CHAPTER 30
URBAN STREET SEGMENTS: SUPPLEMENTAL

CONTENTS

LIST OF EXHIBITS

1. INTRODUCTION

Chapter 30 is the supplemental chapter for Chapter 18, Urban Street Segments, which is found in Volume 3 of the *Highway Capacity Manual* (HCM). This chapter presents detailed information about the following aspects of the Chapter 18 motorized vehicle methodology:

- The adjustments made to the input vehicular demand flow rates at signalized boundary intersections so that they reasonably reflect actual operating conditions during the analysis period,
- The process for analyzing vehicular traffic flow on a segment bounded by signalized intersections, and
- The process for estimating through-vehicle delay due to vehicle turning movements at unsignalized midsegment access points.

This chapter provides a simplified version of the Chapter 18 motorized vehicle methodology that is suitable for planning applications. It describes techniques for measuring free-flow speed and average travel speed in the field and provides details about the computational engine that implements the Chapter 18 motorized vehicle methodology. Chapter 30 provides four example problems that demonstrate the application of the motorized vehicle, pedestrian, bicycle, and transit methodologies to an urban street segment. Finally, the chapter provides an overview of the methodology for evaluating the performance of the motor vehicle mode on an urban street segment bounded by one or more roundabouts.

2. TRAFFIC DEMAND ADJUSTMENTS

This section describes adjustments made to the input vehicular demand flow rates at signalized boundary intersections so that they reasonably reflect actual operating conditions during the analysis period. These adjustments have no effect if existing vehicular flow rates are accurately quantified for the subject segment and all movements operate below their capacity. However, if the demand flow rate for any movement exceeds its capacity or if there is disagreement between the count of vehicles entering and the count exiting the segment, some movement flow rates will need to be adjusted for accurate evaluation of segment operation.

This section describes two procedures that check the input flow rates and make adjustments if necessary. These procedures are

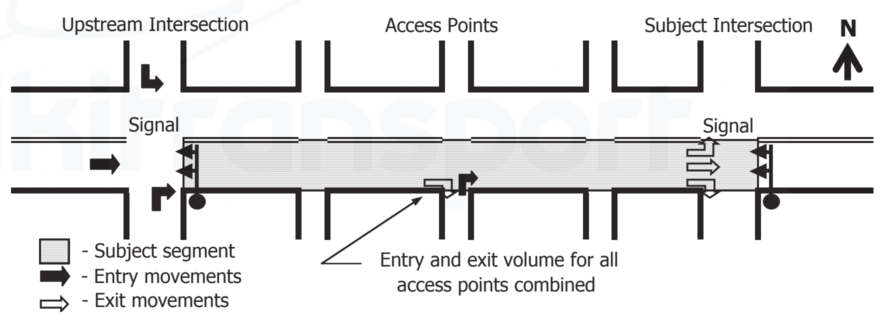
- Capacity constraint and volume balance and
- Origin–destination distribution.

These procedures can be extended to the analysis of unsignalized boundary intersections; however, the mechanics of this extension are not described.

CAPACITY CONSTRAINT AND VOLUME BALANCE

This subsection describes the procedure for determining the turn movement flow rates at each intersection along the subject urban street segment. The analysis is separately applied to each travel direction and proceeds in the direction of travel. The procedure consists of a series of steps that are completed in sequence for the entry and exit movements associated with each segment. These movements are shown in Exhibit 30-1.

Exhibit 30-1
Entry and Exit Movements on the Typical Street Segment



As indicated in Exhibit 30-1, three entry movements are associated with the upstream signalized intersection and three exit movements are associated with the downstream signalized intersection. Entry and exit movements also exist at each access point intersection. However, these movements are aggregated into one entry and one exit movement for simplicity.

The analysis procedure is described in the following steps. Frequent reference is made to “volume” in these steps. In this application, volume is considered to be equivalent to average flow rate for the analysis period and to have units of vehicles per hour (veh/h).

Step 1: Identify Entry and Exit Volumes

The volume for each entry and exit movement is identified during this step. The volume entering the segment from each access point intersection should be identified and added to obtain a total for the segment. Similarly, the volume exiting the segment from each access point intersection should be identified and added for the segment.

A maximum of eight entry volumes are identified in this step. The seven volumes at the upstream boundary intersection include signalized left-turn volume, signalized through volume, signalized right-turn volume, unsignalized left-turn volume, unsignalized through volume, unsignalized right-turn volume, and right-turn-on-red (RTOR) volume. The eighth entry volume is the total access point entry volume.

A maximum of eight exit volumes are identified in this step. The seven volumes at the downstream boundary intersection include signalized left-turn volume, signalized through volume, signalized right-turn volume, unsignalized left-turn volume, unsignalized through volume, unsignalized right-turn volume, and RTOR volume. The eighth exit volume is the total access point exit volume.

Step 2: Estimate Movement Capacity

During this step, the capacity of each signalized entry movement is estimated. This estimate should be a reasonable approximation based on estimates of the saturation flow rate for the corresponding movement and the phase splits established for signal coordination. The capacity of the RTOR movements is not calculated during this step.

If the right-turn movement at the upstream intersection shares a lane with its adjacent through movement, the discharge flow rate for the turn movement can be estimated by using Equation 30-1.

Equation 30-1

$$s_{q|r} = s_{sr}\, P_R$$

where

$s_{q|r}$ = shared lane discharge flow rate for upstream right-turn traffic movement in vehicles per hour per lane (veh/h/ln),

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

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

The procedure described in Section 2 of Chapter 31, Signalized Intersections: Supplemental, is used to estimate the two variables shown in Equation 30-1. A similar equation can be constructed to estimate the shared lane discharge flow rate for an upstream left-turn movement in a shared lane.

The capacity for the right-turn movement in the shared-lane lane group is then computed with Equation 30-2.

Equation 30-2

$$c_{q|r} = s_{q|r}\, g/C$$

where

$c_{q|r}$ = shared lane capacity for upstream right-turn traffic movement (veh/h),

$s_{q|r}$ = shared lane discharge flow rate for upstream right-turn traffic movement (veh/h/ln),

g = effective green time (s), and

C = cycle length (s).

The procedure described in Section 2 of Chapter 31 is used to estimate the signal timing variables shown in Equation 30-2. A similar equation can be constructed for an upstream left-turn movement in a shared lane.

Step 3: Compute Volume-to-Capacity Ratio

During this step, the volume-to-capacity ratio is computed for each signalized entry movement. This ratio is computed by dividing the arrival volume from Step 1 by the capacity estimated in Step 2. Any movements with a volume-to-capacity ratio in excess of 1.0 will meter the volume arriving to the downstream intersection. This ratio is not computed for the RTOR movements.

Step 4: Compute Discharge Volume

The discharge volume from each of the three signalized entry movements is equal to the smaller of its entry volume or its associated movement capacity. The total discharge volume for the combined access point approach is assumed to be equal to the total access point entry volume. Similarly, the discharge volume for each unsignalized and RTOR movement is assumed to equal its corresponding entry volume. As a last calculation, the eight discharge volumes are added to obtain the total discharge volume.

Step 5: Compute Adjusted Exit Volume

The total discharge volume from Step 4 should be compared with the total exit volume. The total exit volume is the sum of the eight exit volumes identified in Step 1. If the two totals do not agree, the eight exit volumes must be adjusted so that their sum equals the total discharge volume. The adjusted exit volume for a movement equals its exit volume multiplied by the “volume ratio.” The volume ratio equals the total discharge volume divided by the total exit volume.

Step 6: Repeat Steps 1 Through 5 for Each Segment

The preceding steps should be completed for each segment in the facility in the subject direction of travel. The procedure should then be repeated for the opposing direction of travel.

ORIGIN–DESTINATION DISTRIBUTION

The volume of traffic that arrives at a downstream intersection for a given downstream movement represents the combined volume from each upstream point of entry weighted by its percentage contribution to the downstream exit movement. The distribution of these contribution percentages between each upstream and downstream pair is represented as an origin–destination distribution matrix.

The origin–destination matrix is important for estimating the arrival pattern of vehicles at the downstream intersection. Hence, the focus here is on upstream entry movements that are signalized, because (*a*) they are typically the higher-volume movements and (*b*) the signal timing influences their time of arrival downstream. For these reasons, the origin–destination distribution is focused on the three upstream signalized movements. All other movements (i.e., unsignalized movements at the boundary intersections, access point movements, RTOR movements) are combined into one equivalent movement—referred to hereafter as the “access point” movement—that is assumed to arrive uniformly throughout the signal cycle.

Ideally, an origin–destination survey would be conducted for an existing segment, or the origin–destination data would be available from traffic forecasts by planning models. One matrix would be available for each direction of travel on the segment. In the absence of such information, origin–destination volumes can be estimated from the entry and exit volumes for a segment, where the exit volumes equal the adjusted arrival volumes from the procedure described in the previous subsection, Capacity Constraint and Volume Balance.

Each of the four entry movements to the segment shown in Exhibit 30-1 is considered an origin. Each of the four exit movements is a destination. The problem then becomes one of estimating the origin–destination table given the entering and exiting volumes.

This procedure is derived from research (*1*). It is based on the principle that total entry volume is equal to total exit volume. It uses seed proportions to represent the best estimate of the volume distribution. These proportions are refined through implementation of the procedure. It is derived to estimate the most probable origin–destination volumes by minimizing the deviation from the seed percentages while ensuring the equivalence of entry and exit volumes.

The use of seed percentages allows the procedure to adapt the origin–destination volume estimates to factors or geometric situations that induce greater preference for some entry–exit combinations than is suggested by simple volume proportion (e.g., a downstream freeway on-ramp). The default seed proportions are listed in Exhibit 30-2.

Exhibit 30-2
Default Seed Proportions for Origin–Destination Matrix

Seed Proportion by Origin Movement				**Destination Movement**
Left	**Through**	**Right**	[redacted]	
0.02	0.10	0.05	0.02	Left
0.91	0.78	0.92	0.97	Through
0.05	0.10	0.02	0.01	Right
0.02	0.02	0.01	0.00	Access point
1.00	1.00	1.00	1.00	

Step 1: Set Adjusted Origin Volume

$$O_{a,i} = O_i$$

Equation 30-3

where

$O_{a,i}$ = adjusted volume for origin i (i = 1, 2, 3, 4) (veh/h), and

O_i = volume for origin i (i = 1, 2, 3, 4) (veh/h).

The letter i denotes the four movements entering the segment. This volume is computed for each of the four origins.

Step 2: Compute Adjusted Destination Volume

Equation 30-4

$$D_{a,j} = \sum_{i=1}^{4} O_{a,i}\, p_{i,j}$$

where

$D_{a,j}$ = adjusted volume for destination j (j = 1, 2, 3, 4) (veh/h),

$O_{a,i}$ = adjusted volume for origin i (i = 1, 2, 3, 4) (veh/h), and

$p_{i,j}$ = seed proportion of volume from origin i to destination j (decimal).

The letter j denotes the four movements exiting the segment. This volume is computed for each of the four destinations.

Step 3: Compute Destination Adjustment Factor

Equation 30-5

$$b_{d,j} = \frac{D_j}{D_{a,j}}$$

where

$b_{d,j}$ = destination adjustment factor j (j = 1, 2, 3, 4),

D_j = volume for destination j (j = 1, 2, 3, 4) (veh/h), and

$D_{a,j}$ = adjusted volume for destination j (j = 1, 2, 3, 4) (veh/h).

This factor is computed for each of the four destinations.

Step 4: Compute Origin Adjustment Factor

Equation 30-6

$$b_{o,i} = \sum_{j=1}^{4} b_{d,j}\, p_{i,j}$$

where $b_{o,i}$ is the origin adjustment factor i (i = 1, 2, 3, 4). This factor is computed for each of the four origins.

Step 5: Compute Adjusted Origin Volume

Equation 30-7

$$O_{a,i} = \frac{O_i}{b_{o,i}}$$

where $O_{a,i}$ is the adjusted volume for origin i (i = 1, 2, 3, 4) (veh/h). This volume is computed for each of the four origins. It replaces the value previously determined for this variable.

For each origin, compute the absolute difference between the adjusted origin volume from Equation 30-7 and the previous estimate of the adjusted origin volume. If the sum of these four differences is less than 0.01, proceed to Step 6; otherwise, set the adjusted origin volume for each origin equal to the value from Equation 30-7, go to Step 2, and repeat the calculation sequence.

Step 6: Compute Origin–Destination Volume

Equation 30-8

$$v_{i,j} = O_{a,i}\, b_{d,j}\, p_{i,j}$$

where $v_{i,j}$ is the volume entering from origin i and exiting at destination j (veh/h). This volume is computed for all 16 origin–destination pairs.

3. SIGNALIZED SEGMENT ANALYSIS

This section describes the process for analyzing vehicular traffic flow on a segment bounded by signalized intersections. Initially, this process computes the flow profile of discharging vehicles at the upstream intersection as influenced by the signal timing and phase sequence. It uses this profile to compute the arrival flow profile at a downstream junction. The arrival flow profile is then compared with the downstream signal timing and phase sequence to compute the proportion of vehicles arriving during green. The arrival flow profile is also used to compute the proportion of time that a platoon blocks one or more traffic movements at a downstream access point intersection. These two platoon descriptors are used in subsequent procedures to compute delay and other performance measures.

This section describes six procedures that are used to define the arrival flow profile and compute the related platoon descriptors. These procedures are

- Discharge flow profile,
- Running time,
- Projected arrival flow profile,
- Proportion of time blocked,
- Sustained spillback, and
- Midsegment lane restriction.

Each procedure is described in the following subsections.

DISCHARGE FLOW PROFILE

A flow profile is a macroscopic representation of steady traffic flow conditions for the average signal cycle during the specified analysis period. The cycle is represented as a series of 1-s time intervals (hereafter referred to as "time steps"). The start time of the cycle is 0.0 s, relative to the system reference time. The time steps are numbered from 1 to C', where C' is the cycle length in units of time steps. The flow rate for step i represents an average of the flows that occur during the time period corresponding to step i for all cycles in the analysis period. This approach is conceptually the same as that used in the TRANSYT-7F model (*2*).

A discharge flow profile is computed for each of the upstream signalized left-turn, through, and right-turn movements. Each profile is defined by the time that the signal is effectively green and by the time that the queue service time ends. During the queue service time, the discharge flow rate is equal to the saturation flow rate. After the queue service time is reached, the discharge rate is set equal to the "adjusted discharge volume." The adjusted discharge volume is equal to the discharge volume computed by using the procedures described in Section 2, but it is adjusted to reflect the "proportion of arrivals during green." The latter adjustment adapts the discharge flow pattern to reflect platoon arrivals on the upstream segment.

The discharge flow profile is dependent on movement saturation flow rate, queue service time, phase duration, and proportion of arrivals during green for the discharging movements. The movement saturation flow rate is computed by using the procedure described in Section 3 of Chapter 19, Signalized Intersections. Procedures for calculating the remaining variables are described in subsequent subsections. This relationship introduces a circularity in the computations that requires an iterative sequence of calculations to converge on the steady-state solution.

RUNNING TIME

The running time procedure describes the calculation of running time between the upstream intersection and a downstream intersection. This procedure is described as Step 2 of the motorized vehicle methodology in Chapter 18, Urban Street Segments.

One component of running time is the delay due to various midsegment sources. One notable source of delay is left or right turns from the segment at an access point intersection. This delay is computed by using the procedure described in Section 4. Other sources of delay include on-street parking maneuvers and pedestrian crosswalks. Delay from these sources represents an input variable to the methodology.

PROJECTED ARRIVAL FLOW PROFILE

This subsection describes the procedure for predicting the arrival flow profile at a downstream intersection (i.e., access point or boundary intersection). This flow profile is based on the discharge flow profile and running time computed previously. The discharge flow profile is used with a platoon dispersion model to compute the arrival flow profile. The platoon dispersion model is summarized in the next part of this subsection. The procedure for using this model to estimate the arrival flow profile is described in the second part.

Platoon Dispersion Model

The platoon dispersion model was originally developed for use in the TRANSYT model (*3*). Input to the model is the discharge flow profile for a specified traffic movement. Output statistics from the model include (*a*) the arrival time of the leading vehicles in the platoon to a specified downstream intersection and (*b*) the flow rate during each subsequent time step.

In general, the arrival flow profile has a lower peak flow rate than the discharge flow profile owing to the dispersion of the platoon as it travels down the street. For similar reasons, the arrival flow profile is spread out over a longer period of time than the discharge flow profile. The rate of dispersion increases with increasing segment running time, which may be caused by access point activity, on-street parking maneuvers, and other midsegment delay sources.

The platoon dispersion model is described by Equation 30-9.

Equation 30-9

$$q'_{a|u,j} = F\, q'_{u,i} + (1 - F)\, q'_{a|u,j-1}$$

with

Equation 30-10

$$j = i + t'$$

where

$q'_{a|u,j}$ = arrival flow rate in time step j at a downstream intersection from upstream source u (veh/step),

$q'_{u,i}$ = departure flow rate in time step i at upstream source u (veh/step),

F = smoothing factor,

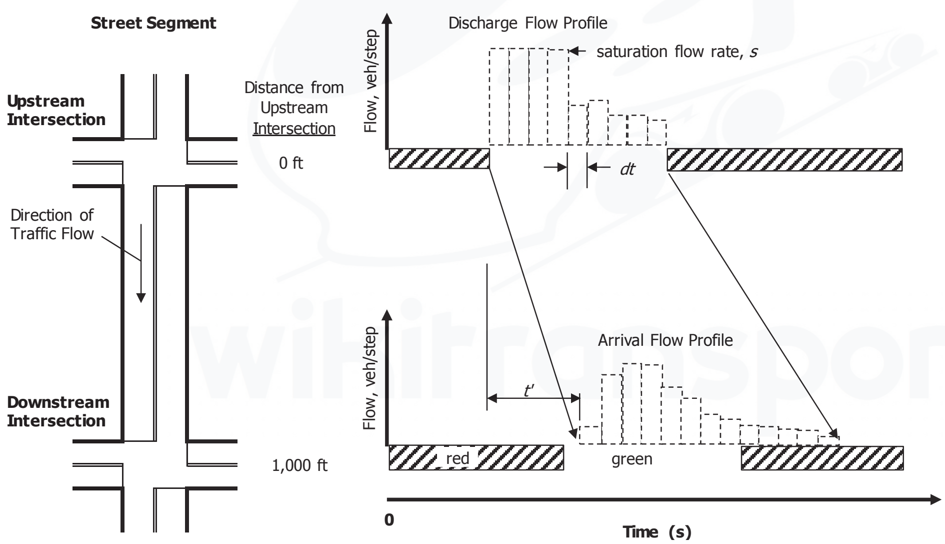
j = time step associated with platoon arrival time t', and

t' = platoon arrival time (steps).

The upstream flow source u can be the left-turn, through, or right-turn movement at the upstream boundary intersection. It can also be the collective set of left-turn or right-turn movements at access point intersections between the upstream boundary intersection and the subject intersection.

Exhibit 30-3 illustrates an arrival flow profile obtained from Equation 30-9. In this figure, the discharge flow profile is input to the model as variable $q'_{u,i}$. The dashed rectangles that form the discharge flow profile indicate the flow rate during each of nine time steps (i = 1, 2, 3, . . . , 9) that are each d_t seconds in duration. The vehicles that depart in the first time step (i = 1) arrive at the downstream intersection after traveling an amount of time equal to t' steps. The arrival flow at any time step j (= i + t') is computed with Equation 30-9.

Exhibit 30-3
Platoon Dispersion Model



Research (4) indicates that Equation 30-11 describes the relationship between the smoothing factor and running time.

$$F = \frac{1}{1 + 0.138\, t'_R + 0.315/d_t}$$

Equation 30-11

where

t'_R = segment running time = t_R/d_t (steps),

t_R = segment running time (s), and

d_t = time step duration (s/step).

The recommended time step duration for this procedure is 1.0 s/step. Shorter values can be rationalized to provide a more accurate representation of the profile, but they also increase the time required for the computations. Experience indicates that 1.0 s/step provides a good balance between accuracy and computation time.

Equation 30-12 is used to compute platoon arrival time to the subject downstream intersection.

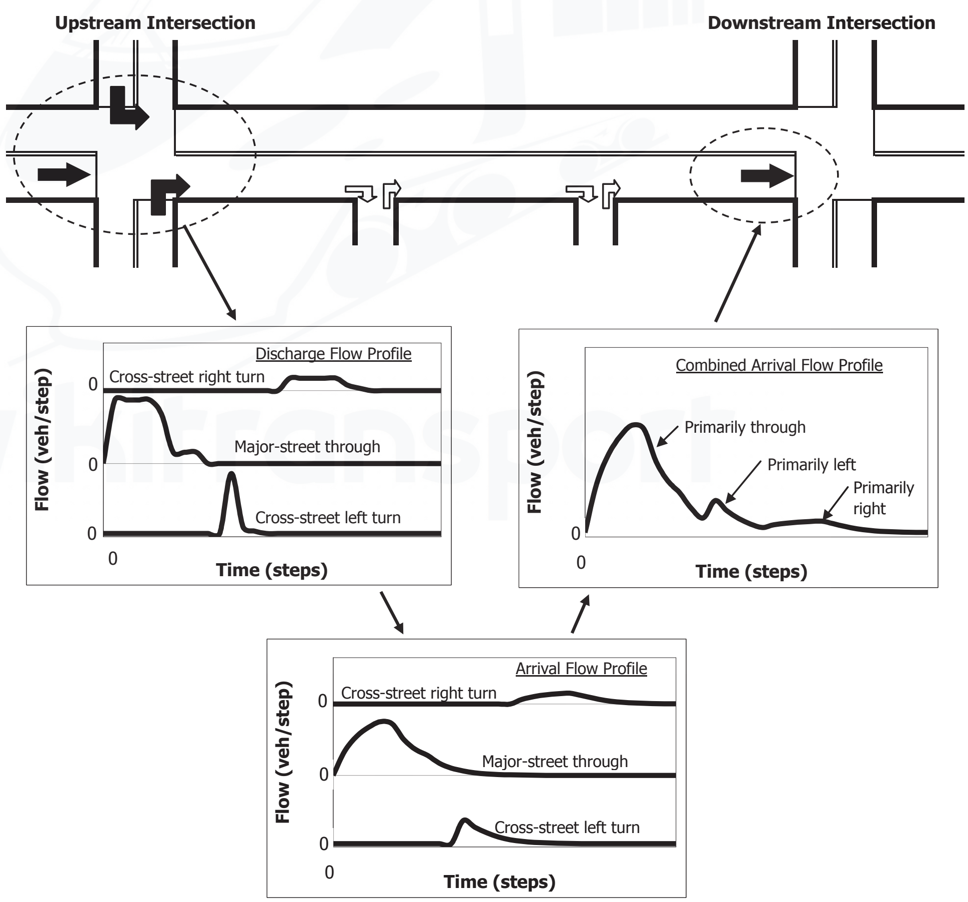
Equation 30-12

$$t' = t'_R - \frac{1}{F} + 1.25$$

Arrival Flow Profile

This subsection describes the procedure for computing the arrival flow profile. Typically, there are three upstream signalized traffic movements that depart at different times during the signal cycle; they are the minor-street right turn, major-street through, and minor-street left turn. Traffic may also enter the segment at various midblock access points or as an unsignalized movement at the boundary intersection. Exhibit 30-4 illustrates how these movements join to form the arrival flow profile for the subject downstream intersection.

Exhibit 30-4
Arrival Flow Profile Estimation Procedure



In application, the discharge flow profile for each of the departing movements is obtained from the discharge flow profile procedure described previously. These profiles are shown in the first of the three *x*-*y* plots in Exhibit

30-4. The platoon dispersion model is then used to estimate the arrival flows for each movement at a downstream intersection. These arrival flow profiles are shown in the second *x-y* plot in the exhibit. Arrivals from midsegment access points, which are not shown, are assumed to have a uniform arrival flow profile (i.e., a constant flow rate for all time steps).

Finally, the origin–destination distribution procedure is used to distribute each arrival flow profile to each of the downstream exit movements. The four arrival flow profiles associated with the subject exit movement are added together to produce the combined arrival flow profile. This profile is shown in the third *x-y* plot. The upstream movement contributions to this profile are indicated by arrows.

Comparison of the profiles in the first and second *x-y* plots of Exhibit 30-4 illustrates the platoon dispersion process. In the first *x-y* plot, the major-street through movement has formed a dense platoon as it departs the upstream intersection. However, by the time this platoon reaches the downstream intersection it has spread out and has a lower peak flow rate. In general, the amount of platoon dispersion increases with increasing segment length. For very long segments, the platoon structure degrades and arrivals become uniform throughout the cycle.

