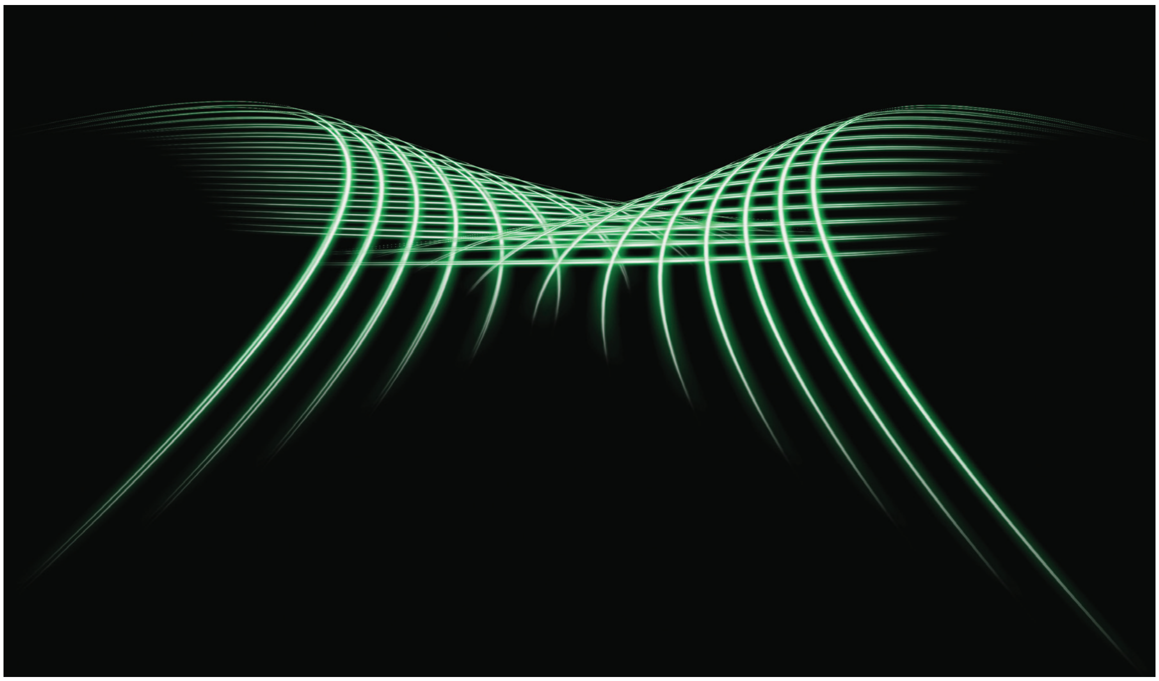
HCM2010

HIGHWAY CAPACITY MANUAL



CHAPTER 21

ROUNDABOUTS

TRB TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

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HCM2010

HIGHWAY CAPACITY MANUAL

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

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

The HCM 2010 consists of four volumes:

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

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

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

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CHAPTER 21
ROUNDABOUTS

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LIST OF EXHIBITS

1. INTRODUCTION

Roundabouts are intersections with a generally circular shape, characterized by yield on entry and circulation around a central island (counterclockwise in the United States). Roundabouts have been used successfully throughout the world and are being used increasingly in the United States, especially since 1990.

Chapter 21, Roundabouts, presents concepts and procedures for analyzing these intersections. National Cooperative Highway Research Program Project 3-65 (*1*) provided a comprehensive database of roundabout operations for U.S. conditions on the basis of a study of 31 sites. The procedures that follow are largely founded on that study's recommendations. These procedures allow the analyst to assess the operational performance of an existing or planned one-lane or two-lane roundabout given traffic demand levels.

INTERSECTION ANALYSIS BOUNDARIES AND TRAVEL MODES

The analytical procedure presented in this chapter assumes that the analysis boundaries are the roundabout itself, including associated pedestrian crosswalks. Alternative tools discussed in this chapter can, in some cases, expand the analysis boundaries to include adjacent intersections. The methodology presented here includes discussion of motor vehicles, pedestrians, and bicycles.

LEVEL OF SERVICE CRITERIA

The level of service (LOS) criteria for automobiles in roundabouts are given in Exhibit 21-1. As the table notes, LOS F is assigned if the volume-to-capacity ratio of a lane exceeds 1.0 regardless of the control delay. For assessment of LOS at the approach and intersection levels, LOS is based solely on control delay.

The thresholds in Exhibit 21-1 are based on the considered judgment of the Transportation Research Board Committee on Highway Capacity and Quality of Service. As discussed later in this chapter, roundabouts share the same basic control delay formulation with two-way and all-way STOP-controlled intersections, adjusting for the effect of YIELD control. However, at the time of publication of this edition of the *Highway Capacity Manual* (HCM), no research was available on traveler perception of quality of service at roundabouts. In the absence of such research, the service measure and thresholds have been made consistent with those for other unsignalized intersections, primarily on the basis of this similar control delay formulation.

Exhibit 21-1
LOS Criteria: Automobile Mode

Control Delay (s/veh)	LOS by Volume-to-Capacity Ratio[a]	
	v/c ≤ 1.0	v/c >1.0
0–10	A	F
>10–15	B	F
>15–25	C	F
>25–35	D	F
>35–50	E	F
>50	F	F

Note: [a] For approaches and intersectionwide assessment, LOS is defined solely by control delay.

REQUIRED INPUT DATA

The following data are required to analyze a roundabout:

1. Number and configuration of lanes on each approach;
2. Either of the following:
   a. Demand volume for each entering vehicular movement and each pedestrian crossing movement during the peak 15 min, or
   b. Demand volume for each entering vehicular movement and each pedestrian crossing movement during the peak hour, and a peak hour factor for the hour;
3. Percentage of heavy vehicles;
4. Volume distribution across lanes for multilane entries; and
5. Length of analysis period, generally a peak 15-min period within the peak hour. Any 15-min period can be analyzed, however.

SCOPE OF THE METHODOLOGY

The methodology presented in this chapter focuses on the operation of roundabouts. The methodology does not account for the effects of adjacent traffic control devices such as nearby traffic signals or signalized pedestrian crossings. This version of the roundabout analysis procedures results primarily from studies conducted by National Cooperative Highway Research Program Project 3-65 (*1*). The chapter also includes a discussion of alternative tools that can model situations beyond the scope of the analytical methodology presented in this chapter.

The methodology does not necessarily apply to other types of circular intersections such as rotaries, neighborhood traffic circles, or signalized traffic circles, because these types of circular intersections usually have geometric or traffic control elements that deviate from those used in roundabouts. As a result, their operational performance may be significantly different from that experienced at roundabouts and thus cannot be accurately modeled by using the procedures in this chapter. More detail on the differentiation between roundabouts and other circular intersections can be found elsewhere (*2*, *3*).

LIMITATIONS OF THE METHODOLOGY

This chapter's methodology applies to isolated roundabouts with up to two entry lanes and up to one bypass lane per approach.

While the database on which these procedures are based is the most comprehensive developed for U.S. conditions, it does not cover all situations that may be encountered in practice. The chapter's methodology applies to isolated roundabouts with up to two entry lanes and up to one bypass lane per approach.

Automobile Mode

The methodology presented for automobiles covers typical roundabout facilities quite well, but it lacks examples of situations in which

- Upstream or downstream signals (including, but not limited to, pedestrian signals) significantly influence the performance of the roundabout;

- Priority reversal occurs, such as unusual forced entry conditions under extremely high flows;
- A high level of pedestrian or bicycle activity is present;
- The roundabout is in close proximity to one or more other roundabouts;
- More than two entry lanes are present on one or more approaches; or
- One or more entry lanes are of limited, or short, length (a flared design).

Priority reversal can occur when entering traffic dominates an entry, causing circulating traffic to yield.

A typical flared entry is one that widens from one approach lane to two entry lanes. Other flaring combinations, including flares of lane width, are possible.

Pedestrian Mode

Research on the operational performance of pedestrians at roundabouts is limited, in terms of the effect of both motor vehicles on pedestrians and pedestrians on motor vehicles. This chapter's methodologies include international models and analytical tools that have not been validated by research in the United States at the time of publication of this edition of the HCM. Additional research on pedestrian operations at roundabouts is needed to develop and refine procedures that adequately address these issues.

Bicycle Mode

Current methodologies to analyze LOS and delay at roundabouts only apply to bicycles in limited situations and have not been validated by research in the United States at the time of publication of this edition of the HCM. Additional research on bicycle behavior and operations at roundabouts is needed to develop procedures that adequately address these issues.

2. METHODOLOGY

OVERVIEW

This chapter presents procedures for analyzing roundabouts, introduces the unique characteristics of roundabout capacity, and presents terminology specific to roundabouts. For ease of reference, the following terms are defined:

v_e = entry flow rate,

v_c = conflicting flow rate, and

v_{ex} = exit flow rate.

Intersection analysis models generally fall into two categories. *Regression models* use field data to develop statistically derived relationships between geometric features and performance measures such as capacity and delay. *Analytical models* are based on traffic flow theory combined with the use of field measures of driver behavior, resulting in an analytic formulation of the relationship between those field measures and performance measures such as capacity and delay.

The procedure in this chapter uses a combination of regression and analytical models.

Both of these types of models are applicable to roundabouts. Gap-acceptance models are an example of an analytical model and are commonly applied for analyzing unsignalized intersections because they capture driver behavior characteristics directly and can be made site-specific by custom-tuning the values used for those parameters. However, simple gap-acceptance models may not capture all of the observed behavior, and more complex gap-acceptance models that account for limited priority or reverse priority are difficult to calibrate. Regression models are often used in these cases in which an understanding of driver behavior characteristics is incomplete. On the basis of recent analysis of U.S. field data, the procedure presented in this chapter incorporates a combination of simple, lane-based regression and gap-acceptance models for both single-lane and double-lane roundabouts.

CAPACITY CONCEPTS

The capacity of a roundabout approach is directly influenced by flow patterns. The three flows of interest, the entering flow, the circulating flow, and the exiting flow, are shown in Exhibit 21-2.

The capacity of a roundabout approach decreases as the circulating flow increases.

The capacity of an approach decreases as the conflicting flow increases. In general, the primary conflicting flow is the circulating flow that passes directly in front of the subject entry. While the circulating flow directly conflicts with the entry flow, the exiting flow may also affect a driver's decision to enter the roundabout. This phenomenon is similar to the effect of the right-turning stream approaching from the left side of a two-way STOP-controlled intersection. Until these drivers complete their exit maneuver or right turn, there may be some uncertainty in the mind of the driver at the yield or stop line about the intentions of the exiting or turning vehicle. However, even though it may have an influence in some cases, including this effect did not significantly improve the overall fit of the capacity models to the data (*1*) and therefore is not included in this chapter's models.

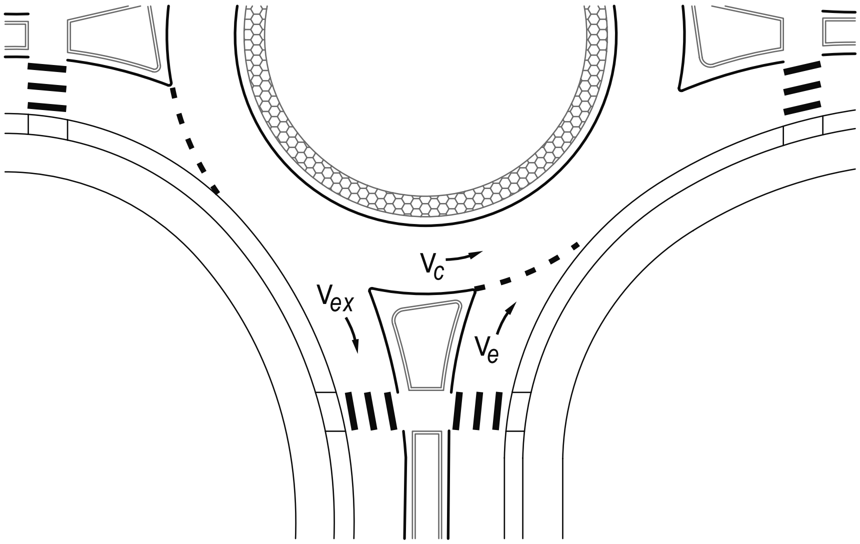


Exhibit 21-2
Analysis on One Roundabout Leg

When the conflicting flow rate approaches zero, the maximum entry flow is given by 3,600 s/h divided by the follow-up headway, which is analogous to the saturation flow rate for a movement receiving a green indication at a signalized intersection. At high levels of both entering and conflicting flow, limited priority (in which circulating traffic adjusts its headways to allow entering vehicles to enter), priority reversal (in which entering traffic forces circulating traffic to yield), and other behaviors may occur. In these cases, more complex analytical models or regression models, such as those incorporated into some of the alternative tools discussed later in this chapter, may give more realistic results.

