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1. INTRODUCTION

Chapter 33 is the supplemental chapter for Chapter 22, Roundabouts, which is found in Volume 3 of the Highway Capacity Manual (HCM). This chapter presents detailed information about the following aspects of the Chapter 22 motorized vehicle methodology:

- Information about the large variability in U.S. driver behavior at roundabouts,
- Guidance on making an appropriate selection of a lane utilization factor, and
- Guidance on calibrating the capacity model to reflect local conditions.

This chapter also provides two example problems that demonstrate the application of the Chapter 22 methodology to single-lane and multilane roundabouts.
2. SUPPLEMENTAL GUIDANCE

This section presents supplemental guidance on the methodology provided in Chapter 22, Roundabouts.

VARIABILITY AND UNCERTAINTY

The analyst should be aware of the large observed variation in driver behavior at roundabouts. Exhibit 33-1 through Exhibit 33-4 show observed combinations of entry flow and conflicting flow at different roundabout configurations, along with the capacity models for the respective configuration as presented in Chapter 22. The bulk of this variation is attributable to variations in driver behavior, truck percentage, and exiting vehicles. As there is no external control device regulating flow interactions at roundabouts, driver interactions govern the operation, and they are highly variable by nature.

This variability should be considered by the analyst when evaluating a roundabout approach.

Exhibit 33-1
Observed Combinations of Entry Flow and Conflicting Flow During 1-min Periods of Continuous Queuing: One-Lane Entry Opposed by One Circulating Lane

Source: Rodegerdts et al. (f).
Exhibit 33-2
Observed Combinations of Entry Flow and Conflicting Flow During 1-min Periods of Continuous Queueing: Both Lanes of Two-Lane Entry Opposed by One Circulating Lane

Exhibit 33-3
Observed Combinations of Entry Flow and Conflicting Flow During 1-min Periods of Continuous Queueing: Left Lane of Two-Lane Entry Opposed by Two Circulating Lanes
Lane-use assignment is best determined by measuring lane use in the field under the conditions being analyzed. In the absence of this information, default values or estimates can be used. This section provides background on the process by which an analyst can make an appropriate selection of a lane utilization factor.

In general, several factors contribute to the assignment of traffic flow to each lane:

1. The assignment of turning movements to each lane (either as exclusive lanes or as shared lanes) directly influences the assignment of traffic volumes to each lane. Lane assignment is generally accomplished through the use of signs and pavement markings that designate the lane use for each lane. Multilane entries with no lane-use signing or pavement markings may be assumed to operate with a shared left–through lane in the left lane and a shared through–right lane in the right lane, although field observations should be made to confirm the lane-use pattern of an existing roundabout.

2. Dominant turning movements may create de facto lane assignments for which there is no advantage for drivers in using both lanes assigned to a given turning movement. For example, at an entry with left–through and through–right lanes and a dominant left-turn movement, there may be no advantage for through drivers in using the left lane. In addition, a lack of lane balance through the roundabout (e.g., two entry lanes but only one downstream circulating lane or one downstream exit lane) can create de facto lane-use assignments for a particular entry.
3. Destinations downstream of a roundabout may influence the lane choice at the roundabout entry. A downstream destination such as a freeway on-ramp may increase use of the right entry lane, for example, even though both lanes could be used.

4. The alignment of the lane relative to the circulatory roadway seems to influence the use of entry lanes where drivers can choose between lanes. Some roundabouts have been designed with rather perpendicular entries that have a natural alignment of the right entry lane into the left lane of the circulatory roadway. Under this design, the left entry lane is naturally aimed at the central island and is thus less comfortable and less desirable for drivers. This phenomenon of poor path alignment, documented elsewhere (2), may result in poor use of the left entry lane. Similarly, poorly aligned multilane exits, where vehicles exiting in the inside lane cross the path of vehicles exiting in the outside lane, may influence lane use on upstream entries. In either case, the effect is most readily measured in the field at existing roundabouts, and it should be avoided in the design of new roundabouts.

5. Drivers may be uncertain about lane use when they use the roundabout, particularly at roundabouts without designated lane assignments approaching or circulating through the roundabout. This uncertainty may contribute to the generally incorrect use of the right entry lane for left turns, for example, because of a perceived or real difficulty in exiting from the inside lane of the circulatory roadway. Proper signing and striping of lane use on the approach and through the roundabout may reduce this uncertainty, although it is likely to be present to some extent at multilane roundabouts.