Platoon structure can also degrade as a result of significant access point activity along the segment. Streets with frequent active access point intersections tend to have more vehicles leave the platoon (i.e., turn from the segment at an access point) and enter the segment after the platoon passes (i.e., turn in to the segment at an access point). Both activities result in significant platoon decay.

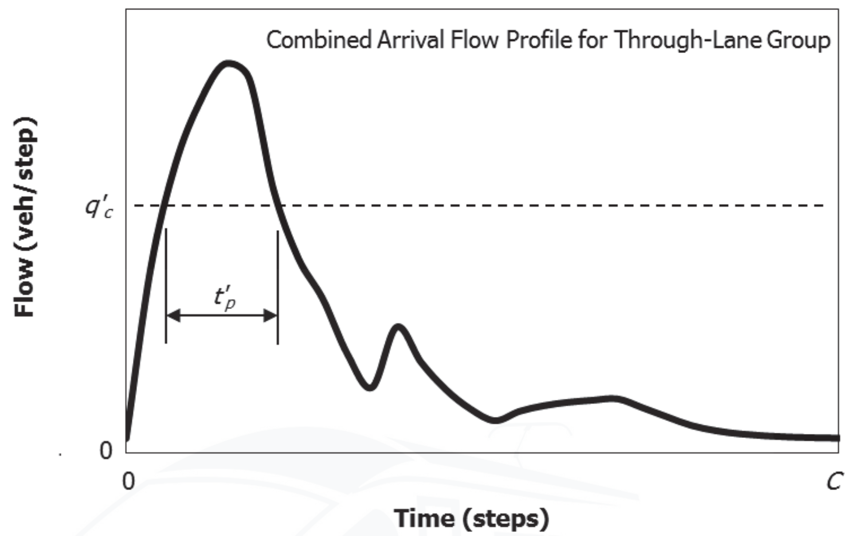
The effect of platoon decay is modeled by using the origin–destination matrix, in which the combined access point activity is represented as one volume assigned to midsegment origins and destinations. A large access point volume corresponds to a smaller volume that enters at the upstream boundary intersection as a defined platoon. This results in a larger portion of the combined arrival flow profile defined by uniform (rather than platoon) arrivals. When a street has busy access points, platoon decay tends to be a more dominant cause of platoon degradation than platoon dispersion.

PROPORTION OF TIME BLOCKED

The combined arrival flow profile can be used to estimate the time that a platoon passes through a downstream access point intersection. During this time period, the platoon can be dense enough to preclude a minor movement driver from finding an acceptable gap.

The use of the arrival flow profile to estimate the blocked period duration is shown in Exhibit 30-5. The profile shown represents the combined arrival flow profile for the through-lane group at a downstream access point intersection. The dashed line represents the critical platoon flow rate. Flow rates in excess of this threshold are rationalized to be associated with platoon headways that are too short to be entered (or crossed) by minor movements. The critical platoon flow rate q_c is equal to the inverse of the critical headway t_c associated with the minor movement (i.e., $q_c = 3{,}600/t_c$). The appropriate critical headway values for various movements are identified in Chapter 20, Two-Way STOP-Controlled Intersections.

Exhibit 30-5
Estimation of Blocked Period Duration



In the situation of a driver desiring to complete a left turn from the major street across the traffic stream represented by Exhibit 30-5, the proportion of time blocked is computed by using Equation 30-13. For this maneuver, the blocked period duration is based on the flow profile of the opposing through-lane group.

Equation 30-13

$$p_b = \frac{t'_p \, d_t}{C}$$

where

p_b = proportion of time blocked (decimal),

t'_p = blocked period duration (steps),

d_t = time step duration (s/step), and

C = cycle length (s).

Equation 30-13 is also used for the minor-street right-turn movement. However, in this situation, the blocked period duration is computed for the through-lane group approaching from the left. For the minor-street left-turn and through movements, the arrival flow profiles from both directions are evaluated. In this instance, the blocked period duration represents the time when a platoon from either direction is present in the intersection.

SUSTAINED SPILLBACK

This subsection describes two procedures that were developed for the evaluation of segments that experience sustained spillback. Sustained spillback occurs as a result of oversaturation (i.e., more vehicles discharging from the upstream intersection than can be served at the subject downstream intersection). The spillback can exist at the start of the study period, or it can occur at some point during the study period. Spillback that first occurs after the study period is not addressed.

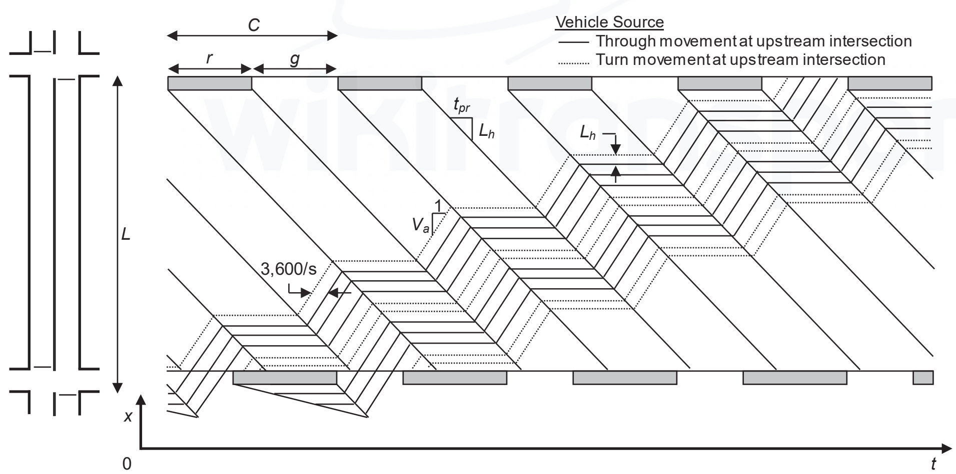
Effective Average Vehicle Spacing

One piece of information needed to evaluate segments experiencing sustained spillback is the effective average vehicle spacing (*5*). A simple estimate of this spacing is computed as the sum of the average vehicle length and the average distance between two queued vehicles (as measured from the back bumper of the lead vehicle to the front bumper of the trailing vehicle).

Presumably, this estimate of average spacing could be divided into the segment length to determine the maximum number of queued vehicles on the segment during spillback. However, this result is biased because it is based on the assumption that all vehicles on the segment will always be stationary during spillback. This is a weak assumption because the downstream signal operation creates backward-traveling waves of starting and stopping. Between the starting wave and the stopping wave, vehicles are moving at the saturation headway and its associated speed. Their spacing exceeds that of the aforementioned “simple” estimate.

The procedure described in this subsection is used to estimate the effective average vehicle spacing L_h^* on a segment with spillback. The derivation of this new variable is based on the vehicle trajectories shown in Exhibit 30-6. The segment of interest is shown on the left side of the figure. Spillback is present for all of the cycles shown; however, trajectories are shown only for two cycles. The solid trajectories coincide with vehicles that enter the segment as a through movement at the upstream intersection. The dashed lines coincide with vehicles that enter the segment as a turn movement. A vehicle that enters the segment traveling north as a through vehicle is shown to experience four cycles before exiting the segment. The trajectories show that the vehicles move forward at a saturation headway of 3,600/s seconds per vehicle and a speed of V_a feet per second.

Exhibit 30-6
Vehicle Trajectories During Spillback Conditions



The lines that slope downward from the upper left to lower right represent the waves of reaction time. They have a slope of t_{pr} seconds per vehicle. The starting wave originates at the onset of the green indication, and the stopping wave originates at the onset of the red indication. The average vehicle spacing when vehicles are stopped is L_h feet per vehicle.

On the basis of the relationships shown in Exhibit 30-6, the following procedure can be used to estimate the effective average vehicle spacing.

Step 1. Compute Wave Travel Time

The time required for the driver reaction wave to propagate backward to the upstream intersection is computed with the following equation:

Equation 30-14

$$t_{max} = \frac{(L - W_i)\ t_{pr}}{L_h}$$

with

Equation 30-15

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

where

t_{max} = wave travel time (s);

L = segment length (ft);

W_i = width of upstream signalized intersection, as measured along the segment centerline (ft);

t_{pr} = driver starting response time (= 1.3) (s/veh);

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

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

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

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

Step 2. Compute Speed of Moving Queue

The average speed of the moving queue is computed with Equation 30-16:

Equation 30-16

$$V_a = \frac{L_h}{2.0 - t_{pr}}$$

where V_a is the average speed of moving queue (ft/s).

Step 3. Compute Effective Average Vehicle Spacing

The relationship between the trajectories of the moving vehicles defines the following association between speed, saturation flow rate, signal timing, and vehicle spacing.

Equation 30-17

$$\text{If } 0.0 \ \le\ t_{max} < r, \text{ then } L_h^* = L_h$$

$$\text{If } r \ \le\ t_{max} < C, \text{ then } L_h^* = 2.0\ \left(\frac{r}{L - W_i} + \frac{1}{V_a}\right)^{-1} \ge L_h$$

$$\text{If } C \ \le\ t_{max}, \text{ then } L_h^* = \frac{L_h}{1.0 - 0.5\ t_{pr}\ g/C}$$

where

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

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

g = effective green time (s), and

C = cycle length (s).

Equation 30-17 has three component equations. The component equation used for a given segment and analysis period will be based on the value of t_{max}, r, and C. The value of average vehicle spacing from the first component equation is the smallest that can be obtained from Equation 30-17. The value from the last equation is the largest that can be obtained. The value obtained from the equation in the middle varies between these two extreme values, depending on the value of t_{max}.

Spillback Check

This subsection describes the procedure for determining whether queue spillback occurs on a segment during a given analysis period (*4*). The analysis is applied separately to each travel direction and proceeds in the direction of travel. The procedure consists of a series of steps that are completed in sequence for the signalized exit movements associated with each segment. These movements were shown in Exhibit 30-1. Spillback due to the movements associated with the access points is not specifically addressed.

Step 1: Identify Initial Queue

During this step, the initial queue for each signalized exit movement is identified. This value represents the queue present at the start of the analysis period (the total of all vehicles in all lanes serving the movement). The initial queue estimate would likely be available for the evaluation of an existing condition for which field observations indicate the presence of a queue at the start of the analysis period. For planning or preliminary design applications, it can be assumed to equal 0.0 vehicles.

Step 2: Identify Queue Storage Length

The length of queue storage for each exit movement is identified during this step. For turn movements served from a turn bay, this length equals the length of the turn bay. For through movements, this length equals the segment length less the width of the upstream intersection. For turn movements served from a lane equal in length to that of the segment, the queue storage length equals the segment length less the width of the upstream intersection.

Step 3: Compute Maximum Queue Storage

The maximum queue storage for the exiting through movement is computed with Equation 30-18:

$$N_{qx,thru} = \frac{(N_{th} - P_L - P_R)\, L_{a,thru}}{L_h^*}$$

Equation 30-18

where

$N_{qx,thru}$ = maximum queue storage for the through movement (veh),

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

P_L = proportion of left-turning vehicles in the shared lane (decimal),

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

$L_{a,thru}$ = available queue storage distance for the through movement (ft/ln), and

L_h^* = effective average vehicle spacing in stationary queue (ft/veh).

The procedure described in Section 2 of Chapter 31, Signalized Intersections: Supplemental, is used to estimate P_L and P_R. If there are no shared lanes, $P_L = 0.0$ and $P_R = 0.0$.

The maximum queue storage for a turn movement is computed with Equation 30-19:

Equation 30-19

$$N_{qx,\text{turn}} = \frac{N_{\text{turn}}\, L_{a,\text{turn}} + P_{\text{turn}}\, L_{a,thru}}{L_h}$$

where

$N_{qx,\text{turn}}$ = maximum queue storage for a turn movement (veh),

N_{turn} = number of lanes in the turn bay (ln),

$L_{a,\text{turn}}$ = available queue storage distance for the turn movement (ft/ln),

P_{turn} = proportion of turning vehicles in the shared lane = P_L or P_R (decimal), and

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

This equation is applicable to turn movements in exclusive lanes (i.e., $P_{\text{turn}} = 0.0$) and to turn movements that share a through lane.

Step 4: Compute Available Storage Length

The available storage length is computed for each signalized exit movement by using Equation 30-20.

Equation 30-20

$$N_{qa} = N_{qx} - Q_b \geq 0.0$$

where

N_{qa} = available queue storage (veh),

N_{qx} = maximum queue storage for the movement (veh), and

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

The analysis thus far has treated the three signalized exit movements as if they were independent. At this point, the analysis must be extended to include the combined through and left-turn movement when the left-turn movement has a bay (i.e., it does not have a lane that extends the length of the segment). The analysis must also be extended to include the combined through and right-turn movement when the right-turn movement has a bay (but not a full-length lane).

The analysis of these newly formed "combined movements" is separated into two parts. The first part is the analysis of just the bay. This analysis is a continuation of the exit movement analysis using the subsequent steps of this procedure. The second part is the analysis of the length of the segment shared by the turn movement and the adjacent through movement. The following rules are used to evaluate the combined movements for the shared segment length:

1. The volume for each combined movement equals the sum of the adjusted arrival volumes for the two contributing movements. These volumes are

obtained from the procedure described in a previous subsection, Origin–Destination Distribution.

2. The initial queue for each combined movement is computed with Equation 30-21.

$$Q_{b,comb} = \max\left(0.0, Q_{b,\text{turn}} - \frac{L_{a,\text{turn}}\, N_{\text{turn}}}{L_h^*}, Q_{b,thru} - \frac{L_{a,\text{turn}}\, N_{th}}{L_h^*}\right)$$

Equation 30-21

where $Q_{b,comb}$ is the initial queue for the combined movement (veh). The other variables were defined previously and are evaluated for the movement indicated by the variable subscript.

3. The queue storage length for a combined movement $L_{a,comb}$ equals the queue storage length for the through movement less the queue storage length of the turn movement (i.e., $L_{a,comb} = L_{a,thru} - L_{a,\text{turn}}$).

4. The number of lanes available to the combined movement N_{comb} equals the number of lanes available to the through movement.

5. The maximum queue storage for the combined movement $N_{qx,comb}$ is computed with the following equation:

$$N_{qx,comb} = \frac{N_{th}\, L_{a,thru}}{L_h^*}$$

Equation 30-22

6. The available storage length for the combined movement $N_{qa,comb}$ is computed with the following equation:

$$N_{qa,comb} = N_{qx,comb} - Q_{b,comb} \geq 0.0$$

Equation 30-23

Step 5: Compute Capacity

The capacity for both the exit movements and the combined movements is established in this step. The capacity for each exit movement was computed in Step 2 in the subsection titled Capacity Constraint and Volume Balance. The capacity of the combined movements is computed by using Equation 30-24.

$$c = \frac{v_{a,1}}{X_1} + \frac{c_{thru}(N_{th} - 1)}{N_{th}}$$

Equation 30-24

with

$$v_{a,1} = \max\left(v_{a,\text{turn}}, \frac{v_{a,\text{turn}} + v_{a,thru}}{N_{th}}\right)$$

Equation 30-25

$$X_1 = \frac{v_{a,\text{turn}}}{c_{\text{turn}}} + \frac{v_{a,1} - v_{a,\text{turn}}}{c_{thru}/N_{th}}$$

Equation 30-26

where

c = capacity of the combined movements (veh/h),

$v_{a,1}$ = adjusted arrival volume in the shared lane (veh/h),

X_1 = volume-to-capacity ratio in the shared lane,

c_{thru} = capacity for the exiting through movement (veh/h),

c_{turn} = capacity for the exiting turn movement (veh/h),

$v_{a,\text{turn}}$ = adjusted arrival volume for the subject turn movement (veh/h),

$v_{a,thru}$ = adjusted arrival volume for the subject through movement (veh/h), and

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

The two adjusted arrival volumes $v_{a,\text{turn}}$ and $v_{a,thru}$ are obtained from the procedure described in the Origin–Destination Distribution subsection.

Step 6: Compute Queue Growth Rate

During this step, the queue growth rate is computed for each signalized exit movement for which the storage extends the length of the segment. Typically, the through movement satisfies this requirement. A turn movement may also satisfy this requirement if it is served by an exclusive lane that extends the length of the segment. The queue growth rate is computed as the difference between the adjusted arrival volume v_a and the capacity c for the subject exit movement. Equation 30-27 is used to compute this rate.

Equation 30-27

$$r_{qg} = v_a - c \geq 0.0$$

where r_{qg} is the queue growth rate (veh/h).

The queue growth rate is also computed for the combined movements formulated in Step 4. The adjusted volume used in Equation 30-27 represents the sum of the through and turn movement volumes in the combined group. The capacity for the group was computed in Step 5.

Step 7: Compute Time Until Spillback

During this step, the time until spillback is computed for each signalized exit movement for which the storage extends the length of the segment. This time is computed with Equation 30-28 for any movement with a nonzero queue growth rate.

Equation 30-28

$$T_c = \frac{N_{qa}}{r_{qg}}$$

where T_c is the time until spillback (h).

For turn movements served by a bay, the computed spillback time is the time required for the bay to overflow. It does not represent the time at which the turn-related queue reaches the upstream intersection.

Equation 30-28 is also used to compute the spillback time for the combined movements formulated in Step 4. However, this spillback time is the additional time required for the queue to grow along the length of segment shared by the turn movement and the adjacent through movement. This time must be added to the time required for the corresponding turn movement to overflow its bay to obtain the actual spillback time for the combined movement.

Step 8: Repeat Steps 1 Through 7 for Each Segment

The preceding steps should be completed for each segment in the facility in the subject direction of travel. The procedure should then be repeated for the opposing direction of travel.

Step 9: Determine Controlling Spillback Time

During this step, the shortest time until spillback for each of the exit movements (or movement groups) for each segment and direction of travel is identified. If the segment supports two travel directions, two values are identified (one value for each direction). The smaller of the two values is the controlling spillback time for the segment. If a movement (or movement group) does not spill back, it is not considered in this process for determining the controlling spillback time.

Next, the controlling segment times are compared for all segments that make up the facility. The shortest time found is the controlling spillback time for the facility.

If the controlling spillback time exceeds the analysis period, the results from the motorized vehicle methodology are considered to reflect the operation of the facility accurately. If spillback occurs before the end of the desired analysis period, the analyst should consider either (*a*) reducing the analysis period so that it ends before spillback occurs or (*b*) using the sustained spillback evaluation procedure in Chapter 29, Urban Street Facilities: Supplemental.

MIDSEGMENT LANE RESTRICTION

When one or more lanes on an urban street segment are temporarily closed, the flow in the lanes that remain open can be adversely affected. The closure can be due to a work zone, an incident, or a similar event. Occasionally, the lane closure can adversely affect the performance of traffic movements that are entering or exiting the segment at the boundary signalized intersection. Logically, the magnitude of the effect will increase as the distance between the intersection and lane closure decreases. The impact on the intersection that has a downstream lane closure is the subject of discussion in this subsection.

The procedure described in this subsection is used to adjust the saturation flow rate of the movements entering a segment when one or more downstream lanes are blocked. The procedure is developed for incorporation within the motorized vehicle methodology described in Chapters 18 and 19 (*5*). Specifically, the procedure is inserted into the motorized vehicle methodology in Chapter 18, Urban Street Segments, and used to compute a saturation flow rate adjustment factor for the movements entering the segment at the intersection. This adjustment factor is then implemented in the motorized vehicle methodology in Chapter 19, Signalized Intersections, to compute the adjusted saturation flow rate of the affected movements.

This procedure is added to the end of Step 4 of the motorized vehicle methodology described in Chapter 18. It occurs after the saturation flow rate and phase duration have been determined. It is implemented as part of the iterative convergence loop identified in the motorized vehicle methodology framework shown in Exhibit 18-8.

The calculation sequence begins with an estimate of the capacity for each traffic movement discharged to the downstream segment. This estimate is obtained by using the motorized vehicle methodology in Chapter 19. The next step is to compute the capacity of the downstream segment as influenced by the midsegment lane restriction. The estimate of movement capacity is then compared with the downstream segment capacity. If the movement capacity exceeds the downstream segment capacity, the movement saturation flow rate is reduced proportionally by using an adjustment factor for downstream lane blockage.

The lane blockage saturation flow rate adjustment factor is computed for each movement entering the subject segment. The following equations are used to compute the factor value.

Equation 30-29

$$\text{If } c_{ms} < c_i \text{ or } f_{ms,i-1} < 1.0, \text{ then } f_{ms,i} = f_{ms,i-1} \frac{c_{ms}}{c_i} \geq 0.1$$

$$\text{Otherwise, } f_{ms,i} = 1.0$$

with

Equation 30-30

$$c_{ms} = 0.25\, k_j\, N_{unblk}\, S_f \leq 1{,}800\, N_{unblk}$$

where

$f_{ms,i}$ = adjustment factor for downstream lane blockage during iteration i,

c_{ms} = midsegment capacity (veh/h),

c_i = movement capacity during iteration i (veh/h),

k_j = jam density (= 5,280 / L_h) (veh/mi/ln),

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

S_f = free-flow speed (mi/h), and

N_{unblk} = number of open lanes when blockage is present (ln).

The number of lanes used in Equation 30-30 equals the number of unblocked lanes (i.e., the open lanes) while the blockage is present.

The variable i in the adjustment factor subscript indicates that the factor's value is incrementally revised during each iteration of the convergence loop associated with the motorized vehicle methodology. Ultimately, the factor converges to a value that results in a movement capacity matching the available midsegment capacity. For the first iteration, the factor value is set to 1.0 for all movements. The factor value is also set to 1.0 if the segment is experiencing spillback. In this situation, a saturation flow rate adjustment factor for spillback (which incorporates the downstream lane blockage effect) is computed for the movement. The calculation of the factor for spillback is described in Chapter 29, Urban Street Facilities: Supplemental.

Equation 30-29 indicates that the factor is less than 1.0 when the midsegment capacity is smaller than the movement capacity. If the factor has been set to a value less than 1.0 in a previous iteration, it continues to be adjusted during each subsequent iteration until convergence is achieved. A minimum factor value of 0.1 is imposed as a practical lower limit.

4. DELAY DUE TO TURNS

This section describes a process for estimating the delay to through vehicles that follow vehicles turning from the major street into an unsignalized access point intersection. This delay can be incurred at any access point intersection along the street. For right-turn vehicles, the delay results when the following vehicles' speed is reduced to accommodate the turning vehicle. For left-turn vehicles, the delay results when the following vehicles must wait in queue while a vehicle ahead executes a left-turn maneuver at the access point. This delay occurs primarily on undivided streets; however, it can occur on divided streets when the left-turn queue exceeds the available storage and spills back into the inside through lane.

The delay estimation process consists of the following two procedures:

- Delay due to left turns and
- Delay due to right turns.

Each procedure is described in the following subsections. These procedures are based on the assumption that the segment traffic flows are random. While this assumption may not be strictly correct for urban streets, it is conservative in that it will yield slightly larger estimates of delay. Moreover, expansion of the models to accommodate platooned flows would not likely be cost-effective given the small amount of delay caused by turning vehicles.

DELAY DUE TO LEFT TURNS

Through vehicles on the major-street approach to an unsignalized intersection can incur delay when the left-turn queue exceeds the available storage and blocks the adjacent through lane (in this context, the undivided cross section is considered a major-street approach having no left-turn storage). The through vehicles that follow are delayed when they stop behind the queue of turning vehicles. This delay ends when the left-turn vehicle departs or the through vehicle merges into the adjacent through lane. By merging into the adjacent lane, drivers reduce their delay relative to the delay they would have incurred had they waited for the left-turn queue to clear. This delay is computed by using Equation 30-31.

$$d_{ap,l} = p_{ov}\, d_{t,1} \left(\frac{1}{P_L} - 1\right) \frac{P_{lt}}{1 - P_{lt} - P_{rt}}$$

Equation 30-31

where

$d_{ap,l}$ = through-vehicle delay due to left turns (s/veh),

p_{ov} = probability of left-turn bay overflow (decimal),

$d_{t,1}$ = average delay to through vehicles in the inside lane (s/veh),

P_L = proportion of left-turning vehicles in the shared lane (decimal),

P_{lt} = proportion of left-turning vehicles on the subject approach (decimal), and

P_{rt} = proportion of right-turning vehicles on the subject approach (decimal).

As indicated by Equation 30-31, the delay due to left turns is based on the value of several variables. The following sequence of computations can be used to estimate these values (*6*).

Step 1: Compute the Probability of a Lane Change

Equation 30-32

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

with

Equation 30-33

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

where

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 in which a lane change can occur = 3,600/t_{lc} (veh/h/ln),

t_{lc} = critical merge headway = 3.7 (s),

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),

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), and

N_{sr} = number of lanes in shared right-turn and through-lane group (ln).