When an approach operates over capacity during the analysis period, a condition known as *capacity constraint* may occur. During this condition, the actual circulating flow downstream of the constrained entry will be less than demand. The reduction in actual circulating flow may therefore increase the capacity of the affected downstream entries during this condition.

In addition, it has been suggested that origin–destination patterns have an influence on the capacity of a given entry (*4*, *5*). This effect was not identified in a recent study (*1*) and has not been incorporated into this chapter's models.

Both roundabout design practices and the public's use of roundabouts are still maturing in the United States. Many of the sites that formed the database for this chapter were less than 5 years old when the data were collected. Although the available data were insufficient to definitively answer the question of whether capacity increases with driver familiarity, anecdotal observations suggest that this may well be the case. At this early stage of their introduction to roundabouts, American drivers seem to be displaying more hesitation and caution in the use of roundabouts than their international counterparts, which in turn has resulted in a lower observed capacity than might be ultimately achievable. It is therefore likely that capacity (and volumes) will increase in the years to come as more roundabouts are constructed in the United States and as user familiarity grows. Such an increase in capacity over time would be consistent with the historically observed trends in capacity for freeway facilities and signalized intersections, for example. On the other hand, capacities in the

U.S. drivers presently seem to display more hesitation and caution in using roundabouts than drivers in other countries, which results in lower observed capacities. It is likely that capacities will increase in the future as U.S. drivers become more familiar with roundabouts.

United States over time may still be fundamentally different from those observed in other countries due to a variety of factors. These include limited use of turn indicators at roundabout exits by American drivers, differences in vehicle types, and the effect that the common use of STOP-controlled intersections (versus YIELD-controlled intersections) has had on drivers in the United States.

Single-Lane Roundabouts

The capacity of a single entry lane conflicted by one circulating lane (e.g., a single-lane roundabout, illustrated in Exhibit 21-3) is based on the conflicting flow. The equation for estimating the capacity is given as Equation 21-1:

Equation 21-1

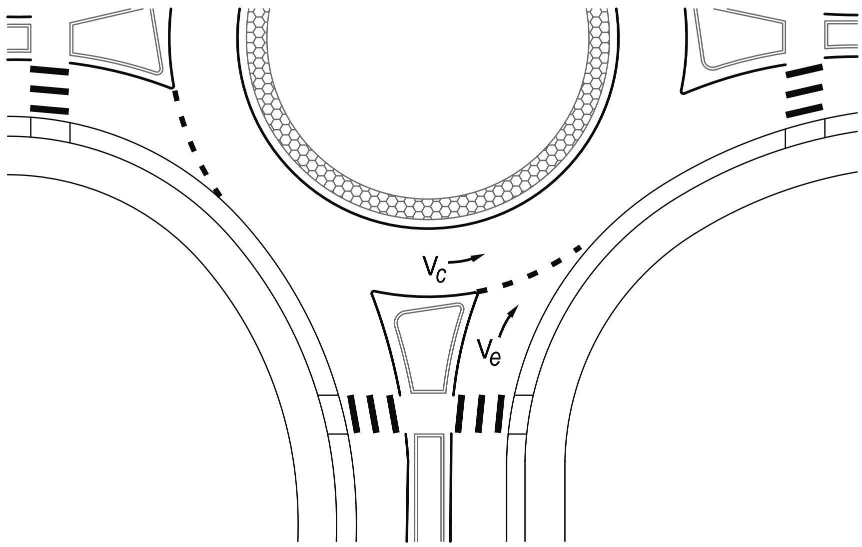
$$c_{e,pce} = 1{,}130 e^{\left(-1.0\times10^{-3}\right) v_{c,pce}}$$

where

$c_{e,pce}$ = lane capacity, adjusted for heavy vehicles (pc/h), and

$v_{c,pce}$ = conflicting flow rate (pc/h).

Exhibit 21-3
Example of One-Lane Entry Conflicted by One Circulating Lane



The capacity model given above reflects observations made at U.S. roundabouts in 2003. As noted previously, it is probable that U.S. roundabout capacity will increase to some degree with increased driver familiarity. In addition, communities with higher densities of roundabouts or generally more aggressive drivers may experience higher capacities. Therefore, local calibration of the capacity models is recommended to best reflect local driver behavior. This topic is discussed later in this chapter.

Multilane Roundabouts

Multilane roundabouts have more than one lane on at least one entry and at least part of the circulatory roadway. The number of entry, circulating, and exiting lanes may vary throughout the roundabout. Because of the many possible variations, the computational complexity is higher than for single-lane roundabouts.

The definition of headways and gaps for multilane facilities is more complicated than for single-lane facilities. If the circulating roadway truly functions as a multilane facility, then motorists at the entry perceive gaps in both the inside and outside lanes in some integrated fashion. Some drivers who choose to enter the roundabout via the right entry lane will yield to all traffic in the circulatory roadway due to their uncertainty about the path of the circulating vehicles. This uncertainty is more pronounced at roundabouts than at other unsignalized intersections due to the curvature of the circulatory roadway. However, some drivers in the right entry lane will enter next to a vehicle circulating in the inside lane if the circulating vehicle is not perceived to conflict. In addition, the behavior of circulating vehicles may be affected by the presence or absence of lane markings within the circulatory roadway. As a result, the gap-acceptance behavior of the right entry lane, in particular, is imperfect and difficult to quantify with a simple gap-acceptance model. This leads to an inclination toward using a regression-based model that implicitly accounts for these factors. More detail on the nuances of geometric design, pavement markings, and their relationship with operational performance can be found elsewhere (*2*, *3*).

For roundabouts with up to two circulating lanes, which is the only type of multilane roundabout addressed by the analytical methodology in this chapter, the entries and exits can be either one or two lanes wide (plus a possible right-turn bypass lane). The capacity model given above reflects observations made at a limited number of U.S. roundabouts in 2003. As discussed previously with single-lane roundabouts, local calibration of the capacity models (presented later in this chapter) is recommended to best reflect local driver behavior.

Capacity for Two-Lane Entries Conflicted by One Circulating Lane

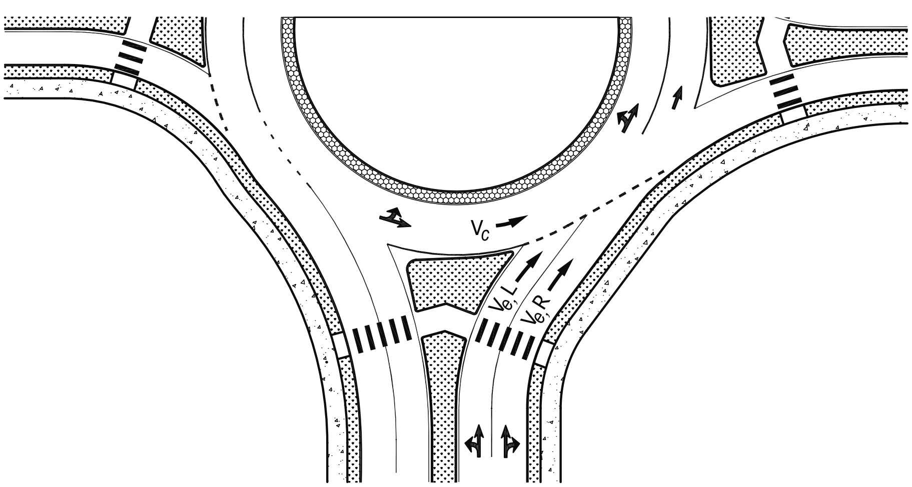
Equation 21-2 gives the capacity of each entry lane conflicted by one circulating lane (illustrated in Exhibit 21-4) as follows:

Equation 21-2

$$c_{e,pce} = 1{,}130e^{(-1.0\times10^{-3})v_{c,pce}}$$

where all variables are as defined previously.

Exhibit 21-4
Example of Two-Lane Entry Conflicted by One Circulating Lane



Capacity for One-Lane Entries Conflicted by Two Circulating Lanes

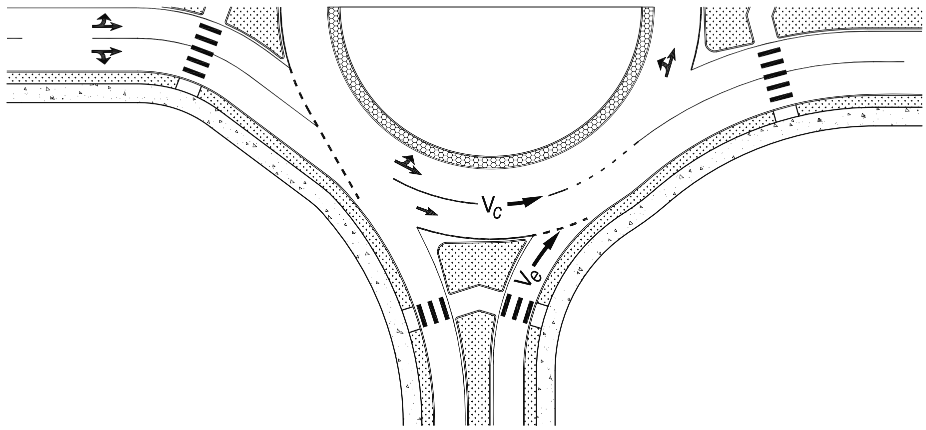
Equation 21-3 gives the capacity of a one-lane roundabout entry conflicted by two circulating lanes (illustrated in Exhibit 21-5) as follows:

Equation 21-3

$$c_{e,pce} = 1{,}130e^{(-0.7\times10^{-3})v_{c,pce}}$$

where all variables are as defined previously ($v_{c,pce}$ is the total of both lanes).

Exhibit 21-5
Example of One-Lane Entry Conflicted by Two Circulating Lanes



Capacity for Two-Lane Entries Conflicted by Two Circulating Lanes

Equation 21-4 and Equation 21-5 give the capacity of the right and left lanes, respectively, of a two-lane roundabout entry conflicted by two circulating lanes (illustrated in Exhibit 21-6):

Equation 21-4

$$c_{e,R,pce} = 1{,}130e^{(-0.7\times10^{-3})v_{c,pce}}$$

Equation 21-5

$$c_{e,L,pce} = 1{,}130e^{(-0.75\times10^{-3})v_{c,pce}}$$

where

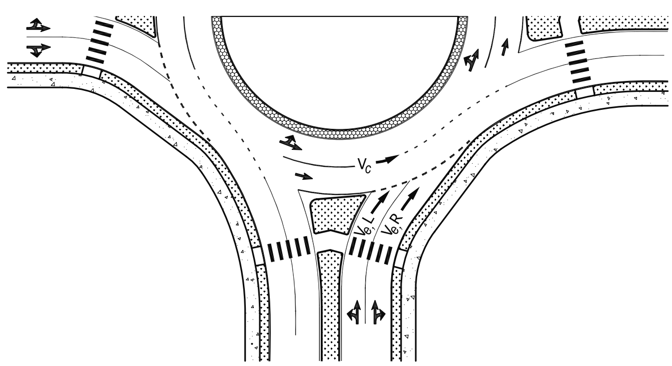
$c_{e,R,pce}$ = capacity of the right entry lane, adjusted for heavy vehicles (pc/h),

$c_{e,L,pce}$ = capacity of the left entry lane, adjusted for heavy vehicles (pc/h), and

$v_{c,pce}$ = conflicting flow rate (total of both lanes) (pc/h).

The capacity of the left lane of a roundabout approach is lower than the capacity of the right lane.

