4 Operation

Chapter 4 Operation

This chapter presents methods for analyzing the operation of an existing or planned roundabout. The methods allow a transportation analyst to assess the operational performance of a facility, given information about the usage of the facility and its geometric design elements. An operational analysis produces two kinds of estimates: (1) the capacity of a facility, i.e., the ability of the facility to accommodate various streams of users, and (2) the level of performance, often measured in terms of one or more measures of effectiveness, such as delay and queues.

The *Highway Capacity Manual* (1) (HCM) defines the *capacity* of a facility as "the maximum hourly rate at which persons or vehicles can reasonably be expected to traverse a point or uniform section of a lane or roadway during a given time period under prevailing roadway, traffic, and control conditions." While capacity is a specific measure that can be defined and estimated, *level of service* (LOS) is a qualitative measure that "characterizes operational conditions within a traffic stream and their perception by motorists and passengers." To quantify level of service, the HCM defines specific *measures of effectiveness* for each highway facility type. *Control delay* is the measure of effectiveness that is used to define level of service at intersections, as perceived by users. In addition to control delay, all intersections cause some drivers to also incur *geometric delays* when making turns. A systems analysis of a roadway network may include geometric delay because of the slower vehicle paths required for turning through intersections. An example speed profile is shown in Chapter 6 to demonstrate the speed reduction that results from geometric delay at a roundabout.

Roundabouts produce both control delay and geometric delay.

While an operational analysis can be used to evaluate the performance of an existing roundabout during a base or future year, its more common function in the U.S. may be to evaluate new roundabout designs.

This chapter:

- Describes traffic operations at roundabouts;
- Lists the data required to evaluate the performance of a roundabout;
- Presents a method to estimate the capacity of five of the six basic roundabout configurations presented in this guide;
- Describes the measures of effectiveness used to determine the performance of a roundabout and a method to estimate these measures; and
- Briefly describes the computer software packages available to implement the capacity and performance analysis procedures.

Appendix A provides background information on the various capacity relationships.

4.1 Traffic Operation at Roundabouts

4.1.1 Driver behavior and geometric elements

A roundabout brings together conflicting traffic streams, allows the streams to safely merge and traverse the roundabout, and exit the streams to their desired directions. The geometric elements of the roundabout provide guidance to drivers approaching, entering, and traveling through a roundabout.

Drivers approaching a roundabout must slow to a speed that will allow them to safely interact with other users of the roundabout, and to negotiate the roundabout. The width of the approach roadway, the curvature of the roadway, and the volume of traffic present on the approach govern this speed. As drivers approach the yield line, they must check for conflicting vehicles already on the circulating roadway and determine when it is safe and prudent to enter the circulating stream. The widths of the approach roadway and entry determine the number of vehicle streams that may form side by side at the yield line and govern the rate at which vehicles may enter the circulating roadway. The size of the inscribed circle affects the radius of the driver's path, which in turn determines the speed at which drivers travel on the roundabout. The width of the circulatory roadway determines the number of vehicles that may travel side by side on the roundabout.

Approach speed is governed by:
- **Approach roadway width**
- **Roadway curvature**
- **Approach volume**

The British (2), French (3), and German (4) analytical procedures are based on empirical relationships that directly relate capacity to both traffic characteristics and roundabout geometry. The British empirical relationships reveal that small sublane changes in the geometric parameters produce significant changes in capacity.

For instance, if some approaches are flared or have additional short lanes, these provide considerably more capacity for two reasons. First, wider entries require wider circulatory roadway widths. This provides for more opportunities for the circulatory traffic to bunch together, thus increasing the number of acceptable opportunities to enter, thereby increasing capacity. Second, the typical size of groups of drivers entering into acceptable opportunities in the circulatory traffic is quite small, so short lanes can be very effective in increasing group sizes, because the short lane is frequently able to be filled.

The British (2) use the inscribed circle diameter, the entry width, the approach (road) half width, the entry radius, and the sharpness of the flare to define the performance of a roundabout. The sharpness of the flare, *S*, is a measure of the rate at which the extra width is developed in the entry flare. Large values of *S* correspond to short, severe flares, and small values of *S* correspond to long, gradual flares (5).

Geometric elements that affect entry capacity include:
- **Approach half width**
- **Entry width**
- **Entry angle**
- **Average effective flare length**

The results of the extensive empirical British research indicate that approach half width, entry width, average effective flare length and entry angle have the most significant effect on entry capacity. Roundabouts fit into two general classes: those with a small inscribed circle diameter of less than 50 m (165 ft.) and those with a diameter above 50 m. The British relationships provide a means of including both of these roundabout types. The inscribed circle diameter has a relatively small effect for inscribed diameters of 50 m (165 ft) or less. The entry radius has little effect on capacity provided that it is 20 m (65 ft) or more. The use of perpendicular entries (70 degrees or more) and small entry radii (less than 15 m [50 ft]) will reduce capacity. The presence of the geometric parameters in the British and French models allow designers to manipulate elements of their design to determine both their operational and safety effects. German research has not been able to find the same influence of geometry, although this may be due to the relatively narrow range of geometries in Germany (4).

Perpendicular entries and small entry radii reduce capacity; inscribed circle diameters of 50 m (165 ft) or less have little effect on capacity.

Thus, the geometric elements of a roundabout, together with the volume of traffic desiring to use a roundabout at a given time, may determine the efficiency with which a roundabout operates.

4.1.2 Concept of roundabout capacity

Roundabout capacity defined.

The capacity of each entry to a roundabout is the maximum rate at which vehicles can reasonably be expected to enter the roundabout from an approach during a given time period under prevailing traffic and roadway (geometric) conditions. An operational analysis considers a precise set of geometric conditions and traffic flow rates defined for a 15-minute analysis period for each roundabout entry. While consideration of Average Annual Daily Traffic volumes (AADT) across all approaches is useful for planning purposes as provided in Exhibit 1-13 and Chapter 3, analysis of this shorter time period is critical to assessing the level of performance of the roundabout and its individual components.

Operational analyses consider 15-minute volumes, as opposed to the daily volumes used in planning analyses.

The capacity of the entire roundabout is not considered, as it depends on many terms. However, Exhibit 1-13 provides threshold average daily traffic volumes for the various categories of roundabouts, assuming four legs. Below these thresholds, a four-legged roundabout with roadways intersecting perpendicularly should have adequate capacity (provided the traffic volumes are reasonably balanced and the geometry does not deviate substantially from those shown on the design templates in Exhibits 1-7 through 1-12). The focus in this chapter on the roundabout entry is similar to the operational analysis methods used for other forms of unsignalized intersections and for signalized intersections. In each case, the capacity of the entry or approach is computed as a function of traffic on the other (conflicting) approaches, the interaction of these traffic streams, and the intersection geometry.

For a properly designed roundabout, the yield line is the relevant point for capacity analysis. The approach capacity is the capacity provided at the yield line. This is determined by a number of geometric parameters in addition to the entry width. On multilane roundabouts it is important to balance the use of each lane, because otherwise some lanes may be overloaded while others are underused. Poorly designed exits may influence driver behavior and cause lane imbalance and congestion at the opposite leg.

The approach capacity is the capacity provided at the yield line.

4.2 Data Requirements

The analysis method described in this chapter requires the specification of traffic volumes for each approach to the roundabout, including the flow rate for each directional movement. Volumes are typically expressed in passenger car vehicles per hour (vph), for a specified 15-minute analysis period. To convert other vehicle types to *passenger car equivalents* (pce), use the conversion factors given in Exhibit 4-1.

Different size vehicles have different capacity impacts; passenger cars are used as the basis for comparison.

Exhibit 4-1. Conversion factors for passenger car equivalents (pce).

Vehicle Type	Passenger Car Equivalent (pce)
Car	1.0
Single-unit truck or bus	1.5
Truck with trailer	2.0
Bicycle or motorcycle	0.5

Source: (6), (7)

Traffic volume data for an urban roundabout should be collected for each directional movement for at least the morning and evening peak periods, since the various movements, and thus approach and circulating volumes, may peak at different times. At rural roundabouts, the analyst should check the requirements of the agency with the jurisdiction of the site. The reader is referred to the *Manual of Transportation Engineering Studies* (8) for a complete discussion of traffic volume data collection methods. Typically, intersection volume counts are made at the intersection stop bar, with an observer noting the number of cars that pass that point over a specified time period. However, particularly with respect to cases in which demand exceeds capacity (when queues do not dissipate within the analysis period), it is important to note that the stop bar counts reflect only the volume that is served, not the demand volume. In this case, care must be taken to collect data upstream of the end of a queue so that true demand volumes are available for analysis.

Entry flow and circulating flow for each approach are the volumes of interest for roundabout capacity analysis, rather than turning movement volumes.

The relationship between the standard origin-to-destination turning movements at an intersection and the circulating and entry flows at a roundabout is important, yet is often complicated to compute, particularly if an intersection has more than four approaches. For conventional intersctions, traffic flow data are accumulated by directional turning movement, such as for the northbound left turn. For roundabouts, however, the data of interest for each approach are the entry flow and the circulating flow. Entry flow is simply the sum of the through, left, and right turn movements on an approach. Circulating flow is the sum of the vehicles from different movements passing in front of the adjacent uptstream splitter island. At existing roundabouts, these flows can simply be measured in the field. Right turns are included in approach volumes and require capacity, but are not included in the circulating volumes downstream because they exit before the next entrance.

For proposed or planned four-legged roundabouts, Equations 4-1 through 4-4 can be applied to determine conflicting (circulating) flow rates, as shown graphically in Exhibit 4-2.

Determining circulating volumes as a function of turning movement volumes.

$$V_{EB,circ} = V_{WB,LT} + V_{SB,LT} + V_{SB,TH} + V_{NB,U\text{-}turn} + V_{WB,U\text{-}turn} + V_{SB,U\text{-}turn} \quad (4\text{-}1)$$

$$V_{WB,circ} = V_{EB,LT} + V_{NB,LT} + V_{NB,TH} + V_{SB,U\text{-}turn} + V_{EB,U\text{-}turn} + V_{NB,U\text{-}turn} \quad (4\text{-}2)$$

$$V_{NB,circ} = V_{EB,LT} + V_{EB,TH} + V_{SB,LT} + V_{WB,U\text{-}turn} + V_{SB,U\text{-}turn} + V_{EB,U\text{-}turn} \quad (4\text{-}3)$$

$$V_{SB,circ} = V_{WB,LT} + V_{WB,TH} + V_{NB,LT} + V_{EB,U\text{-}turn} + V_{NB,U\text{-}turn} + V_{WB,U\text{-}turn} \quad (4\text{-}4)$$

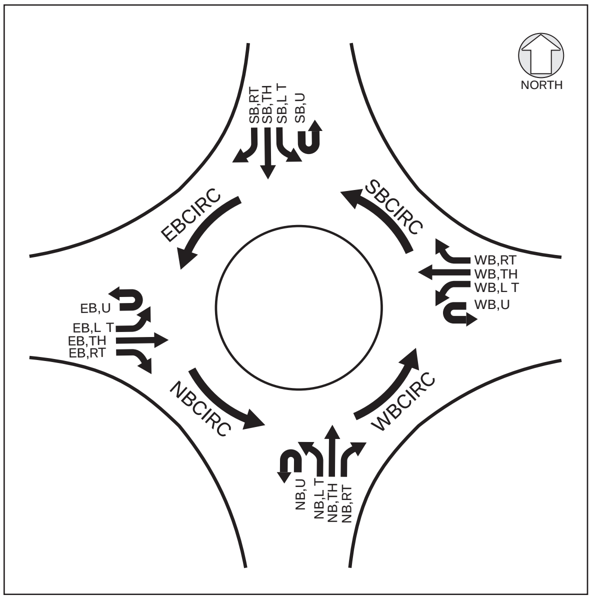


Exhibit 4-2. Traffic flow parameters.

For existing roundabouts, when approach, right-turn, circulating, and exit flows are counted, directional turning movements can be computed as shown in the following example. Equation 4-5 shows the through movement flow rate for the eastbound approach as a function of the entry flow rate for that approach, the exit flow rate for the opposing approach, the right turn flow rate for the subject approach, the right turn flow rate for the approach on the right, and the circulating flow rate for the approach on the right. Other through movement flow rates can be estimated using a similar relationship.

$$V_{EB,TH} = V_{EB,entry} + V_{WB,exit} - V_{EB,RT} - V_{NB,RT} - V_{NB,circ} \quad (4\text{-}5)$$

The left turn flow rate for an approach is a function of the entry flow rate, the through flow rate, and the right turn flow rate for that same approach, as shown in Equation 4-6. Again, other movements' flows are estimated using similar equations.

$$V_{EB,LT} = V_{EB,entry} - V_{EB,TH} - V_{EB,RT} \quad (4\text{-}6)$$

While this method is mathematically correct, it is somewhat sensitive to errors and inconsistencies in the input data. It is important that the counts at all of the locations in the roundabout be made simultaneously. Inconsistencies in the data from counts taken on different days can produce meaningless results, including negative volumes. At a minimum, the sum of the entering and exiting volumes should be checked and adjustments should be made if necessary to ensure that the same amount of traffic enters and leaves the roundabout.

4.3 Capacity

Roundabout approach capacity is dependent on the conflicting circulating flow and the roundabout's geometric elements.

The maximum flow rate that can be accommodated at a roundabout entry depends on two factors: the circulating flow on the roundabout that conflicts with the entry flow, and the geometric elements of the roundabout.

When the circulating flow is low, drivers at the entry are able to enter the roundabout without significant delay. The larger gaps in the circulating flow are more useful to the entering drivers and more than one vehicle may enter each gap. As the circulating flow increases, the size of the gaps in the circulating flow decrease, and the rate at which vehicles can enter also decreases. Note that when computing the capacity of a particular leg, the actual circulating flow to use may be less than demand flows, if the entry capacity of one leg contributing to the circulating flow is less than demand on that leg.

Roundabouts should be designed to operate at no more than 85 percent of their estimated capacity. Beyond this threshold, delays and queues vary significantly from their mean values.

The geometric elements of the roundabout also affect the rate of entry flow. The most important geometric element is the width of the entry and circulatory roadways, or the number of lanes at the entry and on the roundabout. Two entry lanes permit nearly twice the rate of entry flow as does one lane. Wider circulatory roadways allow vehicles to travel alongside, or follow, each other in tighter bunches and so provide longer gaps between bunches of vehicles. The flare length also affects the capacity. The inscribed circle diameter and the entry angle have minor effects on capacity.

As at other forms of unsignalized intersection, when traffic flows on an approach exceed approximately 85 percent of capacity, delays and queue lengths vary significantly about their mean values (with standard deviations of similar magnitude as the means). For this reason, the analysis procedures in some countries (Australia, Germany, and the United Kingdom), and this guide, recommend that roundabouts be designed to operate at no more than 85 percent of their estimated capacity.

As performance data become available for roundabouts designed according to the procedures in this guide in the United States, they will provide a basis for development of operational performance procedures specifically calibrated for U.S. conditions. Therefore, analysts should consult future editions of the *Highway Capacity Manual.*

4.3.1 Single-lane roundabout capacity

Exhibit 4-3 shows the expected capacity for a single-lane roundabout for both the urban compact and urban/rural single-lane designs. The exhibit shows the variation of maximum entry flow as a function of the circulating flow on the roundabout. The calculation of the circulating flow was described previously. The capacity forecast shown in the chart is valid for single-lane roundabouts with inscribed circle diameters of 25 m to 55 m (80 ft to 180 ft). The capacity forecast is based on simplified British regression relationships in Appendix A, which may also be derived with a gap-acceptance model by incorporating limited priority behavior.

Note that in any case, the flow rate downstream of the merge point (between the entry and the next exit) should not be allowed to exceed 1,800 veh/h. Exceeding this threshold may indicate the need for a double-lane entry.

Circulating flow should not exceed 1,800 veh/h at any point in a single-lane roundabout. Exit flows exceeding 1,200 veh/h may indicate the need for a double-lane exit.

The urban compact design is expected to have a reduced capacity, but has significant benefits of reduced vehicle speeds through the roundabout (per the German equations in Appendix A). This increases safety for pedestrians and bicyclists compared with the larger single lane roundabouts. Mini-roundabout capacities may be approximated using the daily maximum service volumes provided for them in Chapter 3, but in any case should not exceed the capacity of the urban compact design.

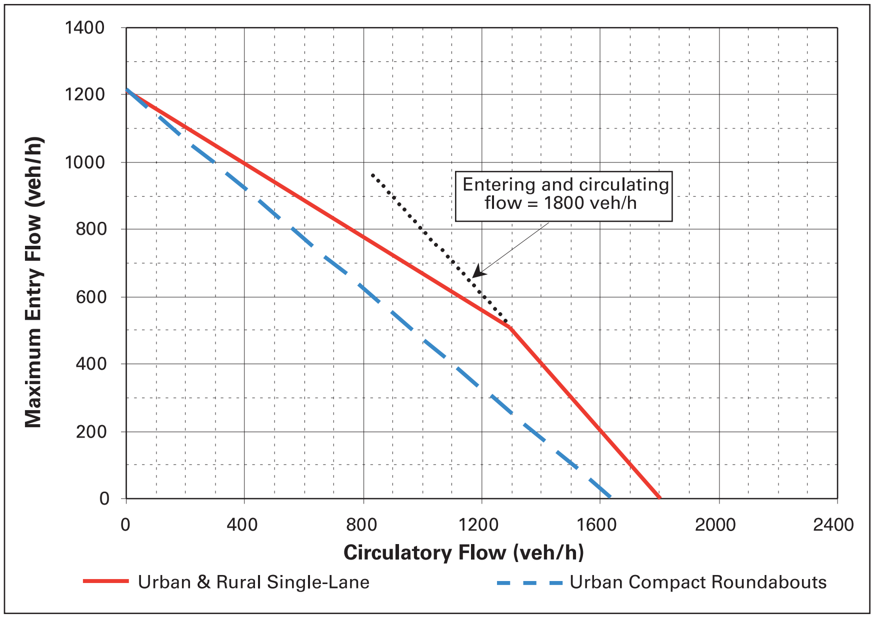


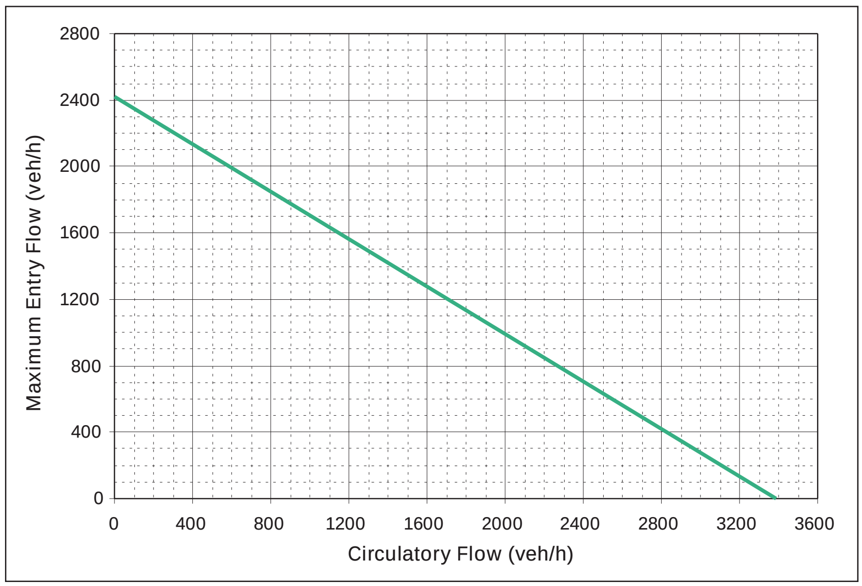
Exhibit 4-3. Approach capacity of a single-lane roundabout.