If the ratio v_{app}/s_{lc} in Equation 30-32 exceeds 1.0, then it should be set to 1.0.

Step 2: Compute Through-Vehicle Equivalent for Left-Turn Vehicle

If there is a left-turn bay on the major street at the access point, the through-vehicle equivalent E_{L1} is 1.0. However, if there is no left-turn bay, the following equation is used to compute the through-vehicle equivalent.

Equation 30-34

$$E_{L1} = \frac{1{,}800}{c_l}$$

with

Equation 30-35

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

where

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

c_l = capacity of a left-turn movement with permitted left-turn operation (veh/h),

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

t_{fh} = follow-up headway = 2.2 (s), and

t_{cg} = critical headway = 4.1 (s).

Step 3: Compute Modified Through-Vehicle Equivalent

$$E_{L1,m} = (E_{L1} - 1)P_{lc} + 1$$ **Equation 30-36**

$$E_{R,m} = \left(E_{R,ap} - 1\right)P_{lc} + 1$$ **Equation 30-37**

where

$E_{L1,m}$ = modified through-car equivalent for a permitted left-turning vehicle,

$E_{R,m}$ = modified through-car equivalent for a protected right-turning vehicle, and

$E_{R,ap}$ = equivalent number of through cars for a protected right-turning vehicle at an access point (2.20 if there is no right-turn bay on the major street at the access point; 1.0 if there is a right-turn bay).

Step 4: Compute Proportion of Left Turns in Inside Through Lane

$$P_L = \frac{-b + \sqrt{b^2 - 4\, I_t\, R\, c}}{2\, I_t\, R} \quad \leq 1.0$$ **Equation 30-38**

with

$$b = R - I_{lt}\, P_{lt}\left\{I_t + (N_{sl} + N_t + N_{sr} - 1)\left[(1 + I_t)E_{L1,m} - 1\right]\right\}$$ **Equation 30-39**

$$c = -I_{lt}\, P_{lt}(N_{sl} + N_t + N_{sr})$$ **Equation 30-40**

$$R = 1 + I_{rt}\, P_{rt}(E_{R,m} - 1)$$ **Equation 30-41**

where

R, b, c = intermediate calculation variables;

I_{lt} = indicator variable (1.0 when there is no left-turn bay on the major street at the access point, 0.0 when there is a left-turn bay);

I_{rt} = indicator variable (1.0 when there is no right-turn bay on the major street at the access point, 0.0 when there is a right-turn bay); and

I_t = indicator variable (1.0 when equations are used to evaluate delay due to left turns, 0.00001 when equations are used to evaluate delay due to right turns).

If the number of through lanes on the subject intersection approach (= $N_{sl} + N_t + N_{sr}$) is equal to 1.0, then $P_L = P_{lt}$.

The indicator variable I_t is used to adapt the equations to the analysis of lane volume for both left-turn- and right-turn-related delays. The variable has a value of 1.0 in the evaluation of left-turn-related delays. In this situation, it models the condition in which one or more left-turning vehicles are blocking the inside lane. In contrast, the variable has a negligibly small value when it is applied to right-turn-related delays. It models flow conditions in which all lanes are unblocked.

Step 5: Compute Proportion of Right Turns in Outside Through Lane

Equation 30-42

$$P_R = I_{rt}\, P_{rt} \frac{\frac{s_1}{1{,}800} + N_{sl} + N_t + N_{sr} - 1}{1 - I_{rt}\, P_{rt}\left(\frac{s_1}{1{,}800} + N_{sl} + N_t + N_{sr} - 2\right)\left(E_{R,m} - 1\right)} \leq 1.0$$

with

Equation 30-43

$$s_1 = \frac{1{,}800\ (1 + P_L\, I_t)}{1 + P_L\left(E_{L1,m} - 1\right) + (P_L\, E_{L1,m}\, I_t)}$$

where s_1 is the saturation flow rate for the inside lane (veh/h/ln). If the number of through lanes on the subject intersection approach (= $N_{sl} + N_t + N_{sr}$) is equal to 1.0, then $P_R = P_{rt}$.

Step 6: Compute Inside Lane and Outside Lane Flow Rates

Equation 30-44

$$v_1 = \frac{v_{lt}}{P_L}$$

Equation 30-45

$$v_n = \begin{cases} \dfrac{v_{rt}}{P_R} & \text{if } P_R > 0.0 \\ \dfrac{v_{lt} + v_{th} + v_{rt} - v_1}{N_{sl} + N_t + N_{sr} - 1} & \text{if } P_R = 0.0 \end{cases}$$

where

v_1 = flow rate for the inside lane (veh/h/ln) and

v_n = flow rate for the outside lane (veh/h/ln).

Step 7: Compute Intermediate Lane Flow Rate

If there are more than two lanes on the subject intersection approach, Equation 30-46 can be used to estimate the flow rate in the intermediate lanes.

Equation 30-46

$$v_i = \frac{v_{lt} + v_{th} + v_{rt} - v_1 - v_n}{N_{sl} + N_t + N_{sr} - 2}$$

where v_i is the flow rate for lane i (veh/h/ln). The flow rates in lanes 2, 3, . . . , $n - 1$ are identical and equal to the value obtained from Equation 30-46.

Step 8: Compute Merge Capacity

Equation 30-47 is used to compute the merge capacity available to through drivers waiting in the inside lane of a multilane approach.

Equation 30-47

$$c_{mg} = \frac{v_2\, e^{-v_2\, t_{lc}/3{,}600}}{1 - e^{-v_2\, t_{lc}/3{,}600}}$$

where

c_{mg} = merge capacity (veh/h),

v_2 = flow rate in the adjacent through lane (veh/h/ln), and

t_{lc} = critical merge headway = 3.7 (s).

Step 9: Compute Delay to Through Vehicles That Merge

$$d_{mg} = 3{,}600\left(\frac{1}{c_{mg}} - \frac{1}{1{,}800}\right) + 900\,T\left[\frac{v_{mg}}{c_{mg}} - 1 + \sqrt{\left(\frac{v_{mg}}{c_{mg}} - 1\right)^2 + \frac{8\,v_{mg}}{c_{mg}^2\,T}}\right]$$ **Equation 30-48**

with

$$v_{mg} = v_1 - v_{lt} \geq 0.0$$ **Equation 30-49**

where

d_{mg} = merge delay (s/veh),

v_{mg} = merge flow rate (veh/h/ln), and

T = analysis period duration (h).

This delay is incurred by through vehicles that stop in the inside lane and eventually merge into the adjacent through lane. The "1/1,800" term included in Equation 30-48 extracts the service time for the through vehicle from the delay estimate, so that the delay estimate represents the increase in travel time resulting from the left-turn queue.

Step 10: Compute Inside Lane Capacity

Equation 30-50 is used to compute the capacity of the inside lane for vehicles that do not merge.

$$c_{nm} = \frac{1{,}800(1 + P_L)}{1 + P_L(E_{L1} - 1) + (P_L E_{L1})}$$ **Equation 30-50**

where c_{nm} is the nonmerge capacity for the inside lane (veh/h). The unadjusted through-vehicle equivalent for a left-turn vehicle E_{L1} is used in this equation to estimate the nonmerge capacity.

Step 11: Compute Delay to Through Vehicles That Do Not Merge

$$d_{nm} = 3{,}600\left(\frac{1}{c_{nm}} - \frac{1}{1{,}800}\right) + 900\,T\left[\frac{v_1}{c_{nm}} - 1 + \sqrt{\left(\frac{v_1}{c_{nm}} - 1\right)^2 + \frac{8\,v_1}{c_{nm}^2\,T}}\right]$$ **Equation 30-51**

where d_{nm} is the nonmerge delay for the inside lane (s/veh). This delay is incurred by through vehicles that stop in the inside lane and wait for the queue to clear. These vehicles do not merge into the adjacent lane.

Step 12: Compute Delay to Through Vehicles in the Inside Lane

This delay is estimated as the smaller of the delay relating to the merge and nonmerge maneuvers. It is computed with Equation 30-52.

$$d_{t,1} = \min(d_{nm}, d_{mg})$$ **Equation 30-52**

Step 13: Compute the Probability of Left-Turn Bay Overflow

The probability of left-turn bay overflow is computed by using the following equation:

$$p_{ov} = \left(\frac{v_{lt}}{c_l}\right)^{N_{qx,lt}+1}$$ **Equation 30-53**

with

Equation 30-54

$$N_{qx,lt} = \frac{N_{lt}\, L_{a,lt}}{L_h}$$

where

p_{ov} = probability of left-turn bay overflow (decimal),

$N_{qx,lt}$ = maximum queue storage for the left-turn movement (veh),

N_{lt} = number of lanes in the left-turn bay (ln),

$L_{a,lt}$ = available queue storage distance for the left-turn movement (ft/ln), and

L_h = average vehicle spacing in the stationary queue (see Equation 30-15) (ft/veh).

For an undivided cross section, the number of left-turn vehicles that can be stored, $N_{qx,lt}$, is equal to 0.0.

Step 14: Compute Through-Vehicle Delay due to Left Turns

The through-vehicle delay due to left turns $d_{ap,l}$ is computed with Equation 30-31.

DELAY DUE TO RIGHT TURNS

A vehicle turning right from the major street into an access point often delays the through vehicles that follow it. Through vehicles are delayed because they have to reduce speed to avoid a collision with the vehicle ahead, the first of which has reduced speed to avoid a collision with the right-turning vehicle. This delay can be several seconds in duration for the first few through vehicles but will always decrease to negligible values for subsequent vehicles as the need to reduce speed diminishes. For purposes of running time calculation, this delay must be averaged over all through vehicles traveling in the subject direction. The resulting average delay is computed with Equation 30-55.

Equation 30-55

$$d_{ap,r} = 0.67\, d_{t|r} \frac{P_{rt}}{1 - P_{lt} - P_{rt}}$$

where

$d_{ap,r}$ = through-vehicle delay due to right turns (s/veh) and

$d_{t|r}$ = through-vehicle delay per right-turn maneuver (s/veh).

The variable $d_{t|r}$ in Equation 30-55 converges to 0.0 as the proportion of turning vehicles approaches 1.0. The constant 0.67 is a calibration factor based on field data. The steps undertaken to quantify this factor are described in the remainder of this subsection. Equation 30-55 can also be used to estimate the delay due to left-turn vehicles on a one-way street. In this case, variables associated with the right-turn movement would be redefined as applicable to the left-turn movement and vice versa.

As indicated by Equation 30-55, the delay due to right turns is based on the value of several variables. The following sequence of computations can be used to estimate these values (*7*).

Step 1: Compute Minimum Speed for the First Through Vehicle

$$u_m = 1.47\, S_f - r_d(H_1 - h_{|\Delta<h<H_1}) \geq u_{rt}$$ **Equation 30-56**

with

$$h_{|\Delta<h<H_1} = \frac{1}{\lambda} + \frac{\Delta - H_1 e^{-\lambda(H_1-\Delta)}}{1 - e^{-\lambda(H_1-\Delta)}}$$ **Equation 30-57**

$$H_1 = \frac{1.47\, S_f - u_{rt}}{r_d} + t_{cl} + \frac{L_h}{1.47\, S_f} \geq \Delta$$ **Equation 30-58**

$$\lambda = \frac{1}{\frac{1}{q_n} - \Delta}$$ **Equation 30-59**

where

u_m = minimum speed of the first through vehicle given that it is delayed (ft/s),

u_{rt} = right-turn speed = 20 (ft/s),

S_f = free-flow speed (mi/h),

$h_{|\Delta<h<H_1}$ = average headway of those headways between Δ and H_1 (s/veh),

Δ = headway of bunched vehicle stream = 1.5 (s/veh),

H_1 = maximum headway that the first through vehicle can have and still incur delay (s/veh),

r_d = deceleration rate = 6.7 (ft/s^2),

t_{cl} = clearance time of the right-turn vehicle = 0.6 (s),

L_h = average vehicle spacing in stationary queue (see Equation 30-15) (ft/veh),

λ = flow rate parameter (veh/s),

q_n = outside lane flow rate = v_n/3,600 (veh/s), and

v_n = flow rate for the outside lane (veh/h/ln).

The right-turn speed u_{rt} used in Equation 30-56 and Equation 30-58 is likely to be sensitive to access point design, including the approach profile, throat width, and curb radius. For level profiles and nominal throat widths, the speed can vary from 15 to 25 ft/s for radii varying from 20 to 60 ft, respectively. A default turn speed of 20 ft/s is recommended when information is not available to make a more accurate estimate.

The flow rate for the outside lane v_n is computed by using Steps 3, 4, 5, and 6 from the procedure described in the previous subsection, Delay due to Left Turns. However, the probability of a lane change P_{lc} is set equal to 1.0 when the calculations in Step 3 are made. In Steps 4 and 5, the variable I_t is set equal to 0.00001. The proportion of right-turning vehicles in the shared lane P_R is also computed at this point and used in a later step.

Step 2: Compute Delay to the First Through Vehicle

Equation 30-60

$$d_1 = \frac{(1.47\ S_f - u_m)^2}{2\ (1.47\ S_f)}\left(\frac{1}{r_d} + \frac{1}{r_a}\right)$$

where d_1 is the conditional delay to the first through vehicle (s/veh), and r_a is the acceleration rate = 3.5 (ft/s²).

Step 3: Compute Delay to the Second Through Vehicle

Equation 30-61

$$d_2 = d_1 - \left(h_{|\Delta<h<H_2} - \Delta\right)$$

with

Equation 30-62

$$h_{|\Delta<h<H_2} = \frac{1}{\lambda} + \frac{\Delta - H_2 e^{-\lambda(H_2-\Delta)}}{1 - e^{-\lambda(H_2-\Delta)}}$$

Equation 30-63

$$H_2 = d_1 + \Delta$$

where d_2 is the conditional delay to Vehicle 2 (s/veh).

Step 4: Compute Delay to the Third and Subsequent Through Vehicles

Equation 30-64

$$d_i = d_{i-1} - \left(h_{|\Delta<h<H_i} - \Delta\right)$$

with

Equation 30-65

$$h_{|\Delta<h<H_i} = \frac{1}{\lambda} + \frac{\Delta - H_i e^{-\lambda(H_i-\Delta)}}{1 - e^{-\lambda(H_i-\Delta)}}$$

Equation 30-66

$$H_i = d_{i-1} + \Delta$$

where d_i is the conditional delay to vehicle i (i = 3, 4, . . . ,) (s/veh). As shown by Equation 30-61 and Equation 30-64, the delay to each subsequent through vehicle is less than or equal to that of the preceding vehicle. In fact, the sequence of delays always converges to zero when the average flow rate in the outside lane is less than $1/\Delta$.

Step 4 should be repeated for the third and subsequent through vehicles until the delay computed for vehicle i is less than 0.1 s. In general, this criterion results in delay being computed for only the first two or three vehicles.

Step 5: Compute Through-Vehicle Delay per Right-Turn Maneuver

The through-vehicle delay for the first two vehicles is computed with Equation 30-67.

Equation 30-67

$$d_{t|r} = d_1\left(1 - e^{-\lambda(H_1-\Delta)}\right)(1 - P_R) + d_2\left(1 - e^{-\lambda(H_1-\Delta)}\right)\left(1 - e^{-\lambda(H_2-\Delta)}\right)(1 - P_R)^2$$

where $d_{t|r}$ is the through-vehicle delay per right-turn maneuver (s/veh). If three or more vehicles are delayed, an additional term needs to be added to Equation 30-67 for each subsequent vehicle. In this situation, Equation 30-68 can be used to compute the delay for any number of vehicles.

Equation 30-68

$$d_{t|r} = \sum_{i=1}^{\infty}\left[d_i \times \prod_{j=1}^{i}\left(1 - e^{-\lambda(H_j-\Delta)}\right) \times (1 - P_R)^i\right]$$

Step 6: Compute Through-Vehicle Delay due to Right Turns

The through-vehicle delay due to right turns $d_{ap,r}$ is computed with Equation 30-55.

5. PLANNING-LEVEL ANALYSIS APPLICATION

OVERVIEW OF THE APPLICATION

This section describes a simplified method for evaluating the operation of a coordinated street segment with signalized boundary intersections. The application addresses motorized vehicle operation. It is focused on the analysis of the through movement at the boundary intersections. This method can be used when minimal data are available for the analysis and only approximate results are desired.

REQUIRED DATA AND SOURCES

The overall data requirements are summarized in Exhibit 30-7. Some of the input requirements may be met by assumed values or default values. Other data items are site-specific and must be obtained in the field. The objective of using the planning-level analysis application is to minimize the need for the collection of detailed field data.

Exhibit 30-7
Required Input Data for the Planning-Level Analysis Application

Data Category	Location	Input Data Element
Traffic characteristics	Boundary intersection	Through-demand flow rate Through-saturation flow rate Volume-to-capacity ratio of the upstream movements
	Segment	Platoon ratio Midsegment flow rate Midsegment delay
Geometric design	Boundary intersection	Number of through lanes Upstream intersection width
	Segment	Number of through lanes Segment length Restrictive median length Nonrestrictive median length Proportion of segment with curb Number of access point approaches Proportion of segment with on-street parking
Signal control	Boundary intersection	Effective green-to-cycle-length ratio Cycle length
Other	Segment	Analysis period duration Speed limit

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

METHODOLOGY

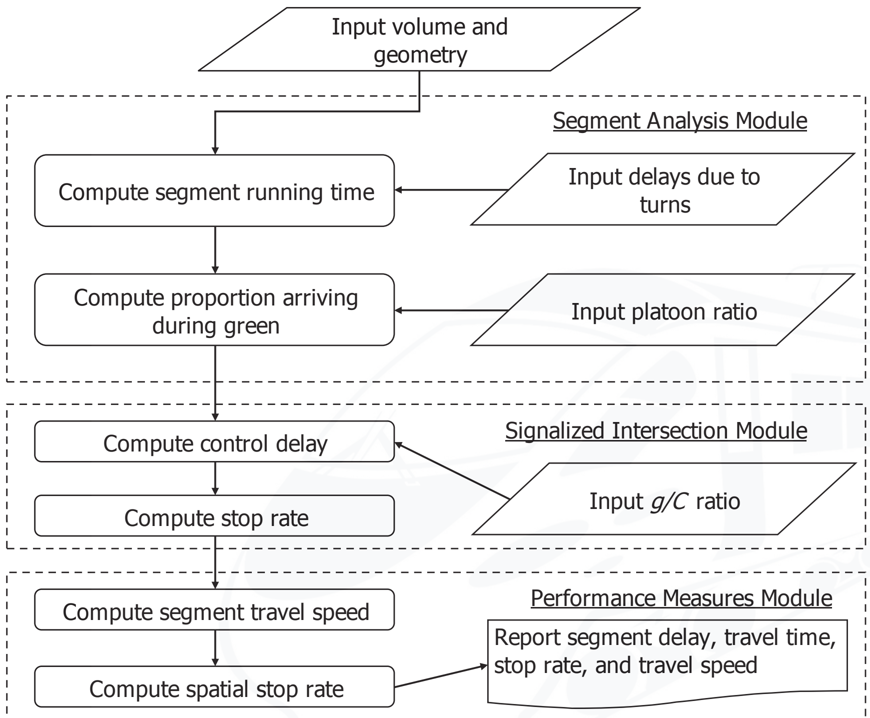
The methodology consists of five computational steps. These steps are

- Determine running time;
- Determine proportion arriving during green;
- Determine through control delay;

- Determine through stop rate; and
- Determine travel speed, spatial stop rate, and level of service (LOS).

Each step is executed in the sequence presented in the preceding list. This sequence is illustrated by the flowchart in Exhibit 30-8. The rectangles with rounded corners indicate the computational steps. The parallelograms indicate where input data are needed.

Exhibit 30-8
Planning-Level Analysis Application for Urban Street Segments



The computations associated with each step identified in Exhibit 30-8 are described in Section 3 of Chapter 18. These computations are conveniently illustrated here in a series of worksheets; each worksheet corresponds to one or two of the calculation steps.

The first of the computational worksheets is the Running Time worksheet. It is shown as Exhibit 30-9 (values shown apply to the Example Problem, as discussed in a subsequent section).

Exhibit 30-9
Planning-Level Analysis: Running Time Worksheet

RUNNING TIME WORKSHEET			
General Information		**Site Information**	
Analyst	JME	Street	Texas Avenue
Agency or Company	ACME Engr.	Jurisdiction	
Date Performed	9/30/15	Analysis Year	2015
Analysis Time Period	5:30 p.m. to 5:45 p.m.	Analysis Level	planning
Base free-flow speed calibration factor (S_{calib}), mi/h: 0.0			

Input Data	**Segment 1**		**Segment 2**	
Direction of travel	**EB/NB**	**WB/SB**	**EB/NB**	**WB/SB**
Segment Data				
Number of through lanes for length of segment N_{th} (ln)	2	2		
Speed limit S_{pl} (mi/h)	35	35		
Midsegment volume v_m (veh/h)	1,150	1,150		
Total delay due to turns into access points Σd_{ap} (s/veh)	0.52	0.52		
Delay due to other midsegment sources d_{other} (s/veh)	0	0		
Length of segment L (ft)	1,800	1,800		
Width of upstream boundary intersection W_i (ft)	50	50		
Length of segment with restrictive median L_{rm} (ft)	0	0		
Length of segment with nonrestrictive median L_{nr} (ft)	0	0		
Start-up lost time l_1 (s)	2.0	2.0		
Access Data				
Proportion of segment with curb on right-hand side p_{curb}	0.70	0.70		
Number of access points on right-hand side N_{ap}	4	4		
Proportion of segment with on-street parking p_{pk}	0.00	0.00		
Running Time Computation				
Adjusted segment length L_{adj} (ft) $L_{adj} = L - W_i$	1,750	1,750		
Proportion of segment length with restrictive median p_{rm}, $p_{rm} = L_{rm}/L_{adj}$	0.0	0.0		
Speed constant S_0 (mi/h), $S_0 = 25.6 + 0.47\ S_{pl}$	42.1	42.1		
Adjustment for cross section f_{CS} (mi/h), $f_{CS} = 1.5\ p_{rm} - 0.47\ p_{curb} - 3.7\ p_{curb}\ p_{rm}$	-0.3	-0.3		
Access point density D_a (access points/mi), $D_a = 5{,}280\ (N_{ap,EB/NB} + N_{ap,WB/SB})/L_{adj}$	24.1	24.1		
Adjustment for access points f_A (mi/h), $f_A = -0.078\ D_a/N_{th}$	-0.9	-0.9		
Adjustment for on-street parking f_{pk} (mi/h), $f_{pk} = -3\ p_{pk}$	0.0	0.0		
Base free-flow speed S_{fo} (mi/h), $S_{fo} = S_{calib} + S_0 + f_{CS} + f_A + f_{pk}$	40.8	40.8		
Segment length adjustment factor f_L, $f_L = 1.02 - 4.7\ (S_{fo} - 19.5)/\max(L, 400) \le 1.0$	0.96	0.96		
Free-flow speed S_f (mi/h), $S_f = S_{fo}\ f_L \ge S_{pl}$	39.3	39.3		
Proximity adjustment factor f_v $\quad f_v = \dfrac{2}{1 + \left(1 - \dfrac{v_m}{52.8\ N_{th}\ S_f}\right)^{0.21}}$	1.03	1.03		
Running time t_R (s) $\quad t_R = \dfrac{6.0 - l_1}{0.0025\ L} + \dfrac{3{,}600\ L}{5{,}280\ S_f} f_v + \Sigma d_{ap} + d_{other}$	33.7	33.7		

Note: The first term in the running time equation is only applicable to segments with signal-controlled, STOP-controlled, or YIELD-controlled through movement at the boundary intersection.

The Running Time worksheet combines input data describing the segment geometric design, speed limit, volume, and access point frequency to estimate the base free-flow speed. This speed is then adjusted for segment length effects to obtain the expected free-flow speed. The free-flow speed is then used to estimate a free-flow travel time, which is adjusted for the proximity of other vehicles. Delay that is caused by turns into access points or other sources is added to the adjusted travel time. Default values for the delay due to turns at midsegment access points are listed in Exhibit 18-13 in Chapter 18. These defaults can be used when more accurate estimates of this delay are not available. The result of these adjustments is an estimate of the expected segment running time.

The second of the computational worksheets is the Proportion Arriving During Green worksheet. It is shown as Exhibit 30-10. This worksheet is designed for the analysis of the segment through-lane group. It documents the calculation of the proportion of vehicles that arrive during the green indication. Input data include the effective green-to-cycle-length ratio and platoon ratio.