Exhibit 21-6
Example of Two-Lane Entry Conflicted by Two Circulating Lanes

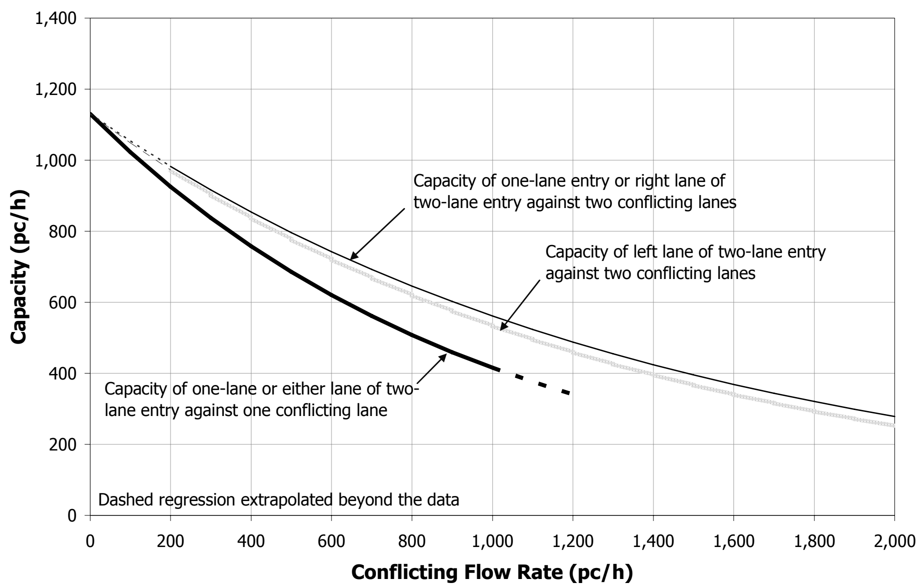


Field data (*1*) have found that drivers in the left lane have longer critical headways than drivers in the right lane. As a result, the capacity of the left lane is lower. Note that this research was able to observe sustained-queue conditions for only the right lane; Equation 21-4 represents a regression best fit that is also consistent with observed critical headways. The left-lane capacity given in Equation 21-5 is based on observed critical headways under both queued and nonqueued conditions.

The calculated capacities for each lane in passenger car equivalents per hour will be adjusted back to vehicles per hour, as described later in this section.

Exhibit 21-7 presents a plot showing Equation 21-1, Equation 21-4, and Equation 21-5. The dashed lines represent portions of the curves that lie outside the range of observed field data.

Exhibit 21-7
Capacity of Single-Lane and Multilane Entries



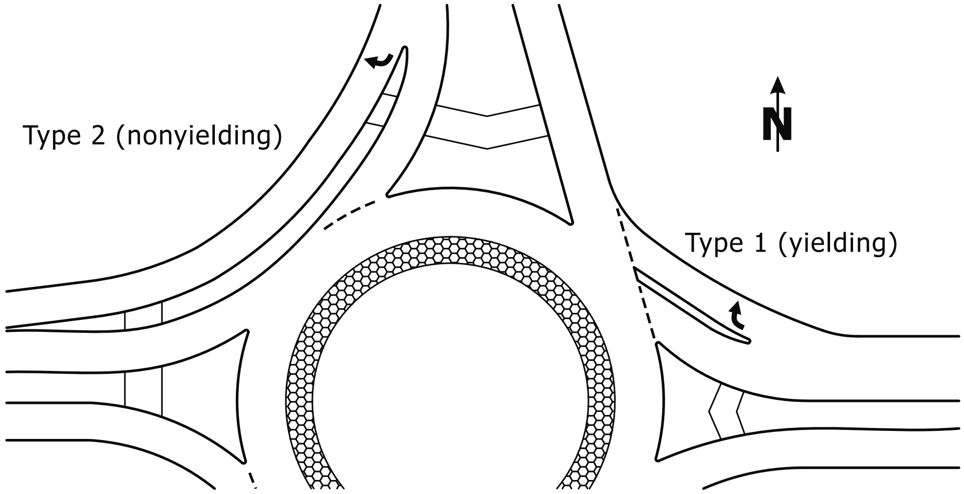
Right-Turn Bypass Lanes

Two common types of right-turn bypass lanes are used at both single-lane and multilane roundabouts. These are illustrated in Exhibit 21-8.

The bypass lane capacity procedure does not include the effect of drivers yielding to pedestrians.

The following sections describe each type of bypass lane. Note that in the United States, drivers in both types of bypass lane would generally be required to yield to pedestrians crossing the bypass lane. The capacity effect of drivers yielding to pedestrians has not been included in this analysis procedure.

Exhibit 21-8
Right-Turn Bypass Lanes



Type 1 (Yielding Bypass Lane)

A Type 1 bypass lane terminates at a high angle, with right-turning traffic yielding to exiting traffic. Right-turn bypass lanes were not explicitly included in the recent national research. However, the capacity of a yield bypass lane may be approximated by using one of the capacity formulas given previously by treating the exiting flow from the roundabout as the circulatory flow and treating the flow in the right-turn bypass lane as the entry flow.

The capacity for a bypass lane opposed by one exiting lane can be approximated by using Equation 21-6:

Equation 21-6

$$c_{\text{bypass},pce} = 1{,}130e^{\left(-1.0\times10^{-3}\right)v_{ex,pce}}$$

The capacity for a bypass lane opposed by two exiting lanes can be approximated by using Equation 21-7:

Equation 21-7

$$c_{\text{bypass},pce} = 1{,}130e^{\left(-0.7\times10^{-3}\right)v_{ex,pce}}$$

where

$c_{\text{bypass},pce}$ = capacity of the bypass lane, adjusted for heavy vehicles (pc/h); and

$v_{ex,pce}$ = conflicting exiting flow rate (pc/h).

Type 2 (Nonyielding Bypass Lane)

A Type 2 bypass lane merges at a low angle with exiting traffic or forms a new lane adjacent to exiting traffic. The capacity of a merging bypass lane has not been assessed in the United States. Its capacity is expected to be relatively high due to a merging operation between two traffic streams at similar speeds.

Exit Capacity

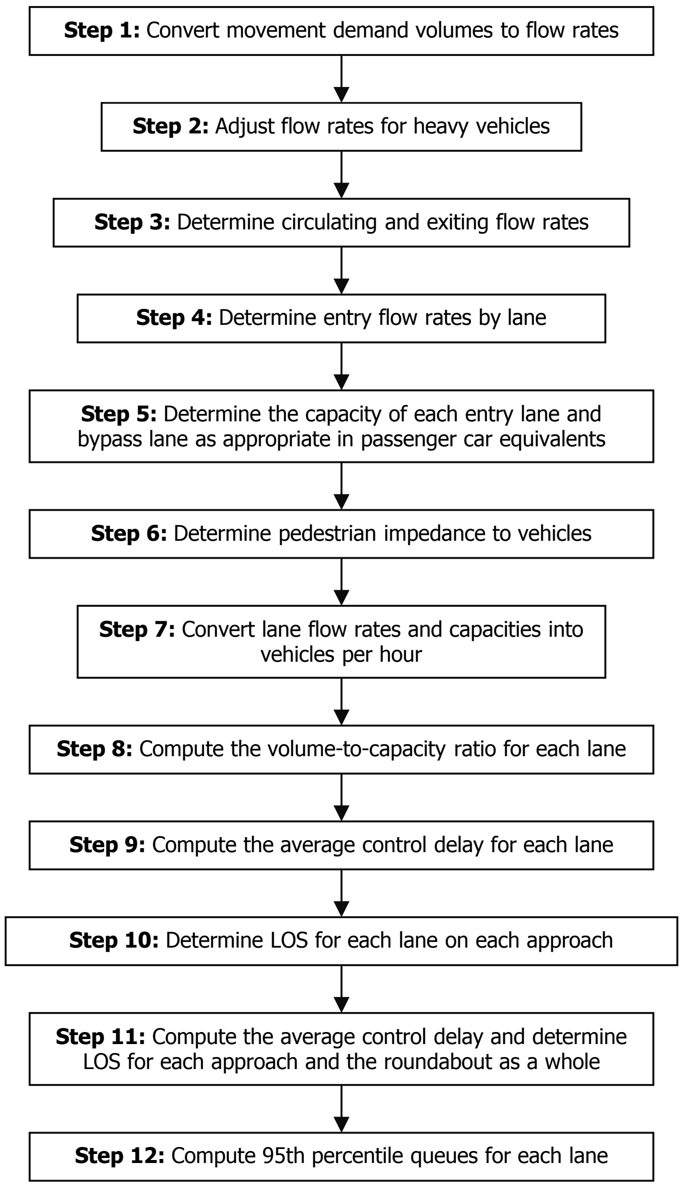
German research (*6*) has suggested that the capacity of an exit lane, accounting for pedestrian and bicycle traffic in a typical urban area, is in the range of 1,200 to 1,300 vehicles per hour (veh/h). A Federal Highway Administration document used this information to provide guidance that exit flows exceeding 1,200 veh/h may indicate the need for a double-lane exit (*2*).

However, the analyst is cautioned to also evaluate exit lane requirements on the basis of vehicular lane numbers and arrangements. For example, a double-lane exit might be required to receive two through lanes in order to provide basic lane continuity along a corridor, regardless of the volume at the exit. Further guidance can be found elsewhere (*2*).

AUTOMOBILE MODE

The capacity of a given approach is computed by using the process illustrated in Exhibit 21-9.

Exhibit 21-9
Roundabout Analysis Methodology



Step 1: Convert Movement Demand Volumes to Flow Rates

For an analysis of existing conditions in which the peak 15-min period can be measured in the field, the volumes for the peak 15-min period are converted to a peak 15-min demand flow rate by multiplying the peak 15-min volumes by 4.

For analysis of projected conditions or when 15-min data are not available, hourly demand volumes for each movement are converted to peak 15-min demand flow rates in vehicles per hour, as shown in Equation 21-8, through the use of a peak hour factor for the intersection:

Equation 21-8

$$v_i = \frac{V_i}{PHF}$$

where

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

V_i = demand volume for movement i (veh/h), and

PHF = peak hour factor.

Step 2: Adjust Flow Rates for Heavy Vehicles

The flow rate for each movement may be adjusted to account for vehicle stream characteristics by using factors given in Exhibit 21-10.

Exhibit 21-10
Passenger Car Equivalencies

Vehicle Type	Passenger Car Equivalent, E_T
Passenger car	1.0
Heavy vehicle	2.0

The calculation to incorporate these values is given in Equation 21-9 and Equation 21-10:

Equation 21-9

$$v_{i,pce} = \frac{v_i}{f_{HV}}$$

Equation 21-10

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1)}$$

where

$v_{i,pce}$ = demand flow rate for movement i (pc/h),

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

f_{HV} = heavy-vehicle adjustment factor,

P_T = proportion of demand volume that consists of heavy vehicles, and

E_T = passenger car equivalent for heavy vehicles.

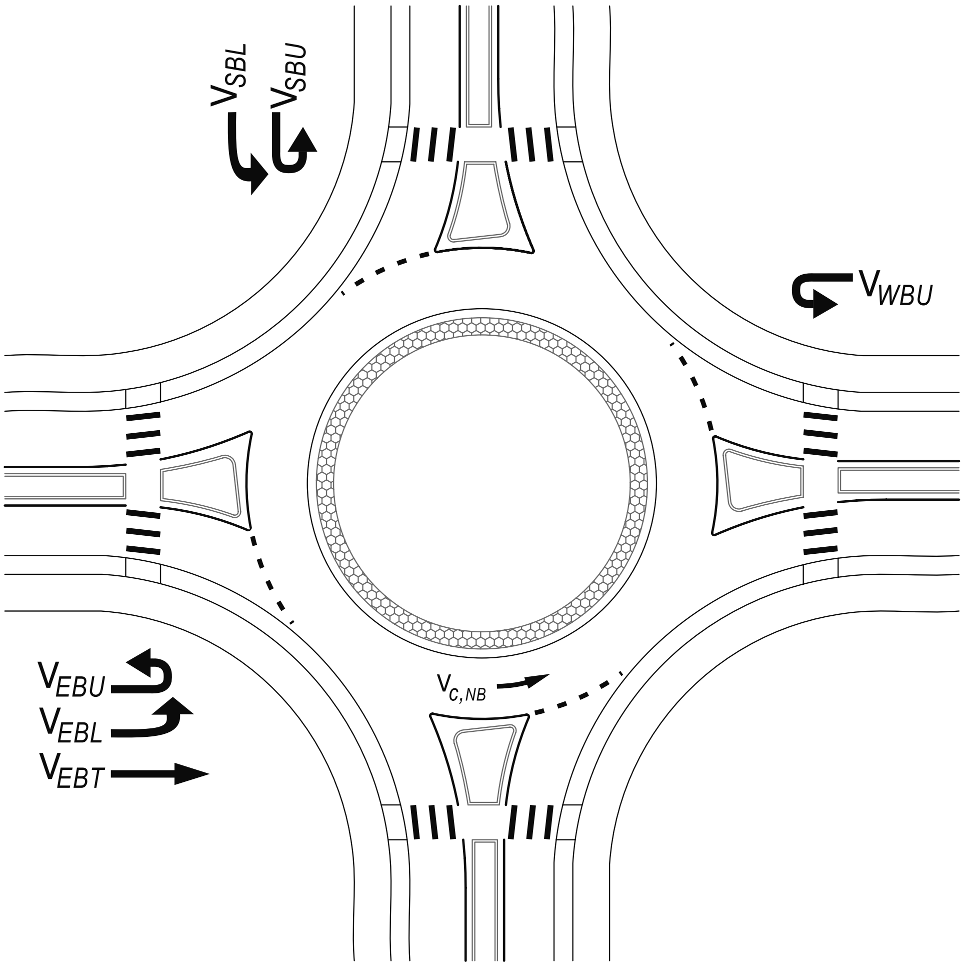
Step 3: Determine Circulating and Exiting Flow Rates

Circulating and exiting flow rates are calculated for each roundabout leg. Although the following sections present a numerical methodology for a four-leg roundabout, this methodology can be extended to any number of legs.