The slope of the upper line changes because circulating flow downstream from a roundabout entry should not exceed 1,800 veh/h.

4.3.2 Double-lane roundabout capacity

Exhibit 4-4 shows the expected capacity of a double-lane roundabout that is based on the design templates for the urban/rural double-lane roundabouts. The capacity forecast shown in the chart is valid for double-lane roundabouts with inscribed circle diameters of 40 m to 60 m (130 ft to 200 ft). The capacity forecast is based on simplified British regression relationships in Appendix A, which may also be derived with a gap-acceptance model by incorporating limited priority behavior. Larger inscribed diameter roundabouts are expected to have slightly higher capacities at moderate to high circulating flows.

Exhibit 4-4. Approach capacity of a double-lane roundabout.



When flared approaches are used, the circulatory road width must be widened.

See Appendix A for further information on the effects of short lanes at flared entries.

4.3.3 Capacity effect of short lanes at flared entries

By flaring an approach, short lanes may be added at the entry to improve the performance. If an additional short lane is used, it is assumed that the circulatory road width is also increased accordingly. The capacity of the entry is based on the assumption that all entry lanes will be effectively used. The capacity is given by the product of the appropriate factor in Exhibit 4-5 and the capacity of a two-lane roundabout in Exhibit 4-4. Refer to Appendix A for a derivation of these factors (9).

Number of vehicle spaces in the short lane, n_f	Factor (applied to double-lane approach capacity)
0 *	0.500
1	0.707
2	0.794
4	0.871
6	0.906
8	0.926
10	0.939

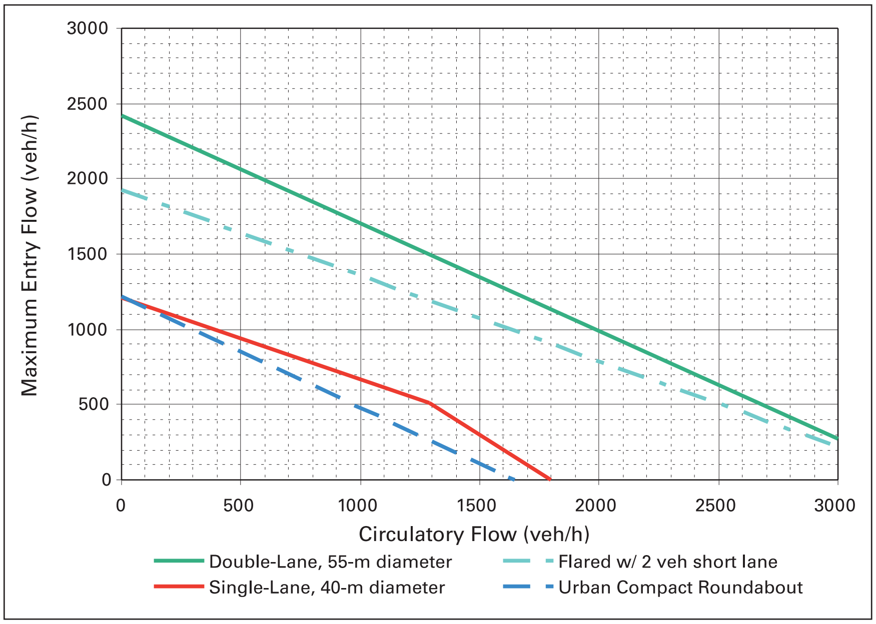
*Used for the case of a single lane entry to a double-lane roundabout.

Exhibit 4-5. Capacity reduction factors for short lanes.

The use of short lanes can nearly double approach capacity, without requiring a two-lane roadway prior to the roundabout.

4.3.4 Comparison of single-lane and double-lane roundabouts

Exhibit 4-6 shows a comparison of the expected capacity for both the single-lane and double-lane roundabouts. Again, it is evident that the number of lanes, or the size of the entry and circulating roadways, has a significant effect on the entry capacity.



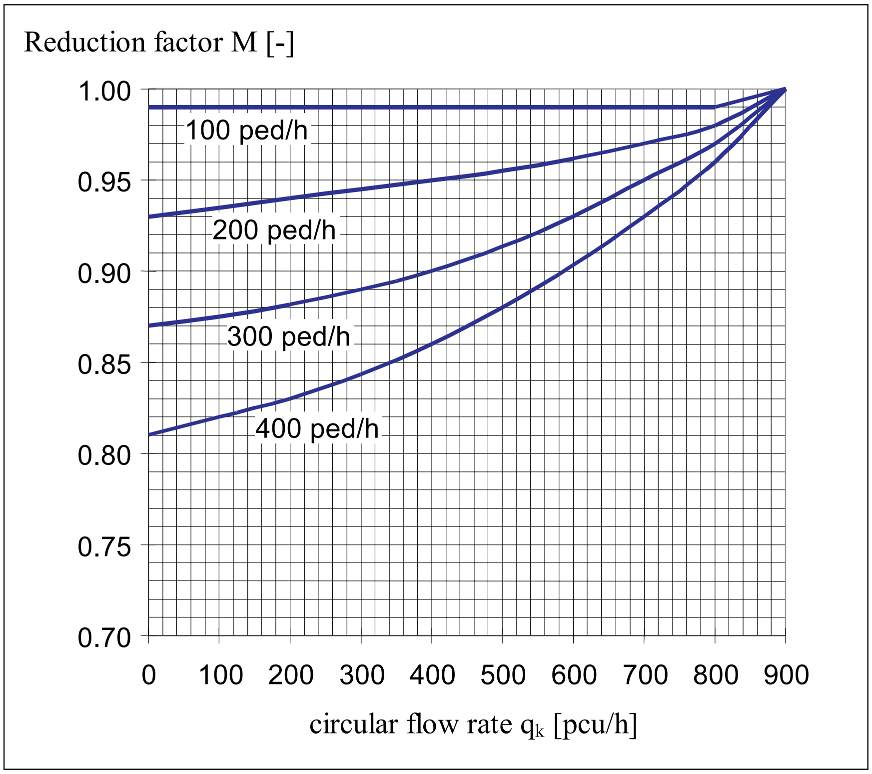
Source (10)

Exhibit 4-6. Capacity comparison of single-lane and double-lane roundabouts.

4.3.5 Pedestrian effects on entry capacity

Pedestrians crossing at a marked crosswalk that gives them priority over entering motor vehicles can have a significant effect on the entry capacity. In such cases, if the pedestrian crossing volume and circulating volume are known, the vehicular capacity should be factored (multiply by *M*) according to the relationship shown in Exhibit 4-7 or Exhibit 4-8 for single-lane and double-lane roundabouts, respectively. Note that the pedestrian impedance decreases as the conflicting vehicle flow increases. The *Highway Capacity Manual* (1) provides additional guidance on the capacity of pedestrian crossings and should be consulted if the capacity of the crosswalk itself is an issue.

Exhibit 4-7. Capacity reduction factor *M* for a single-lane roundabout assuming pedestrian priority.



Source: (10)

The effects of conflicting pedestrians on approach capacity decrease as conflicting vehicular volumes increase, as entering vehicles become more likely to have to stop regardless of whether pedestrians are present.

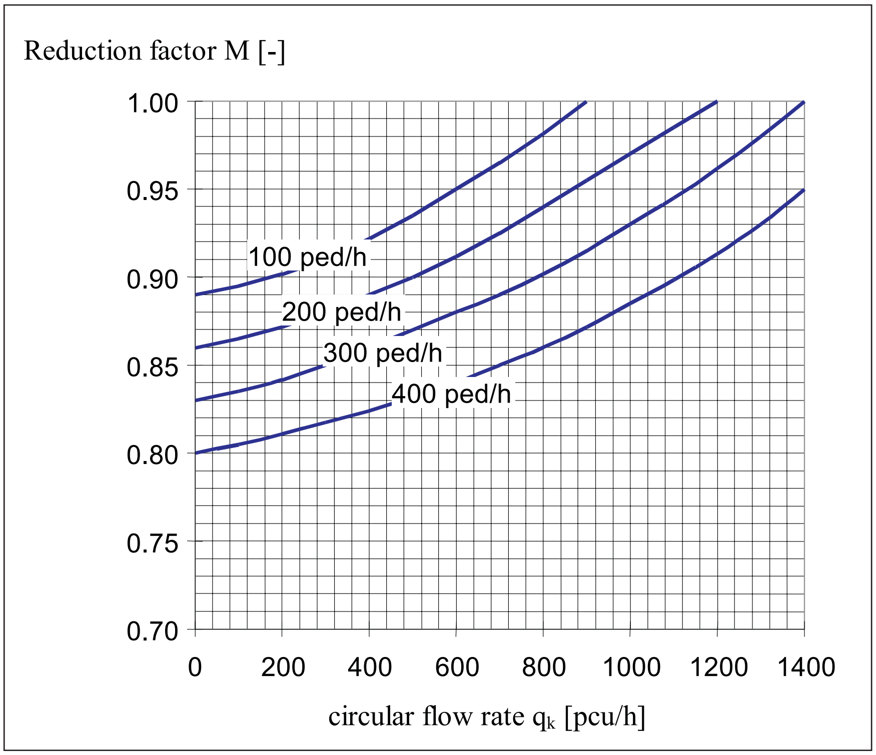


Exhibit 4-8. Capacity reduction factor *M* for a double-lane roundabout assuming pedestrian priority.

Source: (10)

4.3.6 Exit capacity

An exit flow on a single lane of more than 1,400 veh/h, even under good operating conditions for vehicles (i.e., tangential alignment, and no pedestrians and bicyclists) is difficult to achieve. Under normal urban conditions, the exit lane capacity is in the range of 1,200 to 1,300 veh/h. Therefore, exit flows exceeding 1,200 veh/h may indicate the need for a double-lane exit (11).

4.4 Performance Analysis

Three performance measures are typically used to estimate the performance of a given roundabout design: degree of saturation, delay, and queue length. Each measure provides a unique perspective on the quality of service at which a roundabout will perform under a given set of traffic and geometric conditions. Whenever possible, the analyst should estimate as many of these parameters as possible to obtain the broadest possible evaluation of the performance of a given roundabout design. In all cases, a capacity estimate must be obtained for an entry to the roundabout before a specific performance measure can be computed.

Key performance measures for roundabouts:

- **Degree of saturation**
- **Delay**
- **Queue length**

4.4.1 Degree of saturation

Degree of saturation is the ratio of the demand at the roundabout entry to the capacity of the entry. It provides a direct assessment of the sufficiency of a given design. While there are no absolute standards for degree of saturation, the Australian design procedure suggests that the degree of saturation for an entry lane should be less than 0.85 for satisfactory operation. When the degree of saturation exceeds this range, the operation of the roundabout will likely deteriorate rapidly, particularly over short periods of time. Queues may form and delay begins to increase exponentially.

4.4.2 Delay

Delay is a standard parameter used to measure the performance of an intersection. The *Highway Capacity Manual* (1) identifies delay as the primary measure of effectiveness for both signalized and unsignalized intersections, with level of service determined from the delay estimate. Currently, however, the *Highway Capacity Manual* only includes control delay, the delay attributable to the control device. Control delay is the time that a driver spends queuing and then waiting for an acceptable gap in the circulating flow while at the front of the queue. The formula for computing this delay is given in Equation 4-7 (12, based on 13; see also 14). Exhibit 4-9 shows how control delay at an entry varies with entry capacity and circulating flow. Each curve for control delay ends at a volume-to-capacity ratio of 1.0, with the curve projected beyond that point as a dashed line.

$$d = \frac{3600}{c_{m,x}} + 900T \times \left[\frac{v_x}{c_{m,x}} - 1 + \sqrt{\left(\frac{v_x}{c_{m,x}} - 1 \right)^2 + \frac{\left(\frac{3600}{c_{m,x}} \right)\left(\frac{v_x}{c_{m,x}} \right)}{450T}} \right] \tag{4-7}$$

where: d = average control delay, sec/veh;
v_x = flow rate for movement x, veh/h;
c_{mx} = capacity of movement x, veh/h; and
T = analysis time period, h (T = 0.25 for a 15-minute period).

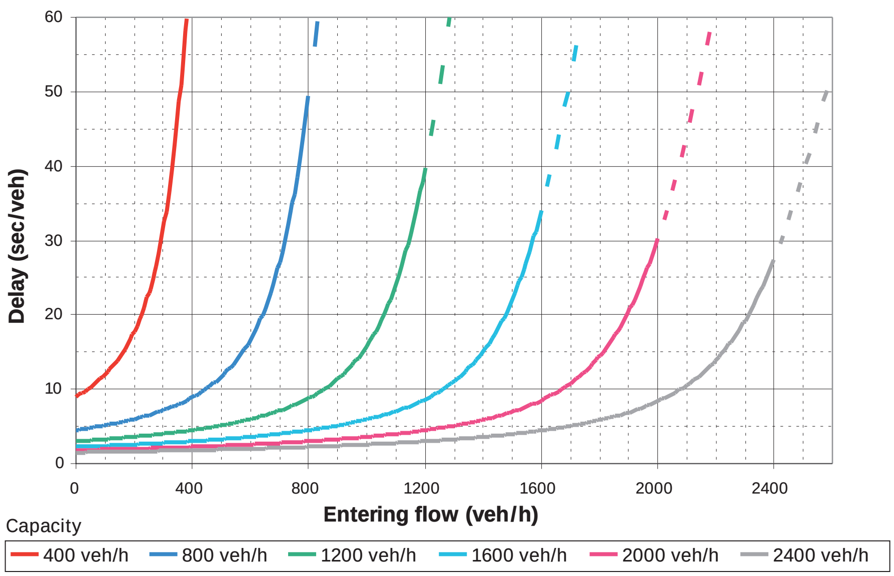


Exhibit 4-9. Control delay as a function of capacity and entering flow.

Note that as volumes approach capacity, control delay increases exponentially, with small changes in volume having large effects on delay. An accurate analysis of delay under conditions near or over saturation requires consideration of the following factors:

- *The effect of residual queues.* Roundabout entries operating near or over capacity can generate significant residual queues that must be accounted for between consecutive time periods. The method presented above does not account for these residual queues. These factors are accounted for in the delay formulae developed by Kimber and Hollis (15); however, these formulae are difficult to use manually.

- *The metering effect of upstream oversaturated entries.* When an upstream entry is operating over capacity, the circulating volume in front of a downstream entry is less than the true demand. As a result, the capacity of the downstream entry is higher than what would be predicted from analyzing actual demand.

For most design applications where target degrees of saturation are no more than 0.85, the procedures presented in this section are sufficient. In cases where it is desired to more accurately estimate performance in conditions near or over capacity, the use of software that accounts for the above factors is recommended.

Geometric delay is the additional time that a single vehicle with no conflicting flows spends slowing down to the negotiation speed, proceeding through the intersection, and accelerating back to normal operating speed. Geometric delay may be an important consideration in network planning (possibly affecting route travel times and choices) or when comparing operations of alternative intersection types. While geometric delay is often negligible for through movements at a signalized or stop-controlled intersection, it can be more significant for turning movements such as those through a roundabout. Calculation of geometric delay requires an estimate of the proportion of vehicles that must stop at the yield line, as well as knowledge of the roundabout geometry as it affects vehicle speeds during entry, negotiation, and exit. Procedures for calculating the number of stops and geometric delay are given in the Australian design guide (16).

4.4.3 Queue length

Queue length is important when assessing the adequacy of the geometric design of the roundabout approaches.

The average queue length (L vehicles) can be calculated by Little's rule, as shown in Equation 4-8 (17):

$$L = v \cdot d / 3600 \qquad (4\text{-}8)$$

where: v = entry flow, veh/h
d = average delay, seconds/veh

Average queue length is equivalent to the vehicle-hours of delay per hour on an approach. It is useful for comparing roundabout performance with other intersection forms, and other planning procedures that use intersection delay as an input.

For design purposes, Exhibit 4-10 shows how the 95th-percentile queue length varies with the degree of saturation of an approach (18, 19). The x-axis of the graph is the degree of saturation, or the ratio of the entry flow to the entry capacity. Individual lines are shown for the product of T and entry capacity. To determine the 95th-percentile queue length during time T, enter the graph at the computed degree of saturation. Move vertically until the computed curve line is reached. Then move horizontally to the left to determine the 95th-percentile queue length. Alternatively, Equation 4-8 can be used to approximate the 95th-percentile queue. Note that the graph and equation are only valid where the volume-to-capacity ratio immediately before and immediately after the study period is no greater than 0.85 (in other words, the residual queues are negligible).

$$Q_{95} \approx 900T\left[\frac{v_x}{c_{m,x}} - 1 + \sqrt{\left(1 - \frac{v_x}{c_{m,x}}\right)^2 + \frac{\left(\frac{3600}{c_{m,x}}\right)\left(\frac{v_x}{c_{m,x}}\right)}{150T}}\right]\left(\frac{c_{m,x}}{3600}\right) \quad (4\text{-}9)$$

where:
Q_{95} = 95th percentile queue, veh,
v_x = flow rate for movement x, veh/h,
$c_{m,x}$ = capacity of movement x, veh/h, and
T = analysis time period, h (0.25 for 15-minute period).