Exhibit 30-10
Planning-Level Analysis: Proportion Arriving During Green Worksheet

PROPORTION ARRIVING DURING GREEN WORKSHEET				
General Information				
Project Description: Texas Avenue, 5:30 p.m. to 5:45 p.m.				
Input Data				
	Segment 1		**Segment 2**	
Direction of travel	**EB/NB**	**WB/SB**	**EB/NB**	**WB/SB**
Signal Timing Data				
Effective green-to-cycle-length ratio g/C	0.47	0.47		
Traffic Data				
Platoon ratio R_p	1.43	0.67		
Proportion Arriving During Green Computation				
Proportion arriving during green P, $P = R_p\,(g/C)$	0.67	0.31		

The third computational worksheet is the Control Delay worksheet. It is shown as Exhibit 30-11. This worksheet is designed for the analysis of the segment through-lane group. Input variables include the analysis period duration, cycle length, effective green-to-cycle-length ratio, volume, saturation flow rate, and lanes. The proportion of arrivals during green is obtained from the previous worksheet.

The equation for computing the progression adjustment factor PF^* that is provided in Exhibit 30-11 is a simplified version of the exact equation (as provided in Section 3 of Chapter 19). The simplified equation, in combination with the supplemental adjustment factor f_{PA}, is sufficiently accurate for purposes of the planning-level analysis application.

The control delay is computed as the sum of two components. The first component to be computed is the uniform delay. The notation "min(1, X)" is shown in the equation used to compute this delay. It means that the value to be substituted for this text is the smaller of 1.0 and the volume-to-capacity ratio.

Exhibit 30-11
Planning-Level Analysis: Control Delay Worksheet

CONTROL DELAY WORKSHEET				
General Information				
Project Description	Texas Avenue, 5:30 p.m. to 5:45 p.m.			
Input Data				
Analysis period T (h): 0.25	**Segment 1**		**Segment 2**	
Direction of travel	**EB/NB**	**WB/SB**	**EB/NB**	**WB/SB**
Signal Timing Data				
Cycle length C (s)	100	100		
Effective green-to-cycle-length ratio g/C	0.47	0.47		
Traffic Data				
Through-lane group volume v_{th} (veh/h)	968	950		
Lane group saturation flow rate s (veh/h/ln)	1,800	1,800		
Proportion of arrivals during green P	0.67	0.31		
Volume-to-capacity ratio X_u of the upstream movements	0.57	0.57		
Geometric Design Data				
Number of through lanes N_{th} (ln)	2	2		
Delay Computation				
Capacity c (veh/h), $c = N_{th}\ s\ g/C$	1,692	1,692		
Volume-to-capacity ratio X, $X = v_{th}/c$	0.57	0.56		
Supplemental adjustment factor for platoons arriving during green f_{PA}, f_{PA} = 1.00 except as noted below: If $0.50 < R_p \le 0.85$, then $f_{PA} = 0.93$ If $1.15 < R_p \le 1.50$, then $f_{PA} = 1.15$	1.15	0.93		
Progression adjustment factor PF^*, $PF^* = f_{PA}(1 - P)/(1 - g/C)$	0.71	1.20		
Uniform delay d_1 (s/veh), $d_1 = \left(PF^*\right)\dfrac{0.5\,C\,(1 - g/C)^2}{1 - [\min(1, X)\,g/C]}$	13.6	23.0		
Upstream filtering adjustment factor I, $I = 1.0 - 0.91\,X_u^{2.68} \ge 0.090$	0.80	0.80		
Incremental delay d_2 (s/veh), $d_2 = 900\,T\left[(X - 1) + \sqrt{(X - 1)^2 + \dfrac{4\,I\,X}{c\,T}}\right]$	1.13	1.08		
Control delay d (s/veh), $d = d_1 + d_2$	14.7	24.1		

The second delay component is the incremental delay, which is based on the upstream filtering adjustment factor. This factor requires the variable X_u, which can be estimated as the volume-to-capacity ratio of the segment through-lane group at the upstream signalized intersection. Additional detail on the calculation of this ratio is provided in Section 3 of Chapter 19, Signalized Intersections.

The fourth computational worksheet is the Stop Rate worksheet. It is shown as Exhibit 30-12. This worksheet is designed for the analysis of the segment through-lane group. The input variables are the same as those needed for the Control Delay worksheet with the addition of speed limit. The average speed during the analysis period is estimated by using the equation provided. If the average speed is known, it should be substituted for the estimated value.

Exhibit 30-12
Planning-Level Analysis: Stop Rate Worksheet

STOP RATE WORKSHEET				
General Information				
Project Description	Texas Avenue, 5:30 p.m. to 5:45 p.m.			
Input Data				
Analysis period T (h): 0.25	**Segment 1**		**Segment 2**	
Direction of travel	**EB/NB**	**WB/SB**	**EB/NB**	**WB/SB**
Signal Timing Data				
Cycle length C (s)	100	100		
Effective green-to-cycle-length ratio g/C	0.47	0.47		
Traffic Data				
Through-lane group volume v_{th} (veh/h)	968	950		
Lane group saturation flow rate s (veh/h/ln)	1,800	1,800		
Proportion of arrivals during green P	0.67	0.31		
Speed limit S_{pl} (mi/h)	35	35		
Incremental delay d_2 (s/veh)	1.13	1.08		
Geometric Design Data				
Number of through lanes N_{th} (ln)	2	2		
Stop Rate Computation				
Effective green time g (s), $g = C\,(g/C)$	47	47		
Effective red time r (s), $r = C - g$	53	53		
Capacity c (veh/h), $c = N_{th}\,s\,g/C$	1,692	1,692		
Volume-to-capacity ratio X, $X = v_{th}/c$	0.57	0.56		
Average speed S_a (mi/h), $S_a = 0.90\,(25.6 + 0.47\,S_{pl})$	37.8	37.8		
Threshold acceleration–deceleration delay (s), $(1 - P)\,g\,X$	8.8	18.1		
Acceleration–deceleration delay d_a (s), $d_a = 0.393\,(S_a - 5.0)^2/S_a$	11.2	11.2		
Deterministic stop rate h_1 (stops/veh), $h_1 = \frac{1 - P\,(1 + d_a / g)}{1 - P\,X}$ if $d_a \le (1 - P)\,g\,X$; $h_1 = \frac{(1 - P)(r - d_a)}{r - (1 - P)\,g\,X}$ if $d_a > (1 - P)\,g\,X$	0.31	0.74		
Second-term back-of-queue size Q_2 (veh/ln), $Q_2 = c\,d_2\,/(3{,}600\,N_{th})$	0.26	0.25		
Full stop rate h (stops/veh), $h = h_1 + 3{,}600\,N_{th}\,Q_2\,/(v_{th}\,C)$	0.33	0.76		

The stop rate is computed as the sum of two components. The first component to be computed is the deterministic stop rate. Two equations are available for this computation. The correct equation to use is based on a check of the acceleration–deceleration delay relative to the computed threshold value.

The second stop rate component is based on the second-term back-of-queue size. This queue represents the average number of vehicles that are unserved at the end of the green interval. It is based on the incremental delay computed for the Control Delay worksheet.

The fifth computational worksheet is the Travel Speed and Spatial Stop Rate worksheet. It is shown as Exhibit 30-13. This worksheet is designed for the analysis of the segment through-lane group. The input values include segment length and the full stop rate associated with other midsegment events (e.g., turns at access points). The other input data listed represent computed values and are obtained from the previous worksheets.

Exhibit 30-13
Planning-Level Analysis: Travel Speed and Spatial Stop Rate Worksheet

TRAVEL SPEED AND SPATIAL STOP RATE WORKSHEET				
General Information				
Project Description	Texas Avenue, 5:30 p.m. to 5:45 p.m.			
Input Data				
	Segment 1		**Segment 2**	
Direction of travel	**EB/NB**	**WB/SB**	**EB/NB**	**WB/SB**
Length of segment L (ft)	1,800	1,800		
Base free-flow speed S_{fo} (mi/h)	40.8	40.8		
Running time t_R (s)	33.7	33.7		
Control delay d (s/veh)	14.7	24.1		
Full stop rate h (stops/veh)	0.33	0.76		
Full stop rate due to other midsegment sources h_{other} (stops/veh)	0	0		
Travel Speed Computation				
Travel time T_T (s), $T_T = t_R + d$	48.4	57.7		
Travel speed $S_{T,seg}$ (mi/h), $S_{T,seg} = \frac{3{,}600\ L}{5{,}280\ T_T}$	25.4	21.3		
Spatial Stop Rate Computation				
Total stop rate h_T (stops/veh), $h_T = h + h_{other}$	0.33	0.76		
Spatial stop rate H_{seg} (stops/mi), $H_{seg} = \frac{5{,}280\, h_T}{L}$	0.96	2.23		
Level-of-Service Computation				
Volume-to-capacity ratio X, $X = v_{th}/c$	0.57	0.56		
Travel speed thresholds for base free-flow speed (S_{fo}) by interpolation of values in Exhibit 18-1 (mi/h)	A: >32.6 B: >27.3 C: >20.4 D: >16.3 E: >12.2	A: >32.6 B: >27.3 C: >20.4 D: >16.3 E: >12.2		
Level of service	C	C		

EXAMPLE PROBLEM

The Urban Street Segment

The total length of an undivided urban street segment is 1,800 ft. It is shown in Exhibit 30-14. Both of the boundary intersections are signalized. The street has a four-lane cross section with two lanes in each direction. There are left-turn bays on the subject segment at each signalized intersection.

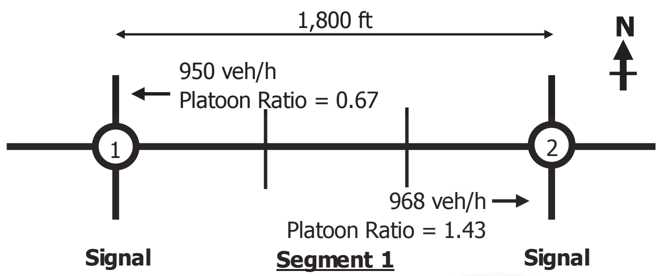


Exhibit 30-14
Planning-Level Analysis: Example Problem

The segment has two access point intersections. Each intersection has two STOP-controlled side-street approaches, and each approach has sufficient traffic volume during the analysis period to be considered active. The segment also has two driveways on each side of the street; however, their turn movement volumes are too low for them to be considered active.

The Question

What are the travel speed, spatial stop rate, and LOS during the analysis hour for through-vehicle traffic in both directions of travel along the segment?

The Facts

Some details of the segment are shown in Exhibit 30-14. Both boundary intersections are signalized. The following additional information is known about the street segment:

Through saturation flow rate: 1,800 veh/h/ln

Midsegment volume: 1,150 veh/h

Midsegment delay: 0.52 s/veh

Number of through lanes at boundary intersection: 2

Upstream intersection width: 50 ft

Number of through lanes on segment: 2

Proportion of street with curb: 0.70

Proportion of street with on-street parking: 0.0

g/C ratio: 0.47

Cycle length: 100 s

Analysis period: 0.25 h

Speed limit: 35 mi/h

Percent left turns at active access points: 6%

Percent right turns at active access points: 8%

Selected Calculations

1. Compute total delay due to turns into access points	Midsegment lanes = 2 lanes Midsegment lane volume = 575 veh/h/ln Interpolate in Exhibit 18-13 to obtain 0.37 s/veh/pt through-vehicle delay. Number of active access points = 2 Percent turns = 7% [= (6 + 8)/2] Total delay per access pt. = 7/10 × 0.37 = 0.26 s/veh/pt Total delay per segment = 2 × 0.26 = 0.52 s/veh
2. Compute upstream filtering factor	No information was available about the volume-to-capacity ratio for the upstream movements, so this ratio was estimated to equal the volume-to-capacity ratio for the subject movement.

Results

The calculations are shown in Exhibit 30-9 to Exhibit 30-13. The travel speed for the eastbound direction is 25.4 mi/h. The travel speed for the westbound direction is 21.3 mi/h. The eastbound and westbound spatial stop rates are 0.96 and 2.23 stops/mi, respectively.

The base free-flow speed is 40.8 mi/h. By interpolating this value between those in Exhibit 18-1, the threshold travel speeds for LOS A, B, C, D, and E are >32.6, >27.3, >20.4, >16.3, and >12.2 mi/h, respectively. Thus, the travel speed for the eastbound direction of 26.3 mi/h corresponds to LOS C. The westbound LOS is similarly determined to be C.

6. FIELD MEASUREMENT TECHNIQUES

This section describes two techniques for estimating key vehicular traffic characteristics by using field data. The first technique is used to estimate free-flow speed. The second technique is used to estimate average travel speed.

The field measurements for both techniques should occur during a time period that is representative of the analysis period. This approach recognizes a possible difference in driver speed choice during different times of day (and, possibly, days of week and months of year).

FREE-FLOW SPEED

The following steps can be used to determine the free-flow speed for vehicular traffic on an urban street segment. The definition of "urban street segment" is provided in Section 2 of Chapter 18.

The speed measured with the technique described in this section describes the free-flow speed for the subject segment. It is not necessarily an accurate measurement of the free-flow speed on an adjacent segment because of possible differences in geometry, access point spacing, or speed limit.

Some urban streets have characteristics that can influence free-flow speed but that are not considered in the predictive procedure. If free-flow speed is measured for these segments, the results should be qualified to acknowledge the possible influence of these characteristics on the measured speed. These characteristics include a change in the posted speed limit along the segment, the display of an advisory speed sign that has an advisory speed lower than the speed limit, a change in the number of through lanes along the segment, significant grade, or a midsegment capacity constraint (e.g., narrow bridge).

Step 1. Conduct a spot-speed study at a midsegment location during low-volume conditions. Record the speed of 100 or more free-flowing passenger cars. A car is free-flowing when it has a headway of 8 s or more to the vehicle ahead and 5 s or more to the vehicle behind in the same traffic lane. In addition, a free-flow vehicle is not influenced (i.e., slowed) by the following factors: (*a*) vehicles turning onto (or off of) the subject segment at the boundary intersection or at a midsegment access point, (*b*) traffic control devices at the boundary intersections, or (*c*) traffic control devices deployed along the segment.

In view of the aforementioned definition of "free-flow vehicle," vehicles turning into (or out of) an access point should not be included in the database. Vehicles that are accelerating or decelerating as a result of driver response to a traffic control signal should not be included in the database. Vehicles should not be included if they are influenced by signs that require a lower speed limit during school hours or signs that identify a railroad crossing.

Step 2. Compute the average of the spot speeds S_{spot} and their standard deviation σ_{spot}.

Step 3. Compute the segment free-flow speed S_f as a space mean speed by using Equation 30-69.

Equation 30-69

$$S_f = S_{\text{spot}} - \frac{\sigma_{\text{spot}}^2}{S_{\text{spot}}}$$

where

S_f = free-flow speed (mi/h),

S_{spot} = average spot speed (mi/h), and

σ_{spot} = standard deviation of spot speeds (mi/h).

Step 4. If the base free-flow speed S_{fo} is also desired, it can be computed by using Equation 30-70.

Equation 30-70

$$S_{fo} = \frac{S_f}{f_L}$$

with

Equation 30-71

$$f_L = 1.02 - 4.7 \frac{S_f - 19.5}{\max(L_s, 400)} \leq 1.0$$

where

S_{fo} = base free-flow speed (mi/h),

S_f = free-flow speed (mi/h),

L_s = distance between adjacent signalized intersections (ft), and

f_L = signal spacing adjustment factor.

Equation 30-71 was originally derived with the intent of using the base free-flow speed S_{fo} in the numerator of the second term. However, use of the free-flow speed S_f in its place is sufficient for this application.

Equation 30-71 was derived by using signalized boundary intersections. For more general applications, the definition of distance L_s is broadened so that it equals the distance between the two intersections that (*a*) bracket the subject segment and (*b*) each have a type of control that can impose on the subject through movement a legal requirement to stop or yield.

AVERAGE TRAVEL SPEED

The following steps can be used to determine the average travel speed for vehicular traffic on an urban street segment.

Step 1. Identify the time of the day (e.g., morning peak, evening peak, off-peak) during which the study will be conducted. Identify the segments to be evaluated.

Step 2. Conduct the test car travel time study for the identified segments during the identified study period. The following factors should be considered before or during the field study:

- The number of travel time runs will depend on the range of speeds found on the street. Six to 12 runs for each traffic volume condition are typically adequate. The analyst should determine the minimum number of runs on the basis of guidance provided elsewhere (*8*).

- The objective of the data collection is to obtain the information identified in the Travel Time Field Worksheet (i.e., vehicle location and arrival and departure times at each boundary intersection). This worksheet is shown in Exhibit 30-15. In general, each row of this worksheet represents the data for one direction of travel on one segment. If the street serves traffic in two travel directions, separate worksheets are typically used to record the data for each direction of travel.
- The equipment used to record the data may include a Global Positioning System–equipped laptop computer or simply a pair of stopwatches. If available, an instrumented test car should be used to reduce labor requirements and to facilitate recording and analysis.
- During the test run, the average-car technique is typically used and requires that the test car travel at the average speed of the traffic stream, as judged by its driver (*8*).
- The cumulative travel time is recorded as the vehicle passes the center of each boundary intersection. Whenever the test car stops or slows (i.e., 5 mi/h or less), the observer uses a second stopwatch to measure the duration of time the vehicle is stopped or slowed. This duration (and the cause of the delay) is recorded on the worksheet on the same row that is associated with the next boundary intersection to be reached. The rows are intentionally tall so that a midsegment delay and the signal delay can both be recorded in the same cell.
- Test car runs should begin at different time points in the signal cycle to avoid having all runs start from a "first in platoon" position.
- Some midsegment speedometer readings should also be recorded to check on unimpeded travel speeds and to see how they relate to the estimated free-flow speed.

Step 3. The cumulative travel time observations between adjacent boundary intersections are subtracted to obtain the travel time for the corresponding segment. This travel time can be averaged for all test runs to obtain an average segment travel time. The average is then divided into the segment length to obtain an estimate of the average travel speed. This speed should be computed for each direction of travel for the segment.

The data should be summarized to provide the following statistics for each segment travel direction: average travel speed, average delay time for the boundary intersection, and average delay time for other sources (pedestrian, parking maneuver, etc.).

The average segment travel time for each of several consecutive segments in a common direction of travel can be added to obtain the total travel time for the facility. This total travel time can then be divided into the facility length (i.e., the total length of all segments) to obtain the average travel speed for the facility. This calculation should be repeated to obtain the average travel speed for the other direction of travel.

Exhibit 30-15
Travel Time Field Worksheet

TRAVEL TIME FIELD WORKSHEET

General Information		**Site Information**	
Analyst		Street	
Agency or Company		Jurisdiction	
Date Performed		Analysis Year	
Analysis Time Period		Direction of Travel	

Field Data

Location (typically a boundary intersection)	Run Number: ______			Run Number: ______		
	Cumulative Travel Time at Location (s)	Delays due to Slow or Stop		Cumulative Travel Time at Location (s)	Delays due to Slow or Stop	
		Cause [a]	Delay Time (s)		Cause [a]	Delay Time (s)

Notes: [a] Cause of delay: Ts = signal; Lt = left turn; Pd = pedestrian; Pk = parking; Ss = STOP sign; Ys = YIELD sign.

7. COMPUTATIONAL ENGINE DOCUMENTATION

This section uses a series of flowcharts and linkage lists to document the logic flow for the computational engine.

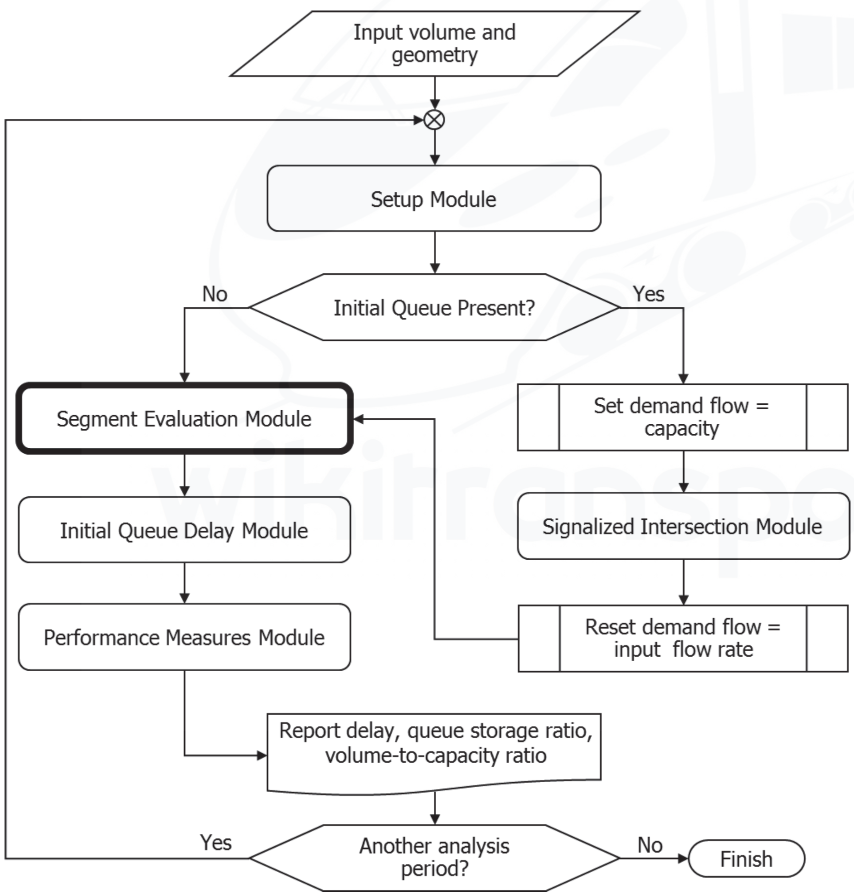
FLOWCHARTS

The methodology flowchart is shown in Exhibit 30-16. The methodology consists of five main modules:

- Setup Module,
- Segment Evaluation Module,
- Segment Analysis Module,
- Delay due to Turns Module, and
- Performance Measures Module.

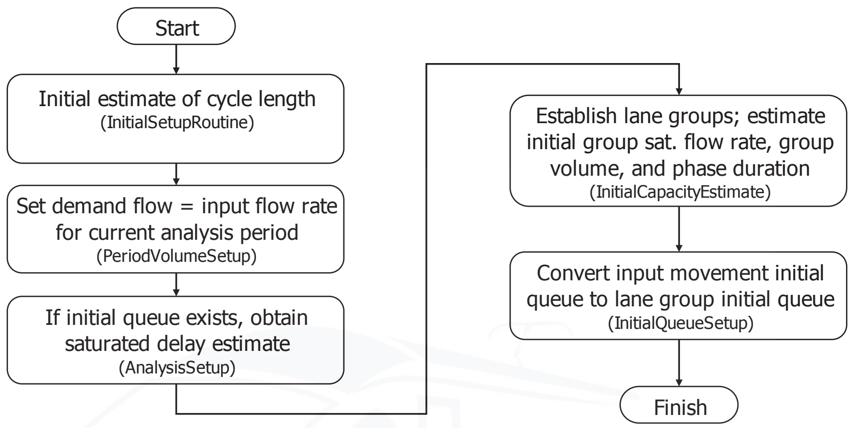
This subsection provides a separate flowchart for each of these modules.

Exhibit 30-16
Methodology Flowchart



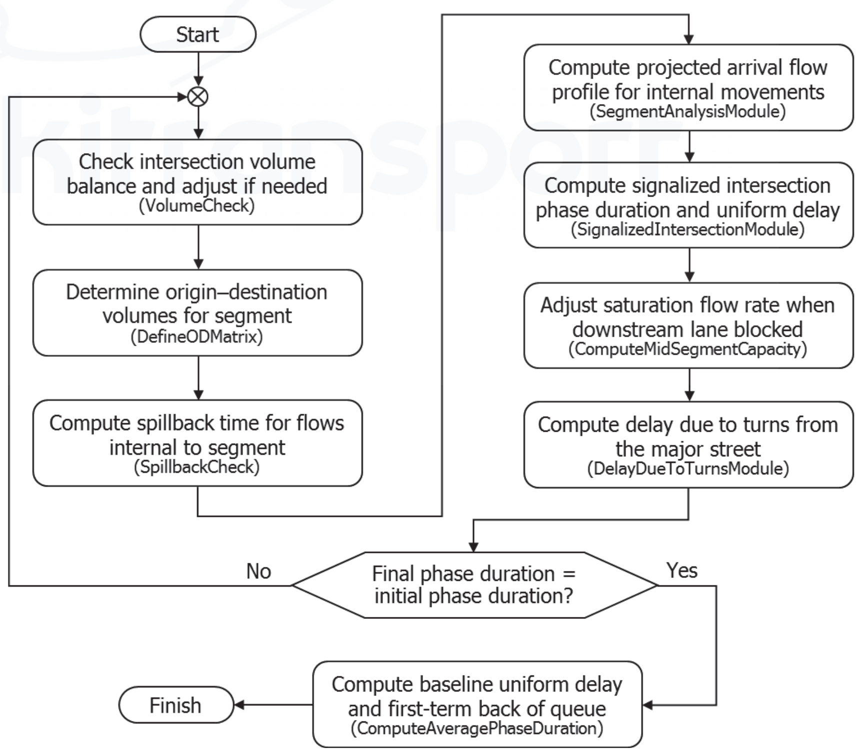
The Setup Module is shown in Exhibit 30-17. This module consists of five main routines, as shown in the large rectangles of the exhibit. The main function of each routine, as well as the name given to it in the computational engine, is also shown in the exhibit. These routines and the Initial Queue Delay Module are described in Chapter 31, Signalized Intersections: Supplemental.