The first three factors described above are common to all intersections and are accounted for in the assignment of turning-movement patterns to individual lanes; the remaining two factors are unique to roundabouts. The fourth factor should be addressed through proper alignment of the entry relative to the circulatory roadway and thus may not need to be considered in the analysis of new facilities. However, existing roundabouts may exhibit poor path alignment, resulting in poor lane utilization. It may be possible to reduce the fifth factor through proper design, particularly through lane-use arrows and striping. These factors collectively make accurate estimation of lane utilization difficult, but it can be measured at existing roundabouts.

For entries with two through lanes, limited field data suggest drivers generally have a bias for the right lane. For entries with two left-turn lanes (e.g., left-turn-only and shared left–through–right lanes), limited field data suggest drivers have a bias for the left lane. Although no field observations have been documented for entries with two right-turn lanes, experience at other types of intersections with two right-turn lanes suggests drivers have a bias for the right lane.
CAPACITY MODEL CALIBRATION

As discussed in Chapter 22, Roundabouts, the capacity model can be calibrated by using one of two methods: using two parameters, the critical headway $t_c$ and the follow-up headway $t_f$, or using only the follow-up headway $t_f$.

An example of calibration using two parameters was performed for roundabouts in California (3). Field-measured values for critical headway and follow-up headway were determined as follows:

- **Critical headway:**
  - Single-lane roundabouts: 4.8 s;
  - Multilane roundabouts, left lane: 4.7 s; and
  - Multilane roundabouts, right lane: 4.4 s.

- **Follow-up headway:**
  - Single-lane roundabouts: 2.5 s;
  - Multilane roundabouts, left lane: 2.2 s; and
  - Multilane roundabouts, right lane: 2.2 s.

By using these values and the expressions in Equation 22-21 through Equation 22-23, the capacity equation for single-lane roundabouts can be expressed as follows:

$$A = \frac{3,600}{t_f} = \frac{3,600}{2.5} = 1,440$$

$$B = \frac{t_c - (t_f/2)}{3,600} = \frac{4.8 - (2.5/2)}{3,600} = 1.0 \times 10^{-3}$$

$$c_{pce} = Ae^{-Bt_c} = 1,440e^{(-1.0\times10^{-3}t_c)}$$

Therefore, the model resulting from the use of California-specific data for critical headway and follow-up time has a higher intercept, and thus higher capacity, over its entire range than does the model based on the national study. These equations replace the equations in Step 5 of the Chapter 22 methodology.

An example of calibration using only follow-up headway can be demonstrated using data collected as part of a national study for the US-9/Warren Street/Hudson Avenue/Glen Street intersection in Glen Falls, New York (1). Field-measured values for follow-up headway for the five-legged roundabout were determined as follows (rounded to the nearest 0.1 s):

- East leg: 2.9 s,
- Northwest leg: 2.8 s,
- South leg: 2.9 s,
- West leg: 2.7 s, and
- North leg: 2.8 s.

The mean value using unrounded values for follow-up time for the intersection is 2.85 s. The intercept can therefore be calculated as follows:
\begin{align*}
A &= \frac{3,600}{t_f} = \frac{3,600}{2.85} = 1,260 \\
\text{With this value for the intercept, the resulting capacity model is} \\
c_{pce} &= Ae^{(-Bv_c)} = 1,260e^{(-1.02 \times 10^{-3}v_c)}
\end{align*}

The resulting model has a lower intercept than the national model. Based on the observations of each approach of this intersection under queued conditions from the national study, this site-specific model has a better goodness of fit than the national model (an improvement in the root mean squared error from 164 to 126 pc/h). Variation in driver behavior between individual drivers or from minute to minute makes eliminating prediction error impossible, but calibration can improve the accuracy of the prediction.
3. EXAMPLE PROBLEMS

This section illustrates the application of the roundabout methodology through the two example problems listed in Exhibit 33-5.

<table>
<thead>
<tr>
<th>Example Problem</th>
<th>Description</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Single-lane roundabout with bypass lanes</td>
<td>Operational analysis</td>
</tr>
<tr>
<td>2</td>
<td>Multilane roundabout</td>
<td>Operational analysis</td>
</tr>
</tbody>
</table>

**EXAMPLE PROBLEM 1: SINGLE-LANE ROUNDABOUT WITH BYPASS LANES**

**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,
- Percentage heavy vehicles for all movements = 2%,
- Peak hour factor = 0.94,
- Demand volumes and lane configurations as shown in Exhibit 33-6, and
- 50 p/h across the south leg and negligible pedestrian activity across the other three legs.

