

## **Transportation Research Board – Privileged Document**

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## PART C. ROUNDABOUTS

### I. INTRODUCTION – PART C

In this section of Chapter 17, procedures for the analysis of roundabouts are presented. The unique characteristics of roundabout capacity are introduced along with terminology. For ease of reference, the following terms are defined:

- $c_a$  = approach capacity
- $v_e$  = entry flow rate, and
- $v_c$  = conflicting flow rate.

Roundabouts have been used successfully throughout the world and are being used increasingly in the United States, especially since 1990. A recently completed study provides a comprehensive database of roundabout operations for U.S. conditions based on a study of 31 sites (1). The capacity and level of service analysis procedures that follow were developed in that study. The procedures allow the analyst to assess the operational performance of an existing or planned one-lane or two-lane roundabout given traffic demand levels.

While the database on which these procedures are based is the most comprehensive yet developed for U.S. conditions, it has limitations. It covers typical roundabout facilities quite well, but lacks examples of situations where:

- upstream/downstream signals influence the performance of the facility;
- 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; or
- more than two entry lanes are present on one or more approaches.

Both roundabout design practices and the public's use of those roundabouts are still maturing in the U.S. Many of the sites that formed the database for this chapter were less than five 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. U.S. 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 quite possible that volumes (and capacity) will increase in the years to come as more roundabouts are constructed in the U.S. 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.

Intersection analysis models generally fall into two categories. Empirical models rely on field data to develop relationships between geometric features and performance measures such as capacity and delay; these are commonly regression models. Analytical models rely on field measures of driver behavior and an analytic formulation of the

relationship between those field measures and performance measures such as capacity and delay. Gap acceptance models are generally the preferable type of analytical model at unsignalized intersections since they capture driver behavior characteristics directly and can be made site-specific by custom-tuning the values that are 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. Empirical models are often used in these cases where an understanding of driver behavior characteristics is incomplete. Based on recent analysis of U.S. field data, simple, lane-based, empirical regression models are recommended for both single-lane and double-lane roundabouts.

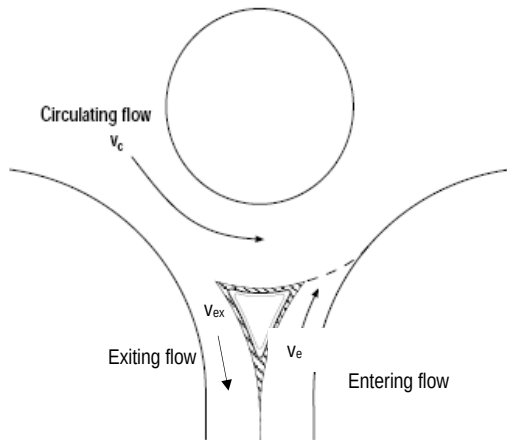
## II. METHODOLOGY – PART C

### OVERVIEW OF METHODOLOGY

#### General

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 17-36.

EXHIBIT 17-36. ANALYSIS ON ONE ROUNDABOUT LEG



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 on when to enter the roundabout. This phenomenon is similar to the effect of the right-turning stream approaching from the left side of a TWSC 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, the inclusion of this effect did not significantly improve the fit of the capacity models to the data and thus is not included herein.

When the conflicting flow approaches zero, the maximum entry flow is given by 3600 divided by the follow-up headway. This condition is similar to the saturation flow rate at an unsignalized intersection. At high levels of conflicting flow, limited priority (where circulating traffic adjusts its headways to allow entering vehicles to enter), priority reversal (where entering traffic forces circulating traffic to yield), and other behaviors may occur, and a simplified gap acceptance model may not give reliable results.

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

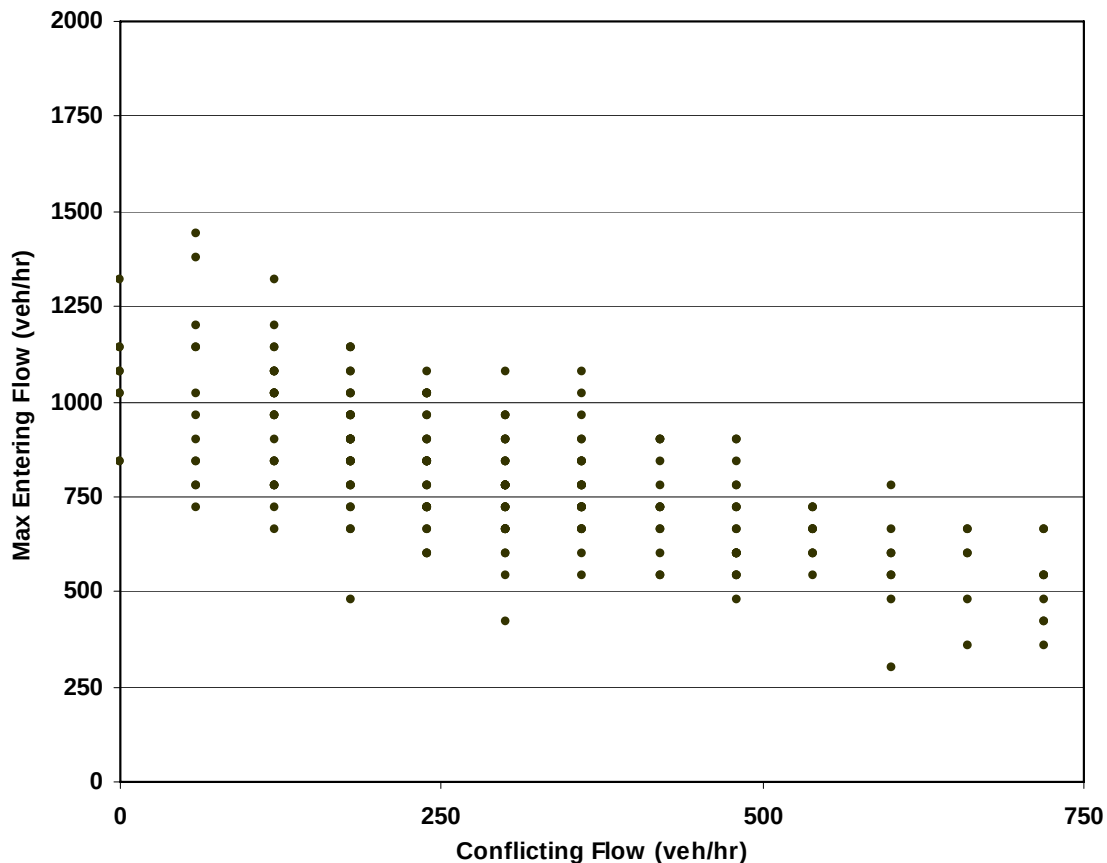
actual circulating flow may therefore increase the capacity of the affected downstream entries during those conditions.