Exhibit 30-17
Setup Module



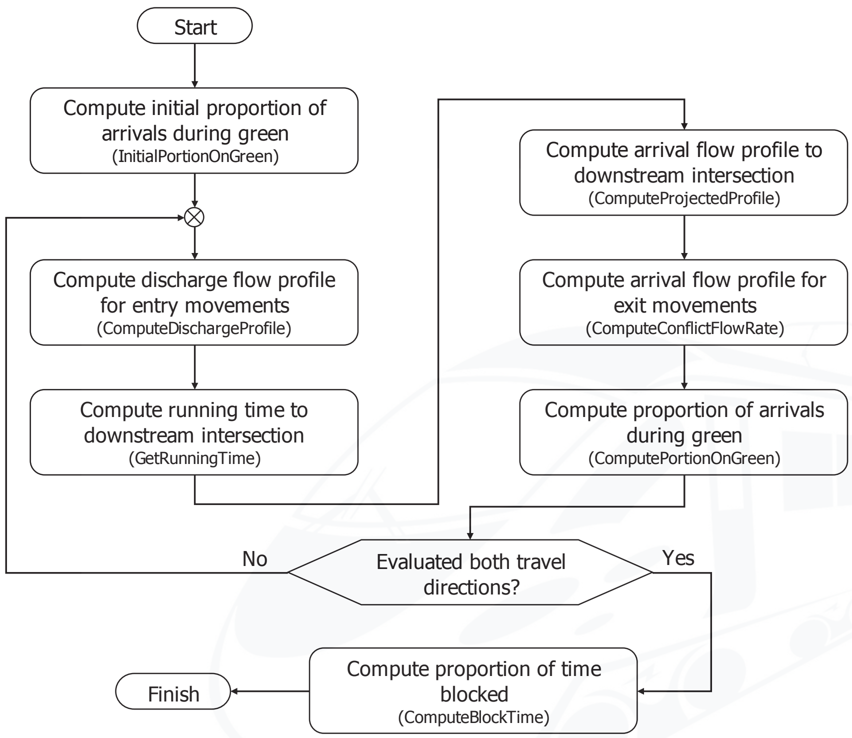
The Segment Evaluation Module is shown in Exhibit 30-18. This module consists of eight main routines. The main function of each routine, as well as the name given to it in the computational engine, is also shown in the exhibit. The Segment Analysis Module and the Delay due to Turns Module are outlined in the next two exhibits. The Signalized Intersection Module and the Compute Average Phase Duration routine are described in Chapter 31. The Volume Check, Define Origin–Destination Matrix, Spillback Check, and Midsegment Capacity routines are described further in the next subsection.

Exhibit 30-18
Segment Evaluation Module



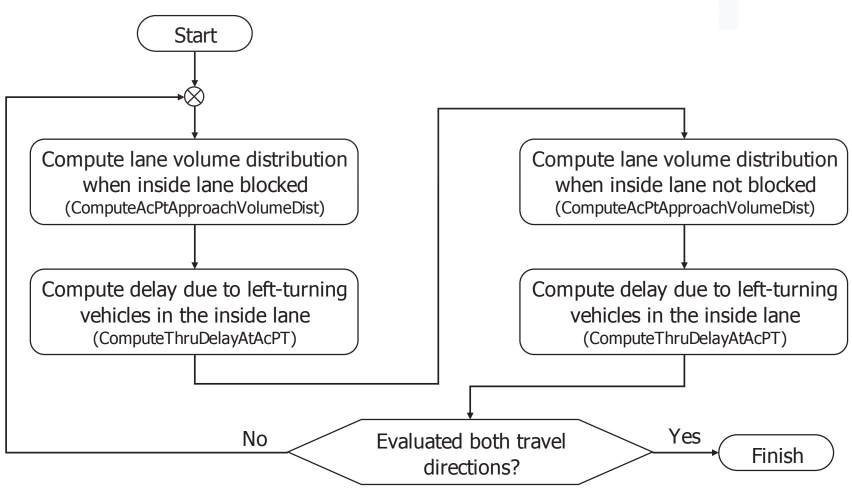
The Segment Analysis Module is shown in Exhibit 30-19. This module consists of seven main routines, six of which are implemented for both segment travel directions. The main function of each routine, as well as the name given to it in the computational engine, is also shown in the exhibit. These routines are described further in the next subsection.

Exhibit 30-19
Segment Analysis Module



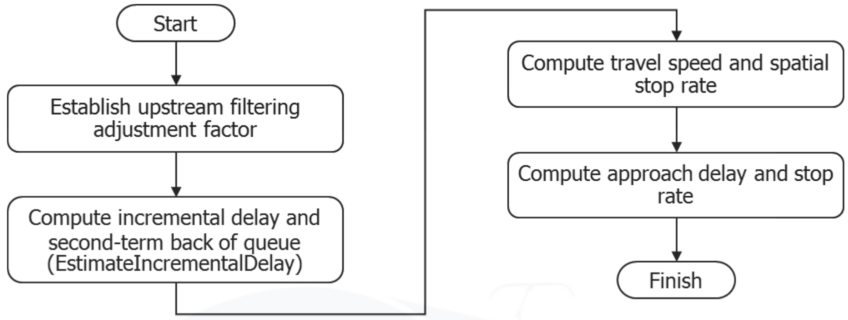
The Delay due to Turns Module is shown in Exhibit 30-20. This module consists of two main routines, each of which is implemented for both segment travel directions. The main function of each routine, as well as the name given to it in the computational engine, is also shown in the exhibit. These routines are described further in the next subsection.

Exhibit 30-20
Delay due to Turns Module



The Performance Measures Module is shown in Exhibit 30-21. This module consists of four routines. The main function of each routine is also shown in the exhibit. One of the routines (i.e., EstimateIncrementalDelay) is complicated enough to justify its development as a separate entity in the computational engine. This routine is described in Chapter 31, Signalized Intersections: Supplemental.

Exhibit 30-21
Performance Measures Module



LINKAGE LISTS

This subsection uses linkage lists to describe the main routines that make up the computational engine. Each list is provided in a table that identifies the routine and the various subroutines that it references. Conditions for which the subroutine is used are also provided.

The lists are organized by module, as described in the previous subsection. A total of three tables are provided to address the following three modules:

- Segment Evaluation Module,
- Segment Analysis Module, and
- Delay due to Turns Module.

The linkage list for the Segment Evaluation Module is provided in Exhibit 30-22. The main routines are listed in Column 1 and were previously identified in Exhibit 30-18.

The linkage list for the Segment Analysis Module is provided in Exhibit 30-23. The main routines are listed in Column 1 and were previously identified in Exhibit 30-19.

Finally, the linkage list for the Delay due to Turns Module is provided in Exhibit 30-24. The main routines are listed in Column 1 and were previously identified in Exhibit 30-20.

Exhibit 30-22
Segment Evaluation Module Routines

Routine	Subroutine	Conditions for Use
VolumeCheck	Ensure that discharge volume for each entry movement does not exceed its capacity.	Apply for both segment travel directions.
DefineODMatrix	ComputeODs (compute origin–destination volume for movements that enter and exit segment)	Apply to all intersections on segment and for both segment travel directions.
SpillbackCheck	ComputeSpillbackTime (compute spillback time for each exit movement at the downstream boundary intersection)	Apply for both segment travel directions.
SegmentAnalysisModule	See Exhibit 30-23.	
SignalizedIntersectionModule	See Chapter 31.	
ComputeMidSegmentCapacity	Compute midsegment capacity when restricted and reduce saturation flow rate of upstream movements so upstream discharge is less than or equal to the midsegment capacity.	Apply to each upstream signalized intersection traffic movement that enters segment.
DelayDueToTurnsModule	See Exhibit 30-24.	
ComputeAveragePhaseDuration	See Chapter 31.	

Exhibit 30-23
Segment Analysis Module Routines

Routine	Subroutine	Conditions for Use
InitialPortionOnGreen	Compute proportion of arrivals during green (*P*) based on current signal timing.	None
ComputeDischargeProfile	Compute discharge flow rate for each 1-s interval of signal cycle at upstream boundary intersection.	Apply to each upstream boundary intersection movement that enters segment.
GetRunningTime	Compute running time on length of street between upstream boundary intersection and subject downstream intersection.	Apply to all intersections on the segment and for both segment travel directions.
ComputeProjectedProfile	Compute arrival flow profile reflecting dispersion of platoons formed at upstream boundary intersection.	Apply to each upstream boundary intersection movement that enters segment.
ComputeConflictFlowRate	Use arrival flow profile and origin–destination matrix to compute arrival flow rate for movements at subject intersection.	Apply to all intersections on the segment and for both segment travel directions.
	Compute conflicting flow rate at access point intersections on basis of the projected arrivals at each intersection.	Apply to all access point intersections and for both segment travel directions.
ComputePortionOnGreen	For each exit movement, compute count of vehicles arriving at downstream boundary intersection during green.	Apply to each downstream boundary intersection.
ComputeBlockTime	Use computed conflicting flow rates at each access point intersection to compute the proportion of time blocked for each nonpriority movement.	Apply to all access point intersections and for both travel segment travel directions.

Exhibit 30-24
Delay due to Turns Module Routines

Routine	Subroutine	Conditions for Use
ComputeAcPtApproach-VolumeDist	Compute the volume for each lane on the approach to the access point intersection when blocked by a left-turning vehicle.	Apply lane volume routine for case in which inside lane is blocked by a turning vehicle. Apply to all access point intersections and for both segment travel directions.
	Compute the volume for each lane on the approach to the access point intersection when *not* blocked by a left-turning vehicle.	Apply lane volume routine for case in which inside lane is *not* blocked by a turning vehicle. Apply to all access point intersections and for both segment travel directions.
ComputeThruDelayAtAcPT	Compute the probability of left-turn bay overflow at access point intersection.	If segment is undivided, the probability of bay overflow is 1.0.
	Compute the delay to through movements due to a left turn at an access point. Based on lane volume estimate for case in which inside lane is blocked by a turning vehicle.	Apply to all access point intersections and for both segment travel directions.
	Compute the delay to through movements due to a right turn at an access point. Based on lane volume estimate for case in which inside lane is *not* blocked by a turning vehicle.	Apply to all access point intersections and for both segment travel directions.

8. EXAMPLE PROBLEMS

This section describes the application of each of the motorized vehicle, pedestrian, bicycle, and transit methodologies through the use of example problems. Exhibit 30-25 provides an overview of these problems. The focus of the examples is on an operational analysis. A planning and preliminary engineering analysis is identical to the operational analysis in terms of the calculations, except that default values are used when field-measured values are not available.

Exhibit 30-25
Example Problems

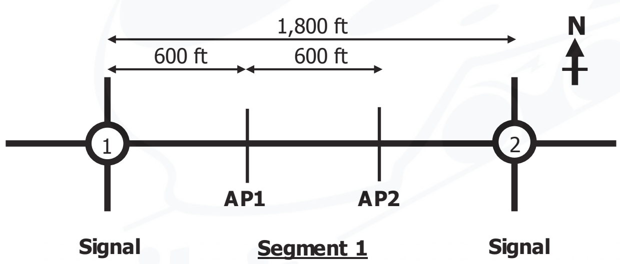
Problem Number	Description	Analysis Type
1	Motorized Vehicle LOS	Operational
2	Pedestrian LOS	Operational
3	Bicycle LOS	Operational
4	Transit LOS	Operational

EXAMPLE PROBLEM 1: MOTORIZED VEHICLE LOS

The Urban Street Segment

The total length of an undivided urban street segment is 1,800 ft. The segment is shown in Exhibit 30-26. Both of the boundary intersections are signalized. The street has a four-lane cross section with two lanes in each direction. There are left-turn bays on the subject segment at each signalized intersection.

Exhibit 30-26
Example Problem 1: Urban Street Segment Schematic



The segment has two active access point intersections, shown in the exhibit as AP1 and AP2. Each intersection has two STOP-controlled side-street approaches. The segment has some additional driveways on each side of the street; however, their turn movement volumes are too low during the analysis period for them to be considered active. The few vehicles that do turn at these locations during the analysis period have been added to the corresponding volumes at the two active access point intersections.

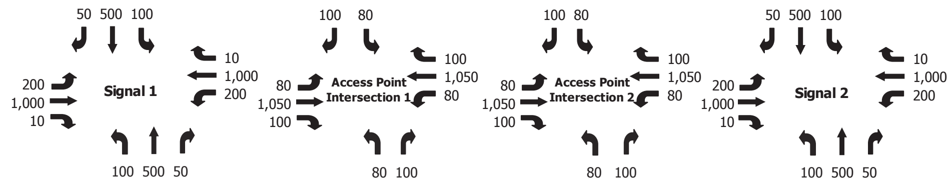
The Question

What are the travel speed, spatial stop rate, and LOS during the analysis period for the segment through movement in both directions of travel?

The Facts

The segment's traffic counts are listed in Exhibit 30-27. The counts were taken during the 15-min analysis period of interest. However, they have been converted to hourly flow rates. Note that the volumes leaving the signalized intersections do not add up to the volume arriving at the downstream access point intersection.

Exhibit 30-27
Example Problem 1: Intersection Turn Movement Counts



The signalization conditions are shown in Exhibit 30-28. The conditions shown are identified as belonging to Signalized Intersection 1; however, they are the same for Signalized Intersection 2. The signals operate with coordinated–actuated control. The left-turn movements on the northbound and southbound approaches operate under protected–permitted control and lead the opposing through movements (i.e., a lead–lead phase sequence). The left-turn movements on the major street operate as protected-only in a lead–lead sequence.

Exhibit 30-28
Example Problem 1: Signal Conditions for Intersection 1

Controller Data Worksheet					
General Information					
Cross street:		First Avenue	Analysis period:		7:15 am to 7:30 am
Phase Sequence					
Phases 1 and 2			***Phases 3 and 8***		
		1. WB left (1) with WB thru (6)			1. NB left (3) with NB thru (8)
Enter choice	2	2. WB left (1) before EB thru (2)	Enter choice	2	2. NB left (3) before SB thru (4)
		3. EB thru (2) before WB left (1)			3. SB thru (4) before NB left (3)
Phases 5 and 6			***Phases 4 and 7***		
		1. EB left (5) with EB thru (2)			1. SB left (7) with SB thru (4)
Enter choice	2	2. EB left (5) before WB thru (6)	Enter choice	2	2. SB left (7) before NB thru (8)
		3. WB thru (6) before EB left (5)			3. NB thru (8) before SB left (7)
Left-Turn Mode					
Phase 1 or 2			***Phase 3 or 8***		
Enter choice	3	2. WB left (1) prot-perm	Enter choice	2	2. NB left (3) prot-perm
		3. WB left (1) protected			3. NB left (3) protected
Phase 5 or 6			***Phase 4 or 7***		
Enter choice	3	2. EB left (5) prot-perm	Enter choice	2	2. SB left (7) prot-perm
		3. EB left (5) protected			3. SB left (7) protected

Phase Settings								
Approach	**Eastbound**		**Westbound**		**Northbound**		**Southbound**	
Phase number	5	2	1	6	3	8	7	4
Movement	L	T+R	L	T+R	L	T+R	L	T+R
Lead/lag left-turn phase	Lead	--	Lead	--	Lead	--	Lead	--
Left-turn mode	Prot.	--	Prot.	--	Pr/Pm	--	Pr/Pm	--
Passage time, s	2.0		2.0		2.0	2.0	2.0	2.0
Phase split, s	20	35	20	35	20	25	20	25
Minimum green, s	5		5		5	5	5	5
Yellow change, s	3.0	4.0	3.0	4.0	3.0	4.0	3.0	4.0
Red clearance, s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Walk+ ped. clear, s		0		0		0		0
Recall?	No		No		No	No	No	No
Dual entry ?	No	Yes	No	Yes	No	Yes	No	Yes
Simultaneous gap-out?	Yes				Yes			
Dallas left-turn phasing?					No			
Coordination settings	Offset, s:	0	Offset Ref.:	End of Green	Force Mode:		Fixed	
	Cycle, s:	100			Reference phase:		2	

Exhibit 30-28 indicates that the passage time for each actuated phase is 2.0 s. The minimum green setting for each actuated phase is 5 s. The offset to Phase 2 (the reference phase) end-of-green interval is 0.0 s. A fixed-force mode is used to ensure that good coordination is maintained. The cycle length is 100 s.

Geometric conditions and traffic characteristics for Signalized Intersection 1 are shown in Exhibit 30-29. They are the same for Signalized Intersection 2. The movement numbers follow the numbering convention shown in Exhibit 19-1 of Chapter 19.

Exhibit 30-29
Example Problem 1: Geometric Conditions and Traffic Characteristics for Signalized Intersection 1

Intersection Data Worksheet												
Approach	Eastbound			Westbound			Northbound			Southbound		
Movement	L	T	R	L	T	R	L	T	R	L	T	R
Movement number	5	2	12	1	6	16	3	8	18	7	4	14
Intersection Geometry												
Number of lanes	1	2	1	1	2	1	1	2	0	1	2	0
Lane assignment	L	T	R	L	T	R	L	TR	n.a.	L	TR	n.a.
Average lane width, ft	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0		12.0	12.0	
Number of receiving lanes		2			2			2			2	
Turn bay or segment length, ft	200	999	200	200	1800	200	200	999		200	999	
Traffic Characteristics												
Volume, veh/h	200	1000	10	200	1000	10	100	500	50	100	500	50
Right-turn-on-red volume, veh/h			0			0			0			0
Percent heavy vehicles, %	0	0	0	0	0	0	0	0	0	0	0	0
Lane utilization adjustment factor		1.000			1.000							
Peak hour factor 1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Start-up lost time, s	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0		2.0	2.0	
Extension of eff. green time, s	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0		2.0	2.0	
Platoon ratio	1.000	1.333	1.000				1.000	1.000		1.000	1.000	
Upstream filtering factor	1.00	1.00	1.00				1.00	1.00		1.00	1.00	
Pedestrian volume, p/h		0			0			0			0	
Bicycle volume, bicycles/h		0			0			0			0	
Opposing right-turn lane influence	Yes			Yes								
Initial queue, veh	0	0	0	0	0	0	0	0		0	0	
Speed limit, mi/h	35	35	35	35	35	35	35	35		35	35	
Unsignalized movement volume, veh/h	0	0	0	0	0	0	0	0	0	0	0	0
Unsignalized movement delay, s/veh	0	0	0	0	0	0	0	0	0	0	0	0
Unsignalized mvmt. stop rate, stops/veh	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Approach Data	*Left Side*		*Right Side*	*Left Side*		*Right Side*	*Left Side*		*Right Side*	*Left Side*		*Right Side*
Parking present?	No		No	No		No	No		No	No		No
Parking maneuvers, maneuvers/h												
Bus stopping rate, buses/h			0			0			0			0
Approach grade, %	0	0	0	0	0	0	0	0	0	0	0	0
Detection Data												
Stop line detector presence	Presence			Presence			Presence	Presence		Presence	Presence	
Stop line detector length, ft	40			40			40	40		40	40	

All signalized intersection approaches have a 200-ft left-turn bay and two through lanes. The east–west approaches have a 200-ft right-turn lane. The north–south approaches have a shared through and right-turn lane. Many of the geometric and traffic characteristics shown in the exhibit are needed to compute the saturation flow rate with the procedure described in Section 3 of Chapter 19.

The platoon ratio is entered for all movements associated with an external approach to the segment. The eastbound through movement at Signalized Intersection 1 is known to be coordinated with the upstream intersection so that favorable progression occurs, as described by a platoon ratio of 1.333. The westbound through movement at Signalized Intersection 2 is also coordinated with its upstream intersection, and arrivals are described by a platoon ratio of 1.33. Arrivals to all other movements are characterized as "random" and are described with a platoon ratio of 1.00. The movements for the westbound approach at Signalized Intersection 1 (and eastbound approach at Signalized Intersection 2) are internal movements, so a platoon ratio (and upstream filtering factor) is not entered for them. More accurate values are computed during subsequent iterations by using a procedure provided in the methodology.

The speed limit on the segment and on the cross-street approaches is 35 mi/h. With a couple of exceptions, detection is located just upstream of the stop line in each traffic lane at the two signalized intersections. A 40-ft detection zone is used in each instance. The exceptions are the traffic lanes serving the major-street through movement at each intersection. There is no detection for these movements because they are not actuated.

The geometric conditions that describe the segment are shown in Exhibit 30-30. These data are used to compute the free-flow speed for the segment.

Exhibit 30-30
Example Problem 1: Segment Data

Segment Data Worksheet		
Input Data		
	EB	**WB**
Basic Segment Data		
Number of through lanes that extend the length of the segment:	2	2
Speed limit, mph	35	35
Segment Length Data		
Length of segment (measured stopline to stopline), ft	1800	1800
Width of upstream signalized intersection, ft	50	50
Adjusted segment length, ft	1750	1750
Length of segment with a restrictive median (e.g, raised-curb), ft	0	0
Length of segment with a non-restrictive median (e.g, two-way left-turn lane), ft	0	0
Length of segment with no median, ft	1750	1750
Percentage of segment length with restrictive median, %	0	0
Access Data		
Percentage of street with curb on right-hand side (in direction of travel), %	70	70
Number of access points on right-hand side of street (in direction of travel)	4	4
Percentage of street with on-street parking on right-hand side (in direction of travel),%	0	0
Other Delay Data		
Mid-segment delay, s/veh	0	0

The traffic and lane assignment data for the two access point intersections are shown in Exhibit 30-31. The movement numbers follow the numbering convention shown in Exhibit 20-1 of Chapter 20, Two-Way STOP-Controlled Intersections. There are no turn bays on the segment at the two access point intersections.

Exhibit 30-31
Example Problem 1: Access Point Data

Access Point Input Data													
Access	Approach	**Eastbound**			**Westbound**			**Northbound**			**Southbound**		
Point	Movement	L	T	R	L	T	R	L	T	R	L	T	R
Location,ft	Movement number	1	2	3	4	5	6	7	8	9	10	11	12
600	Volume, veh/h	80	1,050	100	80	1,050	100	80	0	100	80	0	100
West end	Lanes	0	2	0	0	2	0	1	0	1	1	0	1
1200	Volume, veh/h	80	1,050	100	80	1,050	100	80	0	100	80	0	100
	Lanes	0	2	0	0	2	0	1	0	1	1	0	1

Outline of Solution

Movement-Based Data

Exhibit 30-32 provides a summary of the analysis of the individual traffic movements at Signalized Intersection 1.

Exhibit 30-32
Example Problem 1: Movement-Based Output Data

INTERSECTION 1	**EB**	**EB**	**EB**	**WB**	**WB**	**WB**	**NB**	**NB**	**NB**	**SB**	**SB**	**SB**
	L	**T**	**R**	**L**	**T**	**R**	**L**	**T**	**R**	**L**	**T**	**R**
Movement:	**5**	**2**	**12**	**1**	**6**	**16**	**3**	**8**	**18**	**7**	**4**	**14**
Volume, veh/h	200	1,000	10	194	968	10	100	500	50	100	500	50
Initial Queue, veh	0	0	0	0	0	0	0	0	0	0	0	0
Ped-Bike Adj. Factor (A_pbT)	1.000		1.000	1.000		1.000	1.000		1.000	1.000		1.000
Parking, Bus Adj. Factors (f_bb x f_p)	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Downstream Lane Blockage Factor (f_ms)	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Spillback Factor (f_sp)	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Adjusted Sat. Flow Rate, veh/h/ln	1,900	1,900	1,900	1,900	1,900	1,900	1,900	1,900	1,900	1,900	1,900	1,900
Lanes	1	2	1	1	2	1	1	2	0	1	2	0
Lane Assignment	L	T	R	L	T	R	L	TR	n.a.	L	TR	n.a.
Capacity, veh/h	236	1,856	789	233	1,848	785	217	617	61	217	617	61
Discharge Volume, veh/h	0	1,000	0	0	0	0	0	0	50	100	0	0
Proportion Arriving On Green	0.131	0.651	0.488	0.045	0.493	0.501	0.061	0.181	0.181	0.061	0.181	0.181
Approach Volume, veh/h		1,210			1,172			650			650	
Approach Delay, s/veh		18.0			23.4			39.7			39.7	
Approach Stop Rate, stops/veh		0.442			0.617			0.831			0.831	

With the exception of Initial Queue, Lanes, and Lane Assignment, the variables listed in Exhibit 30-32 have computed values. The volumes shown for the eastbound (EB), northbound (NB), and southbound (SB) movements are identical to the input volumes. The westbound (WB) volumes were computed from the input volumes during Step 1: Determine Traffic Demand Adjustments.