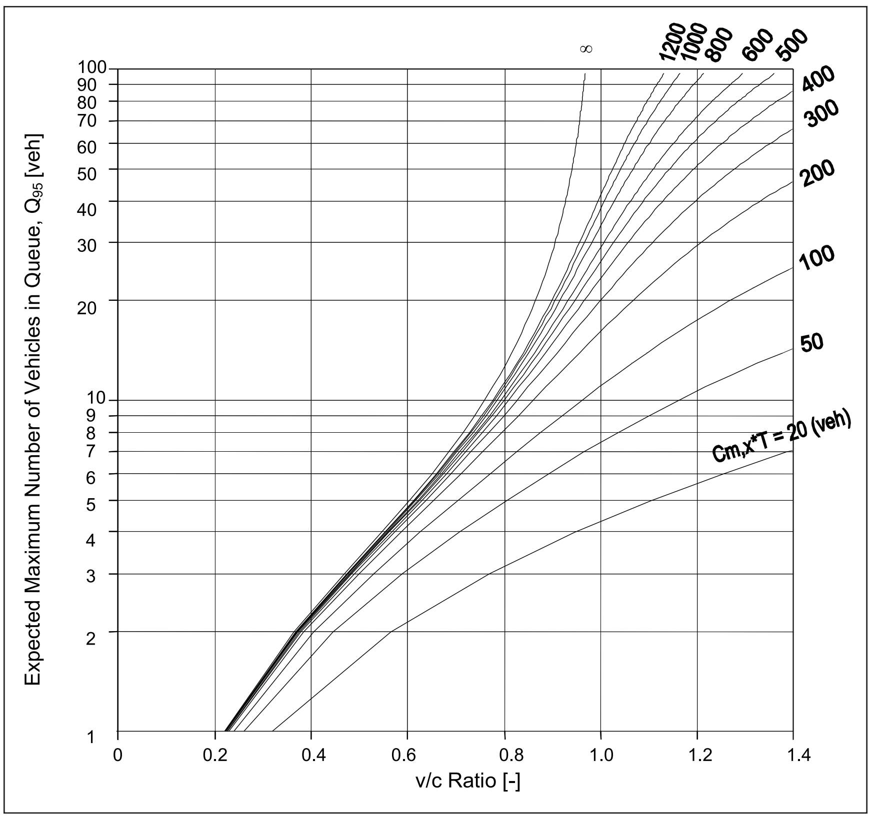


Exhibit 4-10. 95th-percentile queue length estimation.

Source: (19)

4.4.4 Field observations

The analyst may evaluate an existing roundabout to determine its performance and whether changes to its design are needed. Measurements of vehicle delay and queuing can be made using standard traffic engineering techniques. In addition, the analyst can perform a qualitative assessment of the roundabout performance. The following list indicates conditions for which corrective design measures should be taken (20). If the answers to these questions are negative, no corrective actions need be taken.

Points to consider for a qualitative assessment of roundabout performance.

- Do drivers stop unnecessarily at the yield point?
- Do drivers stop unnecessarily within the circulating roadway?
- Do any vehicles pass on the wrong side of the central island?
- Do queues from an external bottleneck back up into the roundabout from an exit road?
- Does the actual number of entry lanes differ from those intended by the design?
- Do smaller vehicles encroach on the truck apron?
- Is there evidence of damage to any of the signs in the roundabout?
- Is there any pedestrian activity on the central island?
- Do pedestrians and cyclists fail to use the roundabout as intended?
- Are there tire marks on any of the curb surfaces to indicate vehicle contact?
- Is there any evidence of minor accidents, such as broken glass, pieces of rim, etc., on the approaches or the circulating roadway?
- Is there any gravel or other debris collected in nontraveled areas that could be a hazard to bicycles or motorcyclists?
- Are the vehicle speeds appropriate?

4.5 Computer Software for Roundabouts

While the analytical procedures of different countries are not very complex, they are repetitive and time consuming, so most of these procedures have been implemented in software. A summary of current (as of 1999) software products and the analytical procedures that they implement is presented in Exhibit 4-11. The reader is also advised to consult the latest version of the U.S. *Highway Capacity Manual.* While the procedures provided in this chapter are recommended for most applications covered by this guide, models such as ARCADY, RODEL, SIDRA, KREISEL, or GIRABASE may be consulted to determine the effects of geometric parameters, particularly for multilane roundabouts outside the realm of this guide, or for fine-tuning designs to improve performance. Note that many of these models represent different underlying data or theories and will thus produce different results. Chapter 8 provides some information on microscopic simulation modeling which may be useful alternatives analysis in systems context.

Exhibit 4-11. Summary of roundabout software products for operational analysis.

Name	Scope	Application and Qualities (1999 versions)
ARCADY	All configurations	British method (50 percent confidence limits). Capacity, delay, and queuing. Includes projected number of crashes per year. Data were collected at extensive field studies and from experiments involving drivers at temporary roundabouts. Empirical relationships were developed from the data and incorporated into ARCADY. This model reflects British driving behavior and British roundabout designs. A prime attribute is that the capacities it predicts have been measured.
RODEL	All configurations including multiple roundabout interactions	British method (user-specified confidence limits). Capacity, delay, and queuing. Includes both an evaluation mode (geometric parameters specified) and a design mode (performance targets specified). Includes a crash prediction model. RODEL uses the British empirical equations. It also assists the user in developing an appropriate roundabout for the traffic conditions.
SIDRA	All configurations and other control types	Australian method, with analytical extensions. Capacity, delay, queue, fuel, and environmental measures. Also evaluates two-way stop-controlled, all-way stop controlled, and signalized intersections. It also gives roundabout capacities from U.S. HCM 1997 and German procedures. SIDRA is based on gap acceptance processes. It uses field data for the gap acceptance parameters to calibrate the model. There has been limited field evaluation of the results although experience has shown that the results fit Australian and U.S. single-lane (21) roundabout conditions satisfactorily. An important attribute is that the user can alter parameters to easily reflect local driving.
HCS-3	Single-lane roundabouts with a limited range of volumes	U.S. HCM 1997 method. Limited to capacity estimation based on entering and circulating volume. Optional gap acceptance parameter values provide both a liberal and conservative estimate of capacity. The data used to calibrate the models were recorded in the U.S. The two curves given reflect the uncertainty from the results. The upper-bound average capacities are anticipated at most roundabouts. The lower bound results reflect the operation that might be expected until roundabouts become more common.
KREISEL	All configurations	Developed in Germany. Offers many user-specified options to implement the full range of procedures found in the literature from U.S. (including this chapter), Europe, Britain, and Australia. KREISEL gives the average capacity from a number of different procedures. It provides a means to compare these procedures.
GIRABASE	All configurations	French method. Capacity, delay, and queuing projections based on regression. Sensitive to geometric parameters. Gives average values.

4.6 References

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5 Safety

Chapter 5 Safety

Roundabouts may improve the safety of intersections by eliminating or altering conflict types, by reducing speed differentials at intersections, and by forcing drivers to decrease speeds as they proceed into and through the intersection. Though roundabout crash records in the United States are limited, the experiences of other countries can be used to help design roundabouts in this country. Understanding the sensitivity of geometric element parameters, along with the crash experience, will assist the designer in optimizing the safety of all vehicle occupants, pedestrians, and bicyclists.

Roundabouts may improve intersection safety by:

- **Eliminating or altering conflicts**
- **Decreasing speeds into and through the intersection**
- **Decreasing speed differentials**

5.1 Introduction

Many studies have found that one of the benefits of roundabout installation is the improvement in overall safety performance. Several studies in the U.S., Europe, and Australia have found that roundabouts perform better in terms of safety than other intersection forms (1, 2, 3, 4). In particular, single-lane roundabouts have been found to perform better than two-way stop-controlled (TWSC) intersections in the U.S. (5). Although the frequency of reported crashes is not always lower at roundabouts, the reduced injury rates are usually reported (6). Safety is better at small and medium capacity roundabouts than at large or multilane roundabouts (1, 7). While overall crash frequencies have been reduced, the crash reductions are most pronounced for motor vehicles, less pronounced for pedestrians, and equivocal for bicyclists, depending on the study and bicycle design treatments (4, 6, 7). Crash statistics for various user groups are reported in Section 5.3.

The reasons for the increased safety level at roundabouts are:

- Roundabouts have fewer conflict points in comparison to conventional intersections. The potential for hazardous conflicts, such as right angle and left turn head-on crashes is eliminated with roundabout use. Single-lane approach roundabouts produce greater safety benefits than multilane approaches because of fewer potential conflicts between road users, and because pedestrian crossing distances are short.
- Low absolute speeds associated with roundabouts allow drivers more time to react to potential conflicts, also helping to improve the safety performance of roundabouts.
- Since most road users travel at similar speeds through roundabouts, i.e., have low relative speeds, crash severity can be reduced compared to some traditionally controlled intersections.
- Pedestrians need only cross one direction of traffic at a time at each approach as they traverse roundabouts, as compared with unsignalized intersections. The conflict locations between vehicles and pedestrians are generally not affected by the presence of a roundabout, although conflicting vehicles come from a more defined path at roundabouts (and thus pedestrians have fewer places to check for conflicting vehicles). In addition, the speeds of motorists entering and exiting a roundabout are reduced with good design. As with other crossings

requiring acceptance of gaps, roundabouts still present visually impaired pedestrians with unique challenges, as described in Chapter 2.

For the design of a new roundabout, safety can be optimized not only by relying on recorded past performance of roundabouts in general, but primarily by applying all design knowledge proven to impact safety. For optimum roundabout safety and operational performance the following should be noted:

- Minimizing the number of potential conflicts at any geometric feature should reduce the multiple vehicle crash rate and severity.
- Minimizing the potential relative speed between two vehicles at the point of conflict will minimize the multiple vehicle crash rate and severity (it may also optimize capacity). To reduce the potential relative speed between vehicles, either the absolute speeds of both vehicles need to be reduced or the angle between the vehicle paths needs to be reduced. Commuter bicyclist speeds can range from 20 to 25 km/h (12 to 15 mph) and designs that constrain the speeds of motor vehicles to similar values will minimize the relative speeds and improve safety. Lower absolute speeds will also assist pedestrian safety.
- Limiting the maximum change in speed between successive horizontal geometric elements will minimize the single vehicle crash rate and severity.

5.2 Conflicts

Conflict points occur where one vehicle path crosses, merges or diverges with, or queues behind the path of another vehicle, pedestrian, or bicycle.

The frequency of crashes at an intersection is related to the number of *conflict points* at an intersection, as well as the magnitude of conflicting flows at each conflict point. A conflict point is a location where the paths of two motor vehicles, or a vehicle and a bicycle or pedestrian queue, diverge, merge, or cross each other.

Besides conflicts with other road users, the central island of a roundabout presents a particular hazard that may result in over-representation of single-vehicle crashes that tend to occur during periods of low traffic volumes. At cross intersections, many such violations may go unrecorded unless a collision with another vehicle occurs.

Conflicts can arise from both legal and illegal maneuvers; many of the most serious crashes are caused by failure to observe traffic control devices.

The following sections present a variety of conflicts among vehicles, bicycles, and pedestrians. Both legal conflicts (queuing at an intersection, merging into a traffic stream) and conflicts prohibited by law or by traffic control devices (failure to yield to pedestrians, running a stop sign) have been included for completeness. Even though traffic control devices can significantly reduce many conflicts, they can not eliminate them entirely due to violations of those devices. Many of the most serious crashes are caused by such violations.

As with crash analyses, conflict analyses are more than the simple enumeration of the number of conflicts. A conflict analysis should account for the following factors:

- Existence of conflict point;

- Exposure, measured by the product of the two conflicting stream volumes at a given conflict point;
- Severity, based on the relative velocities of the conflicting streams (speed and angle); and
- Vulnerability, based on the ability for a member of each conflicting stream to survive a crash.

5.2.1 Vehicle conflicts

5.2.1.1 Single-lane roundabouts

Exhibit 5-1 presents a diagram of vehicle-vehicle conflict points for a traditional three-leg ("T") intersection and a three-leg roundabout. As the figure shows, the number of vehicle-vehicle conflict points for roundabouts decreases from nine to six for three-leg intersections. Note that these diagrams do not take into account the ability to separate conflicts in space (through the use of separate left or right turning lanes) or time (through the use of traffic control devices such as stop signs or traffic signals).

Roundabouts bring the simplicity of a "T" intersection to intersections with more than three legs.

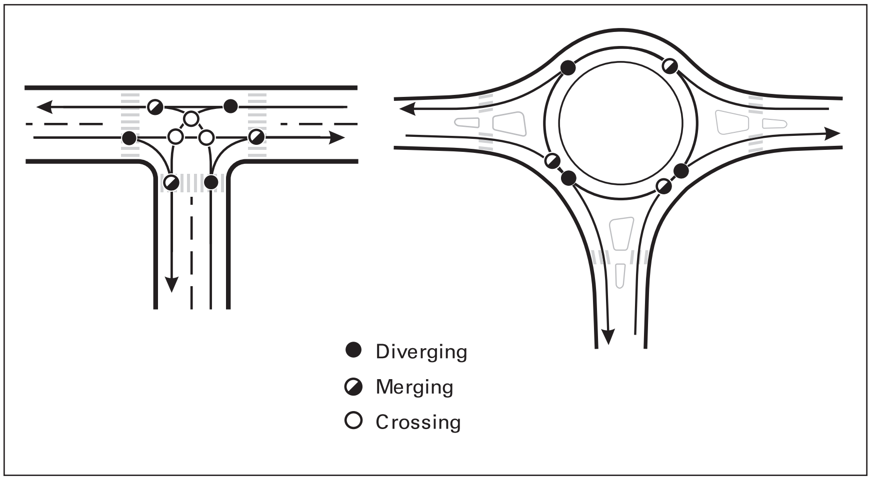
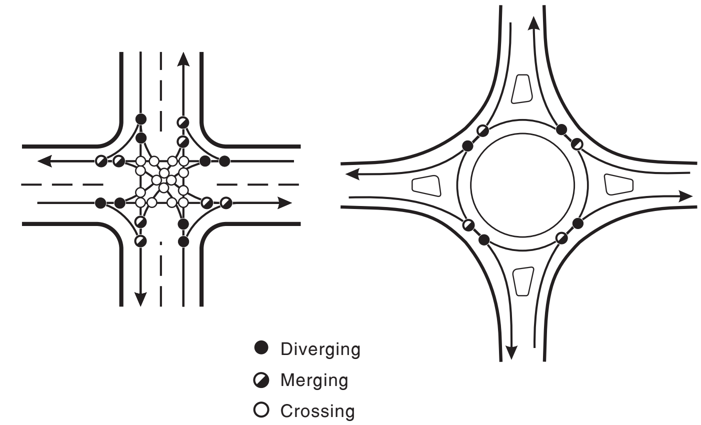


Exhibit 5-1. Vehicle conflict points for "T" Intersections with single-lane approaches.

Exhibit 5-2 presents similar diagrams for a traditional four-leg ("X" or "cross") intersection and a four-leg roundabout. As the figure shows, the number of vehicle-vehicle conflict points for roundabouts decreases from 32 to 8 for four-leg intersections.

Exhibit 5-2. Vehicle conflict point comparison for intersections with single-lane approaches.



A four-leg single-lane roundabout has 75% fewer vehicle conflict points—compared to a conventional intersection.

Conflicts can be divided into three basic categories, in which the degree of severity varies, as follows:

- *Queuing conflicts.* These conflicts are caused by a vehicle running into the back of a vehicle queue on an approach. These types of conflicts can occur at the back of a through-movement queue or where left-turning vehicles are queued waiting for gaps. These conflicts are typically the least severe of all conflicts because the collisions involve the most protected parts of the vehicle and the relative speed difference between vehicles is less than in other conflicts.
- *Merge and diverge conflicts.* These conflicts are caused by the joining or separating of two traffic streams. The most common types of crashes due to merge conflicts are sideswipes and rear-end crashes. Merge conflicts can be more severe than diverge conflicts due to the more likely possibility of collisions to the side of the vehicle, which is typically less protected than the front and rear of the vehicle.
- *Crossing conflicts.* These conflicts are caused by the intersection of two traffic streams. These are the most severe of all conflicts and the most likely to involve injuries or fatalities. Typical crash types are right-angle crashes and head-on crashes.

Crossing conflicts are the most severe and carry the highest public cost.

As Exhibit 5-1 and Exhibit 5-2 show, a roundabout reduces vehicular crossing conflicts for both three- and four-leg intersections by converting all movements to right turns. Again, separate turn lanes and traffic control (stop signs or signalization) can often reduce but not eliminate the number of crossing conflicts at a traditional intersection by separating conflicts in space and/or time. However, the most severe crashes at signalized intersections occur when there is a violation of the traffic control device designed to separate conflicts by time (e.g., a right-angle collision due to running a red light, and vehicle-pedestrian collisions). Therefore, the ability of single-lane roundabouts to reduce conflicts through physical, geometric features has been demonstrated to be more effective than the reliance on driver obedience of traffic control devices.

5.2.1.2 Double-lane roundabouts

In general, double-lane roundabouts have some of the same safety performance characteristics as their simpler single-lane counterparts. However, due to the presence of additional entry lanes and the accompanying need to provide wider circulatory and exit roadways, double lane roundabouts introduce additional conflicts not present in single-lane roundabouts. This makes it important to use the minimum required number of entry, circulating and exit lanes, subject to capacity considerations. For example, according to United Kingdom roundabout crash models, for a 10,000 entering Average Daily Traffic (ADT), flaring the entry width from one to two lanes is likely to increase injury crashes by 25 percent (8).

Double-lane roundabouts have some of the same safety performance characteristics as single-lane roundabouts, but introduce additional conflicts.