In addition, it has been suggested that an influence of origin-destination patterns on the capacity of a given entry (2, 3). This effect was not identified in a recent study and has not been incorporated into the recommended models herein.

### One-Lane Roundabouts

The analyst should be aware of the large observed variation in driver behavior at roundabouts. Exhibit 17-37 shows observed combinations of entry flow and conflicting flow during one-minute periods of constant queuing, demonstrating the wide scatter of measured entry flows during capacity conditions. Part of this variation can be explained by the instability of one-minute measurements. The remainder of the variation is attributable primarily to the variation in driver behavior, truck percentage, and exiting vehicles. Since there is no external control device regulating flow interactions at roundabouts, driver interactions govern the operation, and this, by its nature, is highly variable.

Exhibit 17-37. Observed Combinations of Entry Flow and Conflicting Flow During One-Minute Periods of Continuous Queuing at Single-Lane Roundabout Entries



The average critical headway also shows a wide variation between sites. Exhibit 17-38 shows the estimated values of critical headway for sixteen roundabout approaches that were considered in the development of the single-lane models (1). The primary sources for the observed variability appear to be the conflicting volume, the characteristics of the vehicle stream, and variations in driver behavior among sites. The data suggest that the effect of minor changes in geometry appears to have a lesser-order effect.

Exhibit 17-38 – Estimated critical headway values for single-lane approaches

| Site (approach)                                               | Sample Size | Mean Critical Headway (seconds) | Standard Deviation of Critical Headway (seconds) |
|---------------------------------------------------------------|-------------|---------------------------------|--------------------------------------------------|
| MD 2/MD 408/MD 422, Lothian, MD (north)                       | 32          | 5.2                             | 1.8                                              |
| MD 2/MD 408/MD 422, Lothian, MD (south)                       | 38          | 5.0                             | 1.0                                              |
| MD 140/MD 832/Antrim Blvd., Taneytown, MD (east)              | 174         | 5.4                             | 1.5                                              |
| US 202/State Route 237, Gorham, ME (east)                     | 198         | 4.5                             | 1.0                                              |
| US 202/State Route 237, Gorham, ME (north)                    | 51          | 5.4                             | 1.2                                              |
| Colorado Ave./Simpson Dr., Bend, OR (south)                   | 225         | 4.7                             | 1.2                                              |
| SR 16 SB Ramp/Borgen Blvd., Gig Harbor, WA (north)            | 43          | 4.7                             | 0.7                                              |
| SR 16 SB Ramp/Borgen Blvd., Gig Harbor, WA (west)             | 121         | 4.4                             | 1.0                                              |
| High School Rd./Madison Ave., Bainbridge Island, WA (south)   | 332         | 5.0                             | 1.5                                              |
| Mile Hill Dr. (Hwy 166)/Bethel Ave., Port Orchard, WA (east)  | 240         | 5.3                             | 1.1                                              |
| Mile Hill Dr. (Hwy 166)/Bethel Ave., Port Orchard, WA (north) | 1627        | 5.2                             | 1.3                                              |
| Mile Hill Dr. (Hwy 166)/Bethel Ave., Port Orchard, WA (south) | 63          | 4.2                             | 0.8                                              |
| NE Inglewood Hill/216th Ave. NE, Sammamish, WA (west)         | 36          | 5.9                             | 1.6                                              |
| I-5 NB Ramp/Quinault Dr./Galaxy Dr., Lacey, WA (south)        | 22          | 5.0                             | 0.8                                              |
| 27th Ave/Union St./Union Loop Rd., Kennewick, WA (north)      | 37          | 5.8                             | 1.1                                              |
| 27th Ave/Union St./Union Loop Rd., Kennewick, WA (south)      | 60          | 5.5                             | 1.5                                              |
| <b>Average</b>                                                | <b>3299</b> | <b>5.1</b>                      | <b>1.2</b>                                       |
| <b>Minimum</b>                                                |             | <b>4.2</b>                      |                                                  |
| <b>Maximum</b>                                                |             | <b>5.9</b>                      |                                                  |

The average follow-up headways showed less variation among sites, as shown in Exhibit 17-39, with most sites exhibiting follow-up headways of 1.0 s to 1.2 s.

