CHAPTER 31
SIGNALIZED INTERSECTIONS: SUPPLEMENTAL

CONTENTS

LIST OF EXHIBITS

1. INTRODUCTION

Chapter 31 is the supplemental chapter for Chapter 19, Signalized Intersections, which is found in Volume 3 of the *Highway Capacity Manual* (HCM). This chapter presents detailed information about the following aspects of the Chapter 19 motorized vehicle methodology:

- Procedures are described for computing actuated phase duration and pretimed phase duration.
- Procedures are described for computing saturation flow rate adjustment factors to account for the presence of pedestrians, bicycles, and work zones.
- A procedure is described for computing uniform delay by using the queue accumulation polygon (QAP) concept. The procedure is extended to shared-lane lane groups and lane groups with permitted turn movements.
- A procedure is described for computing queue length and queue storage ratio.

This chapter provides a simplified version of the Chapter 19 motorized vehicle methodology that is suitable for planning applications. The chapter also describes techniques for measuring control delay and saturation flow rate in the field and provides details about the computational engine that implements the Chapter 19 motorized vehicle methodology. Finally, this chapter provides three example problems that demonstrate the application of the motorized vehicle, pedestrian, and bicycle methodologies to a signalized intersection.

2. CAPACITY AND PHASE DURATION

This section describes five procedures related to the calculation of capacity and phase duration. The first procedure is used to calculate the average duration of an actuated phase, and the second 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, and the fifth computes the work zone saturation flow rate adjustment factor. 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. When 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 the list above 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 31-1. 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 31-1

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

where

D_p = phase duration (s),

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

Y = yellow change interval (s),

R_c = red clearance interval (s),

g_s = queue service time (s),

g_e = green extension time (s).

The relationship between the variables in Equation 31-1 is shown in Exhibit 31-1 with a QAP. Key variables shown in the exhibit are defined for Equation 31-1 and in the following list:

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

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

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

g = effective green time (s),

s = adjusted saturation flow rate (veh/h/ln),

q_g = arrival flow rate during the effective green time = $P\, q\, C/g$ (veh/s),

q = arrival flow rate (veh/s),

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

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

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

Exhibit 31-1
Time Elements Influencing Actuated Phase Duration

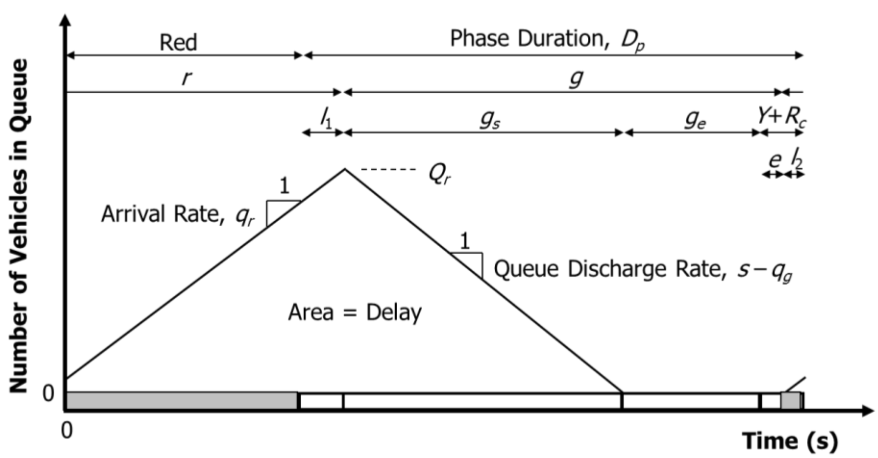


Exhibit 31-1 shows the relationship between phase duration and queue size for the average signal cycle. During the red interval, vehicles arrive at a rate of q_r and form a queue. The queue reaches its maximum size l_1 seconds after the green interval starts. At this time, the queue begins to discharge 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.

Equation 31-2

The effective green time for the phase is computed with Equation 31-2.

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

where all variables are as previously defined.

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 at which each noncoordinated phase must end. The force-off settings are used to ensure 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 for 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.

Right-Turn Overlap Duration

If a right-turn lane group is operated in a protected or protected-permitted mode, then the protected indication is assumed to be provided as a right-turn overlap with the complementary left-turn phase on the intersecting roadway. In this manner, the right-turn protected interval duration is dictated by the duration of the complementary left-turn phase (which is determined by the left-turn phase settings, left-turn detection, and left-turn volume). The procedures described in this subsection are used to determine the average duration of the complementary left-turn lane phase (and thus the protected right-turn interval duration).

The right-turn permitted interval duration is dictated by the phase settings, detection, and volume associated with the right-turn movement and its adjacent through movement. The procedures described in this subsection are used to determine the average duration of the phase serving the right-turn movement in a permitted manner.

Volume Computations

This subsection 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. The call rate is represented in the analysis by the flow rate parameter. This parameter represents an adjusted flow rate that accounts for the tendency of drivers to form "bunches" (i.e., randomly formed platoons). The flow rate parameter for the phase is computed as shown by Equation 31-3 with Equation 31-4 and Equation 31-5.

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

Equation 31-3

with

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

Equation 31-4

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

Equation 31-5

where

- λ^* = flow rate parameter for the phase (veh/s);
- λ_i = flow rate parameter for lane group i (i = 1, 2, . . . , 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).

Using Equation 31-6, Equation 31-7, and Equation 31-8, 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 31-6

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

Equation 31-7

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

Equation 31-8

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), and

all other variables are as previously defined.

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 a common barrier (i.e., one phase in each ring) and simultaneous gap-out is enabled, then the call rate for either phase is based on the combined set of lane groups being served by the two phases. To model this behavior, 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 19-2). 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 the lane groups associated with Phase 6 in applying Equation 31-3 through Equation 31-8 for Phase 6. Similarly, the lane groups associated with Phase 6 are combined with the lane groups associated with Phase 2 in applying 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 the lane groups associated with Phase 8 in evaluating Phase 8. Similarly, the lane groups associated with Phase 8 are combined with the lane groups 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 subsection summarizes the procedure used to construct the QAP associated with a lane group. This polygon defines the queue size for a traffic movement as a function of time during the cycle. The procedure is described more fully in Section 3; it is discussed here to illustrate its use in calculating queue service time.

For polygon construction, all flow rate variables are converted to common units of vehicles per second per lane. The presentation in this subsection 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 31-1 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 Equation 31-9 for estimating queue service time.

Equation 31-9

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

where P is the proportion of vehicles arriving during the green indication (decimal), s is the adjusted saturation flow rate (veh/h/ln), and all other variables are as previously defined.

The polygon in Exhibit 31-1 applies to some types of lane groups. Other polygon shapes are possible. A detailed procedure for constructing polygons is described in Section 3.

Maximum Allowable Headway

This subsection 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 MAH for each lane group served by the subject phase. Step B combines 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 the detector is located so that only the subject traffic movement travels over this detector during normal operation.

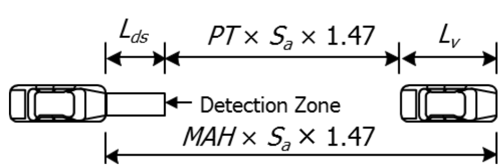
The detector length and detection mode input data are specified by movement group. When these data describe a through movement group, it is reasonable to assume they also describe the detection in any shared-lane lane groups that serve the through movement. This assumption allows the movement group inputs 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 MAHs would then be combined for the phase that serves these lanes.

Concepts

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. 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 31-2. The two vehicles shown are traveling from left to right and have a headway equal to MAH so that the second vehicle arrives at the detector the instant the passage time is set to time out.

Exhibit 31-2
Detection Design and Maximum Allowable Headway



According to Exhibit 31-2, Equation 31-10 with Equation 31-11 can be derived for estimating MAH for stop-line detection operating in the presence mode.

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

Equation 31-10

with

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

Equation 31-11

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} = percentage 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 31-12.

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

Equation 31-12

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

Equation 31-10 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 MAH equals the passage time setting PT.

A. Determine Maximum Allowable Headway

Equation 31-10 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 MAH equals the passage time setting PT.

MAH for lane groups serving through vehicles is calculated with Equation 31-13.

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

Equation 31-13

where

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

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

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

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

MAH for a left-turn movement served in exclusive lanes with the protected mode (or protected-permitted mode) is based on Equation 31-13, but the equation is adjusted as shown in Equation 31-14 to account for the slower speed of the left-turn movement.

Equation 31-14

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

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).

MAH for left-turning vehicles served in a shared lane with the protected-permitted mode is calculated as shown in Equation 31-15.

Equation 31-15

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

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

MAH 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 31-16 addresses these adjustments.

Equation 31-16

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

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 = 2.5 (s).

MAH for right-turning vehicles served in an exclusive lane with the protected mode is computed with Equation 31-17.

Equation 31-17

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

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 31-17 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.

Equation 31-18 and Equation 31-19, respectively, are used to estimate MAH for left- and right-turning vehicles that are served in a shared lane with the permitted mode.

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

Equation 31-18

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

Equation 31-19

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 *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 do 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 *MAH** for the phase is computed from Equation 31-20.

Equation 31-20

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

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 31-21 is applicable.

Equation 31-21

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

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 *MAH** for the phase is computed with Equation 31-22.

Equation 31-22

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

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 *MAH** for the phase is computed with Equation 31-23.