The number of vehicular and pedestrian conflicts points in both conventional intersections and roundabouts increases considerably when they have additional approach lanes. The designer is encouraged to graphically determine conflicts for a particular location, as this information can raise awareness of design issues and may be useful in public presentations.

The types of conflicts present in multilane roundabouts that do not exist in single-lane roundabouts occur when drivers use the incorrect lane or make an improper turn. These types of conflicts are depicted in Exhibit 5-3 and Exhibit 5-4, respectively. While these types of conflicts can also be present in other intersection forms, they can be prevalent with drivers who are unfamiliar with roundabout operation. The conflicts depicted in Exhibit 5-4, in particular, can be created by not providing a proper design geometry that allows vehicles to travel side-by-side throughout the entire roundabout (see Chapter 6). Crashes resulting from both types of conflicts can also be reduced through proper driver education.

Incorrect lane use and incorrect turns are multilane roundabout conflicts that do not exist in single-lane roundabouts.

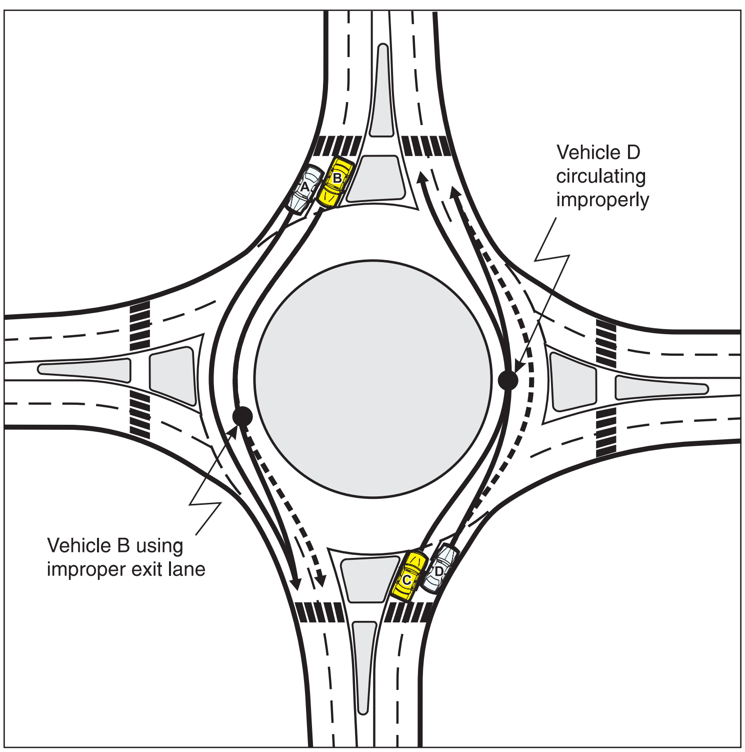
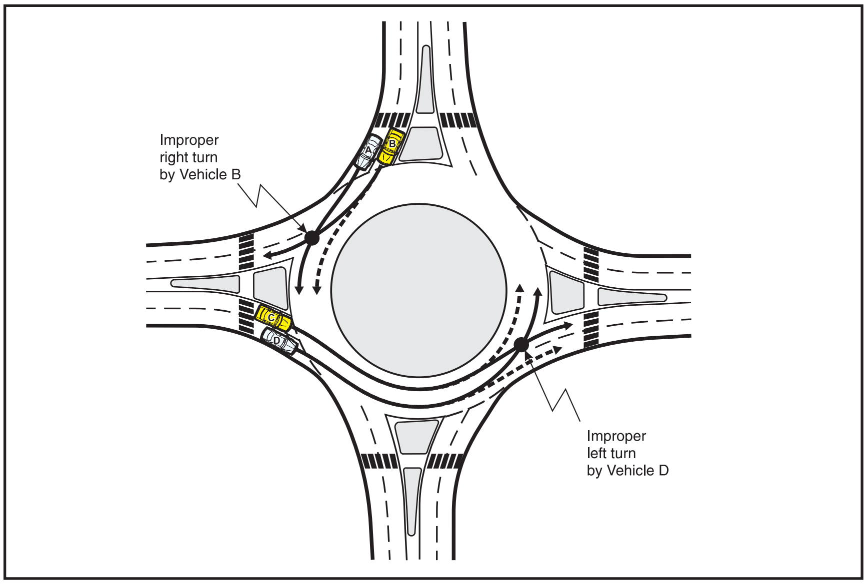


Exhibit 5-3. Improper lane-use conflicts in double-lane roundabouts.

Exhibit 5-4. Improper turn conflicts in double-lane roundabouts.



As with single-lane roundabouts, the most severe vehicular crossing conflicts are eliminated and replaced by less severe merging conflicts. The additional conflicts unique to multilane roundabouts are generally low-speed sideswipe conflicts that typically have low severity. Therefore, although the number of conflict points increases at multilane roundabouts when compared to a single lane roundabouts, the overall severity of conflicts is generally less than alternative intersection control.

5.2.2 Pedestrian conflicts

Vehicle-pedestrian conflicts can be present at every intersection, even those with minimal pedestrian volume. The following sections examine pedestrian conflicts at signalized intersections and at roundabouts.

Signalized intersections offer the opportunity to reduce the likelihood of pedestrian-vehicle conflicts through the use of signal phasing that allows only a few movements to move legally at any given time. Exhibit 5-5 summarizes the typical pedestrian conflicts present on one approach to a signalized intersection. As the exhibit shows, a pedestrian crossing at a typical signalized intersection (permitted or protected-permitted left turns, right turns on red allowed) faces four potential vehicular conflicts, each coming from a different direction:

- Crossing movements on red (typically high-speed, illegal)
- Right turns on green (legal)
- Left turns on green (legal for protected-permitted or permitted left turn phasing)
- Right turns on red (typically legal)

Types of pedestrian crossing conflicts present at signalized intersections.

In terms of exposure, the illegal movements should be accorded a lower weight than legal conflicts. However, they may be accorded an offsetting higher weight in terms of severity. For an intersection with four single-lane approaches, this results in a total of 16 pedestrian-vehicle conflicts.

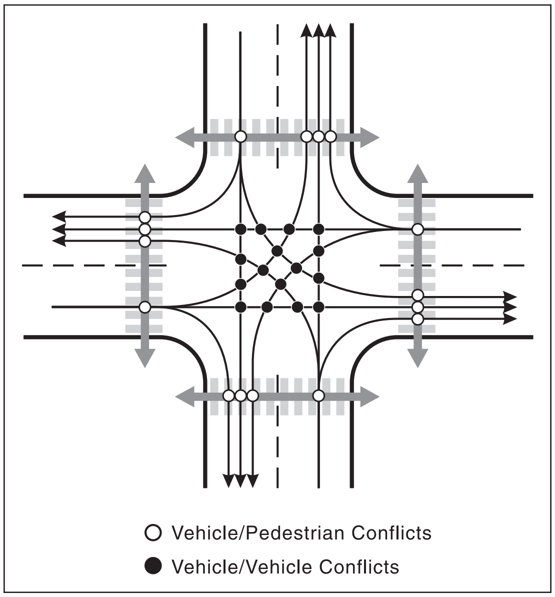


Exhibit 5-5. Vehicle-pedestrian conflicts at signalized intersections.

Pedestrians at roundabouts, on the other hand, face two conflicting vehicular movements on each approach, as depicted in Exhibit 5-6:

- Conflict with entering vehicles; and
- Conflict with exiting vehicles.

The direction conflicting vehicles will arrive from is more predictable for pedestrians at roundabouts.

At conventional and roundabout intersections with multiple approach lanes, an additional conflict is added with each additional lane that a pedestrian must cross.

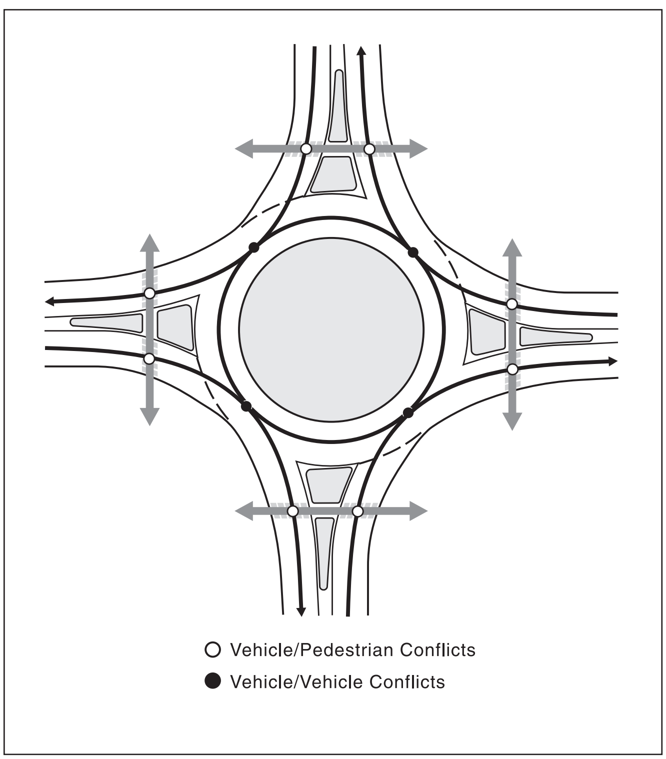
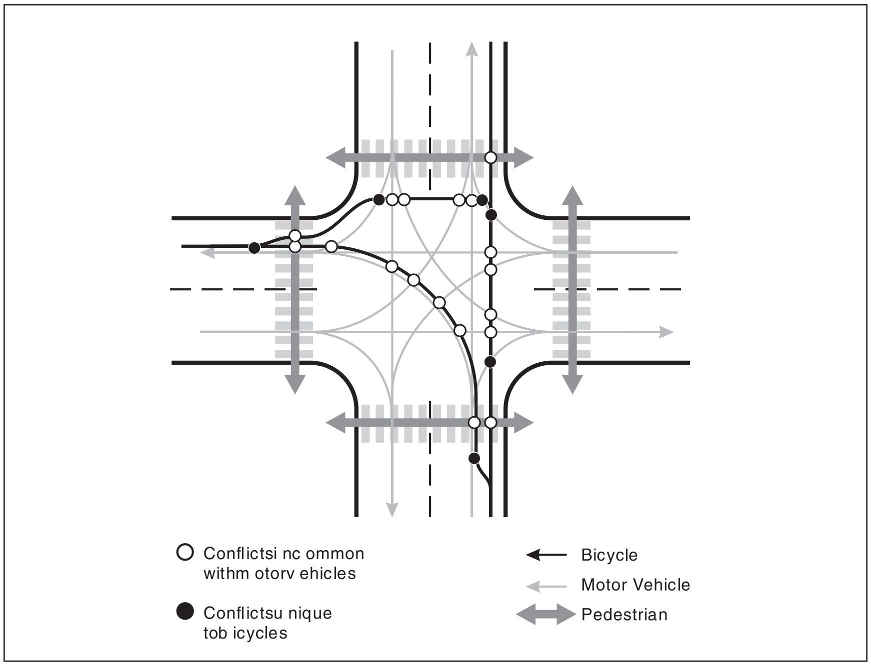


Exhibit 5-6. Vehicle-pedestrian conflicts at single-lane roundabouts.

5.2.3 Bicycle conflicts

Bicycles face similar conflicts as motor vehicles at both signalized intersections and roundabouts. However, because bicyclists typically ride on the right side of the road between intersections, they face additional conflicts due to overlapping paths with motor vehicles. Conflicts unique to bicyclists occur on each approach to conventional four-leg intersections, as depicted in Exhibit 5-7 (showing left turns like motor vehicles or left turns like pedestrians).

Exhibit 5-7. Bicycle conflicts at conventional intersections (showing two left-turn options).



Bicycles can be provided with the option of traveling as either a vehicle or a pedestrian through a roundabout.

At roundabouts, bicycles may be provided the option of traveling as a vehicle or as a pedestrian. As a result, the conflicts experienced by bicyclists are dependent on how they choose to negotiate the roundabout, as shown in Exhibit 5-8. When traveling as a vehicle at a single-lane roundabout, an additional conflict occurs at the point where the bicyclist merges into the traffic stream; the remainder are similar to those for motor vehicles. At double-lane and larger roundabouts where bicycles are typically traveling on the outside part of the circulatory roadway, bicyclists face a potential conflict with exiting vehicles where the bicyclist is continuing to circulate around the roundabout. Bicyclists may feel compelled to "negotiate" the circle (e.g., by indicating their intentions to drivers with their arms) while avoiding conflicts where possible. Bicyclists are less visible and therefore more vulnerable to the merging and exiting conflicts that happen at double-lane roundabouts.

When traveling as a pedestrian, an additional conflict for bicyclists occurs at the point where the bicyclist gets onto the sidewalk, at which point the bicyclist continues around the roundabout like a pedestrian. On shared bicycle-pedestrian paths or on sidewalks, if bicyclists continue to ride, additional bicycle-pedestrian conflicts occur wherever bicycle and pedestrian movements cross (not shown on the exhibit).

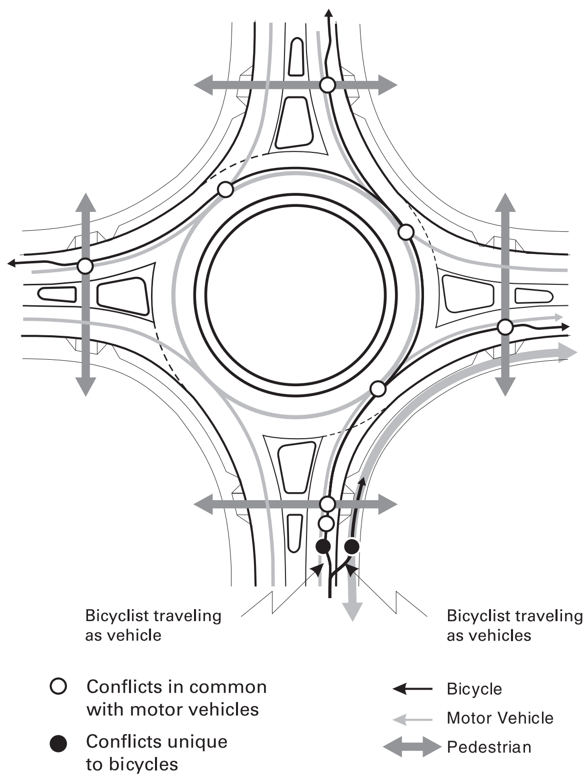


Exhibit 5-8. Bicycle conflicts at roundabouts (showing two left-turn options).

Bicycle-pedestrian conflicts can also occur on shared pathways adjacent to the roundabout.

5.3 Crash Statistics

This section summarizes the overall safety performance of roundabouts in various countries (including the U.S.) and then examines the detailed collision types experienced in France and Queensland, Australia. Pedestrian and bicycle crash statistics are discussed separately, including design issues for visually impaired pedestrians.

5.3.1 Comparisons to previous intersection treatment

Exhibit 5-9 shows the crash frequencies (average annual crashes per roundabout) experienced at eleven intersections in the U.S. that were converted to roundabouts. As the exhibit shows, both types of roundabouts showed a reduction in both injury and property-damage crashes after installation of a roundabout. It should be noted that due to the small size of the data sample, the only result that is statistically significant is the injury crash reduction for small and moderate roundabouts.

Exhibit 5-9. Average annual crash frequencies at 11 U.S. intersections converted to roundabouts.

Type of Roundabout	Sites	Before Roundabout Total	Before Roundabout Inj.[3]	Before Roundabout PDO[4]	Roundabout Total	Roundabout Inj.	Roundabout PDO	Percent Change[5] Total	Percent Change[5] Inj.	Percent Change[5] PDO
Small/Moderate[1]	8	4.8	2.0	2.4	2.4	0.5	1.6	-51%	73%	-32%
Large[2]	3	21.5	5.8	15.7	15.3	4.0	11.3	-29%	-31%	-10%
Total	11	9.3	3.0	6.0	5.9	1.5	4.2	-37%	-51%	-29%

Notes:
1. Mostly single-lane roundabouts with an inscribed circle diameter of 30 to 35 m (100 to 115 ft).
2. Multilane roundabouts with an inscribed circle diameter greater than 50 m (165 ft).
3. Inj. = Injury crashes
4. PDO = Property Damage Only crashes
5. Only injury crash reductions for small/moderate roundabouts were statistically significant.
Source: (9)

Compared to results from Australia, France, and the United Kingdom, these crash frequencies are quite high. Annual crash frequencies in France, Australia, and United Kingdom of 0.15, 0.6, and 3.31 injury crashes per roundabout, respectively, have been reported (1, 10). The reader should note that the UK has many high-volume, multilane roundabouts.

In spite of the higher frequencies, injury crash *rates*, which account for traffic volume exposure, are significantly lower at U.S. roundabout sites. In a recent study of eight single-lane roundabouts in Maryland and Florida, the injury crash rate was found to be 0.08 crashes per million entering vehicles (5). By comparison, the injury crash rate was reported to be 0.045 crashes per million entering vehicles in France and 0.275 crashes per million entering vehicles in the United Kingdom (1, 10).

Experiences in the United States show a reduction in crashes after building a roundabout of about 37 percent for all crashes and 51 percent for injury crashes. These values correspond with international studies with much larger sample sizes, as shown in Exhibit 5-10.

Exhibit 5-10. Mean crash reductions in various countries.

Country	Mean Reduction (%) All Crashes	Mean Reduction (%) Injury Crashes
Australia	41 - 61%	45 - 87%
France		57 - 78%
Germany	36%	
Netherlands	47%	
United Kingdom		25 - 39%
United States	37%	51%

Source: (2), France: (11)

The findings of these studies show that injury crashes are reduced more dramatically than crashes involving property damage only. This again is in part due to the configuration of roundabouts, which eliminates severe crashes such as left turn, head-on, and right angle collisions. Most of these studies also show that crash reduction in rural areas is much higher than in urban areas.

Caveats for comparing the results of crash studies.

Note that the geometry of many studied sites may not necessarily conform to good roundabout design. Improved design principles, such as an emphasis on achieving consistent speeds, may result in better safety performance. It should also be noted that these crash reductions are generally for sites where roundabouts were selected to replace problem intersections. Therefore, they do not necessarily represent a universal safety comparison with all other intersection types.