**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 by using Equation 22-8:

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

Step 2: Adjust Flow Rates for Heavy Vehicles

The flow rate for each movement may be adjusted to account for vehicle stream characteristics by using Equations 22-9 and 22-10 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 shown in Exhibit 33-7:

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 by using the process illustrated by Equation 22-11 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, \( v_{c, SB,pce} = 769 \text{ pc/h}; v_{c, EB,pce} = 487 \text{ pc/h}; \) and \( v_{c, WR,pce} = 655 \text{ pc/h}. \)

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 by using the process illustrated by Equation 22-12 as follows:
\[ v_{ex,NB,pce} = v_{SBU,pce} + v_{EBL,pce} + v_{NBT,pce} + v_{WBR,pce} - v_{WBR, bypass,pce} \]
\[ v_{ex,NB,pce} = 21 + 206 + 227 + 662 - 662 = 454 \text{ pc/h} \]

**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 all right-turn volumes on the westbound and southbound approaches use the bypass lane provided and not the entry:

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

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

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

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

**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 22-1), the capacity for each entry lane is given as follows:

\[ c_{pce,NB} = 1,380e^{(-1.02 \times 10^{-3})}v_{pce,NB} = 1,380e^{(-1.02 \times 10^{-3})(796)} = 613 \text{ pc/h} \]

\[ c_{pce,SB} = 1,380e^{(-1.02 \times 10^{-3})}v_{pce,SB} = 1,380e^{(-1.02 \times 10^{-3})(769)} = 630 \text{ pc/h} \]

\[ c_{pce,EB} = 1,380e^{(-1.02 \times 10^{-3})}v_{pce,EB} = 1,380e^{(-1.02 \times 10^{-3})(487)} = 840 \text{ pc/h} \]

\[ c_{pce,WB} = 1,380e^{(-1.02 \times 10^{-3})}v_{pce,WB} = 1,380e^{(-1.02 \times 10^{-3})(655)} = 708 \text{ pc/h} \]

By using the equation for a bypass lane opposed by a single exit lane (Equation 22-6), the capacity for the westbound bypass lane is given as follows:

\[ c_{bypass,pce,WB} = 1,380e^{(-1.02 \times 10^{-3})}v_{ex,pce,NB} = 1,380e^{(-1.02 \times 10^{-3})(454)} = 868 \text{ pc/h} \]

**Step 6: Determine Pedestrian Impedance to Vehicles**

The south leg (northbound entry) has a conflicting pedestrian flow rate, \( n_{ped} \), of 50 p/h. The pedestrian impedance factor is calculated by using Exhibit 22-18 as follows:

\[ f_{ped} = 1 - 0.000137n_{ped} = 1 - 0.000137(50) = 0.993 \]

Because the other legs and bypass lanes have negligible pedestrian activity (\( n_{ped} = 0 \)), they 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 (Equation 22-14). For this example, because all turning movements on each entry have the same $f_{HV}$, each entry will also have the same $f_{HV}$, 0.980. The capacities for each of the entries are also adjusted by the pedestrian impedance factor.

\[
\begin{align*}
c_{NB} &= c_{pce,NB}f_{HV,NB}f_{ped} = (613)(0.980)(0.993) = 597 \text{ veh/h} \\
c_{SB} &= c_{pce,SB}f_{HV,SB}f_{ped} = (630)(0.980)(1) = 618 \text{ veh/h} \\
c_{EB} &= c_{pce,EB}f_{HV,EB}f_{ped} = (840)(0.980)(1) = 824 \text{ veh/h} \\
c_{WB} &= c_{pce,WB}f_{HV,WB}f_{ped} = (708)(0.980)(1) = 694 \text{ veh/h} \\
c_{bypass,WB} &= c_{bypass,pce,WB}f_{HV,WB}f_{ped} = (868)(0.980)(1) = 851 \text{ veh/h}
\end{align*}
\]