Equation 31-23

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

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 *MAH** for the phase is computed with Equation 31-24.

Equation 31-24

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

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

Equation 31-25

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

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 *MAH** for the phase equals the MAH computed for the lane group.

ii. If there is more than one lane group, then 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 operation does not influence the duration of the left-turn phase. The left-turn phase will be set to minimum recall and will extend to its minimum value before terminating.

2. If simultaneous gap-out is enabled and the phase ends at the barrier, then MAH^* for the phase is computed with Equation 31-26, where the summations shown are for all lane groups served by the subject (or concurrent) phase.

Equation 31-26

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

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 31-26 does not apply.

Equivalent Maximum Green

In coordinated-actuated operation, the force-off points are used to constrain the duration of the noncoordinated phases. Although the maximum green setting is also available to provide additional constraint, 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.

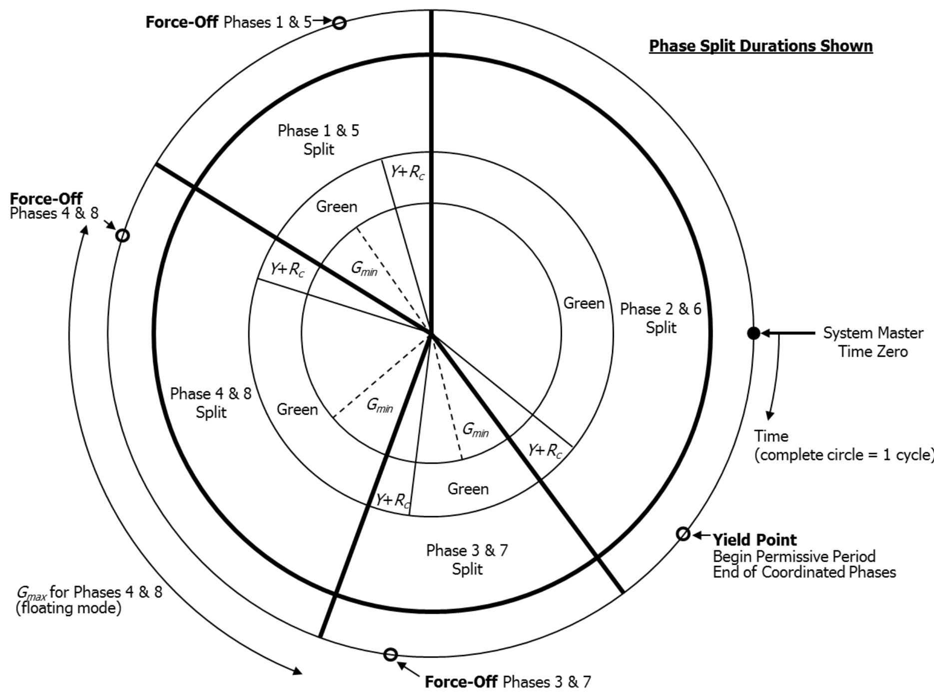
The relationship between the force-off points, yield point, and phase splits is shown in Exhibit 31-3. The yield point is associated with the coordinated phases (i.e., Phases 2 and 6). It coincides with the start of the yellow change interval. If a call for service by one of the noncoordinated phases 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.

The force-off and yield points for common phase pairs are shown in Exhibit 31-3 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 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. These computations are based on the relationships shown in Exhibit 31-3.

Exhibit 31-3
Force-Off Points, Yield Point, and Phase Splits



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 subsection 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 31-3 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 by first establishing the fixed force-off points (as shown in Exhibit 31-3) and then computing the average duration of each noncoordinated phase. The calculation process is iterative. For the first iteration, the equivalent maximum green is set equal to the phase split less the change period. Thereafter, the equivalent maximum green for a specific phase is computed as the difference between its force-off point and the sum of the previous phase durations, starting with the first noncoordinated phase. Equation 31-27 illustrates this computation for Phase 4, using the ring structure shown in Exhibit 19-2. A similar calculation is performed for the other phases.

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

Equation 31-27

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_3 = change period (yellow change interval plus red clearance interval) for Phase 3 (s).

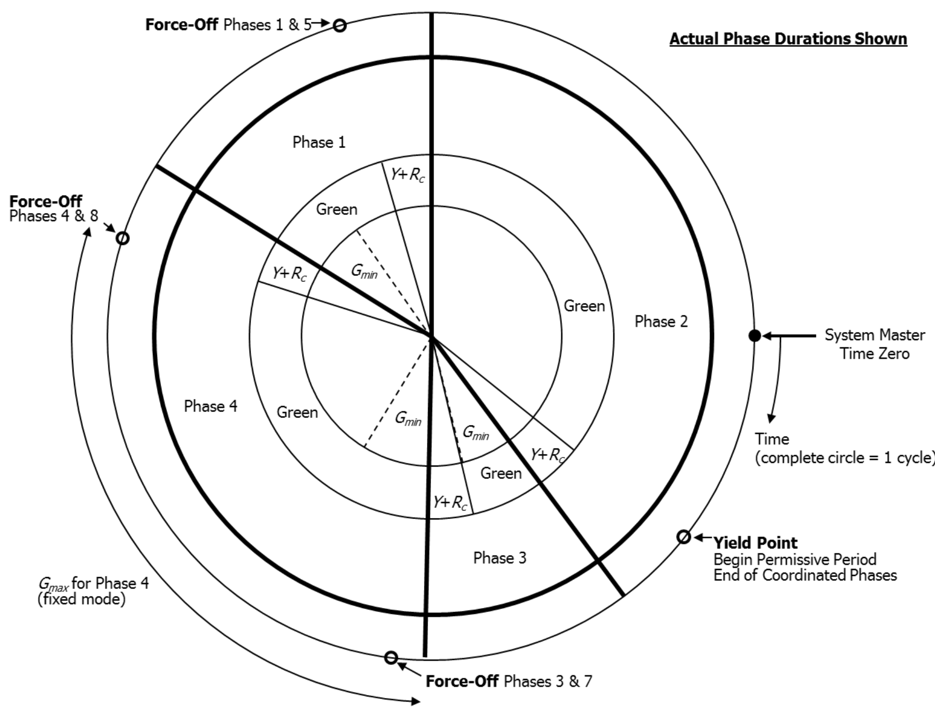
The maximum green obtained from Equation 31-27 is shown in Exhibit 31-4 for the ring that serves Phases 1, 2, 3, and 4. Unlike Exhibit 31-3, Exhibit 31-4 illustrates the *actual* average phase durations for a given cycle. In this example, Phase 3 timed to its minimum green and terminated. It never reached 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 31-3). 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.

Average Phase Duration

This subsection 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.

Exhibit 31-4
Example Equivalent Maximum Green for Fixed Force Mode



The calculation steps that constitute 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 subsection titled Equivalent Maximum Green describes how to compute this value.

D. Construct Queue Accumulation Polygon

The QAP is constructed for each lane group and corresponding phase by using the known flow rates and signal timing. The procedure for constructing this polygon is summarized in the previous subsection 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 QAP constructed in the previous step. For through movements or left-turn movements served during a left-turn phase, the polygon in Exhibit 31-1 applies and Equation 31-9 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 is then aggregated to a phase-specific value. The procedure for computing this parameter is described in the previous subsection 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 MAH^* is described in the previous subsection 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 Equation 31-28.

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

Equation 31-28

where n is the number of extensions before the green interval reaches its maximum limit, G_{max} is the maximum green setting (s), and all 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 Equation 31-29.

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

Equation 31-29

where p is the probability of a call headway being less than the maximum allowable headway.

J. Compute Green Extension Time

The average green extension time is computed for each actuated phase with Equation 31-30.

Equation 31-30

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

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 subsection 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 by using Equation 31-31 with Equation 31-32 and Equation 31-33.

Equation 31-31

$$p_c = p_v\left(1-p_p\right) + p_p(1-p_v) + p_v\,p_p$$

with

Equation 31-32

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

Equation 31-33

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

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.

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 about 51% of all crossing pedestrians will push the button to place a call for pedestrian service (*1*).

M. Compute Unbalanced Green Duration

The unbalanced average green interval duration is computed for each actuated phase by using Equation 31-34 with Equation 31-35 and Equation 31-36.

Equation 31-34

$$G_u = G_{|veh,call}\,p_v\left(1-p_p\right) + G_{|ped,call}\,p_p(1-p_v) + \max\left(G_{|veh,call}, G_{|ped,call}\right) p_v\,p_p \le G_{max}$$

with

Equation 31-35

$$G_{|veh,call} = \max(l_1 + g_s + g_e, G_{min})$$

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

Equation 31-36

where

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

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

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

$G_{|ped,\mathrm{call}}$ = 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 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 31-37.

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

Equation 31-37

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 Phases 2 and 6 are serving Movements 2 and 6, respectively, on the major street (see Exhibit 19-2). 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 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 31-38 for the major-street phases.

Equation 31-38

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

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 31-39 applies for the minor-street phases.

Equation 31-39

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

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 31-39. 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 31-39.

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 Phases 2 and 6 are the coordinated phases serving Movements 2 and 6, respectively (see Exhibit 19-2). 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 $D_{p,t}$, which is calculated by using Equation 31-40.

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

   Equation 31-40

   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 all other variables are as previously defined.

   If Equation 31-40 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 31-40 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 31-40 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.

$$G = D_p - Y - R_c$$

Equation 31-41

where G is the green interval duration (s).