Collisions at roundabouts tend to be less severe than at conventional intersections. Most crashes reported at roundabouts are a result of drivers failing to yield on entry, referred to as entering-circulating crashes. In addition, rear-end collisions and single vehicle crashes have been reported in many studies. Exhibit 5-11 shows the percentage of the three main crash types reported in different countries.

Exhibit 5-11. Reported proportions of major crash types at roundabouts.

			Type of Crash[1]		
Country	Crash Description	Type of Roundabout	Entering-circulating	Rear-end	Single Vehicle
Australia	All crashes	Single and multilane	51%	22%	18%
France	Injury crashes	Single and multilane	37%	13%	28%
Germany	All crashes	Single lane	30%	28%	17%
Switzerland	All crashes	Single and multilane	46%	13%	35%
United Kingdom	Injury crashes	Single and multilane	20 - 71%	7 - 25%	8 - 30%

1. Percentages do not necessarily sum to 100% because only three major crash categories are shown.
Source: (10)

5.3.2 Collision types

It is instructive for designers to examine details of collision types and location at roundabouts. Statistics are available for roundabouts designed according to local practices in France, Queensland (Australia), and the United Kingdom. It should be noted that the reported frequencies are to some extent related to the specific design standards and reporting processes used in these countries.

Exhibit 5-12 presents a summary of the percentage of crashes by collision type. The numbered items in the list correspond to the numbers indicated on the diagrams given in Exhibit 5-13 as reported in France. The French data illustrate collision types for a sample of 202 injury crashes from 179 urban and suburban roundabouts in France for the period 1984–1988 (12). For comparison purposes, data from Queensland, Australia (13) and the United Kingdom (1) have been superimposed onto the same classification system.

The results in Exhibit 5-12 are instructive for a number of reasons:

- A variety of collision types can take place at roundabouts. A designer should be aware of these collision types when making decisions about alignment and location of fixed objects. It is recommended that these collision types be adopted as conflict types in the U.S. to conduct traffic conflict analysis and report crashes at roundabouts.
- Although reporting methodologies may vary somewhat, crash experience varies from country to country. This may be due to a combination of differences in driver behavior, and design features.

Exhibit 5-12. Comparison of collision types at roundabouts.

Collision Type	France	Queensland (Australia)	United Kingdom[1]
1. Failure to yield at entry (entering-circulating)	36.6%	50.8%	71.1%
2. Single-vehicle run off the circulatory roadway	16.3%	10.4%	8.2%[2]
3. Single vehicle loss of control at entry	11.4%	5.2%	[2]
4. Rear-end at entry	7.4%	16.9%	7.0%[3]
5. Circulating-exiting	5.9%	6.5%	
6. Pedestrian on crosswalk	5.9%		3.5%[4]
7. Single vehicle loss of control at exit	2.5%	2.6%	[2]
8. Exiting-entering	2.5%		
9. Rear-end in circulatory roadway	0.5%	1.2%	
10. Rear-end at exit	1.0%	0.2%	
11. Passing a bicycle at entry	1.0%		
12. Passing a bicycle at exit	1.0%		
13. Weaving in circulatory roadway	2.5%	2.0%	
14. Wrong direction in circulatory roadway	1.0%		
15. Pedestrian on circulatory roadway	3.5%		[4]
16. Pedestrian at approach outside crosswalk	1.0%		[4]
Other collision types		2.4%	10.2%
Other sideswipe crashes		1.6%	

Notes:
1. Data are for "small" roundabouts (curbed central islands > 4 m [13 ft] diameter, relatively large ratio of inscribed circle diameter to central island size)
2. Reported findings do not distinguish among single-vehicle crashes.
3. Reported findings do not distinguish among approaching crashes.
4. Reported findings do not distinguish among pedestrian crashes.
Sources: France (12), Australia (13), United Kingdom (1)

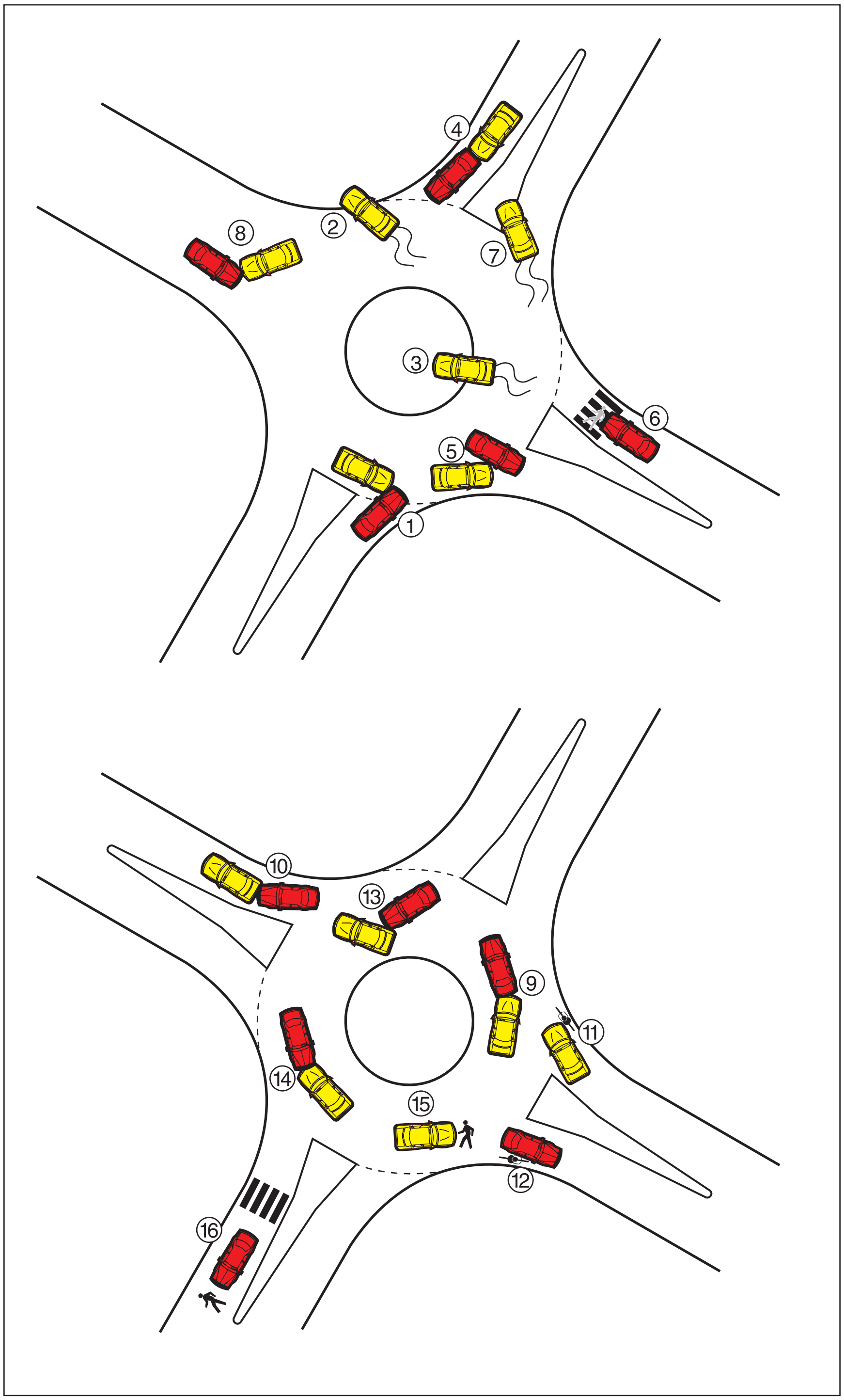


Exhibit 5-13. Graphical depiction of collision types at roundabouts.

Source (8)

Three of the predominant types of collision are: (1) failures to yield at entry to circulating vehicles, (2) single vehicle run-off the circulatory roadway, and (3) single vehicle run-into the central island. A more recent crash study (14) confirmed a high proportion of single vehicle crashes: 49 percent in rural areas, versus 21 percent in urban areas. According to crash models from the United Kingdom, single vehicle crashes range between 20 and 40 percent depending on traffic and design characteristics of sites. In the United Kingdom models, separation by urban and rural areas is not provided.

To reduce the severity of single vehicle crashes, special attention should be accorded to improving visibility and avoiding or removing any hard obstacles on the central island and splitter islands in both urban and rural environments. A French study (14) identified a number of major obstacles that caused fatalities and injuries: trees, guardrail, concrete barriers, fences, walls, piers, sign or light poles, landscaping pots or hard decorative objects, and steep cross-slopes on the central island.

In rural areas, the benefit of lighting has not yet been quantified. In France, only 36 percent of the rural sites are lighted. At these sites, 46 percent of all crashes, and 49 percent of single vehicle crashes occur at night (14).

The French study (7) in 15 towns of 202 urban roundabout crashes compared with all crossroads reported the percentage of crashes by user type, as shown in Exhibit 5-14. The percentage of crashes concerning pedestrians was similar to all crossroads. However, the percentage of crashes involving bicycles and mopeds was larger—15.4 percent for urban crossroads overall versus 24.2 percent for roundabouts, i.e., almost 60 percent more.

Exhibit 5-14. Crash percentage per type of user for urban roundabouts in 15 towns in western France.

User	All Crossroads	Roundabouts
Pedestrians	6.3%	5.6%
Bicycles	3.7%	7.3%
Mopeds	11.7%	16.9%
Motor cycles	7.4%	4.8%
Cars	65.7%	61.2%
Utility vehicles	2.0%	0.6%
Heavy goods vehicles	2.0%	3.0%
Bus/coach	0.8%	0.6%
Miscellaneous	0.4%	0.0%
Total	100.0%	100.0%

Source: (7)

5.3.3 Pedestrians

As was described previously, vehicular injury crashes normally decrease when roundabouts are installed at an existing intersection. The safety benefits of roundabouts have been found to generally carry over to pedestrians as well, as shown in British statistics of Exhibit 5-15. This may be due to the reduced speeds at roundabouts as compared with the previous intersection forms.

Exhibit 5-15. British crash rates for pedestrians at roundabouts and signalized intersections.

Intersection Type	Pedestrian Crashes per Million Trips
Mini-roundabout	0.31
Conventional roundabout	0.45
Flared roundabout	0.33
Signals	0.67

Source: (1, 15)

For pedestrians, the risk of being involved in a severe collision is lower at roundabouts than at other forms of intersections, due to the slower vehicle speeds. Likewise, the number of conflict points for pedestrians is lower at roundabouts than at other intersections, which can lower the frequency of collisions. The splitter island between entry and exit allows pedestrians to resolve conflicts with entering and exiting vehicles separately.

A Dutch study of 181 intersections converted to roundabouts (4) found reductions (percentage) in all pedestrian crashes of 73 percent and in pedestrian injury crashes of 89 percent. In this study, all modes shared in the safety benefits to greater (passenger cars) or lesser extents (bicycles), as shown in Exhibit 5-16.

Exhibit 5-16. Percentage reduction in the number of crashes by mode at 181 converted Dutch roundabouts.

Mode	All Crashes	Injury Crashes
Passenger car	63%	95%
Moped	34%	63%
Bicycle	8%	30%
Pedestrian	73%	89%
Total	51%	72%

Source: (4)

Zebra-stripe markings are recommended at most roundabouts to indicate pedestrian crossings.

A risk analysis of 59 roundabouts and 124 signalized intersections was carried out on crash data in Norway between 1985 and 1989. Altogether, 33 crashes involving personal injury were recorded at the 59 roundabouts. Only 1 of these crashes involved a pedestrian, compared with the signalized intersections, where pedestrians were involved in 20 percent of the personal injury crashes (57 of 287 injury crashes) (16).

Further, there is no quantitative evidence of increased safety for pedestrians at roundabouts with striped (zebra) crossings, where pedestrians have priority. Therefore, striped crossings have generally not been used in other countries. However, in the U.S., it is recommended that all crosswalks be striped except at rural locations with low pedestrian volumes. Although this is not their intended function, striped crosswalks may further alert approaching drivers to a change in their appropriate speed near the yield point.

Safety of visually impaired pedestrians at roundabouts requires further research.

Crash data have not been collected to indicate whether a pedestrian has a disability, and no studies have focused specifically on the safety of visually impaired pedestrians at roundabouts. This is an area requiring further research.

5.3.3.1 Information access for blind or visually impaired pedestrians

Challenges that roundabouts pose to visually impaired pedestrians.

Roundabout crossing skills may be difficult for disabled pedestrians to perform without assistance. For example, audible pedestrian-activated signals may be considered on an approach, although this treatment is not typical. Any leg of any roundabout could be equipped with a pedestrian-activated signal at the pedestrian crossing, if a balanced design requires providing assistance to pedestrians at that location. For example, motorized volume that is too heavy at times to provide a sufficient number of gaps acceptable for pedestrians may warrant a pedestrian signal equipped with audible devices to assist people with visual disabilities.

When crossing a roundabout, there are several areas of difficulty for pedestrians who are blind or visually impaired. It is desirable that a visually impaired pedestrian with good travel skills should be able to arrive at an unfamiliar intersection and cross it with pre-existing skills and without special, intersection-specific training. Roundabouts pose problems at several points of the crossing experience, from the perspective of their access to information:

- The first task of the visually impaired pedestrian is to locate the crosswalk. This can be difficult if the roundabout is not properly landscaped and if the curb edge of the ramp is not marked with a detectable warning surface (see Chapter 6). The crosswalk direction must also be unambiguous.
- Depending upon whether the visually impaired pedestrian is crossing the roundabout in a clockwise or counterclockwise direction, they must listen for a safe gap to cross either the entrance or exit lane(s). The primary problem is the sound of traffic on the roundabout, which may mask the sound of cars approaching the

crosswalk. While crossing the exit lane poses the greater hazard to the pedestrian who is visually impaired because of the higher speed of the vehicles, crossing the entrance may also pose significant problems. Entering traffic, while slower, may also be intimidating as it may not be possible to determine by sound alone whether a vehicle has actually stopped or intends to stop. Sighted pedestrians often rely upon communication through eye contact in these situations; however, that is not a useful or reliable technique for the pedestrian who is visually impaired. Both these problems are further exacerbated at roundabouts with multilane entrances and exits. In these roundabouts, a stopped car in the near lane may mask the sounds of other traffic. It may also block the view of the driver in the far lane of the cane or guide dog of a person who is visually impaired who begins to cross (this is also a problem for children and people using wheelchairs on any crossing of a multilane road).

- The third task is locating the splitter island pedestrian refuge. If this refuge is not ramped, curbed, or equipped with detectable warnings, it is not detectable by a pedestrian who is visually impaired.
- Crossing the remaining half of the crossing (see the second bullet above).
- Locating the correct walkway to either continue their path or locate the adjacent crosswalk to cross the next leg of the roundabout.

Unless these issues are addressed by a design, the intersection is "inaccessible" and may not be permissible under the ADA. Chapters 6 and 7 provide specific suggestions to assist in providing the above information. However, more research is required to develop the information jurisdictions need to determine where roundabouts may be appropriate and what design features are required for people with disabilities. Until specific standards are adopted, engineers and jurisdictions must rely on existing related research and professional judgment to design pedestrian features so that they are usable by pedestrians with disabilities.

Chapters 6 and 7 provide suggestions on designing roundabouts to accommodate persons with disabilities.

Possible design remedies for the difficulties faced by pedestrians include tight entries, raised speed tables with detectable warnings, treatments for visually impaired pedestrians to locate crosswalks, raised pavement markers with yellow flashing lights to alert drivers of crossing pedestrians, pedestrian crossings with actuated signals set sufficiently upstream of the yield line to minimize the possibility of exiting vehicle queues spilling back into the circulatory roadway (6). However, the safety of these treatments at roundabouts has not been tested in the United States.

5.3.4 Bicyclists

As shown in Exhibit 5-17, at British roundabouts bicyclists fare worse in terms of crashes at roundabouts than at signalized intersections.

Exhibit 5-17. British crash rates (crashes per million trips) for bicyclists and motorcyclists at roundabouts and signalized intersections.

Intersection Type	Bicyclists	Motorcyclists
Mini-roundabout	3.11	2.37
Conventional roundabout	2.91	2.67
Flared roundabout	7.85	2.37
Signals	1.75	2.40

Source: (1, 15)

A French study (7) compared the crashes in 1988 in 15 towns in the west of France at both signalized intersections and roundabouts, as shown in Exhibit 5-18. The conclusions from the analysis were:

- There were twice as many injury crashes per year at signalized intersections than at roundabouts;
- Two-wheel vehicles were involved in injury crashes more often (+77 percent) at signalized intersections than on roundabouts;
- People were more frequently killed and seriously injured per crash (+25 percent) on roundabouts than at signalized intersections;
- Proportionally, two-wheel vehicle users were more often involved in crashes (16 percent) on roundabouts than at signalized intersections. Furthermore, the consequences of such crashes were more serious.

Exhibit 5-18. A comparison of crashes between signalized and roundabout intersections in 1998 in 15 French towns.

	Signalized Crossroads	Roundabouts
Number of crossroads	1,238	179
Number of personal injuries	794	59
Number of crashes involving 2-wheel vehicles	278	28
Personal injury crashes/year/crossroad	0.64	0.33
2-wheel vehicle crashes/year/crossroad	0.23	0.13
Crashes to 2-wheel vehicles per 100 crashes	35.0	40.7
Serious crashes/year/crossroad	0.14	0.089
Serious crashes to 2-wheel vehicles/year/crossroad	0.06	0.045
Serious crashes/100 crashes	21.9	27.1
Serious crashes to 2-wheel vehicles/100 crashes to a 2-wheel vehicle	27.0	33.3

Source: (7)

Typical European practice is to provide separated bicycle facilities outside the circulatory roadway when vehicular and bicycle volumes are high.

All European countries report that a more careful design is necessary to enhance bicyclists' safety. The type of bicycle crashes depends on the bicycle facilities provided at the roundabout. If there are no bicycle facilities, or if there is a bike lane on the outer area of the circulatory roadway, crashes typically occur between entering cars and circulating bicyclists as well as between cars heading into an exit and circulating bicyclists. Improperly placed signs on the splitter island may also be a contributing factor.