Specifically, they were reduced because the input westbound volume for this intersection exceeded the volume departing the upstream access point intersection (i.e., AP1).

Four factors are listed in the top half of Exhibit 30-32. These factors represent saturation flow rate adjustment factors. Their values are dependent on signal timing or lane volume, quantities that are computed during the iterative convergence loop (identified in the motorized vehicle methodology framework shown in Exhibit 18-8). As a result, the value of each factor also converges within this loop. The procedure for calculating the pedestrian–bicycle adjustment factor is described in Section 2 of Chapter 31. The procedure for calculating the parking–bus adjustment factor is described in Section 3 of Chapter 19. The procedure for calculating the downstream lane blockage (due to midsegment lane restriction) factor is described in Section 3 of this chapter. The methodology for calculating the spillback factor is described in Chapter 29.

Capacity for a movement is computed by using the movement volume proportion in each approach lane group, lane group saturation flow rate, and corresponding phase duration. This variable represents the capacity of the movement, regardless of whether it is served in an exclusive lane or a shared lane. If the movement is served in a shared lane, the movement capacity represents the portion of the lane group capacity available to the movement, as distributed in proportion to the volume of the movements served by the associated lane group.

Discharge volume is computed for movements that enter a segment during Step 1: Determine Traffic Demand Adjustments. At Signalized Intersection 1, the movements entering the segment are the eastbound through movement, the northbound right-turn movement, and the southbound left-turn movement. A value of 0.0 veh/h is shown for all other movements, which indicates that they are not relevant to this calculation. If volume exceeds capacity for any given movement, the discharge volume is set equal to the capacity. Otherwise, the discharge volume is equal to the movement volume.

The proportion arriving during green P is computed for internal movements during Step 3: Determine the Proportion Arriving During Green. In contrast, it is computed from the input platoon ratio for external movements.

The last three rows in Exhibit 30-32 represent summary statistics for the approach. The approach volume is the sum of the three movement volumes. Approach delay and approach stop rate are computed as volume-weighted averages for the lane groups served on an intersection approach.

Timer-Based Phase Data

Exhibit 30-33 provides a summary of the output data for Signalized Intersection 1 from a signal controller perspective. The controller has eight timing functions (or timers), with Timers 1 to 4 representing Ring 1 and Timers 5 to 8 representing Ring 2. The ring structure and phase assignments are described in Section 2 of Chapter 19. Timers 1, 2, 5, and 6 are used to control the east–west traffic movements on the segment. Timers 3, 4, 7, and 8 are used to control the north–south movements that cross the segment.

Exhibit 30-33
Example Problem 1: Timer-Based Phase Output Data

Timer Data

Timer:	1 WB L	2 EB T.R	3 NB L	4 SB T.T+R	5 EB L	6 WB T.R	7 SB L	8 NB T.T+R
Assigned Phase	1	2	3	4	5	6	7	8
Phase Duration (G+Y+Rc), s	15.90	52.84	9.13	22.13	16.10	52.63	9.13	22.13
Change Period (Y+Rc), s	3.00	4.00	3.00	4.00	3.00	4.00	3.00	4.00
Phase Start Time, s	35.27	51.16	4.00	13.14	35.27	51.37	4.00	13.14
Phase End Time, s	51.16	4.00	13.13	35.27	51.37	4.00	13.13	35.27
Max. Allowable Headway (MAH), s	3.13	0.00	3.13	3.06	3.13	0.00	3.13	3.06
Equivalent Maximum Green (Gmax), s	30.73	0.00	17.00	31.87	30.73	0.00	17.00	31.87
Max. Queue Clearance Time (g_c+l1), s	12.646	0.000	6.442	16.165	12.829	0.000	6.442	16.165
Green Extension Time (g_e), s	0.311	0.000	0.099	1.968	0.322	0.000	0.099	1.968
Probability of Phase Call (p_c)	0.995	0.000	0.938	1.000	0.996	0.000	0.938	1.000
Probability of Max Out (p_x)	0.000	0.000	0.000	0.016	0.000	0.000	0.000	0.016

Cycle Length, s: 100

The timing function construct is essential to the modeling of a ring-based signal controller. *Timers* always occur in the same numeric sequence (i.e., 1 then 2 then 3 then 4 in Ring 1; 5 then 6 then 7 then 8 in Ring 2). The practice of associating movements with phases (e.g., the major-street through movement with Phase 2), coupled with the occasional need for lagging left-turn phases and split phasing, creates the situation in which *phases* do not always time in sequence. For example, with a lagging left-turn phase sequence, major-street through Phase 2 times first and then major-street left-turn Phase 1 times second.

The modern controller accommodates the assignment of phases to timing functions by allowing the ring structure to be redefined manually or by time-of-day settings. Specification of this structure is automated in the computational engine by the assignment of phases to timers.

The methodology is based on modeling *timers*, not on directly modeling movements or phases. The methodology converts movement and phase input data into timer input data. It then models controller response to these inputs and computes timer duration and related performance measures.

The two signalized intersections in this example problem have lead–lead left-turn sequences. Hence, the timer number is equal to the phase number (e.g., the westbound movement is associated with Phase 1, which is assigned to Timer 1).

The phase duration shown in Exhibit 30-33 is the estimated average phase duration during the analysis period. It represents the sum of the green, yellow change, and red clearance intervals. For Timer 2 (i.e., Phase 2), the average green interval duration can be computed as 48.84 s (= 52.84 – 4.00).

The phase start time is the time the timer (and phase) starts, relative to system time 0.0. For Phase 2, the start time is 51.16 s. The end of the green interval associated with this phase is 100.0 s (= 51.16 + 48.84). This time is equal to the cycle length, so the end of green actually occurs at 0.0 s. This result is expected because Phase 2 is the coordinated phase and the offset to the end of Phase 2 (relative to system time 0.0) was input as 0.0 s.

The phase end time is the time the timer (and phase) ends relative to system time 0.0. For Phase 2, the end of the green interval occurs at 0.0 s and the end of the phase occurs 4.0 s later (i.e., the change period duration).

The remaining variables in Exhibit 30-33 apply to the noncoordinated phases (i.e., the actuated phases). These variables describe the phase timing and operation. They are described in more detail in Section 2 of Chapter 19 and Section 2 of Chapter 31.

Timer-Based Movement Data

Exhibit 30-34 summarizes the output for Signalized Intersection 1 as it relates to the movements assigned to each timer. Separate sections of output are shown in the exhibit for the left-turn, through, and right-turn movements. The assigned movement row identifies the movement (previously identified in Exhibit 30-32) assigned to each timer.

The saturation flow rate shown in Exhibit 30-34 is the saturation flow rate for the movement. The procedure for calculating these rates is described in Section 3 of Chapter 19 and Section 3 of Chapter 31. In general, the rate for a movement is the same as for a lane group when the lane group serves one movement. The rate is split between the movements when the lane group is shared by two or more movements.

Exhibit 30-34
Example Problem 1: Timer-Based Movement Output Data

Timer Data								
Timer:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
	WB	**EB**	**NB**	**SB**	**EB**	**WB**	**SB**	**NB**
	L	**T.R**	**L**	**T.T+R**	**L**	**T.R**	**L**	**T.T+R**
Left-Turn Movement Data								
Assigned Movement	1		3		5		7	
Mvmt. Sat Flow, veh/h	1,805.00		1,805.00		1,805.00		1,805.00	
Through Movement Data								
Assigned Movement		2		4		6		8
Mvmt. Sat Flow, veh/h		3,800.00		3,401.19		3,800.00		3,401.19
Right-Turn Movement Data								
Assigned Movement		12		14		16		18
Mvmt. Sat Flow, veh/h		1,615.00		338.99		1,615.00		338.99

Timer-Based Lane Group Data

The motorized vehicle methodology described in Chapter 19 computes a variety of output statistics that portray the operation of each intersection lane group. The example problem in Chapter 19 illustrates these statistics and discusses their interpretation. The output data for the individual lane groups are not repeated in this chapter. Instead, the focus of the remaining discussion is on the access point output and the performance measures computed for the two through movements on the segment (i.e., eastbound through and westbound through).

Access Point Data

Exhibit 30-35 illustrates the output statistics for the two access point intersections located on the segment. The first six rows listed in the exhibit correspond to Access Point Intersection 1 (AP1), and the second six rows correspond to Access Point Intersection 2 (AP2). Additional sets of six rows would be provided in this table if additional access point intersections were evaluated.

Exhibit 30-35
Example Problem 1: Movement-Based Access Point Output Data

Access Point Data	**EB**	**EB**	**EB**	**WB**	**WB**	**WB**	**NB**	**NB**	**NB**	**SB**	**SB**	**SB**
Segment 1	**L**	**T**	**R**	**L**	**T**	**R**	**L**	**T**	**R**	**L**	**T**	**R**
Movement:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Access Point Intersection No. 1												
1: Volume, veh/h	74.80	981.71	93.50	75.56	991.70	94.45	80.00	0.00	100.00	80.00	0.00	100.00
1: Lanes	0	2	0	0	2	0	1	0	1	1	0	1
1: Proportion time blocked	0.150			0.160			0.250	0.250	0.160	0.250	0.250	0.150
1: Delay to through vehicles, s/veh		0.193			0.194							
1: Prob. inside lane blocked by left		0.115			0.115							
1: Dist. from West/South signal, ft	600											
Access Point Intersection No. 2												
2: Volume, veh/h	75.56	991.70	94.45	74.80	981.71	93.50	80.00	0.00	100.00	80.00	0.00	100.00
2: Lanes	0	2	0	0	2	0	1	0	1	1	0	1
2: Proportion time blocked	0.160			0.150			0.250	0.250	0.150	0.250	0.250	0.160
2: Delay to through vehicles, s/veh		0.194			0.193							
2: Prob. inside lane blocked by left		0.115			0.115							
2: Dist. from West/South signal, ft	1,200											

The eastbound and westbound volumes listed in Exhibit 30-35 are not equal to the input volumes. These volumes were adjusted during Step 1: Determine Traffic Demand Adjustments so that they equal the volume discharging from the upstream intersection. This routine achieves balance between all junction pairs (e.g., between Signalized Intersection 1 and Access Point Intersection 1, between Access Point Intersection 1 and Access Point Intersection 2, and so forth).

The "proportion of time blocked" is computed during Step 3: Determine the Proportion Arriving During Green. It represents the proportion of time during the cycle that the associated access point movement is blocked by the presence of a platoon passing through the intersection. For major-street left turns, the platoon of concern approaches from the opposing direction. For the minor-street left turn, platoons can approach from either direction and can combine to block this left turn for extended time periods. This trend can be seen by comparing the proportion of time blocked for the eastbound (major-street) left turn (i.e., 0.15) with that for the northbound (minor-street) left turn (i.e., 0.25) at Access Point Intersection 1.

The "delay to through vehicles" is computed during Step 2: Determine Running Time. It represents the sum of the delay due to vehicles turning left from the major street and the delay due to vehicles turning right from the major street. This delay tends to be small compared with typical signalized intersection delay values. But it can reduce overall travel speed if there are several high-volume access points on a street and only one or two through lanes in each direction of travel.

The "probability of the inside through lane being blocked" is also computed during Step 2: Determine Running Time as part of the delay-to-through-vehicles procedure. This variable indicates the probability that the left-turn bay at an access point will overflow into the inside through lane on the street segment. Hence, it indicates the potential for a through vehicle to be delayed by a left-turn maneuver. The segment being evaluated has an undivided cross section, and no left-turn bays are provided at the access point intersections. In this situation, the probability of overflow is 0.115, indicating that the inside lane is blocked about 11.5% of the time.

Results

Exhibit 30-36 summarizes the performance measures for the segment. Also shown are the results from the spillback check conducted during Step 1: Determine Traffic Demand Adjustments. The movements indicated in the column heading are those exiting the segment at a boundary intersection. Thus, the westbound movements on Segment 1 are those occurring at Signalized Intersection 1. Similarly, the eastbound movements on Segment 1 are those occurring at Signalized Intersection 2.

Exhibit 30-36
Example Problem 1: Performance Measure Summary

Segment Summary		EB	EB	EB	WB	WB	WB
		L	T	R	L	T	R
Seg.No.	**Movement:**	**5**	**2**	**12**	**1**	**6**	**16**
1	Bay/Lane Spillback Time, h	never	never	never	never	never	never
1	ShrdLane Spillback Time, h	never	never	never	never	never	never
1	Base Free-Flow Speed, mph		40.78			40.78	
1	Running Time, s		33.54			33.54	
1	Running Speed, mph		36.59			36.59	
1	Through Delay, s/veh		18.310			18.310	
1	Travel Speed, mph		23.67			23.67	
1	Stop Rate, stops/veh		0.547			0.547	
1	Spatial Stop Rate, stops/mi		1.61			1.61	
1	Through vol/cap ratio		0.52			0.52	
1	Level of Service		C			C	
1	Proportion Left Lanes		0.33			0.33	
1	Auto. Traveler Perception Score		2.53			2.53	
SPILLBACK TIME, h: never							

The spillback check procedure computes the time of spillback for each of the internal movements. For turn movements, the bay/lane spillback time is the time before the turn bay overflows. For through movements, the bay/lane spillback time is the time before the through lane overflows due only to through demand. If a turn bay exists and it overflows, the turn volume will queue in the adjacent through lane. For this scenario, the shared lane spillback time is computed and used instead of the bay/lane spillback time. If several movements experience spillback, the time of first spillback is reported at the bottom of Exhibit 30-36.

The output data for the two through movements are listed in Exhibit 30-36, starting with the third row. The base free-flow speed (FFS) and running time statistics are computed during Step 2: Determine Running Time. The through delay listed is computed during Step 5: Determine Through Control Delay. It is a weighted average delay for the lane groups serving through movements at the downstream boundary intersection. The weight used in this average is the volume of through vehicles served by the lane group.

The base free-flow speed is 40.78 mi/h. By interpolating this value between those in Exhibit 18-1, the threshold travel speeds for LOS A, B, C, D, and E are as follows: >32.6, >27.5, >20.5, >16.3, and >12.3 mi/h, respectively. Thus, the travel speed for the eastbound direction of 23.67 mi/h corresponds to LOS C. The same conclusion is reached for the westbound travel direction.

Each travel direction has one left-turn bay and three intersections. Thus, the proportion of intersections with left-turn lanes is 0.33. This proportion is used in Step 10: Determine Automobile Traveler Perception Score to compute the score of 2.53, which suggests that most automobile travelers would find segment service to be very good.

EXAMPLE PROBLEM 2: PEDESTRIAN LOS

The Segment

The sidewalk of interest is located along a 1,320-ft urban street segment. The segment is part of a collector street located near a community college. It is shown in Exhibit 30-37. Sidewalk is only shown for the south side of the segment for the convenience of illustration. It also exists on the north side of the segment.

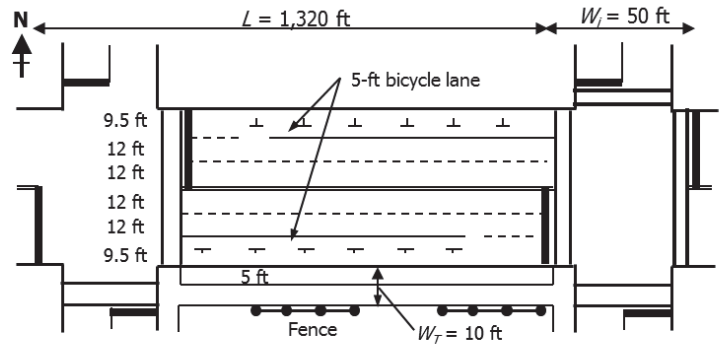


Exhibit 30-37
Example Problem 2: Segment Geometry

The Question

What is the pedestrian LOS for the sidewalk on the south side of the segment?

The Facts

The geometric details of the sidewalk and street cross section are shown in Exhibit 30-37. Both boundary intersections are signalized. Crossing the segment at uncontrolled midsegment locations is legal. The following additional information is known about the sidewalk and street segment:

Traffic characteristics:

Midsegment flow rate in eastbound direction: 940 veh/h

Pedestrian flow rate in south sidewalk (walking in both directions): 2,000 p/h

Proportion of on-street parking occupied during analysis period: 0.20

Geometric characteristics:

Outside shoulder width: none

Parking lane width: 9.5 ft

Cross section has raised curb along outside edge of roadway

Effective width of fixed objects on sidewalk: 0.0 ft (no objects present)

Presence of trees, bushes, or other vertical objects in buffer: No

Other data:

Pedestrians can cross the segment legally and do so somewhat uniformly along its length

Proportion of sidewalk adjacent to window display: 0.0

Proportion of sidewalk adjacent to building face: 0.0

Proportion of sidewalk adjacent to fence: 0.50

Performance measures obtained from supporting methodologies:

Motorized vehicle running speed: 33 mi/h

Pedestrian delay when walking parallel to the segment: 40 s/p

Pedestrian delay when crossing the segment at the nearest signal-controlled crossing: 80 s/p

Pedestrian waiting delay: 740 s/p

Pedestrian LOS score for the downstream intersection: 3.6

Outline of Solution

First, the pedestrian space will be calculated for the sidewalk. This measure will then be compared with the qualitative descriptions of pedestrian space listed in Exhibit 18-15. Next, the pedestrian travel speed along the sidewalk will be calculated. Finally, LOS for the segment will be determined by using the computed pedestrian LOS score and the pedestrian space variables.

Computational Steps

Step 1: Determine Free-Flow Walking Speed

The average free-flow walking speed is estimated to be 4.4 ft/s on the basis of the guidance provided.

Step 2: Determine Average Pedestrian Space

The shy distance on the inside of the sidewalk is computed with Equation 18-24.

$$W_{s,i} = \max(W_{buf}, 1.5)$$

$$W_{s,i} = \max(5.0, 1.5)$$

$$W_{s,i} = 5.0 \text{ ft}$$

The shy distance on the outside of the sidewalk is computed with Equation 18-25.

$$W_{s,o} = 3.0\, p_{\text{window}} + 2.0\, p_{\text{building}} + 1.5\, p_{\text{fence}}$$

$$W_{s,o} = 3.0(0.0) + 2.0(0.0) + 1.5(0.50)$$

$$W_{s,o} = 0.75 \text{ ft}$$

There are no fixed objects present on the sidewalk, so the adjusted fixed-object effective widths for the inside and outside of the sidewalk are both equal to 0.0 ft. The effective sidewalk width is computed with Equation 18-23.

$$W_E = W_T - W_{O,i} - W_{O,o} - W_{s,i} - W_{s,o} \geq 0.0$$

$$W_E = 10 - 0.0 - 0.0 - 5.0 - 0.75$$

$$W_E = 4.25 \text{ ft}$$

The pedestrian flow per unit width of sidewalk is computed with Equation 18-28 for the subject sidewalk.

$$v_p = \frac{v_{ped}}{60\, W_E}$$

$$v_p = \frac{2{,}000}{60(4.25)}$$

$$v_p = 7.84 \text{ p/ft/min}$$

The average walking speed S_p is computed with Equation 18-29.

$$S_p = (1 - 0.00078\, v_p^2)\, S_{pf} \geq 0.5\, S_{pf}$$

$$S_p = [1 - 0.00078(7.84)^2](4.4)$$

$$S_p = 4.19 \text{ ft/s}$$

Finally, Equation 18-30 is used to compute average pedestrian space.

$$A_p = 60\frac{S_p}{v_p}$$

$$A_p = 60\frac{4.19}{7.84}$$

$$A_p = 32.0\ \text{ft}^2/\text{p}$$

The pedestrian space can be compared with the ranges provided in Exhibit 18-15 to make some judgments about the performance of the subject intersection corner. The criteria for platoon flow are considered applicable given the influence of the signalized intersections. According to the qualitative descriptions provided in this exhibit, walking speed will be restricted, as will the ability to pass slower pedestrians.

Step 3: Determine Pedestrian Delay at Intersection

The pedestrian methodology in Chapter 19, Signalized Intersections, was used to estimate two pedestrian delay values. One is the delay at the boundary intersection experienced by a pedestrian walking parallel to segment d_{pp}. This delay was computed to be 40 s/p. The second is the delay experienced by a pedestrian crossing the segment at the nearest signal-controlled crossing d_{pc}. This delay was computed to be 80 s/p.

The pedestrian methodology in Chapter 20, Two-Way STOP-Controlled Intersections, was used to estimate the delay incurred while waiting for an acceptable gap in traffic d_{pw}. This delay was computed to be 740 s/p.

Step 4: Determine Pedestrian Travel Speed

The pedestrian travel speed is computed with Equation 18-31.

$$S_{Tp,seg} = \frac{L}{\frac{L}{S_p} + d_{pp}}$$

$$S_{Tp,seg} = \frac{1{,}320}{\frac{1{,}320}{4.19} + 40}$$

$$S_{Tp,seg} = 3.72\ \text{ft/s}$$

This walking speed is slightly less than 4.0 ft/s and is considered acceptable, but a higher speed is desirable.

Step 5: Determine Pedestrian LOS Score for Intersection

The pedestrian methodology in Chapter 19 was used to determine the pedestrian LOS score for the downstream boundary intersection $I_{p,int}$. It was computed to be 3.60.

Step 6: Determine Pedestrian LOS Score for Link

The pedestrian LOS score for the link is computed from three factors. However, before these factors can be calculated, several cross-section variables need to be adjusted and several coefficients need to be calculated. These variables and coefficients are calculated first. Then, the three factors are computed. Finally, they are combined to determine the desired score.

The midsegment demand flow rate is greater than 160 veh/h. The street cross section is curbed but there is no shoulder, so the adjusted width of paved outside shoulder W_{os}^* is 0.0 ft. Therefore, the effective total width of the outside through lane, bicycle lane, and shoulder W_v is computed as

$$W_v = W_{ol} + W_{bl} + W_{os}^* + W_{pk}$$
$$W_v = 12 + 5 + 0 + 9.5$$
$$W_v = 26.5 \text{ ft}$$

Because the proportion of occupied on-street parking is less than 0.25 and the sum of the bicycle lane and parking lane widths exceeds 10.0 ft, the effective width of the combined bicycle lane and parking lane W_l is set to 10.0 ft.

The adjusted available sidewalk width W_{aA} is computed as

$$W_{aA} = \min(W_T - W_{buf}, 10)$$
$$W_{aA} = \min(10 - 5, 10)$$
$$W_{aA} = 5 \text{ ft}$$

The sidewalk width coefficient f_{sw} is computed as

$$f_{sw} = 6.0 - 0.3\, W_{aA}$$
$$f_{sw} = 6.0 - 0.3(5.0)$$
$$f_{sw} = 4.5 \text{ ft}$$

The buffer area coefficient f_b is equal to 1.0 because there is no continuous barrier at least 3.0 ft high located in the buffer area.

The motorized vehicle methodology described in Section 3 of Chapter 18 was used to determine the motorized vehicle running speed S_R for the subject segment. This speed was computed to be 33.0 mi/h.

The cross-section adjustment factor is computed with Equation 18-33.

$$F_w = -1.2276 \ln(W_v + 0.5\, W_l + 50\, p_{pk} + W_{buf} f_b + W_{aA} f_{sw})$$
$$F_w = -1.2276 \ln[26.5 + 0.5(10) + 50(0.20) + 5.0(1.0) + 5.0(4.5)]$$
$$F_w = -5.20$$

The motorized vehicle volume adjustment factor is computed with Equation 18-34.

$$F_v = 0.0091 \frac{v_m}{4\, N_{th}}$$
$$F_v = 0.0091 \frac{940}{4(2)}$$
$$F_v = 1.07$$

The motorized vehicle speed adjustment factor is computed with Equation 18-35.

$$F_s = 4\left(\frac{S_R}{100}\right)^2$$

$$F_s = 4\left(\frac{33.0}{100}\right)^2$$

$$F_s = 0.44$$

Finally, the pedestrian LOS score for the link $I_{p,\text{link}}$ is calculated with Equation 18-32.

$$I_{p,\text{link}} = 6.0468 + F_w + F_v + F_s$$

$$I_{p,\text{link}} = 6.0468 + (-5.20) + 1.07 + 0.44$$

$$I_{p,\text{link}} = 2.35$$

Step 7: Determine Link LOS

The pedestrian LOS for the link is determined by using the pedestrian LOS score from Step 6. This score is compared with the link-based pedestrian LOS thresholds on the right side of Exhibit 18-2 to determine that the LOS for the specified direction of travel along the subject link is B.