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, then the equilibrium cycle length is computed with Equation 31-42.

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

Equation 31-42

where C_e is the equilibrium cycle length (s) and i is the phase number. The sum in this equation includes all phases in Ring 1. The equilibrium cycle length is used in all subsequent calculations in which 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 provides useful information about phase performance. When max-out occurs, the phase ends without consideration of whether the queue is served or vehicles are in the dilemma zone. Hence, a phase that frequently terminates by max-out may have inadequate capacity and may be associated with more frequent rear-end crashes.

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 by using Equation 31-43 with Equation 31-44 and Equation 31-45.

Equation 31-43

$$p_x = p^{n_x}$$

with

Equation 31-44

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

Equation 31-45

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

where

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

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

n_x = number of calls necessary to extend the green to max-out.

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 there is an equilibrium lane flow rate that characterizes the collective choices of the population of drivers. Research indicates 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 (*2*).

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 31-46 is derived from this representation.

Equation 31-46

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

where

v_i = demand flow rate in lane i (veh/h/ln),

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

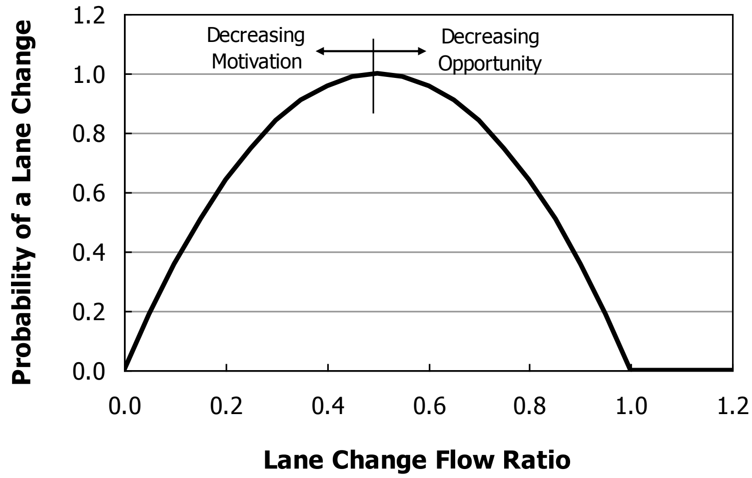
N_{th} = number of through lanes (shared or exclusive) (ln).

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 (*3*). 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 these field observations (*3*), 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) (*4*). Exhibit 31-5 illustrates the modeled relationship between lane change probability and the flow ratio in the traffic lanes upstream of the intersection, before deceleration occurs (*3*).

Exhibit 31-5
Probability of a Lane Change



Procedure

The procedure described in this subsection is generalized so 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 31-6:

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, area type, work zone presence, downstream lane blockage, and spillback) (veh/h/ln),

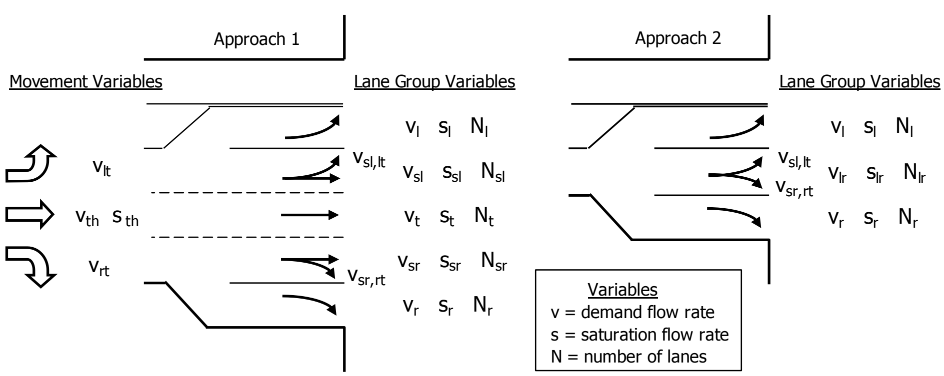
g_p = effective green time for permitted left-turn operation (s),

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 31-6
Input Variables for Lane Group Flow Rate Procedure



A. Compute Modified Through-Car Equivalents

Three modified through-car equivalent factors are computed for the left-turn movement. These factors are computed with Equation 31-47 through Equation 31-51.

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

Equation 31-47

Equation 31-48

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

Equation 31-49

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

with

Equation 31-50

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

Equation 31-51

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

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_L = equivalent number of through cars for a protected left-turning vehicle (= 1.05),

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 31-49 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 (as shown in Approach 2 in Exhibit 31-6), then Equation 31-52 is used to compute the average demand flow rate per lane (with N_{lr} = 1.0).

Equation 31-52

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

The modified through-car equivalent for permitted right-turning vehicles is computed with Equation 31-53.

Equation 31-53

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

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, E_R is the equivalent number of through cars for a protected right-turning vehicle (= 1.18), and all other variables are as previously defined.

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

If the opposing approach has two lanes serving through vehicles and the inside lane serves through and left-turn vehicles, then Equation 31-54 is used to compute the adjusted duration of permitted left-turn green time that is not blocked by an opposing queue g_u^*. This variable is then used in Equation 31-59 in replacement of the variable g_u. This adjustment is intended to reflect the occasional hesitancy of drivers to shift from the inside lane to the outside lane during higher-volume conditions for this approach-lane geometry. In all other cases of opposing approach-lane geometry, the variable g_u^* is not computed and Equation 31-59 is used as described in the text.

$$g_u^* = g_u + (g_{diff} \times P_{lc})$$

Equation 31-54

where

g_u^* = adjusted duration of permitted left-turn green time that is not blocked by an opposing queue (s), and

g_{diff} = supplemental service time (s).

Equation 31-107 in Section 3 can be used to calculate g_{diff}.

B. Estimate Shared-Lane Lane Group Flow Rate

The procedure to estimate the shared-lane lane group flow rate 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 are 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. The flow rate in the exclusive through lane group is then computed with Equation 31-56.

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

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.

Equation 31-57

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

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.

Equation 31-58

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

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 by using Equation 31-59 with Equation 31-60.

Equation 31-59

$$s_{sl} = \frac{s_{th}}{g_p}\left(g_f + \frac{g_{diff}}{1 + P_L\left[E_{L2,m} - 1\right]} + \frac{\min[g_p - g_f, g_u]}{1 + P_L\left[E_{L1,m} - 1\right]} + \frac{3{,}600\, n_s^*\, f_{ms}\, f_{sp}}{s_{th}}\right)$$

with

Equation 31-60

$$n_s^* = \begin{cases} \dfrac{P_L}{1 - P_L}\left(1 - P_L^{n_s}\right) & \text{if } P_L < 0.999 \\ n_s\, P_L & \text{if } P_L \geq 0.999 \end{cases}$$

where g_{diff} is the supplemental service time (s), n_s^* is the expected number of sneakers per cycle in a shared left-turn lane, f_{ms} is the adjustment factor for downstream lane blockage, f_{sp} is the adjustment factor for sustained spillback, and all other variables are as previously defined.

Equation 31-107 in Section 3 can be used to calculate g_{diff}.

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 31-112). 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.

$$s_t = s_{th}\, f_s$$

Equation 31-62

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.

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

Equation 31-63

F. Compute Flow Ratio

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

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

Equation 31-64

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.

$$v_l = s_l\, y^*$$

Equation 31-65

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, such as the choice of the timing strategy, are beyond the scope of this manual. 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 can 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. This strategy is described briefly in the next subsection. It is also used in the planning-level analysis application 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 that in the motorized vehicle methodology in Chapter 19, but other products use minor departures from it.

A third strategy is to equalize the level of service (LOS) for all critical lane groups. This strategy promotes a LOS on all approaches that is consistent with the overall intersection LOS. 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 LOS).

Determining Phase Duration on the Basis of Vehicle Demand

Signal timing based on equalization of the volume-to-capacity ratio is described in this subsection. Equation 31-67, Equation 31-68, and Equation 31-69 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 occurs in sequence whose combined flow ratio is the largest for the signal cycle.

Procedure

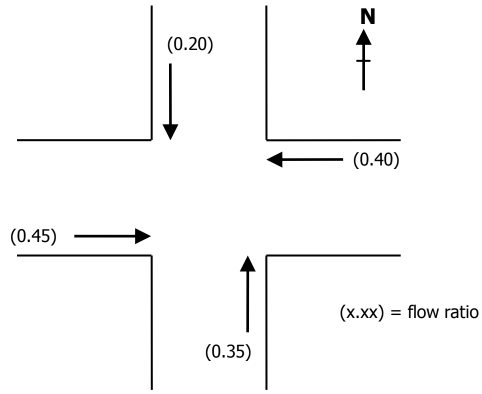
The following steps summarize the procedure for estimating the cycle length and effective green time for the critical phases:

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, then 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 Section 4 of Chapter 19, 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 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 31-7.

Exhibit 31-7
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 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 31-7. 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 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 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 subsection 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.

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

Equation 31-70

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

Equation 31-71

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

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

Equation 31-72

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

with

Equation 31-73

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

where

t_{ps} = pedestrian service time (s),

W = effective width of crosswalk (ft),

$v_{ped,i}$ = pedestrian flow rate in the subject crossing for travel direction i (p/h), and

N_{ped} = number of pedestrians crossing during an interval (p).