As a result, most European countries have the following policies:

- Avoid bike lanes on the outer edge of the circulatory roadway.
- Allow bicyclists to mix with vehicle traffic without any separate facility in the circulatory roadway when traffic volumes are low, on single lane roundabouts operating at lower speeds (e.g., up to 8,000 vehicles per day in the Netherlands (4)).
- Introduce separated bicycle facilities outside the circulatory roadway when vehicular and bicycle volumes are high. These separated bicycle facilities cross the exits and entries at least one car length from the edge of the circulatory roadway lane, adjacent to the pedestrian crossings. In some countries, bicyclists have priority over entering and exiting cars, especially in urban areas (e.g., Germany). Other countries prefer to give priority to car traffic showing a yield sign to bicyclists (e.g., Netherlands). The latter solution (i.e., separate bicycle facilities with vehicular traffic priority at the crossing points) is the standard solution for rural areas in most European countries.

Speed is a fundamental risk factor in the safety of bicyclists and pedestrians. Typical bicyclist speeds are in the range of 20 to 25 km/h (12 to 15 mph), and designs that constrain the speeds of vehicles to similar values will minimize the relative speeds and thereby improve safety. Design features that slow traffic such as tightening entry curvature and entry width, and radial alignment of the legs of a roundabout, such as with the urban compact design, are considered safe treatments for bicyclists (17).

In the Netherlands, a 90 percent decrease in injury crashes was experienced with separate bicycle paths around roundabouts where bicyclists do not have right-of-way at the crossings (17).

A bicycle crash prediction model from Sweden has been validated against data for Swedish, Danish, and Dutch roundabouts (18). The model provides reasonable results for roundabouts with up to 12,000 vehicles per day and 4,000 bicycles per day. The model tends to over-predict crashes (i.e., is conservative) for roundabouts carrying more than 12,000 vehicles per day that are also designed with separate bicycle paths with crossings on the approach legs. It is calibrated for crossroad intersections as well as roundabouts. To obtain the expected cycling crashes per year at roundabouts, the value derived from the general junction model is factored by 0.71, implying that bicycle crashes at roundabouts are 71 percent less frequent than at junctions in general. However, the reader is cautioned when extrapolating European bicycling experience to the U.S., as drivers in Europe are more accustomed to interacting with bicyclists.

5.4 Crash Prediction Models

Crash prediction models have not been developed for U.S. roundabouts.

Crash prediction models have been developed for signalized intersections in the U.S., as discussed previously in Chapter 3. However, no crash prediction models exist yet for U.S. roundabouts and driver behavior. Given the relatively recent introduction of roundabouts to the U.S. and driver unfamiliarity with them, crash prediction models from other countries should be used cautiously. As reported earlier in Section 5.3, crash statistics vary from country to country, both in terms of magnitude and in terms of collision types. Consequently, the application of a crash prediction model from another country may not accurately predict crash frequencies at U.S. locations. Nonetheless, these crash prediction models from other countries can be useful in understanding the *relative* effects of various geometric features on the number of crashes that might be expected. The user is thus cautioned to use these models only for comparative purposes and for obtaining insights into the refinement of individual geometric elements, not to use them for predicting *absolute* numbers of crashes under U.S. conditions.

Crash models relating crash frequency to roundabout characteristics are available from the United Kingdom. The sample consisted of 84 four-leg roundabouts of all sizes, small to large and with various number of approach lanes and entry lanes (flared or parallel entries) (1). Approach speeds were also evenly represented between 48 to 64 km/h (30 to 40 mph) and 80 to 113 km/h (50 to 70 mph). Crash data were collected for periods of 4 to 6 years, a total of 1,427 fatal, serious, and slight injuries only. The proportion of crashes with one casualty was 83.7 percent, and those with two casualties was 12.5 percent. The models are based on generalized linear regression of the exponential form, which assumes a Poisson distribution. Their goodness of fit is expressed in terms of scaled deviations that are moderately reliable. No additional variables, other than those listed below, could further improve the models significantly (see also (8)).

The British crash prediction equations (1), for each type of crash are listed in Equations 5-1 through 5-5. Note that these equations are only valid for roundabouts with four legs. However, the use of these models for relative comparisons may still be reasonable.

Entry-Circulating: (5-1)

$$A = 0.052 Q_e^{0.7} Q_c^{0.4} \exp\left(-40C_e + 0.14e - 0.007ev - \frac{1}{1 + \exp(4R - 7)} + 0.2P_m - 0.01\theta\right)$$

where: A = personal injury crashes (including fatalities) per year per roundabout approach;
- Q_e = entering flow (1,000s of vehicles/day)
- Q_c = circulating flow (1,000s of vehicles/day)
- C_e = entry curvature = $1/R_e$
- e = entry width (m)
- v = approach width (m)
- R = ratio of inscribed circle diameter/central island diameter
- P_m = proportion of motorcycles (%)
- θ = angle to next leg, measured centerline to centerline (degrees)

Approaching: $A = 0.0057 Q_e^{1.7} \exp(20C_e - 0.1e)$ (5-2)

where: A = personal injury crashes (including fatalities) per year at roundabout approach or leg;
Q_e = entering flow (1,000s of vehicles/day)
C_e = entry curvature = $1/R_e$
R_e = entry path radius for the shortest vehicle path (m)
e = entry width (m)

Single Vehicle: $A = 0.0064 Q_e^{0.8} \exp(25C_e + 0.2v - 45C_a)$ (5-3)

where: A = personal injury crashes (including fatalities) per year at roundabout approach or leg
Q_e = entering flow (1,000s of vehicles/day)
C_e = entry curvature = $1/R_e$
R_e = entry path radius for the shortest vehicle path (m)
V = approach width (m)
C_a = approach curvature = $1/R_a$
R_a = approach radius (m), defined as the radius of a curve between 50 m (164 ft) and 500 m (1,640 ft) of the yield line

Other (Vehicle): $A = 0.0064 Q_e^{0.8} \exp(25C_e + 0.2v - 45C_a)$ (5-4)

where: A = personal injury crashes (including fatalities) per year at roundabout approach or leg
Q_{ec} = product $Q_e \cdot Q_c$
Q_e = entering flow (1,000s of vehicles/day)
Q_c = circulating flow (1,000s of vehicles/day)
P_m = proportion of motorcycles

Pedestrian: $A = 0.029 Q_{ep}^{0.5}$ (5-5)

where: A = personal injury crashes (including fatalities) per year at roundabout approach or leg
Q_{ep} = product $(Q_e + Q_{ex}) .\ Q_p$
Q_e = entering flow (1,000s of vehicles/day)
Q_{ex} = exiting flow (1,000s of vehicles/day)
Q_p = pedestrian crossing flow (1,000s of pedestrians/day)

According to the U.K. crash models, the major physical factors that were statistically significant are entry width, circulatory width, entry path radius, approach curvature, and angle between entries. Some of the effects of these parameters are as follows:

- *Entry width*: For a total entry flow of 20,000 vehicles per day, widening an entry from one lane to two lanes is expected to cause 30 percent more injury crashes. At 40,000 vehicles per day, widening an entry from two lanes to three lanes will cause a 15 percent rise in injury crashes. Moreover, the models could not take into account the added hazard to bicyclists and pedestrians who will have to travel longer exposed distances. (8)

- *Circulatory width*: Widening the circulatory roadway has less impact on crashes than entry width. Crashes are expected to rise about 5 percent for a widening of two meters. (8)
- *Entry path radius*: Entry-circulating collision type increases with entry path radius (for the fastest path), while single vehicle and approach collision types decrease. For a double-lane approach, an optimum entry path radius is 50 to 70 m (165 to 230 ft). (8)
- *Approach curvature*: Approach curvature is safer when the approach curve is to the right and less so when the curve is to the left. This implies that a design is slightly safer when reverse curves are provided to gradually slow drivers before entry. For a double-lane approach roundabout with entering flow of 50,000 vehicles per day, changing a straight approach to a right-turning curve of 200 m (650 ft) radius reduces crash frequency by 5 percent. (8)

Maximize angles between entries.

- *Angle between entries*: As the angle between entries decreases, the frequency of crashes increases. For example, an approach with an angle of 60 degrees to the next leg of the roundabout increases crash frequency by approximately 35 percent over approaches at 90-degree angles. Therefore, the angle between entries should be maximized to improve safety.

An approach suggested in Australia (13) differs from the British approach in that the independent variables are based on measures related to driver behavior. For instance, the collision rate for single vehicle crashes was found to be:

$$A_{sp} = 1.64 \times 10^{-12} \times Q^{1.17} \times L \times (S + \Delta S)^{4.12} / R^{1.91} \quad (5\text{-}6)$$

and

$$A_{sa} = 1.79 \times 10^{-9} \times Q^{0.91} \times L \times (S + \Delta S)^{1.93} / R^{0.65} \quad (5\text{-}7)$$

where: A_{sp} = the number of single vehicle crashes per year per leg for vehicle path segments prior to the yield line.
A_{sa} = the number of single vehicle crashes per year per leg for vehicle path segments after the yield line.
Q = the average annual daily traffic in the direction considered—one way traffic only (veh/d)
L = the length of the driver's path on the horizontal geometric element (m).
S = the 85th-percentile speed on the horizontal geometric element (km/h).
ΔS = the decrease in the 85th-percentile speed at the start on the horizontal geometric element (km/h). This indicates the speed change from the previous geometric element.
R = the vehicle path radius on the geometric element (m).

These equations demonstrate a direct relationship between the number of crashes, overall speed magnitudes, and the change in speed between elements. Therefore, this equation can be used to estimate the *relative* differences in safety benefits between various geometric configurations by estimating vehicle speeds through the various parts of a roundabout.

5.5 References

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6 Geometric Design

Chapter 6 Geometric Design

6.1 Introduction

Roundabout design involves trade-offs among safety, operations, and accommodating large vehicles.

Designing the geometry of a roundabout involves choosing between trade-offs of safety and capacity. Roundabouts operate most safely when their geometry forces traffic to enter and circulate at slow speeds. Horizontal curvature and narrow pavement widths are used to produce this reduced-speed environment. Conversely, the capacity of roundabouts is negatively affected by these low-speed design elements. As the widths and radii of entry and circulatory roadways are reduced, so also the capacity of the roundabout is reduced. Furthermore, many of the geometric parameters are governed by the maneuvering requirements of the largest vehicles expected to travel through the intersection. Thus, designing a roundabout is a process of determining the optimal balance between safety provisions, operational performance, and large vehicle accommodation.

Some roundabout features are uniform, while others vary depending on the location and size of the roundabout.

While the basic form and features of roundabouts are uniform regardless of their location, many of the design techniques and parameters are different, depending on the speed environment and desired capacity at individual sites. In rural environments where approach speeds are high and bicycle and pedestrian use may be minimal, the design objectives are significantly different from roundabouts in urban environments where bicycle and pedestrian safety are a primary concern. Additionally, many of the design techniques are substantially different for single-lane roundabouts than for roundabouts with multiple entry lanes.

This chapter is organized so that the fundamental design principles common among all roundabout types are presented first. More detailed design considerations specific to multilane roundabouts, rural roundabouts, and mini-roundabouts are given in subsequent sections of the chapter.

6.1.1 Geometric elements

Exhibit 6-1 provides a review of the basic geometric features and dimensions of a roundabout. Chapter 1 provided the definitions of these elements.

6.1.2 Design process

Roundabout design is an iterative process.

The process of designing roundabouts, more so than other forms of intersections, requires a considerable amount of iteration among geometric layout, operational analysis, and safety evaluation. As described in Chapters 4 and 5, minor adjustments in geometry can result in significant changes in the safety and/or operational performance. Thus, the designer often needs to revise and refine the initial layout attempt to enhance its capacity and safety. It is rare to produce an optimal geometric design on the first attempt. Exhibit 6-2 provides a graphical flowchart for the process of designing and evaluating a roundabout.

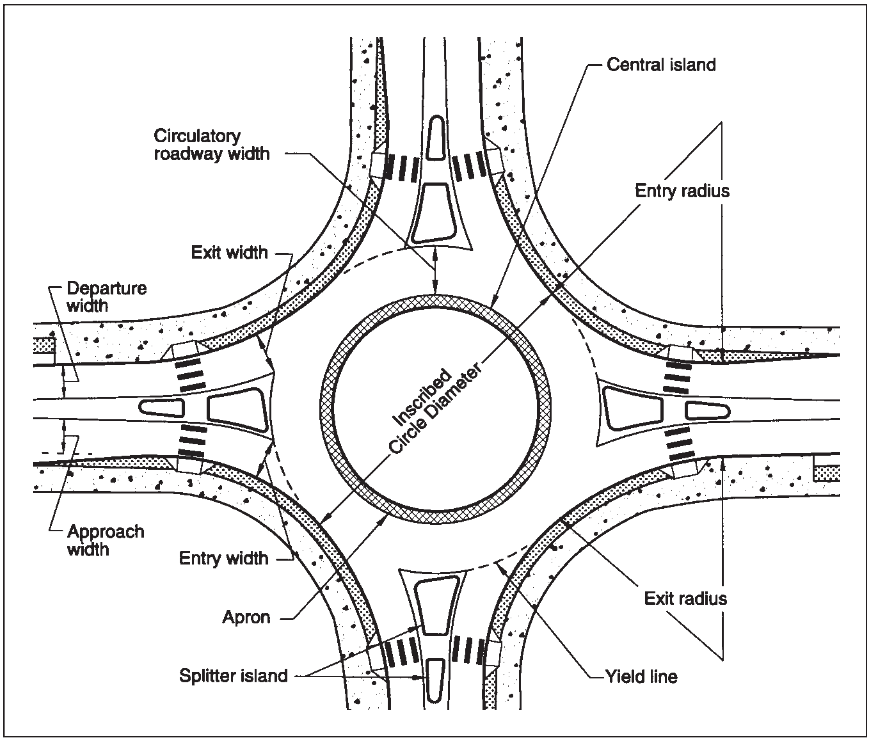


Exhibit 6-1. Basic geometric elements of a roundabout.

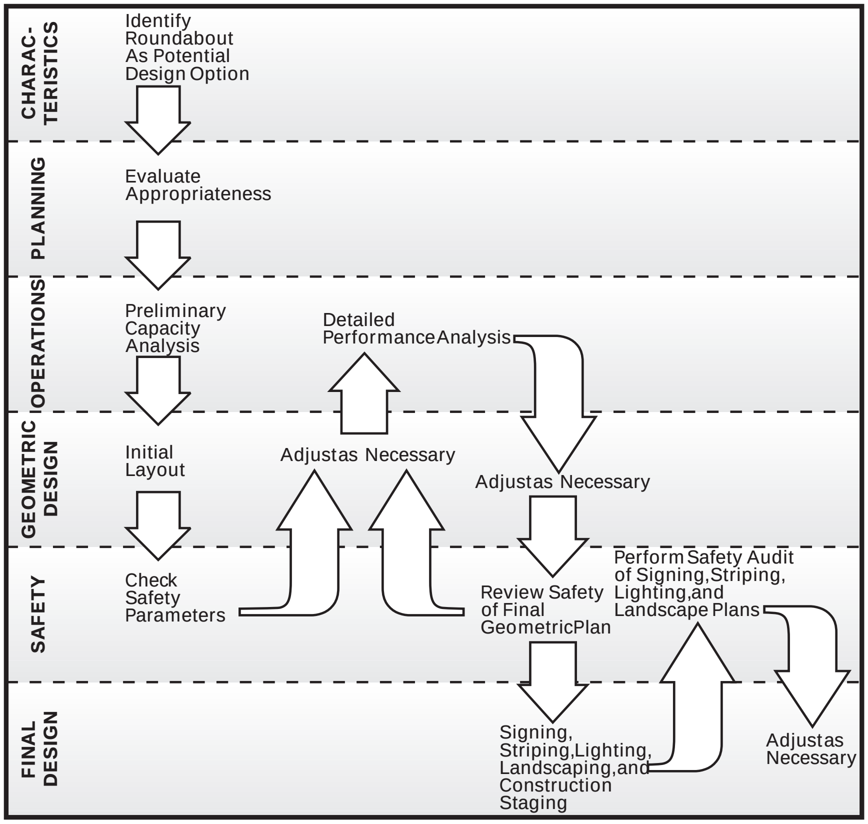


Exhibit 6-2. Roundabout design process.

Because roundabout design is such an iterative process, in which small changes in geometry can result in substantial changes to operational and safety performance, it may be advisable to prepare the initial layout drawings at a sketch level of detail. Although it is easy to get caught into the desire to design each of the individual components of the geometry such that it complies with the specifications provided in this chapter, it is much more important that the individual components are compatible with each other so that the roundabout will meet its overall performance objectives. Before the details of the geometry are defined, three fundamental elements must be determined in the preliminary design stage:

1. The optimal roundabout size;
2. The optimal position; and
3. The optimal alignment and arrangement of approach legs.

6.2 General Design Principles

This section describes the fundamental design principles common among all categories of roundabouts. Guidelines for the design of each geometric element are provided in the following section. Further guidelines specific to double-lane roundabouts, rural roundabouts, and mini-roundabouts are given in subsequent sections. Note that double-lane roundabout design is significantly different from single-lane roundabout design, and many of the techniques used in single-lane roundabout design do not directly transfer to double-lane design.

6.2.1 Speeds through the roundabout

The most critical design objective is achieving appropriate vehicular speeds through the roundabout.

Because it has profound impacts on safety, achieving appropriate vehicular speeds through the roundabout is the most critical design objective. A well-designed roundabout reduces the relative speeds between conflicting traffic streams by requiring vehicles to negotiate the roundabout along a curved path.

6.2.1.1 Speed profiles

Exhibit 6-3 shows the operating speeds of typical vehicles approaching and negotiating a roundabout. Approach speeds of 40, 55, and 70 km/h (25, 35, and 45 mph, respectively) about 100 m (325 ft) from the center of the roundabout are shown. Deceleration begins before this time, with circulating drivers operating at approximately the same speed on the roundabout. The relatively uniform negotiation speed of all drivers on the roundabout means that drivers are able to more easily choose their desired paths in a safe and efficient manner.