Step 8: Determine Roadway Crossing Difficulty Factor

Crossings occur somewhat uniformly along the length of the segment, and the segment is bounded by two signalized intersections. Thus, the distance D_c is assumed to equal one-third of the segment length, or 440 ft (= 1,320/3), and the diversion distance D_d is computed as 880 ft (= 2 × 440 ft).

The delay incurred due to diversion is calculated by using Equation 18-37.

$$d_{pd} = \frac{D_d}{S_p} + d_{pc}$$

$$d_{pd} = \frac{880}{4.19} + 80$$

$$d_{pd} = 290 \text{ s/p}$$

The crossing delay used to estimate the roadway crossing difficulty factor is computed with the following equation.

$$d_{px} = \min(d_{pd}, d_{pw}, 60)$$

$$d_{px} = \min(290, 740, 60)$$

$$d_{px} = 60 \text{ s/p}$$

The roadway crossing difficulty factor is computed with Equation 18-38.

$$F_{cd} = 1.0 + \frac{0.10\, d_{px} - (0.318\, I_{p,\text{link}} + 0.220\, I_{p,int} + 1.606)}{7.5} \leq 1.20$$

$$F_{cd} = 1.0 + \frac{0.10(60) - [0.318(2.35) + 0.220(3.60) + 1.606]}{7.5}$$

$$F_{cd} = 1.20$$

Step 9: Determine Pedestrian LOS Score for Segment

The pedestrian LOS score for the segment is computed with Equation 18-39.

$$I_{p,seg} = 0.75 \left[\frac{\left(F_{cd}\, I_{p,\text{link}} + 1\right)^3 \frac{L}{S_p} + \left(I_{p,int} + 1\right)^3 d_{pp}}{\frac{L}{S_p} + d_{pp}} \right]^{\frac{1}{3}} + 0.125$$

$$I_{p,seg} = 0.75 \left[\frac{[1.20(2.35) + 1]^3 \left(\frac{1{,}320}{4.19}\right) + (3.60 + 1)^3 (40)}{\frac{1{,}320}{4.19} + 40} \right]^{\frac{1}{3}} + 0.125$$

$$I_{p,seg} = 3.07$$

Step 10: Determine Segment LOS

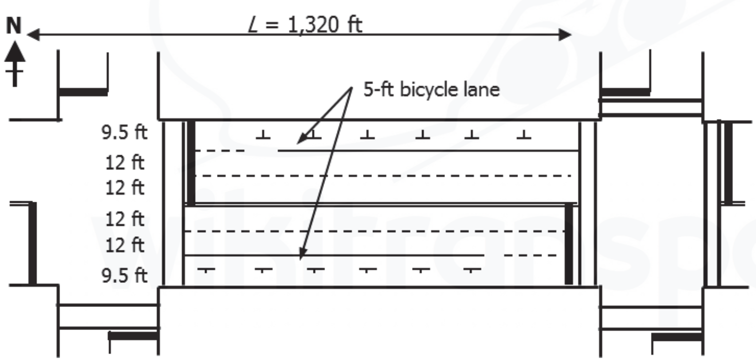
The pedestrian LOS for the segment is determined by using the pedestrian LOS score from Step 9 and the average pedestrian space from Step 2. These two performance measures are compared with their respective thresholds on the left side of Exhibit 18-2 to determine that the LOS for the specified direction of travel along the subject segment is C.

EXAMPLE PROBLEM 3: BICYCLE LOS

The Segment

The bicycle lane of interest is located along a 1,320-ft urban street segment. The segment is part of a collector street located near a community college. The bicycle lane is provided for the eastbound direction of travel, as shown in Exhibit 30-38.

Exhibit 30-38
Example Problem 3: Segment Geometry



The Question

What is the bicycle LOS for the eastbound bicycle lane?

The Facts

The geometric details of the street cross section are shown in Exhibit 30-38. Both boundary intersections are signalized. The following additional information is known about the street segment:

Traffic characteristics:

Midsegment flow rate in eastbound direction: 940 veh/h

Percent heavy vehicles: 8.0%

Proportion of on-street parking occupied during analysis period: 0.20

Geometric characteristics:

Outside shoulder width: none

Parking lane width: 9.5 ft

Median type: undivided

Cross section has raised curb along the outside edge of the roadway

Number of access point approaches on right side of segment in subject travel direction: 3

Other data:

Pavement condition rating: 2.0

Performance measures obtained from supporting methodologies:

Motorized vehicle running speed: 33 mi/h

Bicycle control delay: 40 s/bicycle

Bicycle LOS score for the downstream intersection: 0.08

Outline of Solution

First, the bicycle delay at the boundary intersection will be computed. This delay will then be used to compute the bicycle travel speed. Next, a bicycle LOS score will be computed for the link. It will then be combined with a similar score for the boundary intersection and used to compute the bicycle LOS score for the segment. Finally, LOS for the segment will be determined by using the computed score and the thresholds in Exhibit 18-3.

Computational Steps

Step 1: Determine Bicycle Running Speed

The average bicycle running speed S_b could not be determined from field data. Therefore, it was estimated to be 15 mi/h on the basis of the guidance provided.

Step 2: Determine Bicycle Delay at Intersection

The motorized vehicle methodology in Chapter 19, Signalized Intersections, was used to estimate the bicycle delay at the boundary intersection d_b. This delay was computed to be 40.0 s/bicycle.

Step 3: Determine Bicycle Travel Speed

The segment running time of through bicycles is computed as

$$t_{Rb} = \frac{3{,}600\ L}{5{,}280\ S_b}$$

$$t_{Rb} = \frac{3{,}600(1{,}320)}{5{,}280(15)}$$

$$t_{Rb} = 60.0\ \text{s}$$

The average bicycle travel speed is computed with Equation 18-40.

$$S_{Tb,seg} = \frac{3{,}600\ L}{5{,}280\ (t_{Rb} + d_b)}$$

$$S_{Tb,seg} = \frac{3{,}600(1{,}320)}{5{,}280\ (60.0 + 40.0)}$$

$$S_{Tb,seg} = 9.0 \text{ mi/h}$$

This travel speed is adequate, but a speed of 10 mi/h or more is considered desirable.

Step 4: Determine Bicycle LOS Score for Intersection

The bicycle methodology in Chapter 19 was used to determine the bicycle LOS score for the boundary intersection $I_{b,int}$. It was computed to be 0.08.

Step 5: Determine Bicycle LOS Score for Link

The bicycle LOS score is computed from four factors. However, before these factors can be calculated, several cross-section variables need to be adjusted. These variables are calculated first, and then the four factors are computed. Finally, they are combined to determine the desired score.

The street cross section is curbed but there is no shoulder, so the adjusted width of the paved outside shoulder W_{os}^* is 0.0 ft. Therefore, the total width of the outside through lane, bicycle lane, and paved shoulder W_t is computed as

$$W_t = W_{ol} + W_{bl} + W_{os}^*$$

$$W_t = 12 + 5 + 0$$

$$W_t = 17 \text{ ft}$$

The variable W_t does not include the width of the parking lane in this instance because the proportion of occupied on-street parking exceeds 0.0.

The total width of shoulder, bicycle lane, and parking lane W_l is computed as

$$W_l = W_{bl} + W_{os}^* + W_{pk}$$

$$W_l = 5 + 0 + 9.5$$

$$W_l = 14.5 \text{ ft}$$

The midsegment demand flow rate is greater than 160 veh/h. Therefore, the effective total width of the outside through lane, bicycle lane, and shoulder as a function of traffic volume W_v is equal to W_t.

The total width of shoulder, bicycle lane, and parking lane W_l exceeds 4.0 ft. Therefore, the effective width of the outside through lane is computed as

$$W_e = W_v + W_l - 20\ p_{pk} \geq 0.0$$

$$W_e = 17 + 14.5 - 20(0.20) \geq 0.0$$

$$W_e = 27.5 \text{ ft}$$

The percent heavy vehicles is less than 50%, so the adjusted percent heavy vehicles P_{HVa} is equal to the input percent heavy vehicles P_{HV} of 8.0%.

The motorized vehicle methodology described in Section 3 of Chapter 18 was used to determine the motorized vehicle running speed S_R for the subject segment. This speed was computed to be 33.0 mi/h, which exceeds 21 mi/h. Therefore, the adjusted motorized vehicle speed S_{Ra} is also equal to 33.0 mi/h.

The midsegment demand flow rate is greater than 8 veh/h (= 4 N_{th}), so the adjusted midsegment demand flow rate v_{ma} is equal to the input demand flow rate of 940 veh/h.

The cross-section adjustment factor is computed with Equation 18-42.

$$F_w = -0.005\, W_e^2$$

$$F_w = -0.005(27.5)^2$$

$$F_w = -3.78$$

The motorized vehicle volume adjustment factor comes from Equation 18-43.

$$F_v = 0.507 \ln\left(\frac{v_{ma}}{4\, N_{th}}\right)$$

$$F_v = 0.507 \ln\left(\frac{940}{4(2)}\right)$$

$$F_v = 2.42$$

The motorized vehicle speed adjustment factor is computed with Equation 18-44.

$$F_S = 0.199[1.1199 \ln(S_{Ra} - 20) + 0.8103](1 + 0.1038 P_{HVa})^2$$

$$F_S = 0.199[1.1199 \ln(33.0 - 20) + 0.8103][1 + 0.1038(8.0)]^2$$

$$F_S = 2.46$$

The pavement condition adjustment factor is computed with Equation 18-45.

$$F_p = \frac{7.066}{P_c^2}$$

$$F_p = \frac{7.066}{(2.0)^2}$$

$$F_p = 1.77$$

Finally, the bicycle LOS score for the link $I_{b,\text{link}}$ is calculated with Equation 18-41.

$$I_{b,\text{link}} = 0.760 + F_w + F_v + F_S + F_p$$

$$I_{b,\text{link}} = 0.760 - 3.78 + 2.42 + 2.46 + 1.77$$

$$I_{b,\text{link}} = 3.62$$

Step 6: Determine Link LOS

The bicycle LOS for the link is determined by using the bicycle LOS score from Step 5. This score is compared with the link-based bicycle LOS thresholds in Exhibit 18-3 to determine that the LOS for the specified direction of travel along the subject link is D.

Step 7: Determine Bicycle LOS Score for Segment

The unsignalized conflicts factor is computed with Equation 18-47.

$$F_c = 0.035\left(\frac{5{,}280\ N_{ap,s}}{L} - 20\right)$$

$$F_c = 0.035\left[\frac{5{,}280\ (3)}{1{,}320} - 20\right]$$

$$F_c = -0.28$$

The bicycle LOS score for the segment is computed with Equation 18-46.

$$I_{b,seg} = 0.75\left[\frac{\left(F_c + I_{b,\text{link}} + 1\right)^3 t_{R,b} + \left(I_{b,int} + 1\right)^3 d_b}{t_{R,b} + d_b}\right]^{\frac{1}{3}} + 0.125$$

$$I_{b,seg} = 0.75\left[\frac{[(-0.28) + 3.62 + 1]^3(60) + (0.08 + 1)^3(40)}{60 + 40}\right]^{\frac{1}{3}} + 0.125$$

$$I_{b,seg} = 2.88$$

Step 8: Determine Segment LOS

The bicycle LOS for the segment is determined by using the bicycle LOS score from Step 7. This score is compared with the segment-based bicycle LOS thresholds in Exhibit 18-3 to determine that the LOS for the specified direction of travel along the subject segment is C.

EXAMPLE PROBLEM 4: TRANSIT LOS

The Segment

The transit route of interest travels east along a 1,320-ft urban street segment. The segment is part of a collector street located near a community college. It is shown in Exhibit 30-39. A bus stop is provided on the south side of the segment for the subject route.

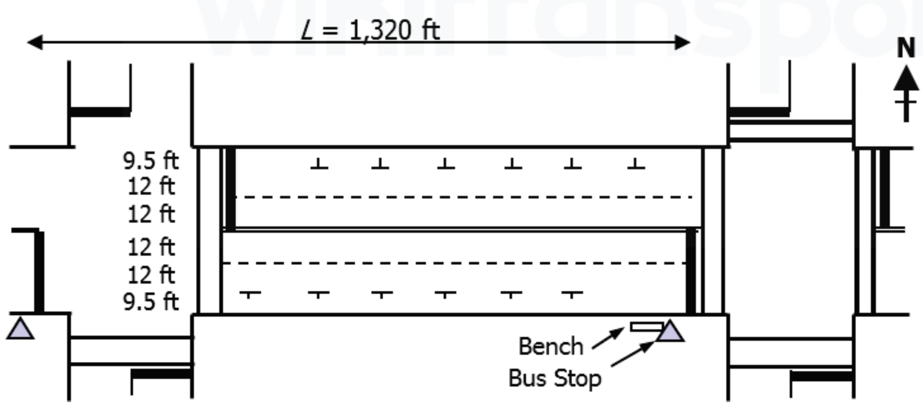


Exhibit 30-39
Example Problem 4: Segment Geometry

The Question

What is the transit LOS for the eastbound bus route on the subject segment?

The Facts

The geometric details of the segment are shown in Exhibit 30-39. Both boundary intersections are signalized. There is one stop in the segment for the eastbound route. The following additional information is known about the bus stop and street segment:

Transit characteristics:

Dwell time: 20.0 s

Transit frequency: 4 veh/h

Excess wait time data are not available for the stop, but the on-time performance of the route (based on a standard of up to 5 min late being considered "on time") at the previous time point is known (92%)

Passenger load factor: 0.83 passengers/seat

Other data:

Area type: not in a central business district

g/C ratio at downstream boundary intersection: 0.4729

Cycle length: 140 s

The bus stop in the segment has a bench, but no shelter

Number of routes serving the segment: 1

The bus stop is accessed from the right-turn lane (i.e., the stop is off-line). Buses are exempt from the requirement to turn right but have no other traffic priority

Performance measures obtained from supporting methodologies:

Motorized vehicle running speed: 33 mi/h

Pedestrian LOS score for the link: 3.53

Through vehicle control delay at the downstream boundary intersection: 19.4 s/veh

Reentry delay: 16.17 s

Outline of Solution

First, the transit vehicle segment running time will be computed. Next, the control delay at the boundary intersection will be obtained and used to compute the transit vehicle segment travel speed. Then the transit wait–ride score will be computed. This score will be combined with the pedestrian LOS score for the link to compute the transit LOS score for the segment. Finally, LOS for the segment will be determined by comparing the computed score with the thresholds identified in Exhibit 18-3.

Computational Steps

Step 1: Determine Transit Vehicle Running Time

The transit vehicle running time is based on the segment running speed and delay due to a transit vehicle stop. These components are calculated first, and then running time is calculated.

Transit vehicle segment running speed can be computed with Equation 18-48.

$$S_{Rt} = \min\left(S_R, \frac{61}{1 + e^{-1.00+(1{,}185\ N_{ts}/L)}}\right)$$

$$S_{Rt} = \min\left(33.0, \frac{61}{1 + e^{-1.00+(1{,}185(1)/1{,}320)}}\right)$$

$$S_{Rt} = 32.1 \text{ mi/h}$$

The acceleration and deceleration rates are unknown, so they are assumed to be 3.3 ft/s² and 4.0 ft/s², respectively, on the basis of data given in the *Transit Capacity and Quality of Service Manual* (9).

The bus stop is located on the near side of a signalized intersection. From Equation 18-50, the average proportion of bus stop acceleration–deceleration delay not due to the intersection's traffic control f_{ad} is equal to the g/C ratio for the through movement in the bus's direction of travel (in this case, eastbound). The effective green time g is 66.21 s (calculated as the phase duration minus the change period), and the cycle length is 140 s. Therefore, f_{ad} is 0.4729.

Equation 18-49 can now be used to compute the portion of bus stop delay due to acceleration and deceleration.

$$d_{ad} = \frac{5{,}280}{3{,}600}\left(\frac{S_{Rt}}{2}\right)\left(\frac{1}{r_{at}} + \frac{1}{r_{dt}}\right) f_{ad}$$

$$d_{ad} = \frac{5{,}280}{3{,}600}\left(\frac{32.1}{2}\right)\left(\frac{1}{3.3} + \frac{1}{4.0}\right)(0.4729)$$

$$d_{ad} = 6.15 \text{ s}$$

Equation 18-51 is used to compute the portion of bus stop delay due to serving passengers. The input average dwell time of 20.0 s and an f_{dt} value of 0.4729 are used in the equation, on the basis of the stop's near-side location at a traffic signal and the g/C ratio computed in a previous step. The f_{dt} factor is used to avoid double-counting the portion of passenger service time that occurs during the signal's red indication and is therefore included as part of control delay.

$$d_{ps} = t_d f_{dt}$$

$$d_{ps} = (20.0)(0.4729)$$

$$d_{ps} = 9.46 \text{ s}$$

The bus stop is located in the right-turn lane; therefore, the bus is subject to reentry delay on leaving the stop. On the basis of the guidance for reentry delay for a near-side stop at a traffic signal, the reentry delay d_{re} is equal to the queue service time g_s. This time is calculated to be 16.17 s by following the procedures in Section 3 of Chapter 31, Signalized Intersections: Supplemental.

Equation 18-52 is used to compute the total delay due to the transit stop.

$$d_{ts} = d_{ad} + d_{ps} + d_{re}$$

$$d_{ts} = 6.15 + 9.46 + 16.17$$

$$d_{ts} = 31.78 \text{ s}$$

Equation 18-53 is used to compute transit vehicle running time on the basis of the previously computed components.

$$t_{Rt} = \frac{3{,}600\ L}{5{,}280\ S_{Rt}} + \sum_{i=1}^{N_{ts}} d_{ts,i}$$

$$t_{Rt} = \frac{3{,}600(1{,}320)}{5{,}280(32.1)} + 31.78$$

$$t_{Rt} = 59.9\text{ s}$$

Step 2: Determine Delay at Intersection

The through delay d_t at the boundary intersection is set equal to the through vehicle control delay exiting the segment at this intersection. The latter delay is 19.4 s/veh. Thus, the through delay d_t is equal to 19.4 s/veh.

Step 3: Determine Travel Speed

The average transit travel speed is computed with Equation 18-55.

$$S_{Tt,seg} = \frac{3{,}600\ L}{5{,}280\ (t_{Rt} + d)}$$

$$S_{Tt,seg} = \frac{3{,}600(1{,}320)}{5{,}280(59.9 + 19.4)}$$

$$S_{Tt,seg} = 11.3\text{ mi/h}$$

Step 4: Determine Transit Wait–Ride Score

The wait–ride score is based on the headway factor and the perceived travel time factor. Each of these components is calculated separately. The wait–ride score is then calculated.

The input data indicate that there is one route on the segment, and its frequency is 4 veh/h. The headway factor is computed with Equation 18-56.

$$F_h = 4.00e^{-1.434/(v_s+0.001)}$$

$$F_h = 4.00e^{-1.434/(4+0.001)}$$

$$F_h = 2.80$$

The perceived travel time factor is based on several intermediate variables that need to be calculated first. The first of these calculations is the amenity time rate. It is calculated by using Equation 18-60. A default passenger trip length of 3.7 mi is used in the absence of other information.

$$T_{at} = \frac{1.3\ p_{sh} + 0.2\ p_{be}}{L_{pt}}$$

$$T_{at} = \frac{1.3(0.0) + 0.2(1.0)}{3.7}$$

$$T_{at} = 0.054\text{ min/mi}$$

Since no information is available for actual excess wait time but on-time performance information is available for the route, Equation 18-61 is used to estimate excess wait time.

$$t_{ex} = [t_{late}(1 - p_{ot})]^2$$

$$t_{ex} = [5.0(1 - 0.92)]^2$$

$$t_{ex} = 0.16 \text{ min}$$

The excess wait time rate T_{ex} is then the excess wait time t_{ex} divided by the average passenger trip length L_{pt}: 0.16/3.7 = 0.043 min/mi.

The passenger load waiting factor is computed with Equation 18-59.

$$a_1 = 1 + \frac{4\,(F_l - 0.80)}{4.2}$$

$$a_1 = 1 + \frac{4\,(0.83 - 0.80)}{4.2}$$

$$a_1 = 1.03$$

The perceived travel time rate is computed with Equation 18-58.

$$T_{ptt} = \left(a_1 \frac{60}{S_{Tt,seg}}\right) + (2\,T_{ex}) - T_{at}$$

$$T_{ptt} = \left(1.03 \frac{60}{11.3}\right) + [2(0.043)] - 0.054$$

$$T_{ptt} = 5.50 \text{ min/mi}$$

The segment is not located in a central business district of a metropolitan area with a population of 5 million or more, so the base travel time rate T_{btt} is equal to 4.0 min/mi. The perceived travel time factor is computed with Equation 18-57.

$$F_{tt} = \frac{(e - 1)\,T_{btt} - (e + 1)\,T_{ptt}}{(e - 1)\,T_{ptt} - (e + 1)\,T_{btt}}$$

$$F_{tt} = \frac{(-0.40 - 1)(4.0) - (-0.40 + 1)(5.50)}{(-0.40 - 1)(5.50) - (-0.40 + 1)(4.0)}$$

$$F_{tt} = 0.881$$

Finally, the transit wait–ride score is computed with Equation 18-62.

$$s_{w\text{-}r} = F_h F_{tt}$$

$$s_{w\text{-}r} = (2.80)(0.883)$$

$$s_{w\text{-}r} = 2.47$$

Step 5: Determine Pedestrian LOS Score for Link

The pedestrian methodology described in Chapter 18 was used to determine the pedestrian LOS score for the link $I_{p,\text{link}}$. This score was computed to be 3.53.

Step 6: Determine Transit LOS Score for Segment

The transit LOS score for the segment is computed with Equation 18-63.

$$I_{t,seg} = 6.0 - 1.50\ s_{w\text{-}r} + 0.15\ I_{p,\mathrm{link}}$$

$$I_{t,seg} = 6.0 - 1.50(2.47) + 0.15(3.53)$$

$$I_{t,seg} = 2.83$$

Step 7: Determine LOS

The transit LOS is determined by using the transit LOS score from Step 6. This performance measure is compared with the thresholds in Exhibit 18-3 to determine that the LOS for the specified bus route is C.

9. ROUNDABOUT SEGMENT METHODOLOGY

SCOPE OF THE METHODOLOGY

This subsection provides an overview of the methodology for evaluating the performance of the motor vehicle mode on an urban street segment bounded by one or more roundabouts. The methodology is based on national research that measured the travel time performance of nine facilities containing three or more roundabouts in series (*10*). The methodology is designed to be integrated into the general motorized vehicle methodology for urban street segments described in Chapter 18. Only the relevant deviations from the general methodology are provided in this subsection.

LIMITATIONS OF THE METHODOLOGY

The methodologies in this subsection are based on regression analyses of field-measured data. The limits of these field data are provided in Exhibit 30-40. The analyst is cautioned with regard to the validity of the results when an input or intermediate calculated value is outside the range of the research data. In addition, the methodology does not account for capacity constraint caused by oversaturated conditions or the possible effects of an upstream signal on a downstream roundabout.

Exhibit 30-40
Validity Range of Inputs and Calculated Values for Analysis of Motor Vehicles on an Urban Street Roundabout Segment

Input or Calculated Value	Minimum	Maximum
Input Data		
Inscribed circle diameter (ft)	84	245
Number of circulating lanes	1	2
Segment length (ft)	540	7,900
Posted speed limit (mi/h)	25	50
Intermediate Calculations		
Central island diameter (ft)	48	187
Length of first portion of segment (ft)	270	3,953
Length of second portion of segment (ft)	244	3,993
Free-flow speed (mi/h)	26	53
Roundabout influence area for first portion of segment (ft)	235	1,446
Roundabout influence area for second portion of segment (ft)	73	897
Geometric delay for first portion of segment (s)	0.1	9.5
Geometric delay for second portion of segment (s)	0.1	6.6

REQUIRED INPUT DATA AND SOURCES

Exhibit 30-41 lists the additional required input data, potential data sources, and suggested default values for applying the methodology in this subsection. The reader should refer to Chapter 18 for a complete list of required input data. Guidance on selecting values for inscribed circle diameter and width of circulating lanes can be obtained elsewhere (*11*).