**Exhibit 17-39 – Measured follow-up headways for single-lane approaches**

| Site (approach)                                               | Sample Size | Mean Follow-up Headway (seconds) | Standard Deviation of Follow-up Headway (seconds) |
|---------------------------------------------------------------|-------------|----------------------------------|---------------------------------------------------|
| MD 2/MD 408/MD 422, Lothian, MD (north)                       | 637         | 3.2                              | 1.1                                               |
| MD 2/MD 408/MD 422, Lothian, MD (south)                       | 28          | 3.5                              | 1.3                                               |
| MD 140/MD 832/Antrim Blvd., Taneytown, MD (east)              | 1225        | 3.3                              | 1.1                                               |
| US 202/State Route 237, Gorham, ME (east)                     | 522         | 3.4                              | 1.1                                               |
| US 202/State Route 237, Gorham, ME (north)                    | 39          | 4.3                              | 1.5                                               |
| Colorado Ave./Simpson Dr., Bend, OR (south)                   | 262         | 3.1                              | 1.0                                               |
| SR 16 SB Ramp/Borgen Blvd., Gig Harbor, WA (north)            | 33          | 3.4                              | 1.1                                               |
| SR 16 SB Ramp/Borgen Blvd., Gig Harbor, WA (west)             | 86          | 3.3                              | 1.1                                               |
| High School Rd./Madison Ave., Bainbridge Island, WA (south)   | 753         | 3.6                              | 1.2                                               |
| Mile Hill Dr. (Hwy 166)/Bethel Ave., Port Orchard, WA (east)  | 334         | 3.1                              | 1.4                                               |
| Mile Hill Dr. (Hwy 166)/Bethel Ave., Port Orchard, WA (north) | 2282        | 3.2                              | 1.2                                               |
| Mile Hill Dr. (Hwy 166)/Bethel Ave., Port Orchard, WA (south) | 120         | 3.1                              | 1.0                                               |
| NE Inglewood Hill/216th Ave. NE, Sammamish, WA (west)         | 453         | 3.1                              | 1.0                                               |
| I-5 NB Ramp/Quinault Dr./Galaxy Dr., Lacey, WA (south)        | 80          | 2.9                              | 1.1                                               |
| 27th Ave/Union St./Union Loop Rd., Kennewick, WA (north)      | 400         | 2.9                              | 1.1                                               |
| 27th Ave/Union St./Union Loop Rd., Kennewick, WA (south)      | 438         | 2.6                              | 0.9                                               |
| <b>Average</b>                                                | <b>7692</b> | <b>3.2</b>                       | <b>1.1</b>                                        |
| <b>Minimum</b>                                                |             | <b>2.6</b>                       |                                                   |
| <b>Maximum</b>                                                |             | <b>4.3</b>                       |                                                   |

### Multilane Roundabouts

Multilane roundabouts have more than one lane on the circulating roadway and at least one entry. The number of entry, circulating, and exiting lanes may vary throughout the roundabout.

The definition of headways and gaps for multilane facilities is more complicated than it is for single-lane facilities. If the circulating roadway truly functions as a multilane facility, then there are gaps in both the inside and outside lanes that are perceived in some integrated fashion by the motorists on the approach. Many drivers who choose to enter the roundabout via the outside lane will yield to all traffic in the circulatory roadway due to their uncertainty in the path of the circulating vehicles. This uncertainty is more pronounced at roundabouts than other unsignalized intersections due to the curvature of the circulatory roadway. Some drivers, however, will enter next to a vehicle circulating in the inside lane if the circulating vehicle is not perceived to conflict. As a result, the gap acceptance behavior of the outside 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.

For roundabouts with two circulating lanes, which is the only type of multilane roundabout addressed in this chapter, the entries and exits can be either one or two lanes wide. The conditions represented in the database upon which the multilane model is built are as follows: one one-lane entry with two conflicting lanes, one two-lane entry with a single conflicting lane, one one-lane entry with a short flare in conjunction with two conflicting lanes, and five two-lane entries with two conflicting lanes.

There were few instances in the database used to develop the multilane model in which a steady state queue existed on all lanes of a multilane entry. Most commonly, for the two-lane entries, the outside lane had a sustained queue while the inside lane only had sporadic queuing. In general, several factors contribute to the specific assignment of traffic flow to each lane:

1. The specific 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. This is generally accomplished through the use of signs and pavement markings that specifically 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. 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 outer entry lane, for example, even though both lanes could be used.
3. The alignment of the lane relative to the circulatory roadway seems to influence the use of entry lanes where drivers could choose between lanes. Some roundabouts have been designed with a natural alignment of the outer entry lane into the inner lane of the circulatory roadway. Under this design, the inner entry lane is naturally aimed at the central island and thus less comfortable and desirable for drivers. This phenomenon, documented elsewhere (4) as vehicle path overlap, may result in poor lane utilization of the inner 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 should be avoided in the design of new roundabouts.
4. Drivers may be uncertain about lane use when using the roundabout, particularly at roundabouts without any designated lane assignments approaching or circulating through the roundabout. This may contribute to use of the outer lane for left turns, for example, due to 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 always be present to some extent at multilane roundabouts.

Of these items, factors (1) and (2) are common to all intersections and are accounted for in the specific assignment of turning movement patterns to individual lanes. Of the latter two factors, both of which are unique to roundabouts, factor (3) 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 path overlap resulting in poor lane utilization. Factor (4) can be reduced through proper design, particularly through the effective use of lane use arrows and striping. It is difficult to accurately estimate but may be measured at existing roundabouts.

The lane on a given approach with the highest flow is considered to be the “critical lane,” and its performance is used to determine the performance of the approach. This is analogous to the critical movement approach used for TWSC intersections, although the critical lane may serve more than one movement (e.g., left turns and through movements). Consequently, the capacity model focuses first on the performance of the critical entry lane and then expands that result to address the overall capacity and delay for the approach.

The multilane capacity model for the critical lane is based on one-minute observations of continuous queuing in one or more lanes of a multilane roundabout entry.

## CAPACITY

The capacity of a given approach is computed using the following process:

1. Adjust flows to account for vehicle stream characteristics.
2. Determine the entry and conflicting flows for each approach. For multilane approaches, evaluate the approach to determine the flow in each lane on an approach and identify the critical lane on the approach.
3. Compute the maximum possible entry flow using the appropriate model (single-lane model or multilane critical lane model).
4. Compute performance measures for each entry lane.

## Flow adjustments

The flow rate for each movement may be adjusted to account for vehicle stream characteristics using factors given in Exhibit 17-40.