Circulating Flow Rate

The circulating flow opposing a given entry is defined as the flow conflicting with the entry flow (i.e., the flow passing in front of the splitter island next to the subject entry). The circulating flow rate calculation for the northbound circulating flow rate is illustrated in Exhibit 21-11 and numerically in Equation 21-11. All flows are in passenger car equivalents.

Exhibit 21-11
Calculation of Circulating Flow



Equation 21-11

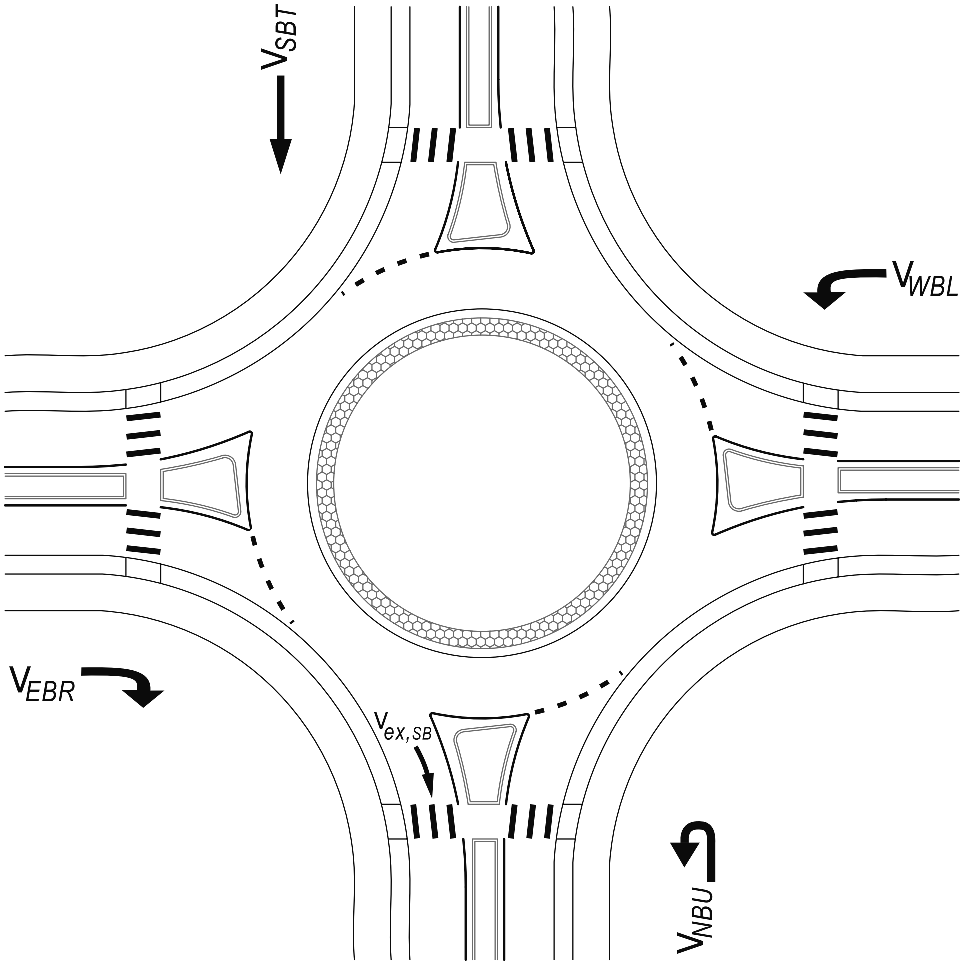
$$v_{c,NB,pce} = v_{WBU,pce} + v_{SBL,pce} + v_{SBU,pce} + v_{EBT,pce} + v_{EBL,pce} + v_{EBU,pce}$$

Exiting Flow Rate

If a bypass lane is present on the immediate upstream entry, the right-turning flow using the bypass lane is deducted from the exiting flow.

The exiting flow rate for a given leg is used primarily in the calculation of conflicting flow for right-turn bypass lanes. The exiting flow calculation for the southbound exit is illustrated in Exhibit 21-12 and numerically in Equation 21-12. If a bypass lane is present on the immediate upstream entry, the right-turning flow using the bypass lane is deducted from the exiting flow. All flows are in passenger car equivalents.

Exhibit 21-12
Calculation of Exiting Flow



Equation 21-12

$$v_{ex,pce} = v_{NBU,pce} + v_{WBL,pce} + v_{SBT,pce} + v_{EBR,pce} - v_{EBR,pce,bypass}$$

Step 4: Determine Entry Flow Rates by Lane

For single-lane entries, the entry flow rate is the sum of all movement flow rates using that entry. For multilane entries or entries with bypass lanes, or both, the following procedure may be used to assign flows to each lane:

1. If a right-turn bypass lane is provided, the flow using the bypass lane is removed from the calculation of the roundabout entry flows.
2. If only one lane is available for a given movement, the flow for that movement is assigned only to that lane.
3. The remaining flows are assumed to be distributed across all lanes, subject to the constraints imposed by any designated or de facto lane assignments and any observed or estimated lane utilization imbalances.

A de facto lane is one designated for multiple movements but that may operate as an exclusive lane due to a dominant movement demand. A common example is a left–through lane with a left-turn flow rate that greatly exceeds the through flow rate.

Five generalized multilane cases may be analyzed with this procedure. For cases in which a movement may use more than one lane, a check should first be made to determine what the assumed lane configuration may be. This may differ from the designated lane assignment based on the specific turning movement patterns being analyzed. These assumed lane assignments are given in Exhibit

21-13. For intersections with a different number of legs, the analyst should exercise reasonable judgment in assigning volumes to each lane.

Exhibit 21-13
Assumed (de facto) Lane Assignments

Designated Lane Assignment	Assumed Lane Assignment
LT, TR	If $v_U + v_L > v_T + v_{R,e}$: L, TR (de facto left-turn lane) If $v_{R,e} > v_U + v_L + v_T$: LT, R (de facto right-turn lane) Else LT, TR
L, LTR	If $v_T + v_{R,e} > v_U + v_L$: L, TR (de facto through–right lane) Else L, LTR
LTR, R	If $v_U + v_L + v_T > v_{R,e}$: LT, R (de facto left–through lane) Else LTR, R

Notes: v_U, v_L, v_T, and $v_{R,e}$ are the U-turn, left-turn, through, and nonbypass right-turn flow rates using a given entry, respectively.
L = left, LT = left–through, TR = through–right, LTR = left–through–right, and R = right.

On the basis of the assumed lane assignment for the entry and the lane utilization effect described above, flow rates can be assigned to each lane by using the formulas given in Exhibit 21-14. In this exhibit, $\%RL$ is the percentage of entry traffic using the right lane, $\%LL$ is the percentage of entry traffic using the left lane, and $\%LL + \%RL = 1$.

Exhibit 21-14
Volume Assignments for Two-Lane Entries

Case	Assumed Lane Assignment	Left Lane	Right Lane
1	L, TR	$v_U + v_L$	$v_T + v_{R,e}$
2	LT, R	$v_U + v_L + v_T$	$v_{R,e}$
3	LT, TR	$(\%LL)v_e$	$(\%RL)v_e$
4	L, LTR	$(\%LL)v_e$	$(\%RL)v_e$
5	LTR, R	$(\%LL)v_e$	$(\%RL)v_e$

Notes: v_U, v_L, v_T, and $v_{R,e}$ are the U-turn, left-turn, through, and nonbypass right-turn flow rates using a given entry, respectively.
L = left, LT = left–through, TR = through–right, LTR = left–through–right, and R = right.

Further discussion of lane use at multilane roundabouts, including conditions that may create unequal lane use, can be found in Chapter 33, Roundabouts: Supplemental, located in HCM Volume 4.

Step 5: Determine the Capacity of Each Entry Lane and Bypass Lane as Appropriate in Passenger Car Equivalents

The capacity of each entry lane and bypass lane is calculated by using the capacity equations discussed previously. Capacity equations for entry lanes are summarized in Exhibit 21-15; capacity equations for bypass lanes are summarized in Exhibit 21-16.

Exhibit 21-15
Capacity Equations for Entry Lanes

Entering Lanes	Conflicting Circulating Lanes	Capacity Equation
1	1	Equation 21-1
2	1	Each lane: Equation 21-2
1	2	Equation 21-3
2	2	Right lane: Equation 21-4; left lane: Equation 21-5

Exhibit 21-16
Capacity Equations for Bypass Lanes

Conflicting Exiting Lanes	Capacity Equation
1	Equation 21-6
2	Equation 21-7

Step 6: Determine Pedestrian Impedance to Vehicles

Pedestrian traffic can reduce the vehicular capacity of a roundabout entry if sufficient pedestrians are present and they assert the right-of-way typically granted pedestrians in most jurisdictions. Under high vehicular conflicting flows, pedestrians typically pass between queued vehicles on entry and thus have negligible additional impact on vehicular entry capacity. However, under low vehicular conflicting flows, pedestrians can effectively function as additional conflicting vehicles and thus reduce the vehicular capacity of the entry. The effect of pedestrians is more pronounced with increased pedestrian volume.

For one-lane roundabout entries, the model shown in Exhibit 21-17 can be used to approximate this effect (*6*). These equations are illustrated in Exhibit 21-18 and are based on the assumption that pedestrians have absolute priority.

Exhibit 21-17
Model of Entry Capacity Adjustment Factor for Pedestrians Crossing a One-Lane Entry (Assuming Pedestrian Priority)

Case	One-Lane Entry Capacity Adjustment Factor for Pedestrians
If $v_{c,pce} > 881$	$f_{ped} = 1$
Else if $n_{ped} \leq 101$	$f_{ped} = 1 - 0.000137 n_{ped}$
Else	$f_{ped} = \dfrac{1{,}119.5 - 0.715 v_{c,pce} - 0.644 n_{ped} + 0.00073 v_{c,pce} n_{ped}}{1{,}068.6 - 0.654 v_{c,pce}}$

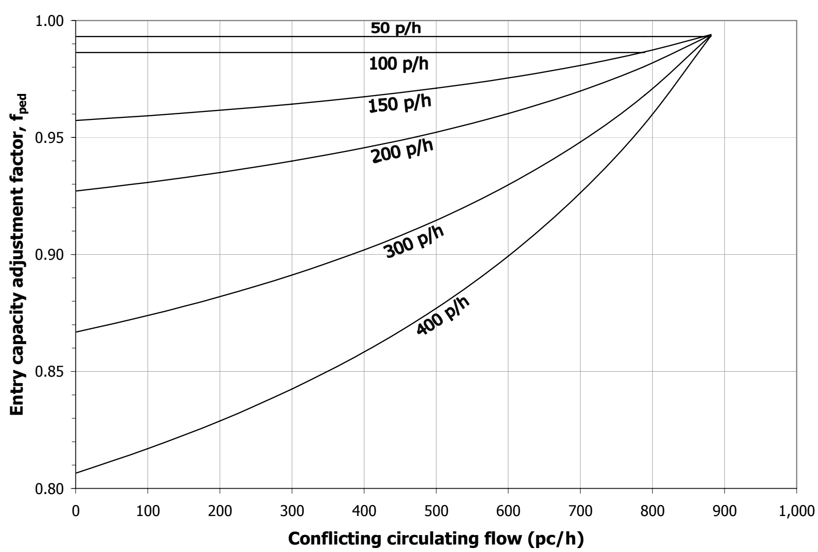
where

f_{ped} = entry capacity adjustment factor for pedestrians,

n_{ped} = number of conflicting pedestrians per hour (p/h), and

$v_{c,pce}$ = conflicting vehicular flow rate in the circulatory roadway, pc/h.

Exhibit 21-18
Illustration of Entry Capacity Adjustment Factor for Pedestrians Crossing a One-Lane Entry (Assuming Pedestrian Priority)



For two-lane entries, the model shown in Exhibit 21-19 can be used to approximate this effect (*6*). These equations are illustrated in Exhibit 21-20 and share the assumption as before that pedestrians have absolute priority.