Calculations for the entry flow rates are as follows (Equation 22-13):

\[
\begin{align*}
v_{NB} &= v_{pce,NB}f_{HV,NB} = (428)(0.980) = 420 \text{ veh/h} \\
v_{SB} &= v_{pce,SB}f_{HV,SB} = (314)(0.980) = 308 \text{ veh/h} \\
v_{EB} &= v_{pce,EB}f_{HV,EB} = (656)(0.980) = 643 \text{ veh/h} \\
v_{WB} &= v_{pce,WB}f_{HV,WB} = (568)(0.980) = 557 \text{ veh/h} \\
v_{bypass,WB} &= v_{bypass,pce,WB}f_{HV,WB} = (662)(0.980) = 649 \text{ veh/h}
\end{align*}
\]

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

The volume-to-capacity ratios for each entry lane are calculated from Equation 22-16 as follows:

\[
\begin{align*}
x_{NB} &= \frac{420}{597} = 0.70 \\
x_{SB} &= \frac{308}{618} = 0.50 \\
x_{EB} &= \frac{643}{824} = 0.78 \\
x_{WB} &= \frac{557}{694} = 0.80 \\
x_{bypass,WB} &= \frac{649}{851} = 0.76
\end{align*}
\]

Step 9: Compute the Average Control Delay for Each Lane

The control delay for the northbound entry lane is computed from Equation 22-17 as follows:

\[
\begin{align*}
d_{NB} &= \frac{3,600}{597} + 900(0.25) \left[ 0.70 - 1 + \sqrt{(0.70 - 1)^2 + \frac{3,600}{450}(0.25)} \right] \\
&+ 5(\min[0.70,1]) \\
d_{NB} &= 22.6 \text{ s/veh}
\end{align*}
\]
Similarly, $d_{SB} = 14.0\text{ s}; d_{bypass,SB} = 0\text{ s (assumed)}; d_{EB} = 22.0\text{ s}; d_{WB} = 26.8\text{ s};$ and $d_{bypass,WB} = 20.2\text{ s}.$

**Step 10: Determine LOS for Each Lane on Each Approach**

From Exhibit 22-8, the level of service (LOS) for each lane is determined as shown in Exhibit 33-8:

<table>
<thead>
<tr>
<th>Lane</th>
<th>Control Delay (s/veh)</th>
<th>LOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northbound entry</td>
<td>22.6</td>
<td>C</td>
</tr>
<tr>
<td>Southbound entry</td>
<td>14.0</td>
<td>B</td>
</tr>
<tr>
<td>Southbound bypass lane</td>
<td>0 (assumed)</td>
<td>A</td>
</tr>
<tr>
<td>Eastbound entry</td>
<td>22.0</td>
<td>C</td>
</tr>
<tr>
<td>Westbound entry</td>
<td>26.8</td>
<td>D</td>
</tr>
<tr>
<td>Westbound bypass lane</td>
<td>20.2</td>
<td>C</td>
</tr>
</tbody>
</table>

**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 22-8, these approaches are both assigned LOS C.

The control delay calculations for the westbound and southbound approaches include the effects of their bypass lanes as follows (Equation 22-18):

$$d_{WB} = \frac{26.8 \times 557 + 20.2 \times 649}{557 + 649} = 23.3 \text{ s/veh}$$

$$d_{SB} = \frac{14.0 \times 308 + 0.0 \times 617}{308 + 617} = 4.7 \text{ s/veh}$$

On the basis of Exhibit 22-8, these approaches are respectively assigned LOS C and LOS A.

Similarly, intersection control delay is computed as follows (Equation 22-19):

$$d_{\text{intersection}} = \frac{22.6 \times 420 + 4.7 \times 925 + 22.0 \times 643 + 23.3 \times 1,206}{420 + 925 + 643 + 1,206} = 17.5 \text{ s/veh}$$

On the basis of Exhibit 22-8, 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 (Equation 22-20):

$$Q_{95,\text{NB}} = 900 \times (0.25) \left[ 0.70 - 1 + \sqrt{(1 - 0.70)^2 + \left( \frac{3,600}{597} \cdot 0.70 \right) \frac{597}{150 \times 0.25}} \right] = 5.7 \text{ veh}$$

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

Similarly, $Q_{95,SB} = 2.8 \text{ veh}; Q_{95,EB} = 7.9 \text{ veh}; Q_{95,WB} = 8.2 \text{ veh};$ and $Q_{95,bypass,WB} = 7.4 \text{ veh}.$
Discussion

The results indicate the overall roundabout is operating at LOS C. However, one lane (the westbound entry) is operating at LOS D. If, for example, the performance standard for this intersection was LOS C, this entry would not meet the standard, even though the overall intersection meets the standard. For these reasons, the analyst should consider reporting 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.