Equation 31-73 assumes 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 the 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 31-8 shows sample conflict zones where intersection users compete for space. This competition reduces the saturation flow rate of the turning vehicles. Its effect is quantified in the pedestrian and bicycle adjustment factors. This subsection describes a procedure for calculating these factors, which are used in the procedure for calculating the adjusted saturation flow rate that is described in Section 3 of Chapter 19.

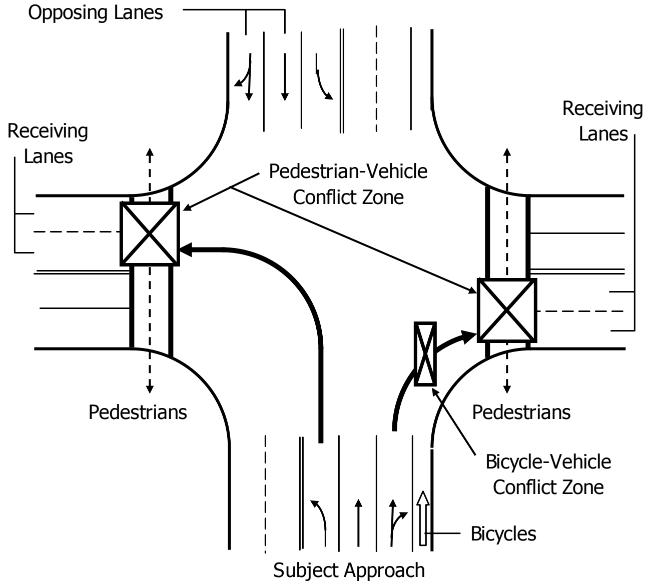


Exhibit 31-8
Conflict Zone Locations

This subsection consists of two subsections. The first subsection 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 subsection describes the procedure for computing the pedestrian adjustment factor for left-turn groups served by permitted or protected-permitted operation.

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 one-way street, then the procedure described in the first subsection below is used to compute f_{Lpb}.
- 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 subsection below is used to calculate 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 subsection below 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 using the procedure described in the previous subsection titled Pretimed Phase Duration. If the intersection is actuated, then the average phase duration and cycle length can be computed by using the procedure described in the previous subsection titled Actuated Phase Duration.

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

Equation 31-74

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

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.

Equation 31-75

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

where OCC_{pedg} is the pedestrian occupancy.

If the pedestrian flow rate during the pedestrian service time 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.

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

Equation 31-78

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.

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

Equation 31-79

where OCC_r is the relevant conflict zone occupancy.

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

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

Equation 31-80

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.

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

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.

Equation 31-83

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

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.

Equation 31-84

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

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 subsection 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 subsection supplement the procedure described in the previous subsection. The calculations described in Steps A and B in the previous subsection must be completed first (substitute the effective permitted green time g_p for g in Step A), after which the calculations described in this subsection 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

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

otherwise

$$OCC_{pedu} = 0.0$$

Equation 31-86

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 all 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.

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

Equation 31-87

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 all other variables are as previously defined.

The opposing demand flow rate v_o is determined to be one of two cases. In Case 1, v_o equals the sum of the opposing through and right-turn volumes. In Case 2, v_o equals the opposing through volume. Case 2 applies when there is a through movement on the opposing approach and one of the following conditions applies: (*a*) there is an exclusive right-turn lane on the opposing approach and the analyst optionally indicates that this lane does not influence the left-turn drivers' gap acceptance, or (*b*) there is no right-turn movement on the opposing approach. Case 1 applies whenever Case 2 does not apply.

When an exclusive right-turn lane exists on the opposing approach, the default condition is to assume this lane influences the subject left-turn drivers' gap acceptance. The determination that the exclusive right-turn lane does not influence gap acceptance should be based on knowledge of local driver behavior, traffic conditions, and intersection geometry.

C. Determine Unoccupied Time

Either Equation 31-81 or Equation 31-82 from the previous subsection (i.e., Step F above) is used to compute A_{pbT}. The choice of which equation to use should be based on a 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.

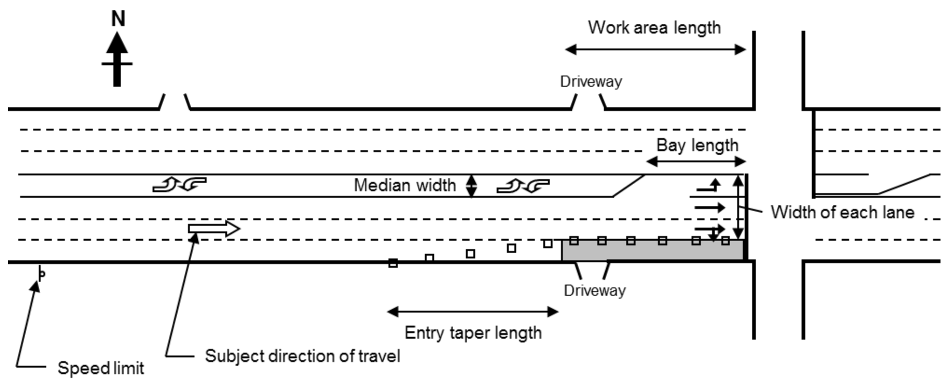
$$f_{Lpb} = A_{pbT}$$

Equation 31-88

WORK ZONE PRESENCE ADJUSTMENT FACTOR

The procedure described in this subsection can be used to evaluate signalized intersection operation when a work zone is present on the intersection approach. The work zone is considered to be on the intersection approach if some (or all) of the work zone is located between the stop line and a point 250 ft upstream of the stop line. The work zone may be located on the shoulder, or it may include the closure of one or more lanes. An intersection with a work zone located on the eastbound approach is shown in Exhibit 31-9.

Exhibit 31-9
Work Zone on an Intersection Approach



Required Input Data

The input data that are needed to estimate the effect of work zone presence on saturation flow rate are listed in Exhibit 31-10. The two data elements listed are described in this subsection. The contents of Exhibit 31-10 are in addition to those listed in Exhibit 19-11.

Exhibit 31-10
Geometric Design Input Data Requirements for Work Zones

Input Data Element and Units	Basis
Number of lanes open on the approach in the work zone (ln)	Approach
Approach lane width during work zone (ft)	Approach

Note: Approach = one value or condition for the intersection approach.

Number of Lanes Open on the Approach in the Work Zone

The number of lanes open on the approach in the work zone represents the count of left-turn and through lanes that are open during work zone presence. The count does not include any exclusive right-turn lanes that may exist. The count is taken in the work zone (not upstream or downstream of the work zone). If the number of lanes in the work zone varies, then the smallest number of lanes provided to motorists is used for this input variable.

Approach Lane Width During Work Zone

The approach lane width represents the total width of all open left-turn, through, and right-turn lanes on the intersection approach when the work zone is present.

Computational Steps

The saturation flow rate adjustment factor for the case in which a work zone is located at the intersection can be computed by using Equation 31-89 with Equation 31-90 and Equation 31-91.

$$f_{wz} = 0.858 \times f_{wid} \times f_{\text{reduce}} \leq 1.0$$

Equation 31-89

with

$$f_{wid} = \frac{1}{1 - 0.0057\,(a_w - 12)}$$

Equation 31-90

$$f_{\text{reduce}} = \frac{1}{1 + 0.0402\,(n_o - n_{wz})}$$

Equation 31-91

where

f_{wz} = adjustment factor for work zone presence at the intersection,

f_{wid} = adjustment factor for approach width,

f_{reduce} = adjustment factor for reducing lanes during work zone presence,

a_w = approach lane width during work zone (= total width of all open left-turn, through, and right-turn lanes) (ft),

n_o = number of left-turn and through lanes open during normal operation (ln), and

n_{wz} = number of left-turn and through lanes open during work zone presence (ln).

This factor is computed during Step 4, Determine Adjusted Saturation Flow Rate, of the motorized vehicle methodology in Chapter 19, Signalized Intersections. One value is computed for (and is applicable to) all lane groups on the subject intersection approach.

3. QUEUE ACCUMULATION POLYGON

This section describes a procedure for using the queue accumulation polygon (QAP) to estimate delay. The section consists of three subsections. The first subsection provides a review of concepts related to the QAP. The second subsection describes a general procedure for developing the QAP, and 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 for specific calculation details, especially as they relate to assignments, groupings, left-turn operations, and phase sequences not addressed in this section. This engine is described in Section 7.

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, capacity, and uniform delay for the corresponding lane group.

A QAP is shown in Exhibit 31-11. 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 = $(1 - P)\, q\, C/r$ (veh/s),

q_g = arrival flow rate during the effective green time = $P\, q\, C/g$ (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).

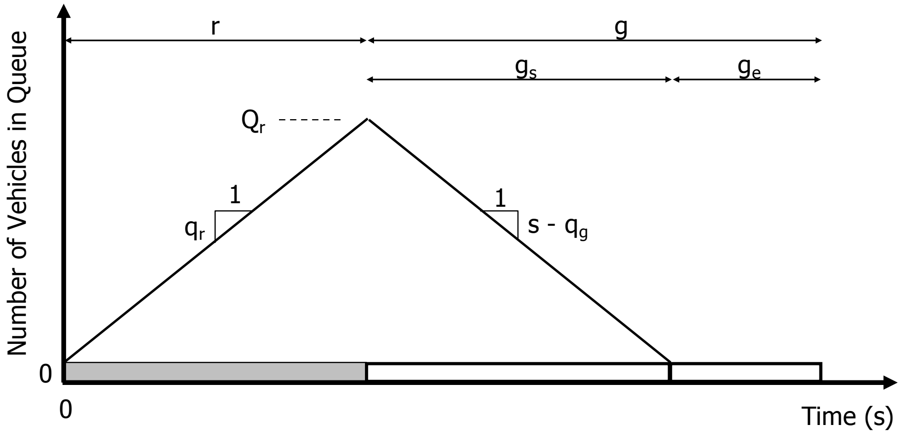


Exhibit 31-11
Queue Accumulation Polygon for Protected Movements

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 31-11 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, or protected-permitted) and phase sequence (i.e., lead, lag, or split). A general procedure for constructing these polygons is described in the next subsection.