Exhibit 17-40. Passenger Car Equivalents

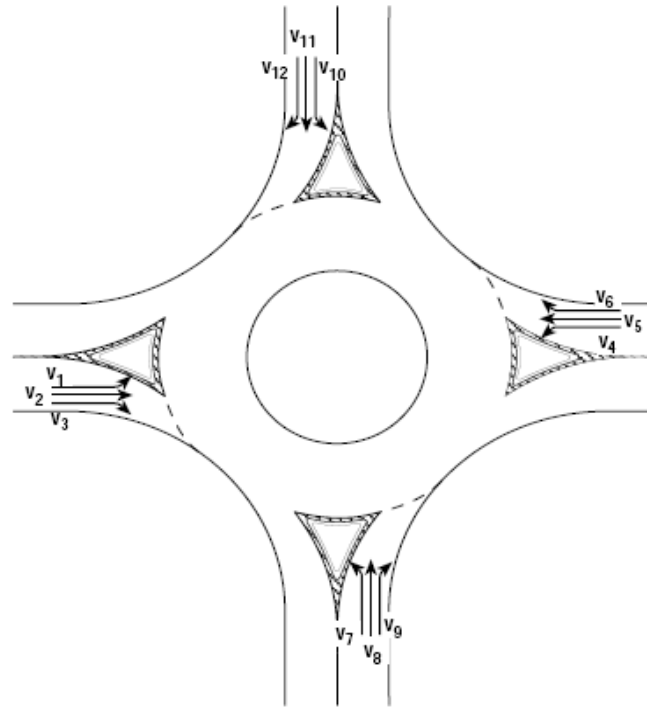
| Vehicle Type  | Passenger Car Equivalent |
|---------------|--------------------------|
| Passenger Car | 1.0                      |
| Heavy Vehicle | 2.0                      |

The flow rate for each movement may also be adjusted to account for peaking characteristics within the peak hour using a Peak Hour Factor. This concept is discussed in more detail, including assumptions for default values where field measurements are unavailable, in Chapter 10.

## Calculation of entry and conflicting flows by lane

In practice, it is necessary to convert the intersection turning movements (volumes  $v_1$  to  $v_{12}$  as shown in Exhibit 17-41) into entry and circulating flows. For example, the conflicting traffic for the entry comprising streams 7, 8 and 9 is streams 1, 2, and 10. Thus for the northbound entry ( $v_7 + v_8 + v_9$ ) the conflicting flow would be equal to  $v_1 + v_2 + v_{10}$ . This methodology can be extended to roundabouts with more or less than four legs. In addition, roundabouts are often used to facilitate U-turns, and these may be readily included in the flow calculations.

Exhibit 17-41. Flow Stream Definitions



The determination of entry flows for multilane approaches is more complicated and requires the determination of flows on a lane-by-lane basis. To determine the assignment of flows to each roundabout entry lane, the following procedure may be used:

1. If the entry has only one lane, the turning movement flows are combined to determine the entry flow.
2. If only one lane is available for left-turning vehicles, 100% of the left-turn traffic is assigned to that lane.
3. If only one lane is available for right-turning vehicles, 100% of the right-turn traffic is assigned to that lane.
4. The remaining traffic is assumed to be distributed equally across all lanes such that the flow in each lane is equal<sup>1</sup>.
5. If a right-turn bypass lane is provided that does not share the same entrance line with the other entry lanes, the flows that are expected to use the right-turn bypass lane are removed from the calculation of the roundabout entry flows.
6. The critical lane is the lane on the approach with the highest flow rate.

### Capacity for Single-Lane Roundabout Entries

The capacity of a one-lane entry to a one-lane roundabout is based on the conflicting flow. The equation for estimating the capacity is given as Equation 17-70.

<sup>1</sup> This assumption may be overridden by real-world observations, knowledge, or judgment that documents a different lane distribution. For example, lane use may be adjusted based on downstream traffic patterns that would bias a particular traffic movement into one or more lanes. In addition, lane use may be adjusted based on the geometric design of the entry to reflect observed or anticipated lane use deficiencies associated with vehicle path overlap.

$$C_{crit} = 1130e^{(-0.0010 v_c)} \quad (17-70)$$

where:

$C_{crit}$  = capacity of the critical lane on the approach, veh/h; and  
 $v_c$  = conflicting flow, veh/h.

The capacity model given above reflects observations made at U.S. roundabouts in 2003. As noted previously, it is expected that capacity at U.S. roundabouts will increase over time with increased driver familiarity. In addition, communities with higher densities of roundabouts may experience a higher degree of driver familiarity and thus potentially higher capacities. Therefore, local calibration of the capacity models is recommended to best reflect local driver behavior.

Substituting variables for the two coefficients in Equation 17-70, it can be shown that the variables can be estimated by field measurements using the expressions in Equations 17-71 through 17-73 as follows:

$$C_{crit} = Ae^{(-Bv_c)} \quad (17-71)$$

$$A = \frac{3600}{t_f} \quad (17-72)$$

$$B = \frac{t_c - t_f / 2}{3600} \quad (17-73)$$

where:

$C_{crit}$  = capacity of the critical lane on the approach, veh/h;  
 $v_c$  = conflicting flow, veh/h;  
 $t_c$  = critical headway, s; and  
 $t_f$  = follow-up headway, s.

Therefore, the proposed capacity model can be calibrated using two parameters: the critical headway,  $t_c$ , and the follow-up headway,  $t_f$ . For reference, the observed values for these parameters were given previously in Exhibits 17-38 and 17-39 and would yield an value for  $A$  of 1125 and a value for  $B$  of 0.00097.

### Capacity for the Critical Lane of Double-Lane Roundabout Entries

Equation 17-74 gives the capacity of the critical lane of a double-lane roundabout entry as follows:

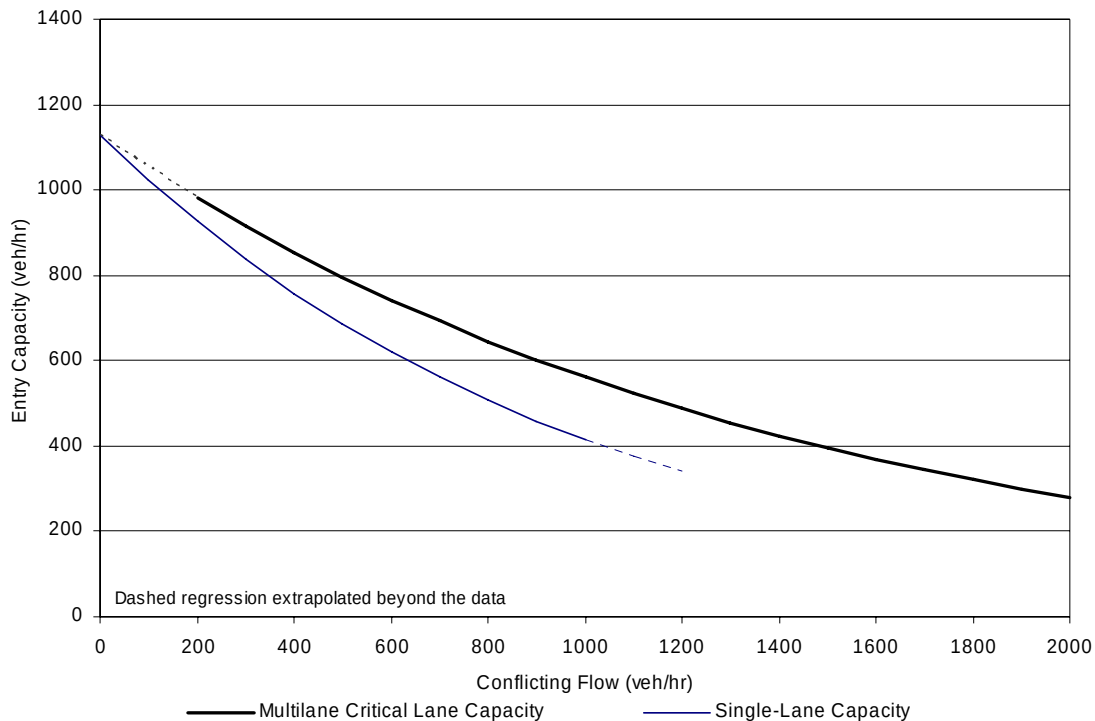
$$C_{crit} = 1130e^{(-0.0007 v_c)} \quad (17-74)$$

where:

$C_{crit}$  = capacity of the critical lane on the approach, veh/h; and  
 $v_c$  = conflicting flow, veh/h.

The intercept of this model has been constrained to match the intercept of the single-lane model due to similar follow-up headways measured in the field for each case. Exhibit 17-42 presents a plot showing Equations 17-70 and 17-74. The dashed lines represent portions of the curves that lie outside the range of observed field data.

Exhibit 17-42: Roundabout entry capacity for single-lane entries and critical lane roundabout entry capacity.



The capacity of the remaining non-critical lanes is assumed to be the same as that of the critical lane if the length of this lane is unlimited. The analysis of a multilane approach relates to the critical lane rather than the approach; therefore, this assumption is not critical to the analysis procedure. If the length of the non-critical lane is short (e.g., it is created by a flare from a single approach lane), the methodology of short lanes (see below) can be used to estimate the capacity of the non-critical lane.

As noted previously, the model given above is based on data collected at roundabouts with up to two entry and two circulating lanes. For design purposes, it may be possible to use the same methodology to determine the capacity for entries with more than two lanes that are opposed by two conflicting lanes. However, the analyst is cautioned that in such cases the overall capacity may be underestimated due to a potential increase in the

number of vehicles in the outer lanes entering adjacent to non-conflicting vehicles circulating in the inner lanes.

The multilane capacity model, as an empirical regression model, has two parameters that can be calibrated: the coefficient in front of the exponential term (1130), and the coefficient within the exponential term ( $-0.0007$ ). As noted previously, the coefficient in front of the exponential term is equivalent to 3600 divided by the follow-up headway, which can be readily measured in the field.

### Short lanes

If a roundabout entry has a flare that creates a second lane of limited length, the capacity of the entry must be modified for taking into account those geometric conditions.

Equation 17-75 gives the total capacity of the roundabout entry with the short-lane effect:

$$C_{appr} = \frac{2}{n+1\sqrt{2}} C_{crit} \quad (17-75)$$

where:

$C_{appr}$  = total capacity on the approach, veh/h; and

$C_{crit}$  = capacity of the critical lane on the approach (Equation 17-70 for entry into a single circulating lane, or Equation 17-74 for entry into two circulating lanes), veh/h

$n$  is the number of vehicle spaces in the flare area in case of single-lane entries and the number of vehicle spaces in the non-critical lane in case of double-lane entries. For normal conditions,  $n = 1$  or  $2$  for single-lane entries and  $n = 3$  to  $6$  for double-lane entries are applicable.

Using Equation 17-75, the capacity of the non-critical lane can be calculated using Equation 17-76.

$$C_{non-crit} = \frac{2}{n+1\sqrt{2}} C_{crit} - C_{crit} \quad (17-76)$$

where the variables are as defined for Equation 17-75.

### Volume-to-Capacity Ratio

The volume-to-capacity ratio for a given approach (for single-lane entries) or critical lane (for multilane entries) can be calculated by dividing the calculated entry capacity into the entry volume for the given approach or lane, respectively.

### Right-Turn Bypass Lanes

Two common types of right-turn bypass lanes are used at both single-lane and multilane roundabouts. These are characterized as follows:

- Type 1 (yield bypass lane): A bypass lane that 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 with the appropriate single-lane or multilane capacity formula given above 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.
- Type 2 (non-yielding bypass lane): This is a bypass lane that merges at a low angle with exiting traffic or that 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.

## Delay, Queues, and Level of Service

### Control Delay

Delay data collected for roundabouts in the U.S. suggest that control delays can be predicted in a manner similar to that used for stop-controlled and signal-controlled intersections. Equation 17-77 shows the model that should be used to estimate average control delay for each lane of an approach of a roundabout.

$$d = \frac{3600}{c} + 900T \left[ \frac{v}{c} - 1 + \sqrt{\left( \frac{v}{c} - 1 \right)^2 + \frac{\left( \frac{3600}{c} \right) \frac{v}{c}}{450T}} \right] \quad (17-77)$$

where:

$d$  = average control delay, sec/veh;

$v$  = flow in subject lane, veh/h;

$c$  = capacity of subject lane, veh/h; and

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

Equation 17-77 is the same as that for stop-controlled intersections except that it does not include the “+ 5” term. 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 if there is no conflicting traffic.

Average control delay for any particular lane is a function of the capacity of the lane and its degree of saturation. The analytical model used to estimate average control delay (Equation 17-77) 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, such as the Kimber-Hollis formulation documented elsewhere (5), may be used.

### Geometric Delay Estimation

A procedure has been developed to estimate geometric delay. This is included in a separate white paper and will be incorporated into this procedure.