Exhibit 21-19
Model of Entry Capacity Adjustment Factor for Pedestrians Crossing a Two-Lane Entry (Assuming Pedestrian Priority)

Case	Two-Lane Entry Capacity Adjustment Factor for Pedestrians
If $n_{ped} < 100$	$f_{ped} = \min\left[1 - \frac{n_{ped}}{100}\left(1 - \frac{1{,}260.6 - 0.329 v_{c,pce} - 0.381 \times 100}{1{,}380 - 0.5 v_{c,pce}}\right), 1\right]$
Else	$f_{ped} = \min\left[\frac{1{,}260.6 - 0.329 v_{c,pce} - 0.381 n_{ped}}{1{,}380 - 0.5 v_{c,pce}}, 1\right]$

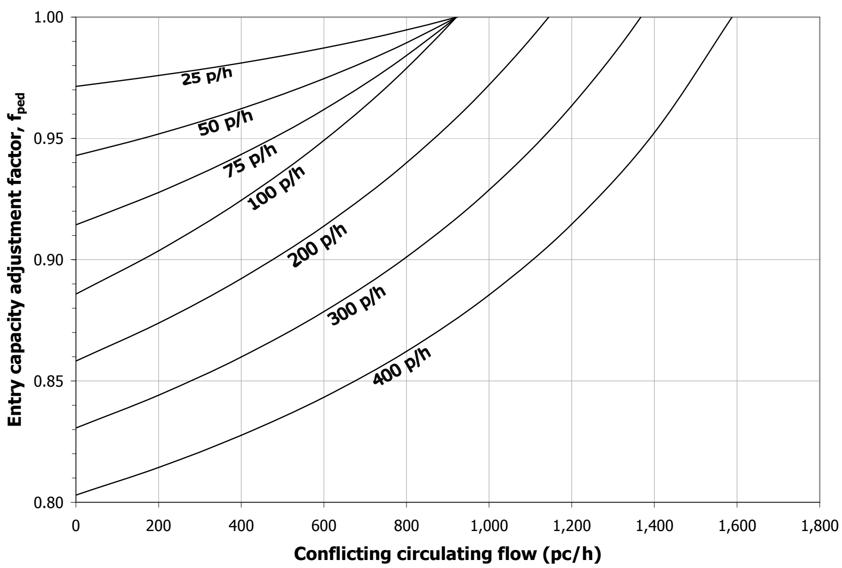
where

f_{ped} = entry capacity adjustment factor for pedestrians,

n_{ped} = number of conflicting pedestrians (p/h), and

$v_{c,pce}$ = conflicting vehicular flow rate in the circulatory roadway (pc/h).

Exhibit 21-20
Illustration of Entry Capacity Adjustment Factor for Pedestrians Crossing a Two-Lane Entry (Assuming Pedestrian Priority)



Step 7: Convert Lane Flow Rates and Capacities into Vehicles per Hour

The flow rate for a given lane is converted back to vehicles per hour by multiplying the passenger-car-equivalent flow rate computed in the previous step by the heavy-vehicle factor for the lane as shown in Equation 21-13:

Equation 21-13

$$v_i = v_{i,PCE} f_{HV,e}$$

where

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

$v_{i,PCE}$ = flow rate for lane *i* (pc/h), and

$f_{HV,e}$ = heavy-vehicle adjustment factor for the lane (see below).

Similarly, the capacity for a given lane is converted back to vehicles per hour as shown in Equation 21-14:

Equation 21-14

$$c_i = c_{i,PCE} f_{HV,e} f_{ped}$$

where

c_i = capacity for lane i (veh/h),

$c_{i,PCE}$ = capacity for lane i (pc/h),

$f_{HV,e}$ = heavy-vehicle adjustment factor for the lane (see below), and

f_{ped} = pedestrian impedance factor.

The heavy-vehicle adjustment factor for each entry lane can be approximated by taking a weighted average of the heavy-vehicle adjustment factors for each movement entering the roundabout (excluding a bypass lane if present) weighted by flow rate, as shown in Equation 21-15:

Equation 21-15

$$f_{HV,e} = \frac{f_{HV,U} v_{U,PCE} + f_{HV,L} v_{L,PCE} + f_{HV,T} v_{T,PCE} + f_{HV,R,e} v_{R,e,PCE}}{v_{U,PCE} + v_{L,PCE} + v_{T,PCE} + v_{R,e,PCE}}$$

where

$f_{HV,e}$ = heavy-vehicle adjustment factor for the entry lane,

$f_{HV,i}$ = heavy-vehicle adjustment factor for movement i, and

$v_{i,PCE}$ = demand flow rate for movement i (pc/h).

If specific lane-use assignment by heavy vehicles is known, heavy-vehicle adjustment factors can be calculated separately for each lane.

Pedestrian impedance is discussed later in this chapter.

Step 8: Compute the Volume-to-Capacity Ratio for Each Lane

For a given lane, the volume-to-capacity ratio x is calculated by dividing the lane's calculated capacity into its demand flow rate, as shown in Equation 21-16. Both input values are in vehicles per hour.

Equation 21-16

$$x_i = \frac{v_i}{c_i}$$

where

x_i = volume-to-capacity ratio of the subject lane i,

v_i = demand flow rate of the subject lane i (veh/h), and

c_i = capacity of the subject lane i (veh/h).

Step 9: Compute the Average Control Delay for Each Lane

Delay data collected for roundabouts in the United States suggest that control delays can be predicted in a manner generally similar to that used for other unsignalized intersections. Equation 21-17 shows the model that should be used to estimate average control delay for each lane of a roundabout approach:

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

Equation 21-17

The third term of this equation uses the calculated volume-to-capacity ratio or 1, whichever is less.

where

d = average control delay (s/veh),

x = volume-to-capacity ratio of the subject lane,

c = capacity of the subject lane (veh/h), and

T = time period (h) (T = 0.25 h for a 15-min analysis).

Equation 21-17 is the same as that for STOP-controlled intersections except that the "+ 5" term has been modified. This modification is necessary to account for the YIELD control on the subject entry, which does not require drivers to come to a complete stop when there is no conflicting traffic. At higher volume-to-capacity ratios, the likelihood of coming to a complete stop increases, thus causing behavior to resemble STOP control more closely.

Average control delay for a given lane is a function of the lane's capacity and degree of saturation. The analytical model used above to estimate average control delay assumes that there is no residual queue at the start of the analysis period. If the degree of saturation is greater than about 0.9, average control delay is significantly affected by the length of the analysis period. In most cases, the recommended analysis period is 15 min. If demand exceeds capacity during a 15-min period, the delay results calculated by the procedure may not be accurate due to the likely presence of a queue at the start of the time period. In addition, the conflicting demand for movements downstream of the movement operating over capacity may not be fully realized (in other words, the flow cannot get past the oversaturated entry and thus cannot conflict with a downstream entry). In these cases, an iterative approach that accounts for this effect and the carryover of queues from one time period to the next may be considered, as discussed elsewhere (*7*).

Step 10: Determine LOS for Each Lane on Each Approach

The LOS for each lane on each approach is determined by using Exhibit 21-1 and the computed or measured values of control delay.

Step 11: Compute the Average Control Delay and Determine LOS for Each Approach and the Roundabout as a Whole

The control delay for an approach is calculated by computing a weighted average of the delay for each lane on the approach, weighted by the volume in each lane. The calculation is shown in Equation 21-18. Note that the volume in the bypass lane should be included in the delay calculation for the approach. The LOS for each approach is determined by using Exhibit 21-1 and the computed or measured values of control delay.

Equation 21-18

$$d_{\text{approach}} = \frac{d_{LL}v_{LL} + d_{RL}v_{RL} + d_{\text{bypass}}v_{\text{bypass}}}{v_{LL} + v_{RL} + v_{\text{bypass}}}$$

The control delay for the intersection as a whole is similarly calculated by computing a weighted average of the delay for each approach, weighted by the volume on each approach. This is shown in Equation 21-19. The LOS for the intersection is determined by using Exhibit 21-1 and the computed or measured values of control delay.

Equation 21-19

$$d_{\text{intersection}} = \frac{\sum d_i v_i}{\sum v_i}$$

where

$d_{\text{intersection}}$ = control delay for the entire intersection (s/veh),

d_i = control delay for approach i (s/veh), and

v_i = flow rate for approach i (veh/h).

Step 12: Compute 95th Percentile Queues for Each Lane

The 95th percentile queue for a given lane on an approach is calculated by using Equation 21-20:

Equation 21-20

$$Q_{95} = 900T\left[x - 1 + \sqrt{(1-x)^2 + \frac{\left(\frac{3{,}600}{c}\right)x}{150T}}\right]\left(\frac{c}{3{,}600}\right)$$

where

Q_{95} = 95th percentile queue (veh),

x = volume-to-capacity ratio of the subject lane,

c = capacity of the subject lane (veh/h), and

T = time period (h) ($T = 1$ for a 1-h analysis, $T = 0.25$ for a 15-min analysis).

The queue length calculated for each lane should be checked against the available storage. The queue in each lane may interact with adjacent lanes in one or more ways:

- If queues in adjacent lanes exceed the available storage, the queue in the subject lane may be longer than anticipated due to additional queuing from the adjacent lane.
- If queues in the subject lane exceed the available storage for adjacent lanes, the adjacent lane may be starved by the queue in the subject lane.

Should one or more of these conditions occur, a sensitivity analysis can be conducted with the methodology by varying the demand in each lane. The analyst may also use an alternative tool that is sensitive to lane-by-lane effects, as discussed in this chapter's Applications section.

PEDESTRIAN MODE

Limited research has been performed to date in the United States on the operational impacts of vehicular traffic on pedestrians at roundabouts. In the United States, pedestrians have the right-of-way either after entering a crosswalk or as they are about to enter the crosswalk, depending on specific state law. This is somewhat different from other countries that may establish absolute pedestrian right-of-way in some situations (typically urban) and absolute vehicular right-of-way in others (typically rural).

Much of the recent research focus on pedestrians in the United States has been in the area of assessing accessibility for pedestrians with vision disabilities. Research has found that some roundabouts present a challenge for blind and visually impaired pedestrians relative to sighted pedestrians, thus potentially bringing them out of compliance with the Americans with Disabilities Act (*8*). A variety of treatments has been or is being considered to improve roundabouts' accessibility to this group of pedestrians, including various types of signalization of pedestrian crossings. The analysis of these treatments can in some cases be performed by simple analytical methods presented in the HCM (e.g., the analysis procedure for the pedestrian mode in Chapter 19). However, in many cases, alternative tools will produce more accurate results. These are discussed later in this chapter.

Techniques to analyze the operational performance of pedestrians as provided in Chapter 19, Two-Way STOP-Controlled Intersections, can be applied with care at roundabouts. As noted in that chapter, vehicular yielding rates vary depending on crossing treatment, number of lanes, posted speed limit, and within individual sites (*9*). This makes modeling of pedestrian interactions imprecise. As a result, models to analyze vehicular effects on pedestrian travel should be applied with caution.

BICYCLE MODE

Use a passenger-car-equivalent factor of 0.5 for bicycles when treating them as motor vehicles.

As of the publication date of this edition of the HCM, no methodology specific to bicyclists has been developed to assess the performance of bicyclists at roundabouts, as few data are available in the United States to support model calibration. Depending on individual comfort level, ability, geometric conditions, and traffic conditions, bicyclists may either circulate as a motor vehicle or as a pedestrian. If bicyclists are circulating as motor vehicles, their effect can be approximated by combining bicyclist flow rates with other vehicles by using a passenger-car-equivalent factor of 0.5 (*2*). If bicyclists are circulating as pedestrians, their effect can be analyzed by using the methodology described previously for pedestrians. Further guidance on accommodating bicyclists at roundabouts can be found elsewhere (*2*).

3. APPLICATIONS

DEFAULT VALUES

No default values have been developed specifically for roundabouts. However, a comprehensive presentation of potential default values for interrupted-flow facilities is available (*10*), with specific recommendations summarized in its Chapter 3, Recommended Default Values. These defaults cover the key characteristics of peak hour factor and percent heavy vehicles. Recommendations are based on geographical region, population, and time of day. All general default values for interrupted-flow facilities may be applied to the analysis of roundabouts in the absence of field data or projections of conditions.

Demand volumes as well as the number and configuration of lanes at a roundabout are site-specific and thus do not lend themselves to default values. The following default values may be applied to a roundabout analysis:

- Peak hour factor = 0.92, and
- Percent heavy vehicles = 3%.

Default values for lane utilization on two-lane roundabout approaches are not provided in the above reference (*10*). In these cases, in the absence of field data, the effect of lane utilization imbalance can be approximated by using the assumed values given in Exhibit 21-21.