6.2.1.2 Design speed

Increasing vehicle path curvature decreases relative speeds between entering and circulating vehicles, but also increases side friction between adjacent traffic streams in multilane roundabouts.

International studies have shown that increasing the vehicle path curvature decreases the relative speed between entering and circulating vehicles and thus usually results in decreases in the entering-circulating and exiting-circulating vehicle crash rates. However, at multilane roundabouts, increasing vehicle path curvature creates greater side friction between adjacent traffic streams and can result in more vehicles cutting across lanes and higher potential for sideswipe crashes (2). Thus, for each roundabout, there exists an optimum design speed to minimize crashes.

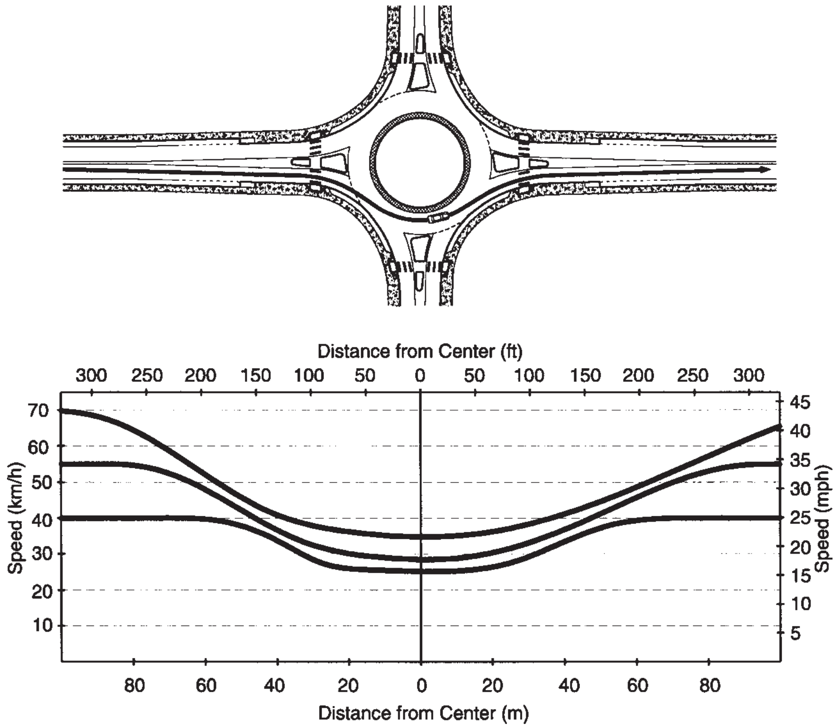


Exhibit 6-3. Sample theoretical speed profile (urban compact roundabout).

Recommended maximum entry design speeds for roundabouts at various intersection site categories are provided in Exhibit 6-4.

Site Category	Recommended Maximum Entry Design Speed
Mini-Roundabout	25 km/h (15 mph)
Urban Compact	25 km/h (15 mph)
Urban Single Lane	35 km/h (20 mph)
Urban Double Lane	40 km/h (25 mph)
Rural Single Lane	40 km/h (25 mph)
Rural Double Lane	50 km/h (30 mph)

Exhibit 6-4. Recommended maximum entry design speeds.

6.2.1.3 Vehicle paths

Roundabout speed is determined by the fastest path allowed by the geometry.

To determine the speed of a roundabout, the fastest path allowed by the geometry is drawn. This is the smoothest, flattest path possible for a single vehicle, in the absence of other traffic and ignoring all lane markings, traversing through the entry, around the central island, and out the exit. Usually the fastest possible path is the through movement, but in some cases it may be a right turn movement.

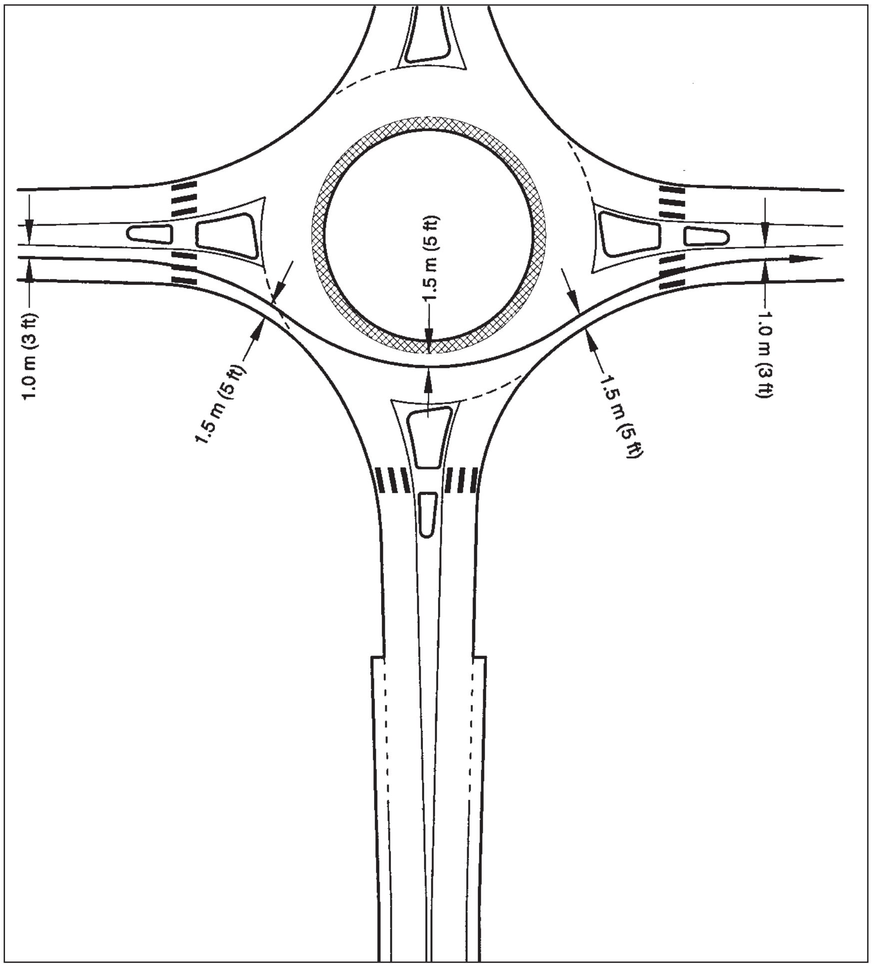
A vehicle is assumed to be 2 m (6 ft) wide and to maintain a minimum clearance of 0.5 m (2 ft) from a roadway centerline or concrete curb and flush with a painted edge line (2). Thus the centerline of the vehicle path is drawn with the following distances to the particular geometric features:

- 1.5 m (5 ft) from a concrete curb,
- 1.5 m (5 ft) from a roadway centerline, and
- 1.0 m (3 ft) from a painted edge line.

Through movements are usually the fastest path, but sometimes right turn paths are more critical.

Exhibits 6-5 and 6-6 illustrate the construction of the fastest vehicle paths at a single-lane roundabout and at a double-lane roundabout, respectively. Exhibit 6-7 provides an example of an approach at which the right-turn path is more critical than the through movement.

Exhibit 6-5. Fastest vehicle path through single-lane roundabout.



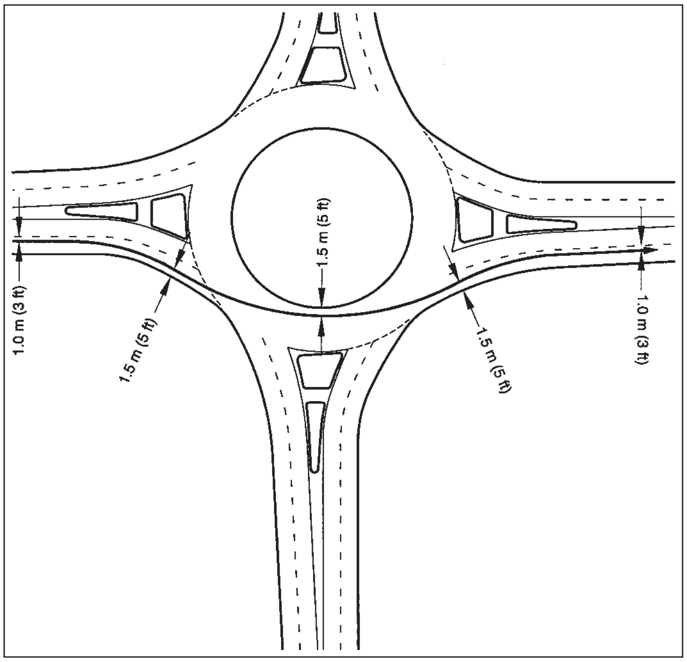


Exhibit 6-6. Fastest vehicle path through double-lane roundabout.

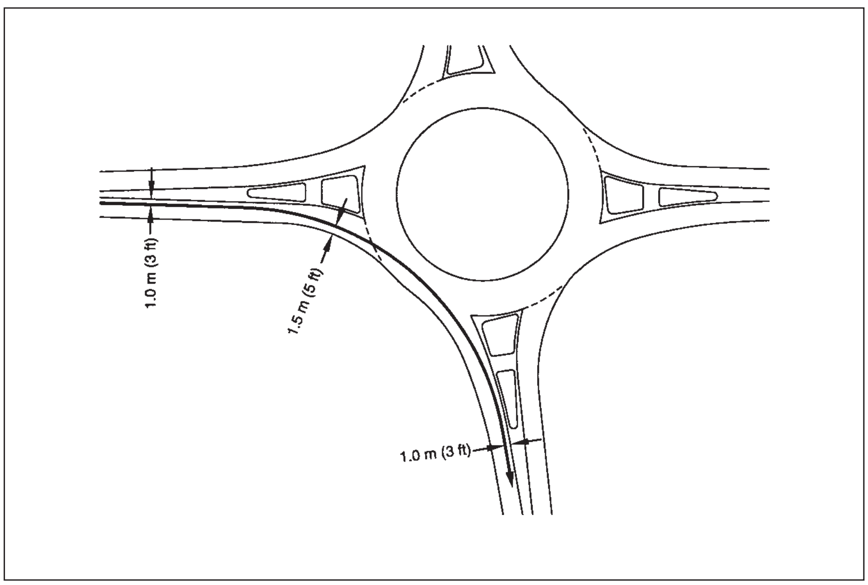


Exhibit 6-7. Example of critical right-turn movement.

As shown in Exhibits 6-5 and 6-6, the fastest path for the through movement is a series of reverse curves (i.e., a curve to the right, followed by a curve to the left, followed by a curve to the right). When drawing the path, a short length of tangent should be drawn between consecutive curves to account for the time it takes for a driver to turn the steering wheel. It may be initially better to draw the path free-hand, rather than using drafting templates or a computer-aided design (CAD) program. The freehand technique may provide a more natural representation of the way a driver negotiates the roundabout, with smooth transitions connecting curves and tangents. Having sketched the fastest path, the designer can then measure the minimum radii using suitable curve templates or by replicating the path in CAD and using it to determine the radii.

The entry path radius should not be significantly larger than the circulatory radius.

The design speed of the roundabout is determined from the smallest radius along the fastest allowable path. The smallest radius usually occurs on the circulatory roadway as the vehicle curves to the left around the central island. However, it is important when designing the roundabout geometry that the radius of the entry path (i.e., as the vehicle curves to the right through entry geometry) not be significantly larger than the circulatory path radius.

Draw the fastest path for all roundabout approaches.

The fastest path should be drawn for all approaches of the roundabout. Because the construction of the fastest path is a subjective process requiring a certain amount of personal judgment, it may be advisable to obtain a second opinion.

6.2.1.4 Speed-curve relationship

The relationship between travel speed and horizontal curvature is documented in the American Association of State Highway and Transportation Officials' document, A Policy on Geometric Design of Highways and Streets, commonly known as the Green Book (4). Equation 6-1 can be used to calculate the design speed for a given travel path radius.

$$V = \sqrt{127R(e+f)} \quad \text{(6-1a, metric)}$$

where:
- V = Design speed, km/h
- R = Radius, m
- e = superelevation, m/m
- f = side friction factor

$$V = \sqrt{15R(e+f)} \quad \text{(6-1b, U.S. customary)}$$

where:
- V = Design speed, mph
- R = Radius, ft
- e = superelevation, ft/ft
- f = side friction factor

Superelevation values are usually assumed to be +0.02 for entry and exit curves and -0.02 for curves around the central island. For more details related to superelevation design, see Section 6.3.11.

Values for side friction factor can be determined in accordance with the AASHTO relation for curves at intersections (see 1994 AASHTO Figure III-19 (4)). The coefficient of friction between a vehicle's tires and the pavement varies with the vehicle's speed, as shown in Exhibits 6-8 and 6-9 for metric and U.S. customary units, respectively.

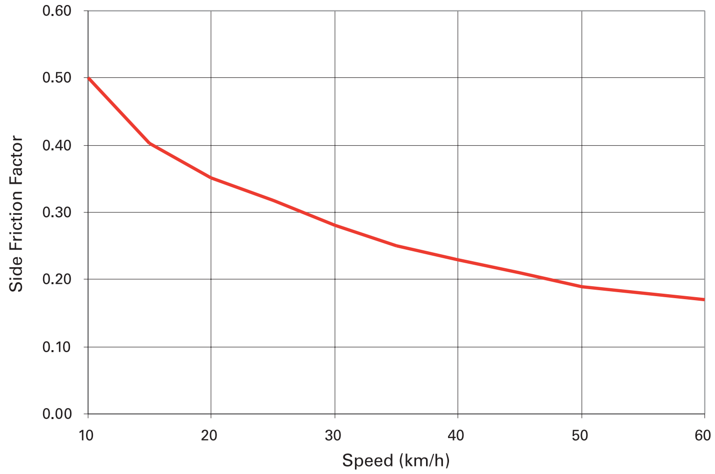


Exhibit 6-8. Side friction factors at various speeds (metric units).

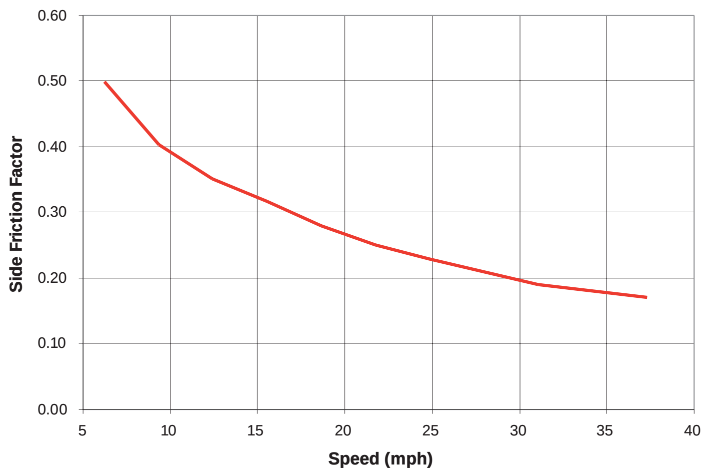


Exhibit 6-9. Side friction factors at various speeds (U.S. customary units).

Using the appropriate friction factors corresponding to each speed, Exhibits 6-10 and 6-11 present charts in metric and U.S. customary units, respectively, showing the speed-radius relationship for curves for both a +0.02 superelevation and -0.02 superelevation.

Exhibit 6-10. Speed-radius relationship (metric units).

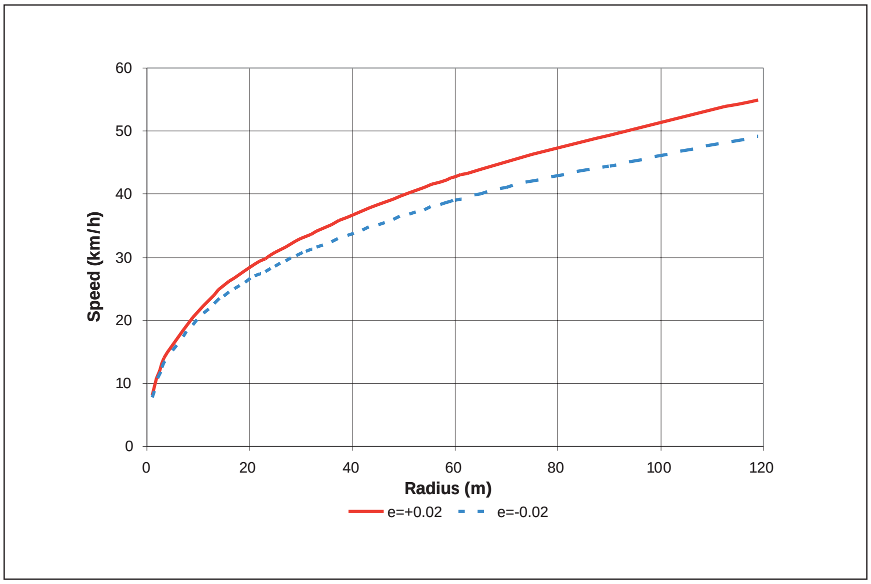
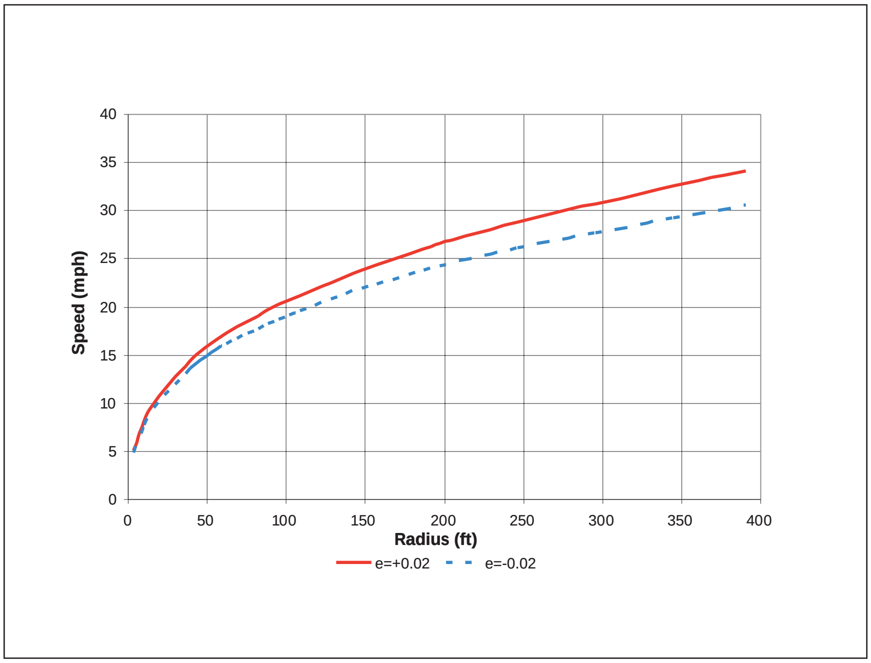


Exhibit 6-11. Speed-radius relationship (U.S. customary units.)