### Queue Estimation

Queues for a given lane on an approach are calculated using Equation 17-78 as follows:

$$Q_{95} = 900T \left[ \frac{v}{c} - 1 + \sqrt{\left(1 - \frac{v}{c}\right)^2 + \frac{\left(\frac{3600}{c}\right)\left(\frac{v}{c}\right)}{150T}} \right] \left(\frac{c}{3600}\right) \quad (17-78)$$

where:

$Q_{95}$  = 95<sup>th</sup>-percentile queue, veh;

$v$  = flow in subject lane, veh/h;

$c$  = capacity of subject lane, veh/h; and

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

### Level of Service

Level of service (LOS) for a roundabout is determined by the computed or measured average control delay and is defined for each lane. LOS is not defined for the intersection as a whole. LOS criteria are given in Exhibit 17-43.

Exhibit 17-43. Level-of-Service Criteria for Roundabouts

| Level of Service | Average Control Delay (s/veh) |
|------------------|-------------------------------|
| A                | 0 – 10                        |
| B                | > 10 – 15                     |
| C                | > 15 – 25                     |
| D                | > 25 – 35                     |
| E                | > 35 – 50                     |
| F                | > 50                          |

### III. APPLICATIONS – PART C

The steps required to perform a roundabout analysis are identified below. A worksheet is provided to assist the analyst in completing the computations.

The steps are:

1. Enter the volume data (leg-to-leg flow rates) for each entry and compute the total entering flow rate for each lane.
2. For multilane entries, compute the flow for each entry lane.
3. Compute the conflicting flow for each entry.
4. Determine the capacity of each entry using Equation 17-70 for single-lane entries into single-lane roundabouts and Equation 17-74 for the critical lane of multilane entries.
5. Compute the volume-to-capacity ratio for the critical lane on an entry and for a yield-controlled right-turn bypass lane, if present.
6. Compute the average control delay for each entry lane based on Equation 17-77.
7. Determine the Level of Service for each entry lane using Exhibit 17-43.
8. Compute the average control delay for each approach and for the roundabout as a whole.
9. Compute 95<sup>th</sup>-percentile queues for each lane based on Equation 17-78.

## PART D. EXAMPLE PROBLEMS (ROUNDAOBOUTS)

### **Buena Vista and El Moro**

This sample calculation illustrates the use of the single-lane roundabout capacity analysis procedure.

#### Description

The intersection of Buena Vista and El Moro is a four-legged roundabout similar to the one depicted in Exhibit 17-R1. The roundabout has two right-turn bypass lanes: a westbound right-turn bypass lane that yields to exiting vehicles, and a southbound right-turn bypass lane that forms its own lane adjacent to exiting vehicles.

Exhibit 17-R1 shows the peak-fifteen-minute turning movement flow rates. Heavy vehicle percentages at the intersection are assumed to be negligible.

Exhibit 17-R1. Geometry and traffic volumes for sample problem 1 (TO BE DEVELOPED).

Exhibit 17-R2 shows the worksheet for the capacity calculations. Lines 1-3 contain the turning movement volumes, and lines 4-6 contain right-turn bypass information. Lines 7-10 contain the entry flow calculations, and lines 11-14 contain the conflicting flow calculations; both show how these flows are derived from the turning movements. Lines 15-18 contain the conflicting flow calculations for a Type 1 right-turn bypass lane.

The calculation for any right-turn bypass lanes depends on the type of right-turn bypass lane. For the westbound approaches with a right-turn bypass lane, the right-turn volume is excluded from the westbound entry volume. In addition, because the westbound right-turn bypass lane yields to the conflicting exiting volume, the conflicting exiting volume must be calculated. In this case, it comprises the northbound through movement and the eastbound left turn movement ( $210 + 245 = 455$ ). For the southbound right-turn bypass lane, the right-turn volume is excluded from the southbound entry volume, and no further calculations are needed due to the type of bypass lane.

Exhibit 17-R2. Solution to roundabout sample calculation 1, Roundabout Worksheet

**Worksheet For Capacity Calculations**

| Given Volumes |            | EB          | WB          | NB          | SB             |
|---------------|------------|-------------|-------------|-------------|----------------|
| 1             | LT traffic | $v_1 = 245$ | $v_4 = 100$ | $v_7 = 145$ | $v_{10} = 255$ |
| 2             | TH traffic | $v_2 = 300$ | $v_5 = 395$ | $v_8 = 210$ | $v_{11} = 95$  |
| 3             | RT traffic | $v_3 = 105$ | $v_6 = 620$ | $v_9 = 75$  | $v_{12} = 580$ |

| Bypass Lanes |                       | EB                  | WB                | NB                 | SB                 |
|--------------|-----------------------|---------------------|-------------------|--------------------|--------------------|
| 4            | Type                  | 0 (none)            | 1 (yield)         | 0 (none)           | 2 (non-yield)      |
| 5            | RT volume             | $v_3 = 105$         | $v_6 = 620$       | $v_9 = 75$         | $v_{12} = 580$     |
| 6            | RT volume using entry | $v_{3,entry} = 105$ | $v_{6,entry} = 0$ | $v_{9,entry} = 75$ | $v_{12,entry} = 0$ |

| Entry Flow (veh/hr) |                                             | Entry Volume, $v_e$                |
|---------------------|---------------------------------------------|------------------------------------|
| 7                   | $v_{e,EB} = v_1 + v_2 + v_{3,entry}$        | $v_{e,EB} = 245 + 300 + 105 = 650$ |
| 8                   | $v_{e,WB} = v_4 + v_5 + v_{6,entry}$        | $v_{e,WB} = 100 + 395 + 0 = 495$   |
| 9                   | $v_{e,NB} = v_7 + v_8 + v_{9,entry}$        | $v_{e,NB} = 145 + 210 + 75 = 430$  |
| 10                  | $v_{e,SB} = v_{10} + v_{11} + v_{12,entry}$ | $v_{e,SB} = 255 + 95 + 0 = 350$    |