Exhibit 21-21
Assumed Default Values for Lane Utilization for Two-Lane Approaches

Lane Configuration	% Traffic in Left Lane[a]	% Traffic in Right Lane[a]
Left–through + through–right	0.47	0.53
Left–through–right + right	0.47	0.53
Left + left–through–right	0.53	0.47

Notes: [a] These values are generally consistent with observed values for through movements at signalized intersections. These values should be applied with care, particularly under conditions estimated to be near capacity.

Obviously, as the number of default values used in any analysis increases, the analysis result becomes more approximate and may be significantly different from the actual outcome, depending on local conditions.

TYPES OF ANALYSIS

The methodology of this chapter can be used in three types of analysis: operational analysis, design analysis, and planning and preliminary engineering analysis.

Operational Analysis

Operational analysis takes traffic flow data and geometric configurations as input to determine operational performance.

The methodology is most easily applied in the operational analysis mode. In operational analysis, all traffic and geometric characteristics of the analysis segment must be specified, including analysis-hour demand volumes for each turning movement (in vehicles per hour), heavy-vehicle percentages for each approach, peak hour factor for all hourly demand volumes (if not provided as 15-min volumes), and lane configuration. The outputs of an operational analysis will be estimates of capacity and control delay. The steps of the methodology, described in the Methodology section, are followed directly without modification.

Design Analysis

Design analysis is used to determine the geometric configuration of a roundabout to produce a desired operational performance.

The operational analysis methodology described earlier in this chapter can be used for design purposes by using a given set of traffic flow data to determine iteratively the number and configuration of lanes that would be required to produce a given LOS.

Planning and Preliminary Engineering Analysis

Planning and preliminary engineering analysis is used to evaluate future conditions for which assumptions and estimates must be made.

The operational analysis method described earlier in this chapter provides a detailed procedure for evaluating the performance of a roundabout. To estimate LOS for a future time horizon, a planning analysis based on the operational method is used. The planning method uses all the geometric and traffic flow data required for an operational analysis, and the computations are identical. However, input variables for percent heavy vehicles and peak hour factor are typically estimated (or defaults used) when planning applications are performed.

CALIBRATION OF CAPACITY MODEL

The capacity models presented previously can be generalized by using the expressions in Equation 21-21 through Equation 21-23 as follows:

Equation 21-21

$$c_{pce} = Ae^{(-B\,v_c)}$$

Equation 21-22

$$A = \frac{3{,}600}{t_f}$$

Equation 21-23

$$B = \frac{t_c - (t_f / 2)}{3{,}600}$$

where

Field measures of critical headway and follow-up headway can be used to calibrate the capacity models.

c_{pce} = lane capacity, adjusted for heavy vehicles (pc/h),

v_c = conflicting flow (pc/h),

t_c = critical headway (s), and

t_f = follow-up headway (s).

Therefore, the capacity model can be calibrated by using two parameters: the critical headway t_c and the follow-up headway t_f. An example illustrating this procedure is provided in Chapter 33, Roundabouts: Supplemental.

USE OF ALTERNATIVE TOOLS

General guidance for the use of alternative traffic analysis tools for capacity and LOS analysis is provided in Chapter 6, HCM and Alternative Analysis Tools, and Chapter 7, Interpreting HCM and Alternative Tool Results. This section contains specific guidance for the application of alternative tools to the analysis of roundabouts. The reader should also be familiar with the information and guidance on the design and evaluation of roundabouts (*2*, *3*).

Two modeling approaches are used in the types of alternative tools commonly applied:

- *Deterministic intersection models.* These models represent vehicle flows as flow rates and are sensitive to various flow and geometric features of the roundabout, including lane numbers and arrangements or specific geometric dimensions (e.g., entry width, inscribed circle diameter), or both. The majority of these models are anchored to research conducted outside the United States (e.g., *11–14)*. Some software implementations may include more than one model or employ extensions beyond the original fundamental research conducted within a particular country. Some deterministic models can model an entire network of intersections but generally assume no interaction effects between intersections, thus potentially limiting their application.
- *Stochastic network models.* These models represent vehicle flows by simulating individual vehicles and their car-following, lane-choice, and gap-acceptance decisions. The models are based on a variety of fundamental research studies on driver behavior (e.g., *15*, *16*). By their nature, most stochastic models used for roundabouts can model an entire network of intersections, thus making them capable of modeling a broader range of problems. However, their data requirements are typically more intensive than for the deterministic intersection models. Most stochastic models are implemented in microsimulation tools.

Strengths of the HCM Procedure

The procedures in this chapter were based on extensive research supported by a significant quantity of field data. They have evolved over several years and represent a body of expert consensus. They produce unique deterministic results for a given set of inputs, and the capacity of each approach is an explicit part of the results. Alternative tools based on deterministic intersection models also produce a unique set of results, including capacities, for a given set of inputs, while those based on simulation may produce different results based on different random number sequences. Unique results from an analysis tool are important for some purposes such as development impact review.

Limitations of the HCM Procedures That Might Be Addressed by Alternative Tools

The procedures presented in this chapter cover many of the typical situations that a user may encounter in practice. However, there are sometimes applications for which alternative tools can produce a more accurate analysis. The following limitations, stated earlier in this chapter, may be addressed by using available simulation tools. The conditions beyond the scope of this chapter that are treated explicitly by alternative tools include

- Adjacent signals or roundabouts,
- Priority reversal under extremely high flows,
- High pedestrian or bicycle activity levels,
- More than two entry lanes on an approach, or

- Flared entry lanes.

A few of the more common applications of alternative tools to overcome the limitations of the procedures presented in this chapter will now be discussed.

Interaction Effects with Other Traffic Control Devices

Several common situations can be modeled with alternative tools:

- *Pedestrian signals or hybrid beacons at roundabout crosswalks.* These devices, described in detail in the *Manual on Uniform Traffic Control Devices for Streets and Highways* (*17*), can be used in a variety of applications, including the following:
    - High vehicle flows in which naturally occurring gaps in vehicle traffic or vehicular yielding for pedestrians is insufficient;
    - High pedestrian flows in which unrestricted pedestrian crossing activity may create insufficient capacity for motor vehicles; and
    - Crossing situations in which pedestrians with vision or other impairments may not receive equivalent access to the crossing. This is a legal requirement in the United States under the Americans with Disabilities Act and is regulated by the U.S. Access Board (*8*).
- *Metering signals on roundabout approaches.* These signals are sometimes used in applications in which a dominant entering flow reduces downstream entry capacity to zero or nearly zero. A metering signal can create gaps in the dominant flow at regular intervals or as dictated by queuing at the downstream entry.
- *Signals used to give priority to other users.* These applications include at-grade rail crossings, emergency vehicle signals, and others.
- *Nearby intersections or traffic control devices at which queues or lane use effects interact.* These nearby intersections can have any type of control, including signalization, STOP control, or YIELD control (as at another roundabout). Applications could also include nonintersection treatments such as freeway ramp meters.

While some deterministic intersection tools can model these situations, they are often treated more satisfactorily by using stochastic network models.

Flared Entries or Short-Lane Applications

Flared entries or short-lane applications are sometimes used at roundabouts to add capacity at the entry without substantially widening the approach upstream of the entry. Common applications include flaring from one lane to two lanes at the entry or from two lanes to three lanes, although some international research has found capacity sensitivity to flaring in sub-lane-width increments (*13*).

The methodology presented in this chapter provides a mechanism for flagging conditions under which queues for a given lane may exceed available storage or block access to adjacent lanes. Alternative tools may provide more accurate modeling of these situations.

Three-Lane Roundabouts

Three-lane roundabouts are not included in the methodology described in this chapter but can be analyzed by a number of alternative tools. Note that no data for three-lane roundabouts are available in the source material (*1*) for this chapter's methodology, so the analyst should use care in estimating calibration parameters.

Adjustment of Simulation Parameters to the HCM Results

Calibration of any model used to analyze roundabouts is essential in producing realistic results that are consistent with field data. Ideally, field data should be used for calibration. For situations involving the assessment of hypothetical or proposed alternatives for which no field data exist, alternative tool results may be made more compatible with HCM results by adjusting alternative tool parameters to obtain a better match with the results obtained from the HCM procedures as follows:

- *Deterministic intersection models.* Typical calibration parameters for deterministic models include global adjustment factors that shift or shape the capacity model used by the model. These include adjustments to the intercept and slope of linear models or other shaping parameters of more complex analytical forms.
- *Stochastic network models.* Calibration of stochastic models is more challenging than for deterministic models because some calibration factors, such as factors related to driver aggressiveness, often apply globally to all elements of the network and not just to roundabouts. In other cases, the specific coding of the model can be fine-tuned to reflect localized driver behavior, including look-ahead points for gap acceptance and locations for discretionary and mandatory lane changes.

Step-by-Step Recommendations for Applying Alternative Tools

The following steps should be taken in applying an alternative tool in the analysis of roundabouts:

1. Identify the limitations of the HCM procedures that dictate the use of alternative tools.
2. Decide between a microscopic and a macroscopic modeling approach.
3. If possible, develop a simpler configuration that can be analyzed by the HCM procedures. Analyze the simple configuration by using both the HCM and the selected alternative tool. Make adjustments to the alternative tool parameters to obtain a better match with the HCM results.
4. Perform the analysis of the full configuration by using the alternative tool.
5. Interpret and present the results.

Sample Calculations Illustrating Alternative Tool Applications

Chapter 29, Urban Street Facilities: Supplemental, includes an example of the application of a simulation tool to assess the effect of using a roundabout within a coordinated arterial signal system. The interactions between the roundabout and the arterial system are examined by using signal timing plans with different progression characteristics.

4. EXAMPLE PROBLEMS

Exhibit 21-22
List of Example Problems

Example Problem	Description	Application
1	Single-lane roundabout with bypass lanes	Operational analysis
2	Multilane roundabout	Operational analysis

EXAMPLE PROBLEM 1: SINGLE-LANE ROUNDABOUT WITH BYPASS LANES

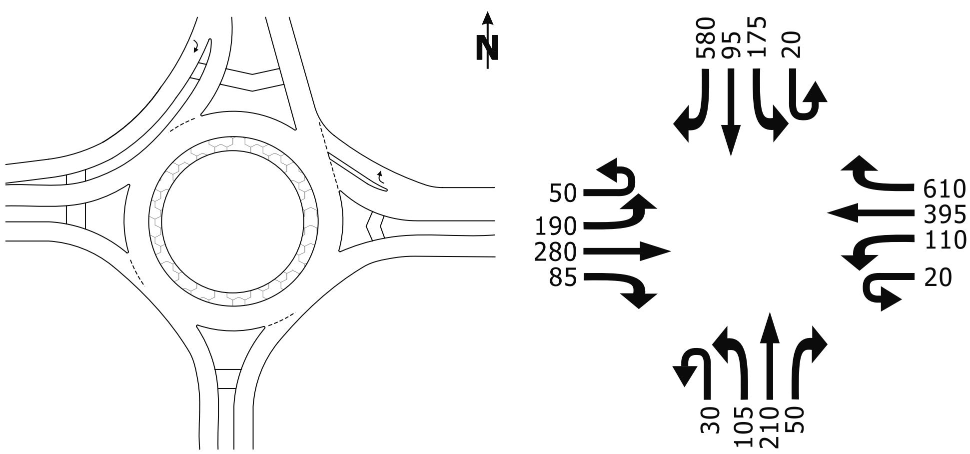
This is an example of an operational analysis. It uses traffic data and geometric characteristics to determine capacities, control delay, and LOS.

The Facts

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

- Four legs,
- One-lane entries on each leg,
- A westbound right-turn bypass lane that yields to exiting vehicles,
- A southbound right-turn bypass lane that forms its own lane adjacent to exiting vehicles,
- Percent heavy vehicles for all movements = 2%,
- Peak hour factor = 0.94,
- Demand volumes and lane configurations as shown in Exhibit 21-23, and
- 50 p/h across the south leg and negligible pedestrian activity across the other three legs.