EXAMPLE PROBLEM 2: MULTILANE ROUNDABOUT

The Facts

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

- Percentage heavy vehicles for eastbound and westbound movements = 5%,
- Percentage 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 33-9.

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%, as specified in Exhibit 22-9.

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 by using Equation 22-8 as follows:
Highway Capacity Manual: A Guide for Multimodal Mobility Analysis

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

**Step 2: Adjust Flow Rates for Heavy Vehicles**

The heavy-vehicle adjustment factor for the eastbound and westbound movements is calculated by using Equation 22-10 as follows:

\[
f_{HV} = \frac{1}{1 + P_T(E_T - 1)} = \frac{1}{1 + 0.05(2 - 1)} = 0.952
\]

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

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

This factor is applied to each movement by using Equation 22-9 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 shown in Exhibit 33-10:

**Exhibit 33-10**
Example Problem 2: Adjusted Flow Rates

**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 by using the process illustrated by Equation 22-11 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, \(v_{c,WR,pce} = 372 \text{ pc/h}; v_{c,NR,pce} = 976 \text{ pc/h}; \) and \(v_{c,SR,pce} = 772 \text{ pc/h}.\)

**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 \(54 + 64 + 129 = 247 \text{ pc/h.}\)
• **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 by using the assumed lane-use factor identified previously:
  - **Right lane**: (806)(0.53) = 427 pc/h, and
  - **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 22-3 is used as follows:
  \[ c_{pce,NB} = 1,420e^{-0.85 \times 10^{-3}(976)} = 619 \text{ pc/h} \]

• **Southbound**: The southbound entry is a two-lane entry opposed by two circulating lanes. Therefore, Equation 22-4 is used for the right lane, and Equation 22-5 is used for the left lane:
  \[ c_{pce,SBR} = 1,420e^{-0.85 \times 10^{-3}(772)} = 737 \text{ pc/h} \]
  \[ c_{pce,SBL} = 1,350e^{-0.92 \times 10^{-3}(772)} = 664 \text{ pc/h} \]
• **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 22-2 as follows:

\[
c_{pce,EB,R} = c_{pce,EB,L} = 1,420e^{-0.91\times10^{-3}(764)} = 709 \text{ pc/h}
\]

• **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:

\[
c_{pce,WB} = 1,420e^{-0.91\times10^{-3}(372)} = 1,012 \text{ pc/h}
\]

There are no bypass lanes in this example problem.

**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 (Equation 22-14). For this example, because 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.

\[
c_{EB,L} = c_{pce,EB,L}f_{HV,EB} = (709)(0.952) = 675 \text{ veh/h}
\]

Similarly, \(c_{WB,L} = 964 \text{ veh/h} \) and \(c_{WB,R} = 964 \text{ veh/h} \).

Because 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.

\[
c_{NB} = c_{pce,NB}f_{HV,NB} = (619)(0.980) = 607 \text{ veh/h}
\]

Similarly, \(c_{SB,L} = 651 \text{ veh/h} \) and \(c_{SB,R} = 723 \text{ veh/h} \).

Calculations for the entry flow rates are as follows (Equation 22-13):

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

\[
v_{WB} = v_{pce,NB}f_{HV,NB} = (247)(0.980) = 242 \text{ veh/h}
\]

Similarly, \(v_{EB,L} = 361 \text{ veh/h} \); \(v_{WB,L} = 421 \text{ veh/h} \); \(v_{WB,R} = 358 \text{ veh/h} \); \(v_{SB,L} = 316 \text{ veh/h} \); and \(v_{SB,R} = 421 \text{ veh/h} \).
Step 8: Compute the Volume-to-Capacity Ratio for Each Lane

The volume-to-capacity ratio for each lane is calculated from Equation 22-16 as follows:

\[ x_{NB} = \frac{242}{607} = 0.40 \]

\[ x_{SB,L} = \frac{316}{651} = 0.48 \]

\[ x_{SB,R} = \frac{421}{723} = 0.58 \]

\[ x_{EB,L} = \frac{361}{675} = 0.53 \]

\[ x_{EB,R} = \frac{407}{675} = 0.60 \]

\[ x_{WB,L} = \frac{421}{964} = 0.44 \]

\[ x_{WB,R} = \frac{358}{964} = 0.37 \]