GENERAL QAP CONSTRUCTION PROCEDURE

This subsection describes a general procedure for constructing a QAP for a lane group at a signalized intersection. It is directly applicable to left-turn lane groups that have exclusive lanes and protected operation, through lane groups with exclusive lanes, and right-turn lane groups with exclusive lanes. Variations that extend this procedure 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 31-11, 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 can be 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 (as in Exhibit 31-11) 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 when 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 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 vehicles.
2. Determine the points in the cycle when the arrival flow rate or the discharge rate changes. The arrival rate may change because of platoons formed in response to 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. Next, 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 31-92.

Equation 31-92

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

   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 all other variables are as previously defined.

7. If the queue at the end of interval i equals 0.0 vehicles, then compute the duration of the trapezoid or triangle with Equation 31-93. 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 vehicles.

Equation 31-93

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

   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 all 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. These areas are then 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.

QAP CONSTRUCTION PROCEDURE FOR SELECTED LANE GROUPS

This subsection describes a seven-step procedure for constructing a 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 circular green 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 31-12 provides equations for computing the unblocked permitted green time for left-turn Movement 1 (see Exhibit 19-1) 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),

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).

Exhibit 31-12
Unblocked Permitted Green Time

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	1, 2 / 5, 6	$G_{U1} = \min[D_{p1} + D_{p2} - D_{p5} - Y_6 - R_{c6}, G_{U1}^*]$ with $G_{U1}^* = D_{p2} - Y_6 - R_{c6} - G_{q2}$	$l_{1,1}^*$	e_1
	1, 2 / 5, 6	$G_{U1} = D_{p2} - Y_6 - R_{c6} - G_{q2}$	$l_{1,1}^*$	e_1
Lead–Lag or Lead–Perm	1, 2 / 6, 5	$G_{U1} = D_{p6} - Y_6 - R_{c6} - D_{p1} - G_{q2}$	0.0	e_1
	1, 2 / 6, 5	No permitted period	Not applicable	Not applicable
	1, 2 / 6	$G_{U1} = D_{p6} - Y_6 - R_{c6} - D_{p1} - G_{q2}$	0.0	e_1
Lag–Lead or Lag–Perm	2, 1 / 5, 6	No permitted period	Not applicable	Not applicable
	2, 1 / 5, 6	$G_{U1} = D_{p2} - Y_2 - R_{c2} - \max[D_{p5}, G_{q2}]$	$l_{1,1}$	0.0
	2, 1 / 6	$G_{U1} = \min[D_{p2} - Y_2 - R_{c2}, D_{p6} - Y_6 - R_{c6}] - G_{q2}$	$l_{1,1}$	0.0
Perm–Lead	2 / 5, 6	$G_{U1} = D_{p2} - Y_2 - R_{c2} - \max[D_{p5}, G_{q2}]$	$l_{1,1}$	e_1
Perm–Lag	2 / 6, 5	$G_{U1} = \min[D_{p2} - Y_2 - R_{c2}, D_{p6} - Y_6 - R_{c6}] - G_{q2}$	$l_{1,1}$	e_1
Perm–Perm	2 / 6	$G_{U1} = D_{p2} - Y_6 - R_{c6} - G_{q2}$	$l_{1,1}$	e_1
Lag–Lag	2, 1 / 6, 5	$G_{U1} = \min[D_{p2} - Y_2 - R_{c2}, D_{p6} - Y_6 - R_{c6}] - G_{q2}$	$l_{1,1}$	e_1^*
	2, 1 / 6, 5	$G_{U1} = \min[D_{p2} - Y_2 - R_{c2}, D_{p6} - Y_6 - R_{c6}] - G_{q2}$	$l_{1,1}$	e_1^*

Notes: [a] G_{q2} is computed for each opposing lane (excluding any opposing shared left-turn 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 $l_1^* = D_{p5} - (D_{p1} - Y_1 - R_{c1}) + l_1 - e_1$; otherwise, $l_1^* = 0.0$. Regardless, the result should not be less than 0.0 or more than l_1.
[c] $e_1^* = D_{p2} - (D_{p6} - Y_6 - R_{c6})$, provided 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 it is used in an Exhibit 31-12 equation. This subscript denotes Movement 1. For the next four variables in the list, a numeric subscript is added to the variable when it is used in an equation from the exhibit. This subscript denotes the phase number associated with the variable. Exhibit 31-12 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 31-12 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 (Displayed Unblocked Permitted Green Time) of Exhibit 31-12 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 31-94 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 31-94

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 31-94 are obtained from the two right-hand columns (Permitted Start-Up Lost Time and Permitted Extension Time, respectively) of Exhibit 31-12.

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_f), and it avoids inclusion of multiple start-up lost times during g_p. In accordance with this rationale, Equation 31-95 is used to compute the permitted left-turn green time that is not blocked by an opposing queue g_u, where all other variables are as previously defined.

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

Equation 31-95

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 31-96.

Equation 31-96

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

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 all other variables are as previously defined.

The value of 0.5 in two locations in Equation 31-96 represents the approximate saturation flow rate (in vehicles per second) 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 31-97 or Equation 31-98, along with Equation 31-99.

If the approach has one lane, then

Equation 31-97

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

otherwise

Equation 31-98

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

with

Equation 31-99

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

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).

The approach is considered to have one lane for this step if (*a*) there is one lane serving all vehicles on the approach and (*b*) the left-turn movement on this approach shares the one lane.

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 31-100.

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

Equation 31-100

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 = 2.5 (s).

The opposing demand flow rate v_o is determined to be one of two cases. In Case 1, v_o equals the sum of the opposing through and right-turn volumes. In Case 2, v_o equals the opposing through volume. Case 2 applies when there is a through movement on the opposing approach and one of the following conditions applies: (*a*) there is an exclusive right-turn lane on the opposing approach and the analyst optionally indicates that this lane does not influence the left-turn drivers' gap acceptance, or (*b*) there is no right-turn movement on the opposing approach. Case 1 applies whenever Case 2 does not apply.

When an exclusive right-turn lane exists on the opposing approach, the default condition is to assume this lane influences the subject left-turn drivers' gap acceptance. The determination that the exclusive right-turn lane does not influence gap acceptance should be based on knowledge of local driver behavior, traffic conditions, and intersection geometry.

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 31-101.

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

Equation 31-101

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 by using Equation 31-102 with Equation 31-103.

Equation 31-102

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

with

Equation 31-103

$$n_q = 0.278(g_p - g_u - g_f) \geq 0.0$$

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),

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

all other variables are as previously defined.

The value of 0.278 in Equation 31-103 represents the approximate saturation flow rate (in vehicles per second) of vehicles in the opposing shared lane. This approximation simplifies the calculation and provides sufficient accuracy in the estimation of n_q.

There is one lane on the opposing approach when this approach has one lane serving through vehicles, a left-turn movement that shares the through lane, and one of the following conditions applies: (*a*) there is an exclusive right-turn lane on the opposing approach and the analyst optionally indicates that this lane does not influence the left-turn drivers' gap acceptance, (*b*) there is a right-turn movement on the opposing approach and it shares the through lane, or (*c*) there is no right-turn movement on the opposing approach.

When an exclusive right-turn lane exists on the opposing approach, the default condition is to assume this lane influences the subject left-turn drivers' gap acceptance. The determination that the exclusive right-turn lane does not influence gap acceptance should be based on knowledge of local driver behavior, traffic conditions, and intersection geometry.

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 motorized vehicle methodology in Section 3 of Chapter 19.

The focus of discussion in this step is the calculation of saturation flow rate for lane groups that are *not* in an exclusive lane or operating in the protected mode. Thus, the discussion in this step focuses on shared-lane lane groups and 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 Exclusive Lane

The saturation flow rate for a permitted right-turn operation in an exclusive lane is computed with Equation 31-104.

$$s_r = s_o\, f_w\, f_{HVg}\, f_p\, f_{bb}\, f_a\, f_{LU}\, f_{RT}\, f_{Rpb}\, f_{wz}\, f_{ms}\, f_{sp}$$

Equation 31-104

where s_r is the saturation flow rate in an exclusive right-turn lane group with permitted operation (veh/h/ln), and the other variables are defined following Equation 19-8 in Chapter 19.

Permitted Right-Turn Operation in Shared Lane

The saturation flow rate for permitted right-turn operation in a shared lane is computed with Equation 31-105.

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

Equation 31-105

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, area type, work zone presence, downstream lane blockage, and spillback) (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.

