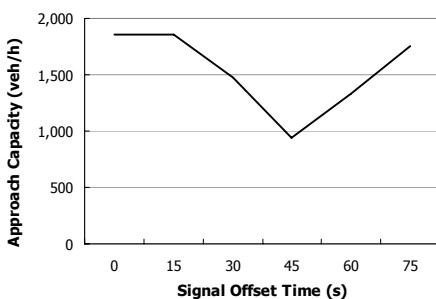
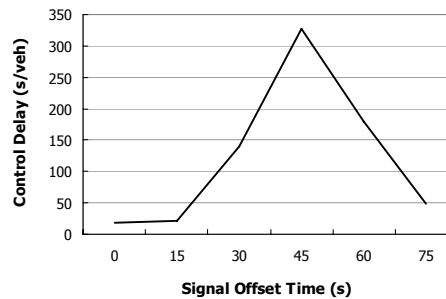


Exhibit 31-67
Closely Spaced Intersections



(a) Approach Capacity



(b) Control Delay

Exhibit 31-68
Effect of Closely Spaced
Intersections on Capacity and
Delay

The effect of signal offset time on the delay to northbound traffic approaching the first intersection is also shown in Exhibit 31-68. As expected, the delay is minimal under favorable offsets, but it increases rapidly as the offset becomes less favorable. Delay is at its maximum value with a 45-s offset time. The large value of delay suggests that approach is severely oversaturated.

The delay reported by most simulation tools represents that incurred by vehicles when they *depart* the system during the analysis period, as opposed to the delay incurred by vehicles that *arrive* during the analysis period. The latter measure represents the delay reported by the automobile methodology.

For oversaturated conditions, the delay reported by a simulation tool may be biased when the street system is not adequately represented. This bias occurs when the street system represented to the tool does not physically extend beyond the limits of the longest queue that occurs during the analysis period.

The issues highlighted in the preceding paragraphs must be considered when an alternative tool is used. Specifically, a multiple-period analysis must be conducted that temporally spans the period of oversaturation. Also, the spatial boundaries of the street system must be large enough to encompass all queues during the saturated time periods. A more detailed discussion of multiple-period analyses is presented in Chapter 7, Interpreting HCM and Alternative Tool Results.

9. REFERENCES

1. *National Transportation Communications for ITS Protocol: Object Definitions for Actuated Traffic Signal Controller (ASC) Units–1202*. National Electrical Manufacturers Association, Rosslyn, Va., Jan. 2005.
2. Messer, C. J., and J. A. Bonneson. *NCHRP Web Document 12: Capacity Analysis of Interchange Ramp Terminals*. Transportation Research Board, National Research Council, Washington, D.C., April 1997.
3. Zegeer, C., K. Opiela, and M. Cynecki. *Pedestrian Signalization Alternatives*. Report FHWA/RD-83/102. Federal Highway Administration, Washington, D.C., 1983.
4. Lieberman, E. B. Determining the Lateral Deployment of Traffic on an Approach to an Intersection. In *Transportation Research Record 772*, Transportation Research Board, National Research Council, Washington, D.C., 1980, pp. 1–5.
5. Bonneson, J. Lane Volume and Saturation Flow Rate for a Multilane Intersection Approach. *Journal of Transportation Engineering*, Vol. 124, No. 3, 1998, pp. 240–246.
6. Bonneson, J. A., and P. T. McCoy. *NCHRP Report 395: Capacity and Operational Effects of Midblock Left-Turn Lanes*. Transportation Research Board, National Research Council, Washington, D.C., 1997.
7. Teply, S. Accuracy of Delay Surveys at Signalized Intersections. In *Transportation Research Record 1225*, Transportation Research Board, National Research Council, Washington, D.C., 1989, pp. 24–32.
8. Reilly, W. R., and C. C. Gardner. Technique for Measuring Delay at Intersections. In *Transportation Research Record 644*, Transportation Research Board, National Research Council, Washington, D.C., 1977, pp. 1–7.
9. Powell, J. L. Field Measurement of Signalized Intersection Delay for 1997 Update of the *Highway Capacity Manual*. In *Transportation Research Record 1646*, Transportation Research Board, National Research Council, Washington, D.C., 1998, pp. 79–86.

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