| Conflicting Flow (veh/hr) |                                    | Conflicting Flow, $v_c$            |
|---------------------------|------------------------------------|------------------------------------|
| 11                        | $v_{c,EB} = v_4 + v_{10} + v_{11}$ | $v_{c,EB} = 100 + 255 + 95 = 450$  |
| 12                        | $v_{c,WB} = v_1 + v_7 + v_8$       | $v_{c,WB} = 245 + 145 + 210 = 600$ |
| 13                        | $v_{c,NB} = v_2 + v_3 + v_{12}$    | $v_{c,NB} = 300 + 105 + 580 = 985$ |
| 14                        | $v_{c,SB} = v_5 + v_6 + v_9$       | $v_{c,SB} = 395 + 620 + 75 = 1090$ |

| Type 1 Right-Turn Bypass Lane Conflicting Flow (veh/hr) |                             | Type 1 Right-Turn Bypass Lane Conflicting Volume, $v_a$ |
|---------------------------------------------------------|-----------------------------|---------------------------------------------------------|
| 15                                                      | $v_{c,EBRT} = v_4 + v_{11}$ | N/A                                                     |
| 16                                                      | $v_{c,WBRT} = v_1 + v_8$    | $v_{c,WBRT} = 245 + 210 = 455$                          |
| 17                                                      | $v_{c,NBRT} = v_2 + v_{10}$ | N/A                                                     |
| 18                                                      | $v_{c,SBRT} = v_5 + v_7$    | N/A                                                     |

Lines 19-25 show the results of the capacity, v/c, control delay, Level of Service, and 95<sup>th</sup>-percentile queue calculations.

|    |                                         | EB   | WB   | WBRT | NB   | SB   | SBRT |
|----|-----------------------------------------|------|------|------|------|------|------|
| 19 | Entry volume, veh/hr                    | 650  | 495  | 620  | 430  | 350  | 580  |
| 20 | Capacity, veh/hr (Eq 17-70)             | 721  | 620  | 717  | 507  | 596  | N/A  |
| 21 | v/c ratio                               | 0.90 | 0.80 | 0.86 | 0.85 | 0.59 | N/A  |
| 22 | Control delay, sec/veh                  | 33.0 | 24.8 | 28.3 | 35.2 | 14.3 | N/A  |
| 23 | LOS                                     | D    | C    | D    | E    | B    | N/A  |
| 24 | Approach control delay, sec/veh         | 33.0 | 26.7 |      | 35.2 | 5.4  |      |
| 25 | Intersection control delay, sec/veh     | 22.9 |      |      |      |      |      |
| 26 | 95 <sup>th</sup> -percentile queue, veh | 11.8 | 7.9  | 10.3 | 8.8  | 3.8  | N/A  |

The calculation of capacity for the eastbound entry given in line 20 is illustrated as follows:

$$c_{EB} = 1130e^{(-0.0010)(450)} = 721 \text{ veh/hr}$$

Further, the v/c ratio for this approach is  $650 / 721 = 0.90$ .

The control delay for the eastbound entry given in line 22 is illustrated as follows:

$$d_{EB} = \frac{3600}{721} + 900(0.25) \left[ \frac{650}{721} - 1 + \sqrt{\left( \frac{650}{721} - 1 \right)^2 + \frac{\left( \frac{3600}{721} \right) \frac{650}{721}}{450(0.25)}} \right] = 33.0 \text{ s/veh}$$

Using Exhibit 17-44, the Level of Service for this entry is LOS D.

The approach control delay is the same as the control delay for the entry for those approaches with no right-turn bypass lanes (eastbound and northbound). For the others, the approach control delay is the average for the entry and bypass lane, weighted by volume. (The control delay for the Type 2 bypass is assumed to be zero.) Similarly, the intersection control delay is the weighted average of the control delays for every movement at the intersection.

## **Walnut and Aspen**

This sample calculation illustrates the use of the multilane roundabout capacity analysis procedure.

### **Description**

The intersection of Walnut and Aspen is a four-legged roundabout similar to the one depicted in Exhibit 17-R3. The roundabout has two lanes on westbound, eastbound, and southbound approaches and one lane on the northbound approach. The two lanes on the southbound approach are designated as left-through and right; the right lane is a short lane with a storage length of 6 vehicles. The eastbound and westbound approaches are designated as left-through and through-right.

Exhibit 17-R3 shows the peak-fifteen-minute turning movement flow rates. Heavy vehicle percentages at the intersection are assumed to be negligible.

Exhibit 27-R3. Geometry and traffic volumes for sample problem 2 (TO BE DEVELOPED).

Exhibit 17-R4 shows the worksheet for the capacity calculations. Lines 1-3 contain the turning movement volumes. Lines 4-10 contain the entry flow calculations by lane, and lines 11-14 contain the conflicting flow calculations; both show how these flows are derived from the turning movements.

Exhibit 17-R4. Solution to roundabout sample calculation 2, Roundabout Worksheet

**Worksheet For Capacity Calculations**

| Given Volumes |            | EB          | WB          | NB          | SB             |
|---------------|------------|-------------|-------------|-------------|----------------|
| 1             | LT traffic | $v_1 = 280$ | $v_4 = 450$ | $v_7 = 50$  | $v_{10} = 240$ |
| 2             | TH traffic | $v_2 = 620$ | $v_5 = 200$ | $v_8 = 60$  | $v_{11} = 60$  |
| 3             | RT traffic | $v_3 = 60$  | $v_6 = 90$  | $v_9 = 120$ | $v_{12} = 400$ |

| Entry Flow (veh/hr) |                                | Entry Volume, $v_e$              |
|---------------------|--------------------------------|----------------------------------|
| 4                   | $v_{e,EB,L} = v_1 + v_{2,L}$   | $v_{e,EB,L} = 280 + 200 = 480$   |
| 5                   | $v_{e,EB,R} = v_{2,R} + v_3$   | $v_{e,EB,R} = 420 + 60 = 480$    |
| 6                   | $v_{e,WB,L} = v_4 + v_{5,L}$   | $v_{e,WB,L} = 450 + 0 = 450$     |
| 7                   | $v_{e,WB,R} = v_{5,R} + v_6$   | $v_{e,WB,R} = 200 + 90 = 290$    |
| 8                   | $v_{e,NB} = v_7 + v_8 + v_9$   | $v_{e,NB} = 50 + 60 + 120 = 230$ |
| 9                   | $v_{e,SB,L} = v_{10} + v_{11}$ | $v_{e,SB,L} = 240 + 60 = 300$    |
| 10                  | $v_{e,SB,R} = v_{12}$          | $v_{e,SB,R} = 400$               |