Protected-Permitted Right-Turn Operation in Exclusive Lane

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

Equation 31-106

$$s_{rt} = s_o\, f_w\, f_{HVg}\, f_p\, f_{bb}\, f_a\, f_{LU}\, f_{RT}\, f_{wz}\, f_{ms}\, f_{sp}$$

where s_{rt} is the saturation flow rate of an exclusive right-turn lane with protected operation (veh/h/ln), and the other variables are defined following Equation 19-8 in Chapter 19.

The saturation flow rate during the permitted period is computed with Equation 31-104.

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 in a shared lane. The first period occurs before the 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 Equation 31-107.

Equation 31-107

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

where g_{diff} is the supplemental service time (s), and all 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 31-108.

Equation 31-108

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

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

There is one lane on the opposing approach when this approach has one lane serving through vehicles, a left-turn movement that shares the through lane, and one of the following conditions applies: (a) there is an exclusive right-turn lane on the opposing approach and the analyst optionally indicates that this lane does not influence the left-turn drivers' gap acceptance, (b) there is a right-turn movement on the opposing approach and it shares the through lane, or (c) there is no right-turn movement on the opposing approach.

When an exclusive right-turn lane exists on the opposing approach, the default condition is to assume this lane influences the subject left-turn drivers' gap acceptance. The determination that the exclusive right-turn lane does not influence gap acceptance should be based on knowledge of local driver behavior, traffic conditions, and intersection geometry.

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 31-109.

Equation 31-109

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

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.

Permitted Left-Turn Operation in Exclusive Lane

There are two possible saturation flow periods during the effective green time associated with permitted left-turn operation in an exclusive lane. The two flow periods are discussed in reverse order, with the second period of flow discussed first.

The second period of flow begins after clearance of the opposing queue. Its duration is g_u. The saturation flow rate for this period is computed with Equation 31-110.

Equation 31-110

$$s_l = s_p\, f_w\, f_{HVg}\, f_p\, f_{bb}\, f_a\, f_{LU}\, f_{Lpb}\, f_{wz}\, f_{ms}\, f_{sp}$$

where s_l is the saturation flow rate in an exclusive left-turn lane group with permitted operation (veh/h/ln), and all other variables are defined following Equation 19-8 in Chapter 19.

The first period of flow begins with the start of the effective green period and ends with the clearance of the opposing queue. It is computed by using Equation 31-107 with the variable g_f equal to 0.0.

If there are two or more opposing traffic lanes, then the saturation flow during the first period s_{l1} equals 0.0 veh/h/ln. However, if the opposing approach has only one traffic lane, then the saturation flow rate is computed with Equation 31-111.

Equation 31-111

$$s_{l1} = \frac{s_l}{\left(\frac{E_{L2}}{f_{Lpb}}\right)}$$

where s_{l1} is the saturation flow rate in the exclusive left-turn lane group during Period 1 (veh/h/ln). The discussion following Equation 31-108 provides guidance for determining whether the opposing approach has only one traffic lane.

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 31-112.

Equation 31-112

$$s_{lt} = s_o\, f_w\, f_{HVg}\, f_p\, f_{bb}\, f_a\, f_{LU}\, f_{LT}\, f_{wz}\, f_{ms}\, f_{sp}$$

where s_{lt} is the saturation flow rate of an exclusive left-turn lane with protected operation (veh/h/ln), and all other variables are defined following Equation 19-8 in Chapter 19.

The saturation flow rate during the permitted period is computed with Equation 31-110. 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 circular green). 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 above).

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 31-113.

Equation 31-113

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

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

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 31-114.

Equation 31-114

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

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

The QAP in Exhibit 31-11 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 31-13 through Exhibit 31-16.

Exhibit 31-13
QAP for Permitted Left-Turn Operation in an Exclusive Lane

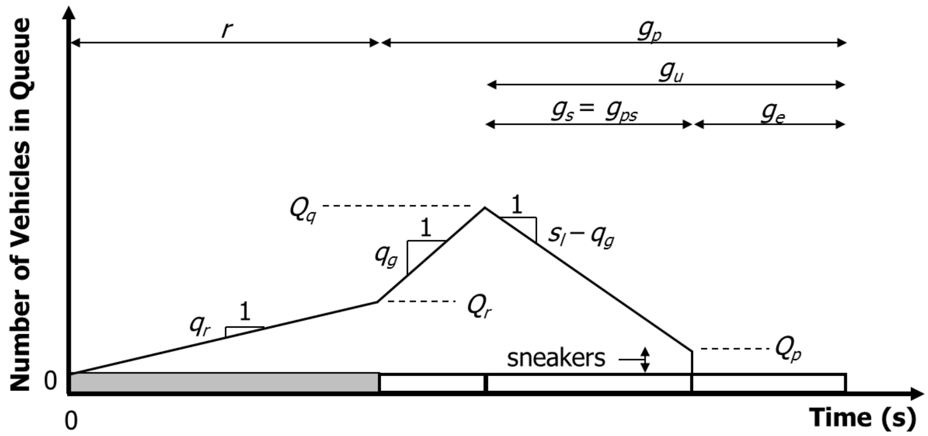


Exhibit 31-14
QAP for Permitted Left-Turn Operation in a Shared Lane

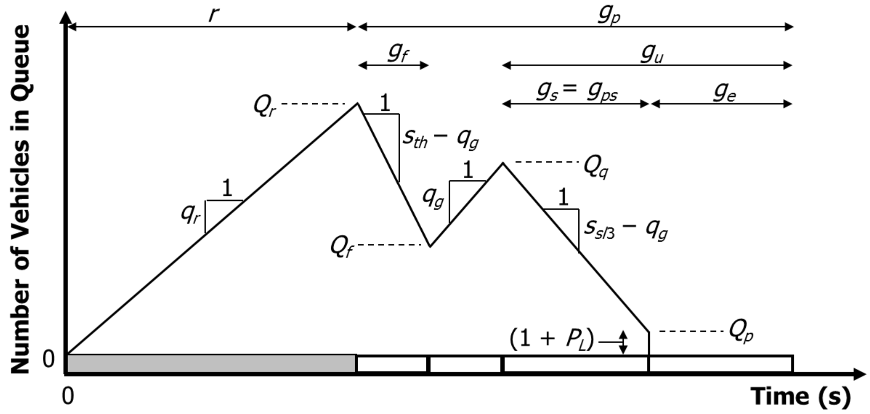
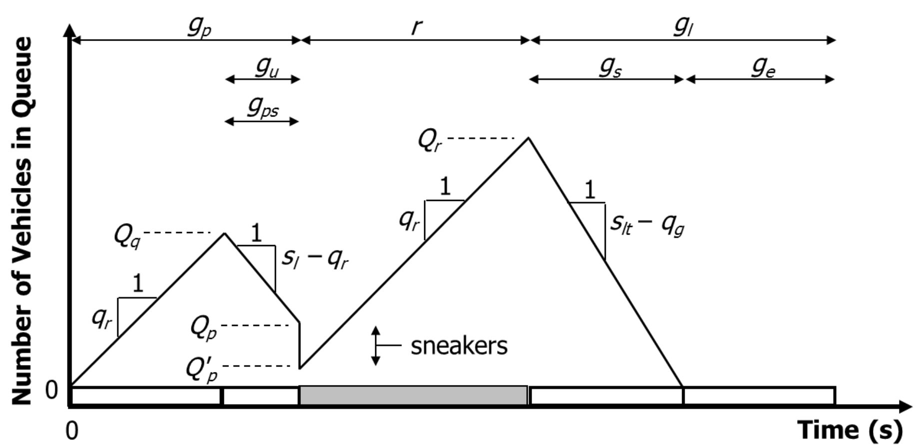


Exhibit 31-15
QAP for Leading, Protected-Permitted Left-Turn Operation in an Exclusive Lane



The concept is extended to shared left-turn and through lane groups with protected-permitted operation in Exhibit 31-17 and Exhibit 31-18. 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.

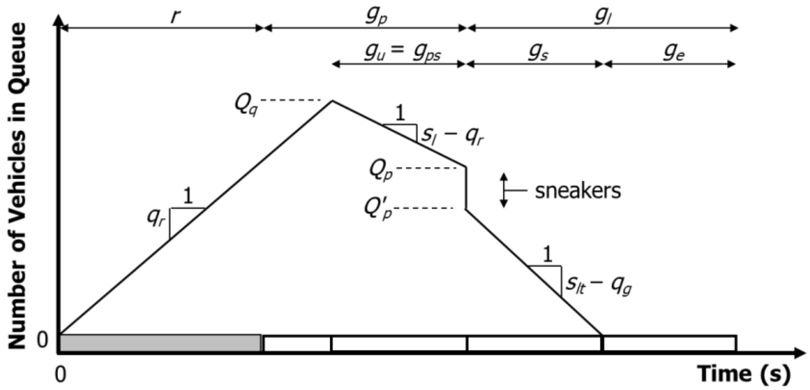


Exhibit 31-16
QAP for Lagging, Protected-Permitted Left-Turn Operation in an Exclusive Lane