Exhibit 30-41
Additional Required Input Data, Potential Data Sources, and Default Values for Analysis of Motor Vehicles on an Urban Street Roundabout Segment

Required Data and Units	Potential Data Source(s)	Suggested Default Value
	Geometric Design Data	
Inscribed circle diameter of upstream and downstream roundabout (ft)	Field data, aerial photo, preliminary design	130 ft for one-lane roundabout 180 ft for two-lane roundabout
Number of circulating lanes of upstream and downstream roundabout (ft)	Field data, aerial photo, preliminary design	Must be provided
Average width of circulating lanes of upstream and downstream roundabout (ft)	Field data, aerial photo, preliminary design	20 ft for one-lane roundabout 15 ft for two-lane roundabout
	Performance Measure Data	
Control delay by lane at boundary roundabout (s/veh)	HCM method output	Must be provided
Capacity by lane at boundary roundabout (veh/h)	HCM method output	Must be provided

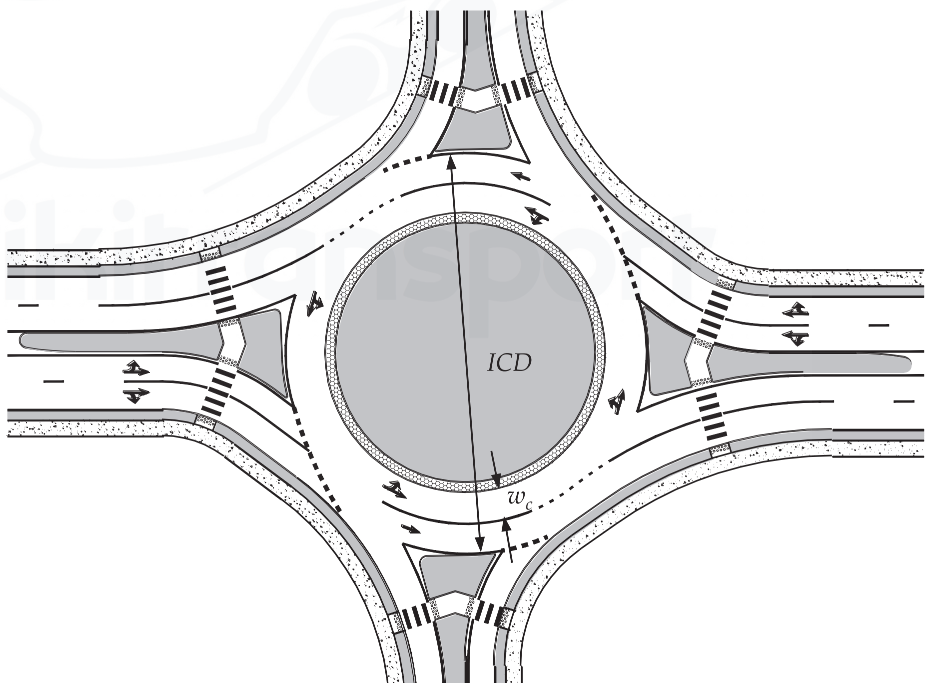
GEOMETRIC DESIGN DATA

This subsection describes the geometric design data listed in Exhibit 30-41. These data describe the additional geometric elements of the roundabouts beyond the geometric elements of the intersections and segments described in Exhibit 18-5.

Inscribed Circle Diameter

The inscribed circle diameter, *ICD*, is the diameter of the largest circle that can be inscribed within the outer edges of the circulatory roadway. The ICD serves as the width of the roundabout. This is illustrated in Exhibit 30-42.

Exhibit 30-42
Illustration of Geometric Design Data



For the purposes of this methodology, if the ICD is variable throughout the roundabout (e.g., to accommodate a variable number of circulating lanes, as illustrated in Exhibit 30-42), the larger dimension should be used.

Number of Circulating Lanes

The number of circulating lanes N_c is the count of circulating lanes immediately downstream of the entry that forms the end of the segment under study.

Average Width of Circulating Lanes

The average width of circulating lanes w_c is measured in the section of circulatory roadway immediately downstream of the entry, that is, the same location where the number of circulating lanes is counted. This is illustrated in Exhibit 30-42.

COMPUTATIONAL STEPS

The computational steps described below are illustrated in the flowchart provided in Exhibit 18-8. The path followed is that of a noncoordinated system with YIELD control.

Step 1: Determine Traffic Demand Adjustments

The models developed for estimating travel speed through a series of roundabouts were calibrated by using roundabouts that were operating below capacity. Neither the capacity estimation procedures for roundabouts in Chapter 22 nor the procedures in this subsection explicitly account for capacity constraint that restricts (or meters) discharge volume from the intersection when the demand volume for an intersection traffic movement exceeds its capacity. Similarly, the methodology does not account for the effect on roundabout operations or travel time that may be created by queue spillback between two roundabouts. The occurrence of any of these conditions should be flagged, and an alternative tool should be considered.

Step 2: Determine Running Time

A procedure for determining running time for a segment bounded by one or more roundabouts is described in this step. It builds on the procedure described in Chapter 18. Each calculation is discussed in the following subparts, which culminate with the calculation of segment running time.

A. Determine Free-Flow Speed

Free-flow speed represents the average running speed of through vehicles traveling along a segment under low-volume conditions and not delayed by traffic control devices or other vehicles. It reflects the effect of the street environment on driver speed choice. Elements of the street environment that influence this choice under free-flow conditions include speed limit, access point density, median type, curb presence, and segment length. Further discussion on free-flow speed can be found in Section 3 of Chapter 18.

Free-flow speed (when the influence of roundabouts at one or both ends of the segment is considered) is calculated by separately determining the free-flow speed influenced by the roundabout at each end of the segment and then comparing these two free-flow speed estimates with the free-flow speed that would be estimated without the presence of roundabouts.

Base Free-Flow Speed

The base free-flow speed is defined to be the free-flow speed on longer segments and is computed the same for segments bounded by roundabouts as for segments bounded by signals. It includes the influence of speed limit, access point density, median type, curb presence, and on-street parking presence. It is computed with Equation 30-72.

Equation 30-72

$$S_{fo} = S_{calib} + S_0 + f_{cs} + f_A + f_{pk}$$

where

S_{fo} = base free-flow speed (mi/h),

S_{calib} = base free-flow speed calibration factor (mi/h),

S_0 = speed constant (mi/h),

f_{CS} = adjustment for cross section (mi/h),

f_A = adjustment for access points (mi/h), and

f_{pk} = adjustment for on-street parking (mi/h).

The speed constant and adjustment factors used in Equation 30-72 are listed in Exhibit 30-43. The exhibit is the same as Exhibit 18-11, except that the width of the signalized intersection used in the calculation for the adjustment for access points f_A has been replaced with the inscribed circle diameter of the roundabout, and the range of speed limits is restricted to the validity range for this method. Equations provided in the table footnote can also be used to compute these adjustment factors for conditions not shown in the exhibit. Further discussion of this equation and adjustment factors can be found in Chapter 18.

Exhibit 30-43
Base Free-Flow Speed Adjustment Factors

Speed Limit (mi/h)	Speed Constant S_0 (mi/h)[a]	Median Type	Percent with Restrictive Median (%)	Adjustment for Cross Section f_{CS} (mi/h)[b] No Curb	Curb
25	37.4	Restrictive	20	0.3	-0.9
30	39.7		40	0.6	-1.4
35	42.1		60	0.9	-1.8
40	44.4		80	1.2	-2.2
45	46.8		100	1.5	-2.7
50	49.1	Nonrestrictive	Not applicable	0.0	-0.5
		No median	Not applicable	0.0	-0.5

Access Density D_a (points/mi)	Adjustment for Access Points f_A by Lanes N_{th} (mi/h)[c] 1 Lane	2 Lanes	3 Lanes	Percent with On-Street Parking (%)	Adjustment for Parking (mi/h)[d]
0	0.0	0.0	0.0	0	0.0
2	-0.2	-0.1	-0.1	20	-0.6
4	-0.3	-0.2	-0.1	40	-1.2
10	-0.8	-0.4	-0.3	60	-1.8
20	-1.6	-0.8	-0.5	80	-2.4
40	-3.1	-1.6	-1.0	100	-3.0
60	-4.7	-2.3	-1.6		

Notes: [a] $S_0 = 25.6 + 0.47 S_{pl}$, where S_{pl} = posted speed limit (mi/h).
[b] $f_{CS} = 1.5\ p_{rm} - 0.47\ p_{curb} - 3.7\ p_{curb}\ p_{rm}$, where p_{rm} = proportion of link length with restrictive median (decimal) and p_{curb} = proportion of segment with curb on the right-hand side (decimal).
[c] $f_A = -0.078\ D_a / N_{th}$ with $D_a = 5{,}280\ (N_{ap,s} + N_{ap,o})/(L - ICD_i)$, where D_a = access point density on segment (points/mi); N_{th} = number of through lanes on the segment in the subject direction of travel (ln); $N_{ap,s}$ = number of access point approaches on the right side in the subject direction of travel (points); $N_{ap,o}$ = number of access point approaches on the right side in the opposing direction of travel (points); L = segment length (ft); and ICD_i = inscribed circle diameter of roundabout (ft).
[d] $f_{pk} = -3.0 \times$ proportion of link length with on-street parking available on the right-hand side (decimal).

Equation 30-72 has been calibrated by using data for many urban street segments collectively located throughout the United States, so the default value of 0.0 mi/h for S_{calib} is believed to yield results that are reasonably representative of driver behavior in most urban areas. However, if desired, a locally representative value can be determined from field-measured estimates of the base free-flow speed for several street segments. The local default value can be established for typical street segments or for specific street types. This calibration factor is determined as the one value that provides a statistically based best fit between the prediction from Equation 30-72 and the field-measured estimates. A procedure for estimating the base free-flow speed from field data is described in Section 6.

Roundabout Geometry and Speed Parameters

The computation of free-flow speed, roundabout influence area, and geometric delay requires measurement or estimation of a series of geometric parameters associated with the roundabout at one or both ends of the segment. These computations are performed separately for each roundabout.

The central island diameter is equal to the inscribed circle diameter minus the width of the circulatory roadway on each side of the central island. The circulatory roadway width is equal to the average width of each circulating lane times the number of circulating lanes. These calculations are combined into a single equation as given in Equation 30-73.

$$CID = ICD - 2N_c w_c$$

Equation 30-73

where

CID = central island diameter (ft),

ICD = inscribed circle diameter (ft),

N_c = number of circulating lane(s), and

w_c = average width of circulating lane(s) (ft).

The circulating speed, S_c, can be approximated by assuming that the circulating path occupies the centerline of the circulatory roadway with a radius equal to half the central island diameter plus half the total width of the circulatory roadway. This radius can be computed with Equation 30-74.

$$r_{c,th} = \frac{ICD}{2} + \frac{N_c w_c}{2}$$

Equation 30-74

where

$r_{c,th}$ = average radius of circulating path of through movement (ft),

ICD = inscribed circle diameter (ft),

N_c = number of circulating lane(s), and

w_c = average width of circulating lane(s) (ft).

The speed associated with this radius can be estimated with Equation 30-75 (*12*), which assumes a negative cross slope of the circulatory roadway of –0.02, typical of many roundabouts.

Equation 30-75

$$S_c = 3.4614 r_{c,th}^{0.3673}$$

where

S_c = circulating speed (mi/h), and

$r_{c,th}$ = average radius of circulating path of through movement (ft).

For the purposes of calculating free-flow speed, roundabout influence area, and geometric delay, the segment length is divided into two subsegments. Subsegment 1 consists of the portion of the segment from the yield line of the upstream roundabout to the midpoint between the two roundabouts, defined as halfway between the cross-street centerlines of the two roundabouts. Subsegment 2 consists of the portion of the segment from this midpoint to the yield line of the downstream roundabout. The lengths of these subsegments are calculated with Equation 30-76 and Equation 30-77. These dimensions are illustrated in Exhibit 30-44.

Equation 30-76

$$L_1 = \frac{1}{2}\left(L - \frac{ICD_1}{2} + \frac{ICD_2}{2}\right) + \frac{ICD_1}{2}$$

Equation 30-77

$$L_2 = L - L_1$$

where

L_1 = length of Subsegment 1 (ft),

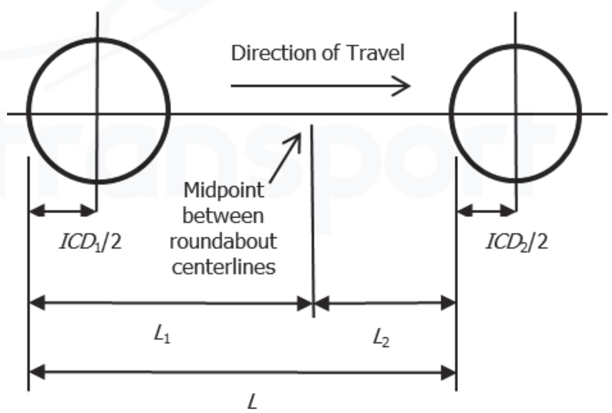
L_2 = length of Subsegment 2 (ft),

L = length of segment (ft),

ICD_1 = inscribed circle diameter of Roundabout 1 (ft), and

ICD_2 = inscribed circle diameter of Roundabout 2 (ft).

Exhibit 30-44
Illustration of Subsegment Dimensions



Free-Flow Speed for Upstream Subsegment (Subsegment 1)

Free-slow speed for Subsegment 1 (the upstream subsegment) is computed in a three-step process by first determining an initial free-flow speed. A roundabout influence area is then computed as the distance over which the geometric features of the roundabout influence travel speed. The initial free-flow speed is then adjusted downward if the roundabout influence area meets or exceeds the length of the subsegment.

The initial free-flow speed for Subsegment 1 is estimated from the subsegment length, posted speed limit, and central island diameter of the roundabout at the upstream end of the segment by using Equation 30-78.

$$S_{f,1,\text{initial}} = 14.6 + 0.0039L_1 + 0.48S_{PL} + 0.02CID_1$$

Equation 30-78

where

$S_{f,1,\text{initial}}$ = initial free-flow speed for Subsegment 1 (mi/h),

L_1 = length of Subsegment 1 (ft),

S_{PL} = posted speed limit (mi/h), and

CID_1 = central island diameter for roundabout at upstream end of Subsegment 1 (ft).

The roundabout influence area for Subsegment 1, RIA_1, is estimated from the free-flow speed and circulating speed with Equation 30-79. This equation yields positive values for inputs within the range limits.

$$RIA_1 = -149.8 + 31.4S_{f,1,\text{initial}} - 22.5S_{c,1}$$

Equation 30-79

where

RIA_1 = roundabout influence area for Subsegment 1 (ft),

$S_{f,1,\text{initial}}$ = initial free-flow speed for Subsegment 1 (mi/h), and

$S_{c,1}$ = through movement circulating speed for roundabout at upstream end of segment (mi/h).

The roundabout influence area is then compared with the length of the subsegment, as shown in Equation 30-80. If the roundabout influence area is equal to or exceeds the length of the subsegment, the subsegment free-flow speed is reduced.

$$S_{f,1} = S_{f,1,\text{initial}} - 4.43 \text{ if } RIA_1 \geq L_1, \text{ else}$$

$$S_{f,1} = S_{f,1,\text{initial}}$$

Equation 30-80

where $S_{f,1}$ is the free-flow speed for Subsegment 1 (mi/h).

Free-Flow Speed for Downstream Subsegment (Subsegment 2)

The initial free-flow speed for Subsegment 2, $S_{f,2,\text{initial}}$, is estimated with Equation 30-81.

$$S_{f,2,\text{initial}} = 15.1 + 0.0037L_2 + 0.43S_{PL} + 0.05CID_2$$

Equation 30-81

where

$S_{f,2,\text{initial}}$ = initial free-flow speed for Subsegment 2 (mi/h),

L_2 = length of Subsegment 2 (ft),

S_{PL} = posted speed limit (mi/h), and

CID_2 = central island diameter for roundabout at downstream end of Subsegment 2 (ft).

The roundabout influence area for the subsegment RIA_2 is estimated from the free-flow speed and downstream circulating speed with Equation 30-82.

Equation 30-82

$$RIA_2 = 165.9 + 13.8S_{f,2,\text{initial}} - 21.1S_{c,2}$$

where

RIA_2 = roundabout influence area for Subsegment 2 (ft),

$S_{f,2,\text{initial}}$ = initial free-flow speed for Subsegment 2 (mi/h), and

$S_{c,2}$ = through movement circulating speed for roundabout at downstream end of subsegment (mi/h).

The roundabout influence area is then compared with the length of the subsegment, as shown in Equation 30-83. If the roundabout influence area is equal to or exceeds the length of the subsegment, the subsegment free-flow speed is reduced to account for the overlap.

Equation 30-83

$$S_{f,2} = S_{f,2,\text{initial}} - 4.73 \text{ if } RIA_2 \geq L_2\text{, else}$$
$$S_{f,2} = S_{f,2,\text{initial}}$$

where $S_{f,2}$ is the free-flow speed for Subsegment 2 (mi/h).

Free-Flow Speed Without Influence of Roundabouts

The calculation for free-flow speed without the geometric influence of roundabouts is the same as for segments bounded by signalized intersections, as provided in Chapter 18. Equation 30-84 is used to compute the value of an adjustment factor that accounts for the influence of short spacing of boundary intersections.

Equation 30-84

$$f_L = 1.02 - 4.7\frac{S_{fo} - 19.5}{\max(L_s, 400)} \leq 1.0$$

where

f_L = boundary intersection spacing adjustment factor;

S_{fo} = base free-flow speed (mi/h); and

L_s = distance between adjacent boundary intersections that (*a*) bracket the subject segment and (*b*) each have a type of control that can impose on the subject through movement a legal requirement to stop or yield, such as a roundabout (ft).

The predicted free-flow speed without the geometric influence of roundabouts is computed with Equation 30-85 on the basis of estimates of base free-flow speed and the signal spacing adjustment factor.

Equation 30-85

$$S_{f,non\text{-}rbt} = S_{fo}\, f_L \geq S_{pl}$$

where $S_{f,non\text{-}rbt}$ is the free-flow speed for nonroundabout segments (mi/h) and S_{pl} is the posted speed limit. If the speed obtained from Equation 30-85 is less than the speed limit, the speed limit is used.

Free-Flow Speed

The free-flow speeds for each subsegment are then compared with each other and with the nonroundabout free-flow speed with Equation 30-86. The lowest of these speeds is the governing free-flow speed for the segment. The analyst is cautioned that if the result of this calculation is outside the validity range presented in Exhibit 30-40, the calculation is an extrapolation of the model. Note that the resulting free-flow speed for a segment bounded by one or more roundabouts may be lower than the posted speed, even though the nonroundabout free-flow speed is constrained by the posted speed in accordance with the motorized vehicle methodology in Chapter 18.

$$S_f = \min(S_{f,1}, S_{f,2}, S_{f,non\text{-}rbt})$$

Equation 30-86

B. Compute Adjustment for Vehicle Proximity

This step is the same as in Chapter 18.

C. Compute Delay due to Turning Vehicles

This step is the same as in Chapter 18.

D. Estimate Delay due to Other Sources

This step is the same as in Chapter 18.

E. Compute Segment Running Time

Equation 30-87 is used to compute the segment running time, which is based on Equation 18-7. It incorporates the conditions specified in Chapter 18 for a yield-controlled boundary exiting the segment: a start-up lost time of 2.5 s and the influence of the volume-to-capacity ratio of the roundabout entry.

$$t_R = \frac{3.5}{0.0025\ L} \times \min\left(\frac{v_{th}}{c_{th}}, 1.00\right) + \frac{3{,}600\ L}{5{,}280\ S_f} f_v + \sum_{i=1}^{N_{ap}} d_{ap,i} + d_{\text{other}}$$

Equation 30-87

where

t_R = segment running time (s),

L = segment length (ft),

v_{th} = through-demand flow rate (veh/h),

c_{th} = through-movement capacity (veh/h),

f_v = proximity adjustment factor,

$d_{ap,i}$ = delay due to left and right turns from the street into access point intersection i (s/veh),

N_{ap} = number of influential access point approaches along the segment = $N_{ap,s} + p_{ap,lt} N_{ap,o}$ (points),

$N_{ap,s}$ = number of access point approaches on the right side in the subject direction of travel (points),

$N_{ap,o}$ = number of access point approaches on the right side in the opposing direction of travel (points),

$p_{ap,lt}$ = proportion of $N_{ap,o}$ that can be accessed by a left turn from the subject direction of travel, and

d_{other} = delay due to other sources along the segment (e.g., curb parking or pedestrians) (s/veh).

The variables v_{th} and c_{th} used in Equation 30-87 apply to the through movement exiting the segment at the boundary roundabout.

Step 3: Determine the Proportion Arriving During Green

This step does not apply to a segment with a downstream roundabout. The methodology does not account for the possible effects of an upstream signal on a downstream roundabout.

Step 4: Determine Signal Phase Duration

This step does not apply to a segment with a downstream roundabout.

Step 5: Determine Through Delay

The through delay for a segment with a roundabout at one or both ends is computed as a combination of control delay and geometric delay.

The procedure for computing the control delay at a roundabout at the downstream end of a segment is provided in Chapter 22, which determines the control delay for a roundabout on a lane-by-lane basis. For an approach with one lane, the through control delay is equal to the control delay of the lane. For an approach with two lanes, the through control delay is computed by allocating the control delay in each lane in proportion to the through traffic in each lane by using Equation 30-88.

Equation 30-88

$$d_{\text{control},t} = \frac{d_{LL}\ v_{LL} P_{LL,T} + d_{RL}\ v_{RL} P_{RL,T}}{v_{th}}$$

where

$d_{\text{control},t}$ = through control delay (s/veh),

v_{th} = through-demand flow rate (veh/h),

d_{LL} = control delay in left lane (s/veh),

v_{LL} = demand flow rate in left lane (veh/h),

d_{RL} = control delay in right lane (s/veh),

v_{RL} = demand flow rate in right lane (veh/h),

$P_{LL,T}$ = proportion of through-movement vehicles in the left lane (decimal), and

$P_{RL,T}$ = proportion of through-movement vehicles in the right lane (decimal).

Geometric delay is calculated separately for the presence of a roundabout on the two subsegments. If a roundabout is present on the upstream end of Subsegment 1 (regardless of the control present at the downstream end of Subsegment 2), the geometric delay for the upstream portion of the segment $d_{geom,1}$ is calculated with Equation 30-89. If the upstream end of the segment is controlled by a signalized or stop-controlled intersection or is uncontrolled, $d_{geom,1} = 0$.

Equation 30-89

$$d_{geom,1} = \max\left[-2.63 + 0.09S_f + 0.625ICD_1\left(\frac{1}{S_{c,1}} - \frac{1}{S_f}\right), 0\right]$$

where $d_{geom,1}$ is the geometric delay for Subsegment 1 (s/veh).

If a roundabout is present on the downstream end of the segment (regardless of the control present at the upstream end), the geometric delay for the downstream portion of the segment $d_{geom,2}$ is calculated with Equation 30-90. If the upstream end of the segment is controlled by a signalized or stop-controlled intersection or is uncontrolled, $d_{geom,2} = 0$.

$$d_{geom,2} = \max(1.57 + 0.11S_f - 0.21S_{c,2}, 0)$$

Equation 30-90

where $d_{geom,2}$ is the geometric delay for Subsegment 2 (s/veh).

The analyst is cautioned that if these calculations result in one or more geometric delay estimates outside the validity range presented in Exhibit 30-40, the calculation is an extrapolation of the model.

The through delay d_t is computed as the sum of control and geometric delays, as given in Equation 30-91.

$$d_t = d_{\text{control},t} + d_{geom,1} + d_{geom,2}$$

Equation 30-91

Step 6: Determine Through Stop Rate

As noted in Chapter 18, the stop rate at a YIELD-controlled approach will vary with conflicting demand. It can be estimated (in stops per vehicle) as equal to the volume-to-capacity ratio of the through movement at the boundary intersection. This approach recognizes that YIELD control does not require drivers to come to a complete stop when there is no conflicting traffic. The through stop rate h is computed as given in Equation 30-92. The methodology does not apply for volume-to-capacity ratios exceeding 1.0.

$$h = \min\left(\frac{v_{th}}{c_{th}}, 1.00\right)$$

Equation 30-92

Step 7: Determine Travel Speed

This step is the same as for Chapter 18.

Step 8: Determine Spatial Stop Rate

This step is the same as for Chapter 18.

Step 9: Determine LOS

This step is the same as for Chapter 18. The base free-flow speed for the estimation of LOS is the same base free-flow speed as determined in Chapter 18.

Step 10: Determine Motor Vehicle Traveler Perception Score

Research has not been conducted on the traveler's perception of service quality for roundabouts in a manner that can be integrated into this methodology. As a result, the motor vehicle traveler perception score for a segment bounded by a roundabout is undefined and this step is not applicable for the evaluation of roundabout segments.

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