| Conflicting Flow (veh/hr) |                                    | Conflicting Flow, $v_c$             |
|---------------------------|------------------------------------|-------------------------------------|
| 11                        | $v_{c,EB} = v_4 + v_{10} + v_{11}$ | $v_{c,EB} = 450 + 240 + 60 = 750$   |
| 12                        | $v_{c,WB} = v_1 + v_7 + v_8$       | $v_{c,WB} = 280 + 50 + 60 = 390$    |
| 13                        | $v_{c,NB} = v_1 + v_2 + v_{10}$    | $v_{c,NB} = 280 + 620 + 240 = 1140$ |
| 14                        | $v_{c,SB} = v_4 + v_5 + v_7$       | $v_{c,SB} = 450 + 200 + 50 = 700$   |

The problem presents several scenarios:

- For the eastbound approach, the through volume distributes over the two lanes to balance the flow in each lane.
- For the westbound approach, the left-turn volume, which is restricted to the left lane, is greater than the sum of the through and right-turn volume. Therefore, the left lane acts as a *defacto* left-turn-only lane, with the right lane serving all of the through and right-turn volume.
- For the northbound approach, all of the entering traffic is combined, as it is a single-lane entry.
- For the southbound approach, the left lane is designated as left-through, so only the left-turn and through movements are combined. The right-turning traffic is assigned to the right lane.

Note that no additional lane use adjustments have been made to account for downstream destinations, approach alignment, or observed driver behavior.

Lines 15-24 show the results of the determination of the critical lane and non-critical lane capacities, v/c, control delay, Level of Service, and 95<sup>th</sup>-percentile queue calculations.

|    |                                                 | EB<br>Left<br>Lane | EB<br>Right<br>Lane | WB<br>Left<br>Lane | WB<br>Right<br>Lane | NB   | SB<br>Left<br>Lane | SB<br>Right<br>Lane |
|----|-------------------------------------------------|--------------------|---------------------|--------------------|---------------------|------|--------------------|---------------------|
| 15 | Entry volume,<br>veh/hr                         | 480                | 480                 | 450                | 290                 | 230  | 300                | 400                 |
| 16 | Critical lane?                                  | *                  | *                   | *                  |                     | *    |                    | *                   |
| 17 | Critical Lane<br>Capacity, veh/hr<br>(Eq 17-74) | 668                | 668                 | 860                |                     | 509  |                    | 692                 |
| 18 | Non-Critical<br>Lane Capacity,<br>veh/hr        |                    |                     |                    | 672                 |      | 692                |                     |
| 21 | v/c ratio                                       | 0.72               | 0.72                | 0.52               | 0.43                | 0.45 | 0.43               | 0.58                |
| 22 | Control delay,<br>sec/veh                       | 17.9               | 17.9                | 8.7                | 9.4                 | 12.8 | 9.1                | 12.1                |
| 23 | LOS                                             | C                  | C                   | A                  | A                   | B    | A                  | B                   |
| 24 | Approach control<br>delay, sec/veh              | 17.9               |                     | 9.0                |                     | 12.8 | 10.8               |                     |
| 25 | Intersection<br>control delay,<br>sec/veh       | 13.1               |                     |                    |                     |      |                    |                     |
| 24 | 95 <sup>th</sup> -percentile<br>queue, veh      | 6.1                | 6.1                 | 3.1                | 2.2                 | 2.3  | 2.2                | 3.7                 |

Notes: <sup>1</sup> The assumption of the same capacity for both critical and non-critical lane is

The calculation of capacity for the eastbound entry given in line 17 is illustrated as follows:

$$c_{EB} = 1130e^{(-0.0007)(750)} = 668 \text{ veh/hr}$$

Further, the v/c ratio for this lane is  $480 / 668 = 0.72$ .

The calculation of capacity for the non-critical right lane on the westbound approach is given in Line 18 as follows:

$$c_{WB,R} = \frac{2}{6+1/\sqrt{2}}(860) - 860 = 672 \text{ veh/hr}$$

The southbound left lane is not a short lane and therefore is assumed to have an infinite

length, or  $n = \infty$ . Therefore, the non-critical lane capacity is assumed to be equal to the critical lane capacity.

The control delay for the eastbound entry given in line 20 is illustrated as follows:

$$d_{EB} = \frac{3600}{668} + 900(0.25) \left[ \frac{480}{668} - 1 + \sqrt{\left( \frac{480}{668} - 1 \right)^2 + \frac{\left( \frac{3600}{668} \right) 480}{450(0.25)}} \right] = 17.9 \text{ s/veh}$$

Using Exhibit 17-44, the Level of Service for each lane of this entry is LOS C.

## REFERENCES

### I. PART C - ROUNDABOUTS

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2. Akcelik, R. *Roundabouts with unbalanced flow patterns*. Compendium of Technical Papers, Institute of Transportation Engineers, 2004 Annual Meeting and Exhibition, Lake Buena Vista, Florida, August 1-4, 2004.
3. Krogscheepers, J. C., and C. S. Roebuck. *Unbalanced traffic volumes at roundabouts*. Fourth International Symposium on Highway Capacity, Transportation Research Circular E-C018, Transportation Research Board, 2000, pp. 446-458.
4. Robinson, B.W., L. Rodegerdts, W. Scarbrough, W. Kittelson, R. Troutbeck, W. Brilon, L. Bondzio, K. Courage, M. Kyte, J. Mason, A. Flannery, E. Myers, J. Bunker, and G. Jacquemart. *Roundabouts: An Informational Guide*. Report No. FHWA-RD-00-067. Washington, DC: USDOT, FHWA, June 2000.
5. Kimber, R. M. and E. M. Hollis. *Traffic queues and delays at road junctions*. TRRL Laboratory Report LR 909. Crowthorne, England: Transportation and Road Research Laboratory, 1979.