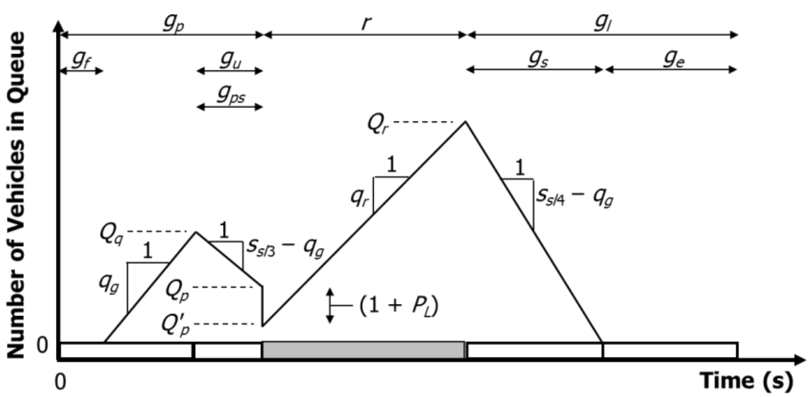


Exhibit 31-17
QAP for Leading, Protected-Permitted Left-Turn Operation in a Shared Lane

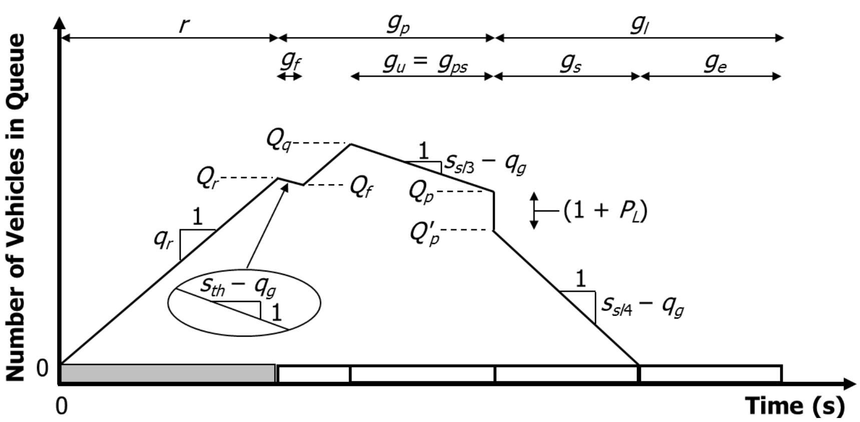


Exhibit 31-18
QAP for Lagging, Protected-Permitted Left-Turn Operation in a Shared Lane

Most of the variables shown in the following exhibits are defined in a previous subsection. Other variables are defined as follows:

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

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

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

Q_p = 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 = queue size at the end of g_f (veh).

The polygon in Exhibit 31-13 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 expected number of sneakers for this mode is reduced if downstream lane blockage or spillback is present [i.e., sneakers = $n_s f_{ms} f_{sp}$, where n_s is the number of sneakers per cycle = 2.0 (veh), f_{ms} is the adjustment factor for downstream lane blockage, and f_{sp} is the adjustment factor for sustained spillback].

The polygon in Exhibit 31-14 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 (shown as $1 + P_L$) is computed as $(1 + P_L) f_{ms} f_{sp}$, where P_L is the proportion of left-turning vehicles in the shared lane.

The polygon in Exhibit 31-15 applies to left-turn movements that have protected-permitted operation with a leading left-turn phase and an exclusive lane. The polygon in Exhibit 31-16 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 (where sneakers = $n_s f_{ms} f_{sp}$).

The polygon in Exhibit 31-17 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 31-18 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 [which is computed as $(1 + P_L) f_{ms} f_{sp}$].

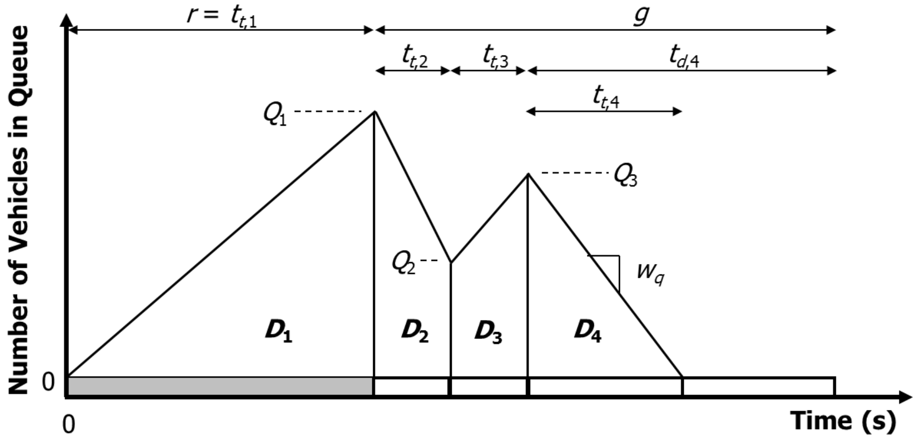
As noted above, all polygons are based on the requirement that lane volume cannot exceed lane capacity for the purpose of estimating the queue service time. This requirement is met in the polygons shown because the queue size equals 0.0 vehicles at some point during the cycle.

Exhibit 31-14 through Exhibit 31-18 are shown to indicate that queue size equals 0.0 vehicles at the start of the cycle (i.e., time = 0.0 s). In fact, the queue may not equal 0.0 vehicles at the start of the cycle for some signal timing and traffic conditions. Rather, there may be a nonzero queue at the start of the cycle, and a queue of 0.0 vehicles may not be reached until a different time in the cycle. Thus, in modeling any of the polygons in Exhibit 31-14 through Exhibit 31-18, an iterative process is required. For the first iteration, the queue is assumed to equal 0.0 vehicles 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 vehicles, 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 vehicles 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 31-19 is used for this purpose.

Exhibit 31-19
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 31-115 with Equation 31-116.

Equation 31-115

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

with

Equation 31-116

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

where d_1 is the uniform delay (s/veh), $t_{t,i}$ is the duration of trapezoid or triangle in interval i (s), w_q is the queue change rate (i.e., slope of the upper boundary of the trapezoid or triangle) (veh/s), and all other variables are as previously defined.

The summation term in Equation 31-115 includes all intervals for which there is a nonzero queue. In general, $t_{t,i}$ will equal the duration of the corresponding interval. However, during some intervals, the queue will decrease to 0.0 vehicles and $t_{t,i}$ 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 31-19.

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 31-117.

Equation 31-117

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

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

The available capacity for the lane group is computed with Equation 31-118.

Equation 31-118

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

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 all other variables are as previously defined.

Equation 31-117 and Equation 31-118 can also be used to calculate the capacity of lane groups composed of through lanes and lane groups 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 31-119.

Equation 31-119

$$c_{l,e} = \frac{g_u\, s_l + 3{,}600\, n_s\, f_{ms}\, f_{sp}}{C} N_l$$

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 all other variables are as previously defined.

The available capacity for the lane group is computed with Equation 31-120.

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

Equation 31-120

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

The saturation flow rate s_l is specifically included in the term with the maximum green setting G_{max} in Equation 31-120 because this rate represents the saturation flow rate present at the end of the green interval. That is, it 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 31-121.

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

Equation 31-121

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 a shared left-turn and through lane group with permitted operation (veh/h/ln), and all other variables are as previously defined.

The saturation flow rate in Equation 31-121 is computed with Equation 31-122 (all variables are as previously defined).

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

Equation 31-122

The available capacity for the lane group is computed with Equation 31-123.

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

Equation 31-123

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

The saturation flow rate s_{sl3} is specifically included in the term with the maximum green setting G_{max} in Equation 31-123 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 31-124.

$$c_{l,e,pp} = \left(\frac{g_l\, s_{lt}}{C} + \frac{g_u\, s_l + 3{,}600\, n_s\, f_{ms}\, f_{sp}}{C} \right) N_l$$

Equation 31-124

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

The available capacity for the lane group is computed with Equation 31-125.

Equation 31-125

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

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 all other variables are as previously defined.

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 31-126.

Equation 31-126

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

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

If the lane group is associated with a leading left-turn phase, then the available capacity for the lane group is computed with Equation 31-127.

Equation 31-127

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

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

When the lane group is associated with a lagging left-turn phase, then the variable s_{sl3} in Equation 31-127 is replaced by s_{sl4}.

Protected-Permitted Right-Turn Operation in Exclusive Lane

The capacity for a protected-permitted right-turn operation in an exclusive-lane lane group is computed with Equation 31-128.

Equation 31-128

$$c_{r,e,pp} = \left(\frac{g_l\, s_{rt}}{C} + \frac{g_r\, s_r}{C}\right) N_r$$

where $c_{r,e,pp}$ is the capacity of an exclusive-lane lane group with protected-permitted right-turn operation (veh/h), g_l is the effective green time for the complementary left-turn phase (s), g_r is the effective green time for the phase serving the subject right-turn movement during its permitted period, and all other variables are as previously defined.

The available capacity for the lane group is computed with Equation 31-129.

Equation 31-129

$$c_{a,r,e,pp} = \left(\frac{G_{max,r}\, s_{rt}}{C} + \frac{g_r\, s_r}{C}\right) N_r$$

where $c_{a,r,e,pp}$ is the available capacity of an exclusive-lane lane group with protected-permitted right-turn operation (veh/h), and $G_{max,r}$ is the maximum green setting for the phase serving the subject right-turn movement during its permitted period (s).

4. QUEUE STORAGE RATIO

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 for specific calculation details, especially as they relate to assignments, groupings, left-turn operation, and phase sequences not addressed in this section. This engine is described in Section 7.