Step 9: Compute the Average Control Delay for Each Lane

The control delay for the northbound entry lane is computed from Equation 22-17 as follows:

\[ d_{NB} = \frac{3600}{607} + 900(0.25) \left[ \frac{242}{607} - 1 + \sqrt{\left( \frac{242}{607} - 1 \right)^2 + \left( \frac{3600}{607} \right)^2} \right] + 5 \min \left[ \frac{242}{607}, 1 \right] \]

\[ d_{NB} = 11.8 \text{ s/veh} \]

Similarly, \( d_{SB,L} = 13.0 \text{ s/veh} \); \( d_{SB,R} = 14.6 \text{ s/veh} \); \( d_{EB,L} = 14.0 \text{ s/veh} \); \( d_{EB,R} = 16.1 \text{ s/veh} \); \( d_{WB,L} = 8.8 \text{ s/veh} \); and \( d_{WB,R} = 7.8 \text{ s/veh} \).

Step 10: Determine LOS for Each Lane on Each Approach

On the basis of Exhibit 22-8, the LOS for each lane is determined as shown in Exhibit 33-11:

<table>
<thead>
<tr>
<th>Critical Lane</th>
<th>Control Delay (s/veh)</th>
<th>LOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northbound entry</td>
<td>11.8</td>
<td>B</td>
</tr>
<tr>
<td>Southbound left lane</td>
<td>13.0</td>
<td>B</td>
</tr>
<tr>
<td>Southbound right lane</td>
<td>14.6</td>
<td>B</td>
</tr>
<tr>
<td>Eastbound left lane</td>
<td>14.0</td>
<td>B</td>
</tr>
<tr>
<td>Eastbound right lane</td>
<td>16.1</td>
<td>C</td>
</tr>
<tr>
<td>Westbound left lane</td>
<td>8.8</td>
<td>A</td>
</tr>
<tr>
<td>Westbound right lane</td>
<td>7.8</td>
<td>A</td>
</tr>
</tbody>
</table>

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, 11.8 s, as the approach has only one lane. The control delays for the other approaches are as follows (Equation 22-18):

\[ d_{SB,L} = 13.0 \text{ s/veh} \; d_{SB,R} = 14.6 \text{ s/veh} \; d_{EB,L} = 14.0 \text{ s/veh} \; d_{EB,R} = 16.1 \text{ s/veh} \; d_{WB,L} = 8.8 \text{ s/veh} \; \text{and} \; d_{WB,R} = 7.8 \text{ s/veh} \]
\[ d_{SB} = \frac{(13.0)(316) + (14.6)(421)}{316 + 421} = 13.9 \text{ s/veh} \]
\[ d_{EB} = \frac{(14.0)(361) + (16.1)(407)}{361 + 407} = 15.1 \text{ s/veh} \]
\[ d_{WB} = \frac{(8.8)(421) + (7.8)(358)}{421 + 358} = 8.3 \text{ s/veh} \]

On the basis of Exhibit 22-8, these approaches are respectively assigned LOS B, LOS B, LOS C, and LOS A.

Similarly, control delay for the intersection is computed as follows (Equation 22-19):
\[ d_{\text{intersection}} = \frac{(11.8)(242) + (13.9)(736) + (15.1)(768) + (8.3)(779)}{242 + 736 + 768 + 779} \]
\[ d_{\text{intersection}} = 12.3 \text{ s/veh} \]

On the basis of Exhibit 22-8, the intersection is assigned LOS B.

**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 (Equation 22-20):
\[ Q_{95, NB} = 900(0.25) \left[ \frac{242}{607} - 1 + \sqrt{ \left( 1 - \frac{242}{607} \right)^2 + \left( \frac{3600}{607} \right)^2 \frac{242}{607} \left( \frac{607}{150(0.25)} \right) } \right] \]
\[ Q_{95, NB} = 1.9 \text{ veh} \]

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

**Discussion**

The results indicate the intersection as a whole operates at LOS B on the basis of control delay during the peak 15 min of the analysis hour. However, the eastbound approach operates at LOS C, as does the right lane of the eastbound approach. The analyst should consider reporting both the overall performance and those of the individual lanes to provide a more complete picture of operational performance.
4. REFERENCES


Many of these references can be found in the Technical Reference Library in Volume 4.