Exhibit 21-23
Demand Volumes and Lane Configurations for Example Problem 1



Comments

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

Step 1: Convert Movement Demand Volumes to Flow Rates

Each turning-movement volume given in the problem is converted to a demand flow rate by dividing by the peak hour factor. As an example, the northbound left-turn volume is converted to a flow rate as follows:

$$v_{NBL} = \frac{V_{NBL}}{PHF} = \frac{105}{0.94} = 112 \text{ pc/h}$$

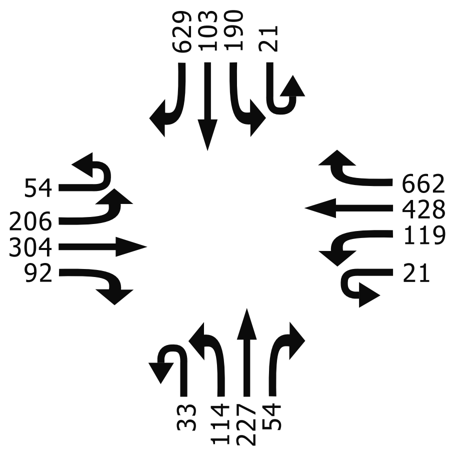
Step 2: Adjust Flow Rates for Heavy Vehicles

The flow rate for each movement may be adjusted to account for vehicle stream characteristics as follows (northbound left turn illustrated):

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1)} = \frac{1}{1 + 0.02(2-1)} = 0.980$$

$$v_{NBL,pce} = \frac{v_{NBL}}{f_{HV}} = \frac{112}{0.980} = 114 \text{ pc/h}$$

The resulting adjusted flow rates for all movements accounting for Steps 1 and 2 are therefore computed as follows:



Step 3: Determine Circulating and Exiting Flow Rates

The circulating and exiting flows are calculated for each leg. For the south leg (northbound entry), the circulating flow is calculated as follows:

$$v_{c,NB,pce} = v_{WBU,pce} + v_{SBL,pce} + v_{SBU,pce} + v_{EBT,pce} + v_{EBL,pce} + v_{EBU,pce}$$

$$v_{c,NB,pce} = 21 + 190 + 21 + 304 + 206 + 54 = 796 \text{ pc/h}$$

Similarly, $v_{c,SB,pce} = 769$ pc/h, $v_{c,EB,pce} = 487$ pc/h, and $v_{c,WB,pce} = 655$ pc/h.

For this problem, one exit flow rate is needed: the northbound exit flow rate, which serves as the conflicting flow for the westbound bypass lane. Because all westbound right turns are assumed to use the bypass lane, they are excluded from the conflicting exit flow as follows:

$$v_{ex,pce,NB} = v_{SBU,pce} + v_{EBL,pce} + v_{NBT,pce} + v_{WBR,e,pce}$$

$$v_{ex,pce,NB} = 21 + 206 + 227 + 0 = 454 \text{ pc/h}$$

Step 4: Determine Entry Flow Rates by Lane

The entry flow rate is calculated by summing the movement flow rates that enter the roundabout (without using a bypass lane). Because this is a single-lane roundabout, no lane-use calculations are needed.

The entry flow rates are calculated as follows, assuming that all right-turn volumes on the westbound and southbound approaches use the bypass lane provided and not the entry:

$$v_{e,NB,pce} = v_{NBU,pce} + v_{NBL,pce} + v_{NBT,pce} + v_{NBR,e,pce} = 33 + 114 + 227 + 54 = 428 \text{ pc/h}$$

$$v_{e,SB,pce} = v_{SBU,pce} + v_{SBL,pce} + v_{SBT,pce} + v_{SBR,e,pce} = 21 + 190 + 103 + 0 = 314 \text{ pc/h}$$

$$v_{e,EB,pce} = v_{EBU,pce} + v_{EBL,pce} + v_{EBT,pce} + v_{EBR,e,pce} = 54 + 206 + 304 + 92 = 656 \text{ pc/h}$$

$$v_{e,WB,pce} = v_{WBU,pce} + v_{WBL,pce} + v_{WBT,pce} + v_{WBR,e,pce} = 21 + 119 + 428 + 0 = 568 \text{ pc/h}$$

Step 5: Determine the Capacity of Each Entry Lane and Bypass Lane as Appropriate in Passenger Car Equivalents

By using the single-lane capacity equation (Equation 21-1), the capacity for each entry lane is given as follows:

$$c_{pce,NB} = 1{,}130e^{(-1.0\times10^{-3})v_{c,pce,NB}} = 1{,}130e^{(-1.0\times10^{-3})(796)} = 510 \text{ pc/h}$$

$$c_{pce,SB} = 1{,}130e^{(-1.0\times10^{-3})v_{c,pce,SB}} = 1{,}130e^{(-1.0\times10^{-3})(769)} = 524 \text{ pc/h}$$

$$c_{pce,EB} = 1{,}130e^{(-1.0\times10^{-3})v_{c,pce,EB}} = 1{,}130e^{(-1.0\times10^{-3})(487)} = 694 \text{ pc/h}$$

$$c_{pce,WB} = 1{,}130e^{(-1.0\times10^{-3})v_{c,pce,WB}} = 1{,}130e^{(-1.0\times10^{-3})(655)} = 587 \text{ pc/h}$$

By using the equation for a bypass lane opposed by a single exit lane (Equation 21-6), the capacity for the westbound bypass lane is given as follows:

$$c_{bypass,pce,WB} = 1{,}130e^{(-1.0\times10^{-3})v_{ex,pce,NB}} = 1{,}130e^{(-1.0\times10^{-3})(454)} = 718 \text{ pc/h}$$

Step 6: Determine Pedestrian Impedance to Vehicles

The south leg (northbound entry) has a conflicting pedestrian flow rate, n_{ped}, of 50 p/h. Therefore, the pedestrian impedance factor is calculated by using Exhibit 21-17 as follows:

$$f_{ped} = 1 - 0.000137n_{ped} = 1 - 0.000137(50) = 0.993$$

The other legs have negligible pedestrian activity and therefore have $f_{ped} = 1$.

Step 7: Convert Lane Flow Rates and Capacities into Vehicles per Hour

The capacity for a given lane is converted back to vehicles by first determining the heavy-vehicle adjustment factor for the lane and then multiplying it by the capacity in passenger car equivalents. For this example, since all turning movements on each entry have the same f_{HV}, each entry will also have the same f_{HV}, 0.980.

$$c_{NB} = c_{pce,NB}f_{HV,e,NB}f_{ped} = (510)(0.980)(0.993) = 497 \text{ veh/h}$$

$$c_{SB} = c_{pce,SB} f_{HV,e,SB} f_{ped} = (524)(0.980)(1) = 514 \text{ veh/h}$$

$$c_{EB} = c_{pce,EB} f_{HV,e,EB} f_{ped} = (694)(0.980)(1) = 680 \text{ veh/h}$$

$$c_{WB} = c_{pce,WB} f_{HV,e,WB} f_{ped} = (587)(0.980)(1) = 575 \text{ veh/h}$$

$$c_{\text{bypass},WB} = c_{\text{bypass},pce,NB} f_{HV,e,WB} f_{ped} = (718)(0.980)(1) = 704 \text{ veh/h}$$

Calculations for the entry flow rates are as follows:

$$v_{NB} = v_{pce,NB} f_{HV,e,NB} = (428)(0.980) = 420 \text{ veh/h}$$

$$v_{SB} = v_{pce,SB} f_{HV,e,SB} = (314)(0.980) = 308 \text{ veh/h}$$

$$v_{EB} = v_{pce,EB} f_{HV,e,EB} = (656)(0.980) = 643 \text{ veh/h}$$

$$v_{WB} = v_{pce,WB} f_{HV,e,WB} = (568)(0.980) = 557 \text{ veh/h}$$

$$v_{\text{bypass},WB} = v_{\text{bypass},pce,NB} f_{HV,e,WB} f_{ped} = (662)(0.980) = 649 \text{ veh/h}$$

Step 8: Compute the Volume-to-Capacity Ratio for Each Lane

The volume-to-capacity ratios for each entry lane are calculated as follows:

$$x_{NB} = \frac{420}{497} = 0.85$$

$$x_{SB} = \frac{308}{514} = 0.60$$

$$x_{EB} = \frac{643}{680} = 0.95$$

$$x_{WB} = \frac{557}{575} = 0.97$$

$$x_{bypass,WB} = \frac{649}{704} = 0.92$$

Step 9: Compute the Average Control Delay for Each Lane

The control delay for the northbound entry lane is computed as follows:

$$d_{NB} = \frac{3{,}600}{497} + 900(0.25)\left[0.85 - 1 + \sqrt{(0.85-1)^2 + \frac{\left(\frac{3{,}600}{497}\right)0.85}{450(0.25)}}\right]$$

$$+ 5 \times \min[0.85, 1] = 39.6 \text{ s/veh (assuming no rounding of } x\text{)}$$

Similarly, d_{SB} = 19.9 s, $d_{\text{bypass},SB}$ = 0 s (assumed), d_{EB} = 46.7 s, d_{WB} = 56.5 s, and $d_{\text{bypass},WB}$ = 41.5 s.

Step 10: Determine LOS for Each Lane on Each Approach

Using Exhibit 21-1, the LOS for each lane is determined as follows:

Lane	Control Delay (s/veh)	LOS
Northbound entry	39.6	E
Southbound entry	19.9	C
Southbound bypass lane	0 (assumed)	A
Eastbound entry	46.7	E
Westbound entry	56.5	F
Westbound bypass lane	41.5	E

Step 11: Compute the Average Control Delay and Determine LOS for Each Approach and the Roundabout as a Whole

The control delays for the northbound and eastbound approaches are equal to the control delay for the entry lanes, as both of these approaches have only one lane. On the basis of Exhibit 21-1, these approaches are both assigned LOS E.

The control delay calculations for the westbound and southbound approaches include the effects of their bypass lanes as follows:

$$d_{WB} = \frac{(56.5)(557) + (41.5)(649)}{557 + 649} = 48.4 \text{ s/veh}$$

$$d_{SB} = \frac{(19.9)(308) + (0.0)(617)}{308 + 617} = 6.6 \text{ s/veh}$$

On the basis of Exhibit 21-1, these approaches are respectively assigned LOS E and LOS A.

Similarly, intersection control delay is computed as follows:

$$d_{\text{intersection}} = \frac{(39.6)(420) + (6.6)(925) + (46.7)(643) + (48.4)(1206)}{420 + 925 + 643 + 1206} = 34.8 \text{ s/veh}$$

On the basis of Exhibit 21-1, the intersection is assigned LOS D.

Step 12: Compute 95th Percentile Queues for Each Lane

The 95th percentile queue is computed for each lane. An example calculation for the northbound entry is given as follows:

$$Q_{95,NB} = 900(0.25)\left[0.85 - 1 + \sqrt{(1 - 0.85)^2 + \frac{\left(\frac{3{,}600}{497}\right)0.85}{150(0.25)}}\right]\left(\frac{497}{3{,}600}\right) = 8.6 \text{ veh}$$

For design purposes, this value is typically rounded up to the nearest vehicle, which for this case would be 9 veh.

Similarly, $Q_{95,SB}$ = 3.9 veh, $Q_{95,EB}$ = 13.4 veh, $Q_{95,WB}$ = 13.3 veh, and $Q_{95,\text{bypass},WB}$ = 12.5 veh.

Discussion

The results indicate that the overall roundabout is operating at LOS D based on a control delay very close to the boundary between LOS D and LOS E. However, three approaches (northbound, eastbound, and westbound) are operating at LOS E, and one lane (westbound entry) is operating at LOS F (based on control delay). In addition, two of the four entries have volume-to-capacity ratios exceeding 0.95 during the peak 15 min of the hour analyzed. If the performance standard for this intersection were LOS D, three approaches would not meet the standard, even though the overall intersection meets the standard. For these reasons, the analyst should report volume-to-capacity ratios, control delay, and queue lengths for each lane, in addition to the aggregated measures, for a more complete picture of operational performance.

The analyst should be careful not to mask key operational performance issues by reporting overall intersection performance without also reporting the performance of each lane, or at least the worst-performing lane.

EXAMPLE PROBLEM 2: MULTILANE ROUNDABOUT

This is also an example of an operational analysis, despite the fact that lane utilization data are unknown and must be assumed.

The Facts

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

- Percent heavy vehicles for eastbound and westbound movements = 5%,
- Percent heavy vehicles for northbound and southbound movements = 2%,
- Peak hour factor = 0.95,
- Negligible pedestrian activity, and
- Volumes and lane configurations as shown in Exhibit 21-24.