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 as 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 31-20. 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 31-20 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 31-20
Time–Space Diagram of Vehicle Trajectory on an Intersection Approach

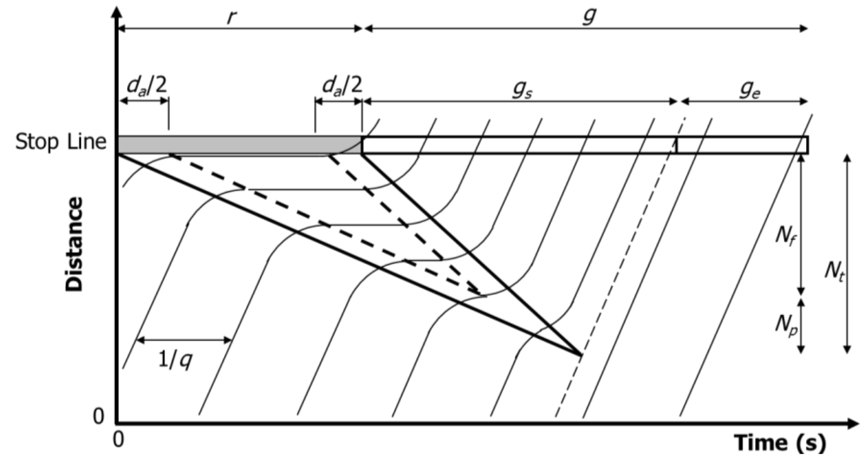


Exhibit 31-20 shows the trajectories of eight vehicles. The first five trajectories (counting from left to right) have a horizontal component to their trajectory that indicates they have reached a full stop as a result of the red indication. The sixth trajectory has some deceleration and acceleration but the vehicle does not stop. This trajectory indicates 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 size 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 31-130.

Equation 31-130

$$Q = Q_1 + Q_2 + Q_3$$

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 31-20. 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 demand that occasionally exceed capacity. This fluctuation results in the occasional overflow queue at the end of the green interval (i.e., cycle failure). The second component accounts for queuing due to a sustained oversaturation during the analysis period. This queuing occurs when aggregate demand during the analysis period exceeds aggregate capacity. It is sometimes referred to as the deterministic queue component and is shown as variable $Q_{2,d}$ in Exhibit 31-21.

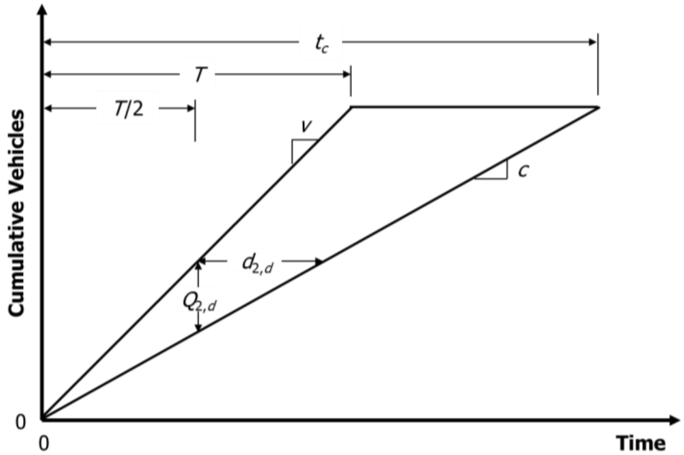


Exhibit 31-21
Cumulative Arrivals and Departures During an Oversaturated Analysis Period

Exhibit 31-21 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 31-22 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 31-22. However, it can be less than the analysis period duration for some lower-volume conditions.

Exhibit 31-22
Third-Term Back-of-Queue Size with Increasing Queue

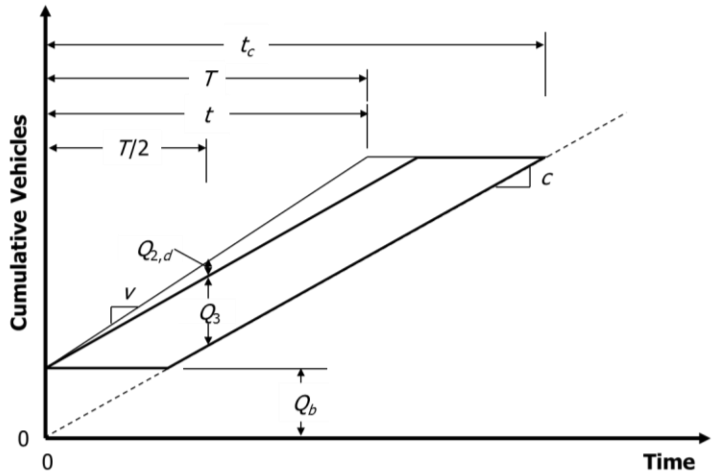


Exhibit 31-22 illustrates the case in which the demand flow rate v exceeds the capacity c during the analysis period. In contrast, Exhibit 31-23 and Exhibit 31-24 illustrate alternative cases in which the demand flow rate is less than the capacity.

Exhibit 31-23
Third-Term Back-of-Queue Size with Decreasing Queue

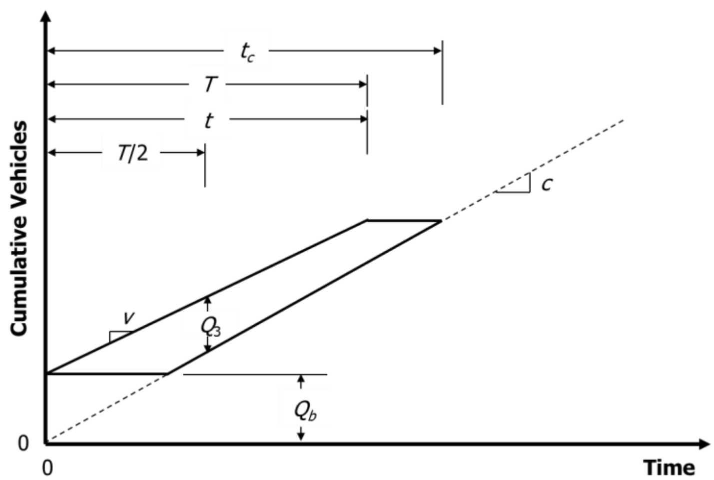
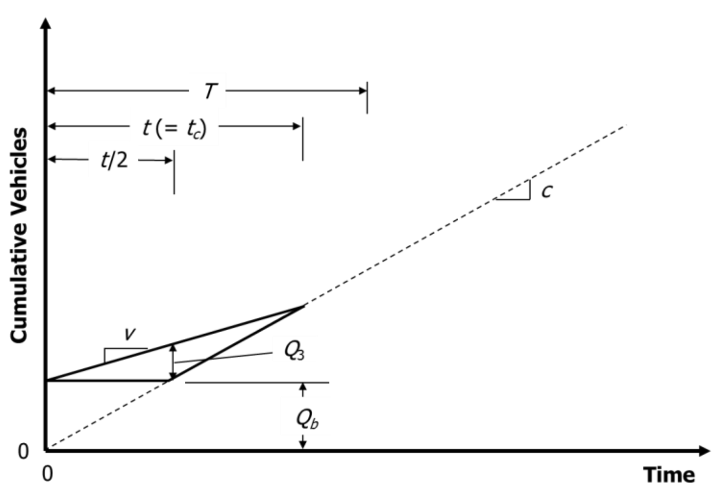


Exhibit 31-24
Third-Term Back-of-Queue Size with Queue Clearing



In this chapter, *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 31-20 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 31-131.

Equation 31-131

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

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/s^2), and

r_d = deceleration rate = 4.0 (ft/s^2).

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 Equation 31-132.

Equation 31-132

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

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 31-131 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 size (*5*).

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, and the QAP is useful for estimating delay and queue service time.

The ADP for a through movement is presented in Exhibit 31-25, which 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 = $(1 - P)\, q\, C/r$ (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 = $P\, q\, C/g$ (veh/s), and

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

Next Page

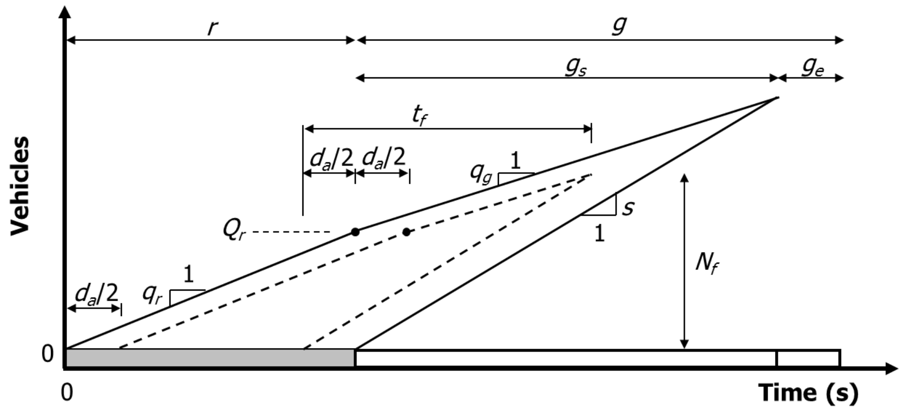


Exhibit 31-25
Arrival–Departure Polygon

The upper solid trend line in Exhibit 31-25 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 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 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 31-133 is used for computing this variable (all other variables are as previously defined).

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

Equation 31-133

Equation 31-134 can also be used for estimating N_f.

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

Equation 31-134

Combining Equation 31-133 and Equation 31-134 to eliminate N_f and solve for t_f yields Equation 31-135.

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

Equation 31-135