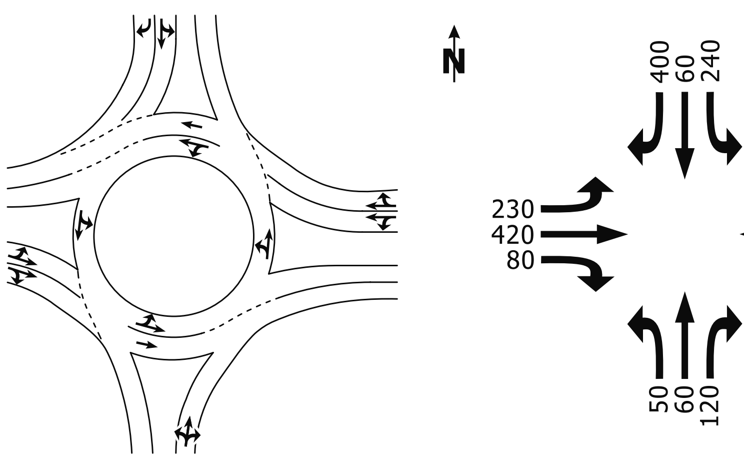


Exhibit 21-24
Demand Volumes and Lane Configurations for Example Problem 2

Comments

Lane use is not specified for the eastbound and westbound approaches; therefore, the percentage flow in the right lane is assumed to be 53%, per Exhibit 21-21.

Step 1: Convert Movement Demand Volumes to Flow Rates

Each turning-movement demand volume given in the problem is converted to a demand flow rate by dividing by the peak hour factor. As an example, the eastbound left demand volume is converted to a demand flow rate as follows:

$$v_{EBL} = \frac{V_{EBL}}{PHF} = \frac{230}{0.95} = 242 \text{ veh/h}$$

Step 2: Adjust Flow Rates for Heavy Vehicles

The heavy-vehicle adjustment factor for the eastbound and westbound movements is calculated as follows:

$$f_{HV} = \frac{1}{1 + P_T\left(E_T - 1\right)} = \frac{1}{1 + 0.05(2-1)} = 0.952$$

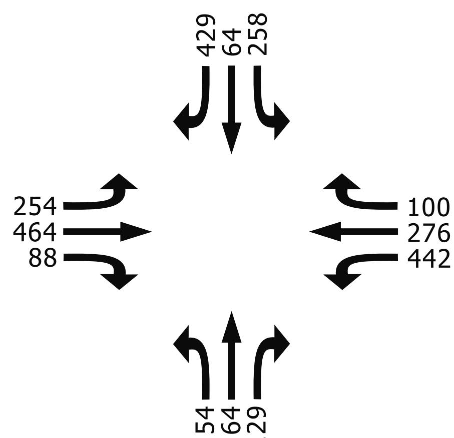
Similarly, the heavy-vehicle adjustment factor for the northbound and southbound movements is calculated as follows:

$$f_{HV} = \frac{1}{1 + P_T\left(E_T - 1\right)} = \frac{1}{1 + 0.02(2-1)} = 0.980$$

This is applied to each movement as follows (eastbound left turn illustrated):

$$v_{EBL,pce} = \frac{v_{EBL}}{f_{HV}} = \frac{242}{0.952} = 254 \text{ pc/h}$$

The resulting adjusted flow rates for all movements, accounting for Steps 1 and 2, are therefore as follows:



Step 3: Determine Circulating and Exiting Flow Rates

For this problem, only circulating flows need to be calculated for each leg. For the west leg (eastbound entry), the circulating flow is calculated as follows:

$$v_{c,EB,pce} = v_{NBU,pce} + v_{WBL,pce} + v_{WBU,pce} + v_{SBT,pce} + v_{SBL,pce} + v_{SBU,pce}$$

$$v_{c,EB,pce} = 0 + 442 + 0 + 64 + 258 + 0 = 764 \text{ pc/h}$$

Similarly, $v_{c,WB,pce}$ = 372 pc/h, $v_{c,NB,pce}$ = 976 pc/h, and $v_{c,SB,pce}$ = 772 pc/h.

Step 4: Determine Entry Flow Rates by Lane

The entry flow rate is calculated by summing up the movement flow rates that enter the roundabout. This problem presents four unique cases.

- *Northbound*: The northbound entry has only one lane. Therefore, the entry flow is simply the sum of the movements, or 54 + 64 + 129 = 247 pc/h.
- *Southbound*: The southbound entry has two lanes: a shared through–left lane and a right-turn-only lane. Therefore, the flow rate in the right lane is simply the right-turn movement flow, or 429 pc/h, and the flow rate in the left lane is the sum of the left-turn and through movements, or 258 + 64 = 322 pc/h.
- *Eastbound*: The eastbound entry has shared left–through and through–right lanes. A check is needed to determine whether any de facto lanes are in effect. These checks are as follows:
    - *Left lane*: The left-turn flow rate, 254 pc/h, is less than the sum of the through and right-turn flow rates, 464 + 88 = 552 pc/h. Therefore, some of the through volume is assumed to use the left lane, and no de facto left-turn lane condition is present.
    - *Right lane*: The right-turn flow rate, 88 pc/h, is less than the sum of the left-turn and through flow rates, 254 + 464 = 718 pc/h. Therefore, some of the through volume is assumed to use the right lane, and no de facto right-turn lane condition is present.
    - The total entry flow (254 + 464 + 88 = 806 pc/h) is therefore distributed over the two lanes, with flow biased to the right lane using the assumed lane-use factor identified previously:
        - Right lane: (806)(0.53) = 427 pc/h
        - Left lane: 806 – 427 = 379 pc/h
- *Westbound*: The westbound entry also has shared left–through and through–right lanes, and so a similar check is needed for de facto lanes. The left-turn flow rate, 442 pc/h, is greater than the sum of the through and right-turn flow rates, 276 + 100 = 376 pc/h. Therefore, the left lane is assumed to operate as a de facto left-turn lane. Therefore, the left-lane flow rate is equal to the left-turn flow rate, or 442 pc/h, and the right-lane flow rate is equal to the sum of the through- and right-turn-movement flow rates, or 376 pc/h.

Step 5: Determine the Capacity of Each Entry Lane and Bypass Lane as Appropriate in Passenger Car Equivalents

The capacity calculations for each approach are calculated as follows:

- *Northbound*: The northbound entry is a single-lane entry opposed by two circulating lanes. Therefore, Equation 21-3 is used as follows:

$$c_{pce,NB} = 1{,}130 e^{\left(-0.7\times10^{-3}\right)(976)} = 571 \text{ pc/h}$$

- *Southbound*: The southbound entry is a two-lane entry opposed by two circulating lanes. Therefore, Equation 21-4 is used for the right lane, and Equation 21-5 is used for the left lane:

$$c_{pce,SB,R} = 1{,}130e^{\left(-0.7\times10^{-3}\right)(772)} = 658 \text{ pc/h}$$

$$c_{pce,SB,L} = 1{,}130e^{\left(-0.75\times10^{-3}\right)(772)} = 633 \text{ pc/h}$$

- *Eastbound*: The eastbound entry is a two-lane entry opposed by one circulating lane. Therefore, the capacity for each lane is calculated by using Equation 21-2 as follows:

$$c_{pce,EB} = 1{,}130e^{\left(-1.0\times10^{-3}\right)(764)} = 526 \text{ pc/h}$$

- *Westbound*: The westbound entry is also a two-lane entry opposed by one circulating lane, so its capacity calculation is similar to that for the eastbound entry:

$$c_{pce,WB} = 1{,}130e^{\left(-1.0\times10^{-3}\right)(372)} = 779 \text{ pc/h}$$

Step 6: Determine Pedestrian Impedance to Vehicles

For this problem pedestrians have been assumed to be negligible, so no impedance calculations are performed.

Step 7: Convert Lane Flow Rates and Capacities into Vehicles per Hour

The capacity for a given lane is converted back to vehicles by first determining the heavy-vehicle adjustment factor for the lane and then multiplying it by the capacity in passenger car equivalents. For this example, since all turning movements on the eastbound and westbound entries have the same f_{HV}, each of the lanes on the eastbound and westbound entries can be assumed to have the same f_{HV}, 0.952.

$$c_{EB,R} = c_{pce,EB,R} f_{HV,e,EB} = (526)(0.952) = 501 \text{ veh/h}$$

Similarly, $c_{EB,L}$ = 501 veh/h, $c_{WB,L}$ = 742 veh/h, and $c_{WB,R}$ = 742 veh/h.

Since all turning movements on the northbound and southbound entries have the same f_{HV}, each of the lanes on those entries can be assumed to have the same f_{HV}, 0.980.

$$c_{NB} = c_{pce,NB} f_{HV,e,NB} = (571)(0.980) = 560 \text{ veh/h}$$

Similarly, $c_{SB,L}$ = 621 veh/h and $c_{SB,R}$ = 645 veh/h.

Calculations for the entry flow rates are as follows:

$$v_{EB,R} = v_{pce,EB,R} f_{HV,e,EB} = (427)(0.952) = 407 \text{ veh/h}$$

$$v_{NB} = v_{pce,NB} f_{HV,e,NB} = (247)(0.980) = 242 \text{ veh/h}$$

Similarly, $v_{EB,L}$ = 361 veh/h, $v_{WB,L}$ = 421 veh/h, $v_{WB,R}$ = 358 veh/h, $v_{SB,L}$ = 316 veh/h, and $v_{SB,R}$ = 421 veh/h.

Step 8: Compute the Volume-to-Capacity Ratio for Each Lane

The volume-to-capacity ratio for each lane is calculated as follows:

$$x_{NB} = 242/560 = 0.43$$

$$x_{SB,L} = 316/621 = 0.51$$

$$x_{SB,R} = 421/645 = 0.65$$

$$x_{EB,L} = 361/501 = 0.72$$

$$x_{EB,R} = 407/501 = 0.81$$

$$x_{WB,L} = 421/742 = 0.57$$

$$x_{WB,R} = 358/742 = 0.48$$

Step 9: Compute the Average Control Delay for Each Lane

The control delay for the northbound entry lane is computed as follows:

$$d_{NB} = \frac{3{,}600}{560} + 900(0.25)\left[\frac{242}{560} - 1 + \sqrt{\left(\frac{242}{560} - 1\right)^2 + \frac{\left(\frac{3{,}600}{560}\right)\frac{242}{560}}{450(0.25)}}\right]$$

$$+ 5 \times \min\left[\frac{242}{560}, 1\right] = 13.4 \text{ s/veh}$$

Similarly, $d_{SB,L}$ = 14.2 s, $d_{SB,R}$ = 18.7 s, $d_{EB,L}$ = 27.2 s, $d_{EB,R}$ = 35.4 s, $d_{WB,L}$ = 13.9 s, and $d_{WB,R}$ = 11.7 s.

Step 10: Determine LOS for Each Lane on Each Approach

On the basis of Exhibit 21-1, the LOS for each lane is determined as follows:

Critical Lane	Control Delay (s/veh)	LOS
Northbound entry	13.4	B
Southbound left lane	14.2	B
Southbound right lane	18.7	C
Eastbound left lane	27.2	D
Eastbound right lane	35.4	E
Westbound left lane	13.9	B
Westbound right lane	11.7	B

Step 11: Compute the Average Control Delay and Determine LOS for Each Approach and the Roundabout as a Whole

The control delay for the northbound approaches is equal to the control delay for the entry lane, 13.4 s, as the approach has only one lane. The control delays for the other approaches are as follows:

$$d_{SB} = \frac{(14.2)(316) + (18.7)(421)}{316 + 421} = 16.8 \text{ s/veh}$$

$$d_{EB} = \frac{(27.2)(361) + (35.4)(407)}{361 + 407} = 31.5 \text{ s/veh}$$

$$d_{WB} = \frac{(13.9)(421) + (11.7)(358)}{421 + 358} = 12.9 \text{ s/veh}$$

On the basis of Exhibit 21-1, these approaches are respectively assigned LOS B, LOS C, LOS D, and LOS B.

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

$$d_{\text{intersection}} = \frac{(13.4)(242) + (16.8)(736) + (31.5)(768) + (12.9)(779)}{242 + 736 + 768 + 779} = 19.7 \text{ s/veh}$$

On the basis of Exhibit 21-1, the intersection is assigned LOS C.

Step 12: Compute 95th Percentile Queues for Each Lane

The 95th percentile queue is computed for each lane. An example calculation for the northbound entry is given as follows:

$$Q_{95,NB} = 900(0.25)\left[\frac{242}{560} - 1 + \sqrt{\left(1 - \frac{242}{560}\right)^2 + \frac{\left(\frac{3{,}600}{560}\right)\left(\frac{242}{560}\right)}{150(0.25)}}\right]\left(\frac{560}{3{,}600}\right) = 2.2 \text{ veh}$$

For design purposes, this value is typically rounded up to the nearest vehicle, in this case 3 veh.

Discussion

The results indicate that the intersection as a whole operates at LOS C on the basis of control delay during the peak 15 min of the analysis hour. However, the eastbound approach operates at LOS D, and the right lane of that approach operates at LOS E (with a control delay very close to the boundary of LOS D and LOS E) and with a volume-to-capacity ratio of 0.81. The analyst should report both the overall performance and those of the individual lanes to provide a more complete picture of operational performance.

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