6.2.1.5 Speed consistency

In addition to achieving an appropriate design speed for the fastest movements, another important objective is to achieve consistent speeds for all movements. Along with overall reductions in speed, speed consistency can help to minimize the crash rate and severity between conflicting streams of vehicles. It also simplifies the task of merging into the conflicting traffic stream, minimizing critical gaps, thus optimizing entry capacity. This principle has two implications:

1. The relative speeds between consecutive geometric elements should be minimized; and
2. The relative speeds between conflicting traffic streams should be minimized.

As shown in Exhibit 6-12, five critical path radii must be checked for each approach. R_1, the *entry path radius,* is the minimum radius on the fastest through path prior to the yield line. R_2, the *circulating path radius,* is the minimum radius on the fastest through path around the central island. R_3, the *exit path radius,* is the minimum radius on the fastest through path into the exit. R_4, the *left-turn path radius,* is the minimum radius on the path of the conflicting left-turn movement. R_5, the *right-turn path radius,* is the minimum radius on the fastest path of a right-turning vehicle. It is important to note that these vehicular path radii are not the same as the curb radii. First the basic curb geometry is laid out, and then the vehicle paths are drawn in accordance with the procedures described in Section 6.2.1.3.

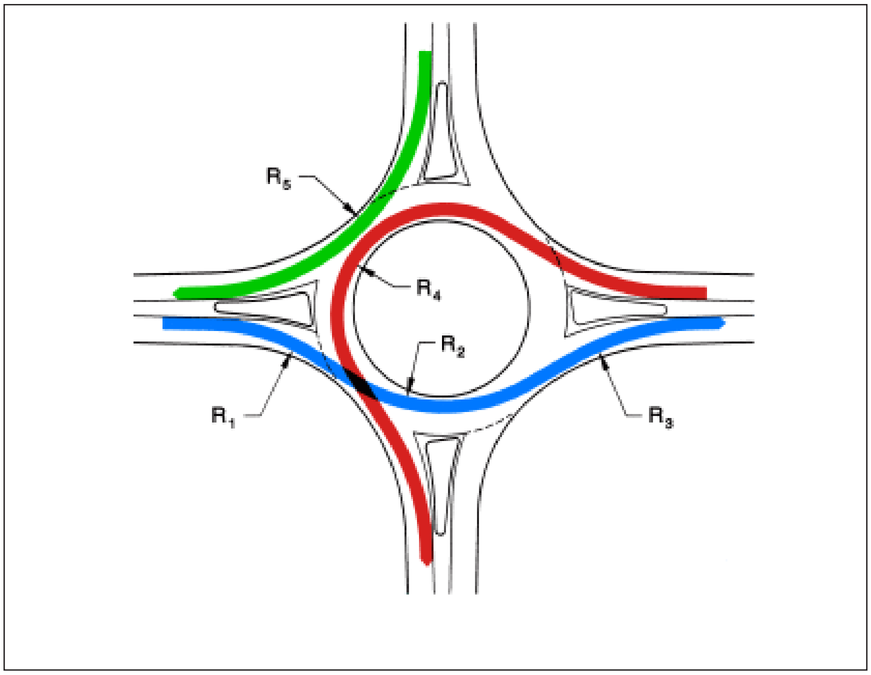


Exhibit 6-12. Vehicle path radii.

On the fastest path, it is desirable for R_1 to be smaller than R_2, which in turn should be smaller than R_3. This ensures that speeds will be reduced to their lowest level at the roundabout entry and will thereby reduce the likelihood of loss-of-control crashes. It also helps to reduce the speed differential between entering and circulating traffic, thereby reducing the entering-circulating vehicle crash rate. However, in some cases it may not be possible to achieve an R_1 value less than R_2 within given right-of-way or topographic constraints. In such cases, it is acceptable for R_1 to be greater than R_2, provided the relative difference in speeds is less than 20 km/h (12 mph) and preferably less than 10 km/h (6 mph).

The *natural path* of a vehicle is the path that a driver would take in the absence of other conflicting vehicles.

At single-lane roundabouts, it is relatively simple to reduce the value of R_1. The curb radius at the entry can be reduced or the alignment of the approach can be shifted further to the left to achieve a slower entry speed (with the potential for higher exit speeds that may put pedestrians at risk). However, at double-lane roundabouts, it is generally more difficult as overly small entry curves can cause the *natural path* of adjacent traffic streams to overlap. Path overlap happens when the geometry leads a vehicle in the left approach lane to naturally sweep across the right approach lane just before the approach line to avoid the central island. It may also happen within the circulatory roadway when a vehicle entering from the right-hand lane naturally cuts across the left side of the circulatory roadway close to the central island. When path overlap occurs at double-lane roundabouts, it may reduce capacity and increase crash risk. Therefore, care must be taken when designing double-lane roundabouts to achieve ideal values for R_1, R_2, and R_3. Section 6.4 provides further guidance on eliminating path overlap at double-lane roundabouts.

The exit radius, R_3, should not be less than R_1 or R_2 in order to minimize loss-of-control crashes. At single-lane roundabouts with pedestrian activity, exit radii may still be small (the same or slightly larger than R_2) in order to minimize exit speeds. However, at double-lane roundabouts, additional care must be taken to minimize the likelihood of exiting path overlap. Exit path overlap can occur at the exit when a vehicle on the left side of the circulatory roadway (next to the central island) exits into the right-hand exit lane. Where no pedestrians are expected, the exit radii should be just large enough to minimize the likelihood of exiting path overlap. Where pedestrians are present, tighter exit curvature may be necessary to ensure sufficiently low speeds at the downstream pedestrian crossing.

The radius of the conflicting left-turn movement, R_4, must be evaluated in order to ensure that the maximum speed differential between entering and circulating traffic is no more than 20 km/h (12 mph). The left-turn movement is the critical traffic stream because it has the lowest circulating speed. Large differentials between entry and circulating speeds may result in an increase in single-vehicle crashes due to loss of control. Generally, R_4 can be determined by adding 1.5 m (5 ft) to the central island radius. Based on this assumption, Exhibits 6-13 and 6-14 show approximate R_4 values and corresponding maximum R_1 values for various inscribed circle diameters in metric and U.S. customary units, respectively.

Finally, the radius of the fastest possible right-turn path, R_5, is evaluated. Like R_1, the right-turn radius should have a design speed at or below the maximum design speed of the roundabout and no more than 20 km/h (12 mph) above the conflicting R_4 design speed.

Exhibit 6-13. Approximated R_4 values and corresponding R_1 values (metric units).

	Approximate R_4 Value		Maximum R_1 Value	
Inscribed Circle Diameter (m)	Radius (m)	Speed (km/h)	Radius (m)	Speed (km/h)
Single-Lane Roundabout				
30	11	21	54	41
35	13	23	61	43
40	16	25	69	45
45	19	26	73	46
Double-Lane Roundabout				
45	15	24	65	44
50	17	25	69	45
55	20	27	78	47
60	23	28	83	48
65	25	29	88	49
70	28	30	93	50

Exhibit 6-14. Approximated R_4 values and corresponding R_1 values (U.S. customary units).

	Approximate R_4 Value		Maximum R_1 Value	
Inscribed Circle Diameter (m)	Radius (ft)	Speed (mph)	Radius (ft)	Speed (mph)
Single-Lane Roundabout				
100	35	13	165	25
115	45	14	185	26
130	55	15	205	27
150	65	15	225	28
Double-Lane Roundabout				
150	50	15	205	27
165	60	16	225	28
180	65	16	225	28
200	75	17	250	29
215	85	18	275	30
230	90	18	275	30

6.2.2 Design vehicle

The design vehicle dictates many of the roundabout's dimensions.

Another important factor determining a roundabout's layout is the need to accommodate the largest motorized vehicle likely to use the intersection. The turning path requirements of this vehicle, termed hereafter the *design vehicle*, will dictate many of the roundabout's dimensions. Before beginning the design process, the designer must be conscious of the design vehicle and possess the appropriate vehicle turning templates or a CAD-based vehicle turning path program to determine the vehicle's swept path.

The choice of design vehicle will vary depending upon the approaching roadway types and the surrounding land use characteristics. The local or State agency with jurisdiction of the associated roadways should usually be consulted to identify the design vehicle at each site. The AASHTO *A Policy on Geometric Design of Highways and Streets* provides the dimensions and turning path requirements for a variety of common highway vehicles (4). Commonly, WB-15 (WB-50) vehicles are the largest vehicles along collectors and arterials. Larger trucks, such as WB-20 (WB-67) vehicles, may need to be addressed at intersections on interstate freeways or State highway systems. Smaller design vehicles may often be chosen for local street intersections.

In general, larger roundabouts need to be used to accommodate large vehicles while maintaining low speeds for passenger vehicles. However, in some cases, land constraints may limit the ability to accommodate large semi-trailer combinations while achieving adequate deflection for small vehicles. At such times, a truck apron may be used to provide additional traversable area around the central island for large semi-trailers. Truck aprons, though, provide a lower level of operation than standard nonmountable islands and should be used only when there is no other means of providing adequate deflection while accommodating the design vehicle.

Exhibits 6-15 and 6-16 demonstrate the use of a CAD-based computer program to determine the vehicle's swept path through the critical turning movements.

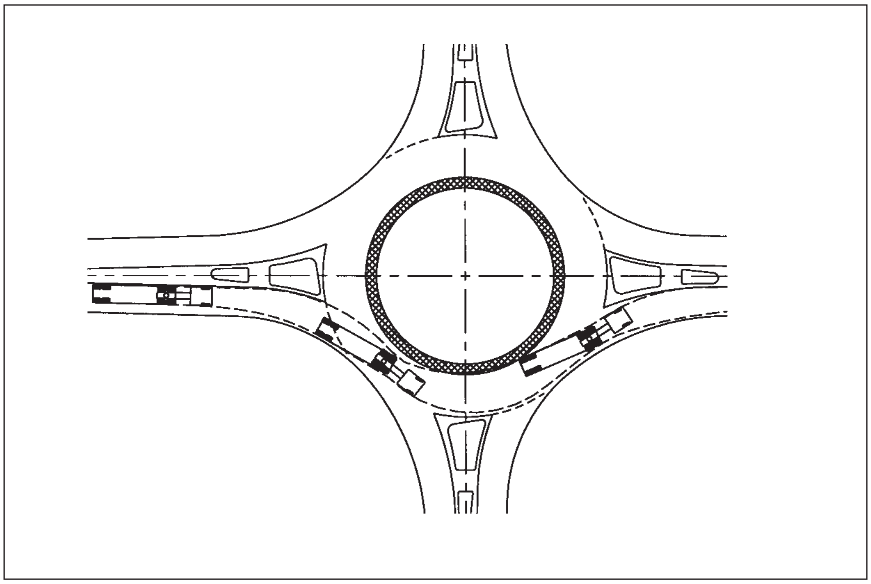


Exhibit 6-15. Through-movement swept path of WB-15 (WB-50) vehicle.

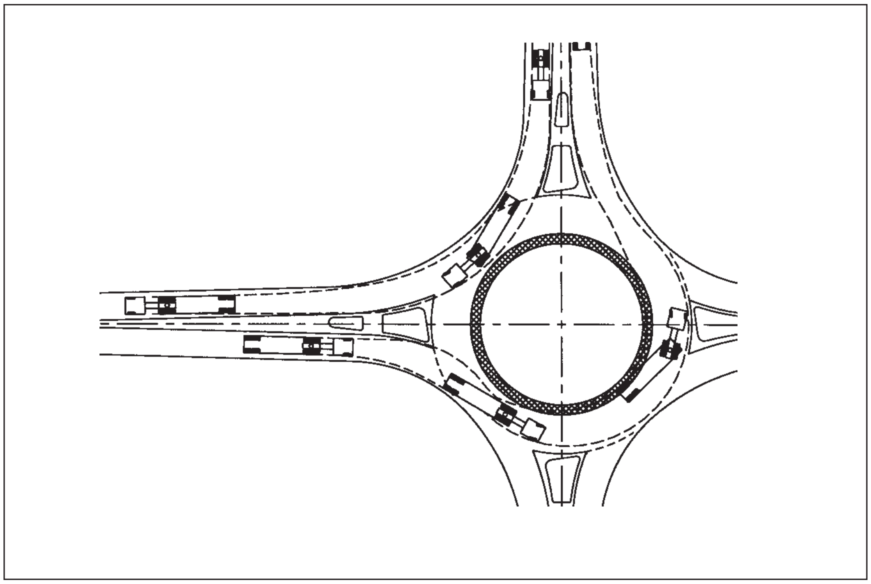


Exhibit 6-16. Left-turn and right-turn swept paths of WB-15 (WB-50) vehicle.

6.2.3 Nonmotorized design users

Like the motorized design vehicle, the design criteria of nonmotorized potential roundabout users (bicyclists, pedestrians, skaters, wheelchair users, strollers, etc.) should be considered when developing many of the geometric elements of a roundabout design. These users span a wide range of ages and abilities that can have a significant effect on the design of a facility.

The basic design dimensions for various design users are given in Exhibit 6-17 (5).

Exhibit 6-17. Key dimensions of nonmotorized design users.

User	Dimension	Affected Roundabout Features
Bicycles		
Length	1.8 m (5.9 ft)	Splitter island width at crosswalk
Minimum operating width	1.5 m (4.9 ft)	Bike lane width
Lateral clearance on each side	0.6 m (2.0 ft);	Shared bicycle-pedestrian path width
	1.0 m (3.3 ft) to obstructions	
Pedestrian (walking)		
Width	0.5 m (1.6 ft)	Sidewalk width, crosswalk width
Wheelchair		
Minimum width	0.75 m (2.5 ft)	Sidewalk width, crosswalk width
Operating width	0.90 m (3.0 ft)	Sidewalk width, crosswalk width
Person pushing stroller		
Length	1.70 m (5.6 ft)	Splitter island width at crosswalk
Skaters		
Typical operating width	1.8 m (6 ft)	Sidewalk width

Source: (5)

6.2.4 Alignment of approaches and entries

Roundabouts are optimally located when all approach centerlines pass through the center of the inscribed circle.

In general, the roundabout is optimally located when the centerlines of all approach legs pass through the center of the inscribed circle. This location usually allows the geometry to be adequately designed so that vehicles will maintain slow speeds through both the entries and the exits. The radial alignment also makes the central island more conspicuous to approaching drivers.

If it is not possible to align the legs through the center point, a slight offset to the left (i.e., the centerline passes to the left of the roundabout's center point) is acceptable. This alignment will still allow sufficient curvature to be achieved at the entry, which is of supreme importance. In some cases (particularly when the inscribed circle is relatively small), it may be beneficial to introduce a slight offset of the approaches to the left in order to enhance the entry curvature. However, care must be taken to ensure that such an approach offset does not produce an excessively tangential exit. Especially in urban environments, it is important that the exit geometry produce a sufficiently curved exit path in order to keep vehicle speeds low and reduce the risk for pedestrians.

It is almost never acceptable for an approach alignment to be offset to the right of the roundabout's center point. This alignment brings the approach in at a more tangential angle and reduces the opportunity to provide sufficient entry curvature. Vehicles will be able to enter the roundabout too fast, resulting in more loss-of-control crashes and higher crash rates between entering and circulating vehicles. Exhibit 6-18 illustrates the preferred radial alignment of entries.

Approach alignment should not be offset to the right of the roundabout's center point.

In addition, it is desirable to equally space the angles between entries. This provides optimal separation between successive entries and exits. This results in optimal angles of 90 degrees for four-leg roundabouts, 72 degrees for five-leg roundabouts, and so on. This is consistent with findings of the British accident prediction models described in Chapter 5.

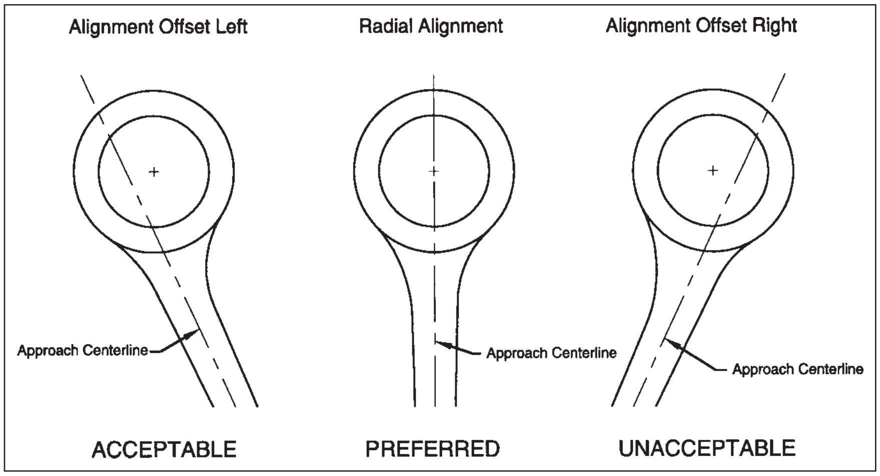


Exhibit 6-18. Radial alignment of entries.

6.3 Geometric Elements

This section presents specific parameters and guidelines for the design of each geometric element of a roundabout. The designer must keep in mind, however, that these components are not independent of each other. The interaction between the components of the geometry is far more important than the individual pieces. Care must be taken to ensure that the geometric elements are all compatible with each other so that the overall safety and capacity objectives are met.

6.3.1 Inscribed circle diameter

The inscribed circle diameter is the distance across the circle inscribed by the outer curb (or edge) of the circulatory roadway. As illustrated in Exhibit 6-1, it is the sum of the central island diameter (which includes the apron, if present) and twice the circulatory roadway. The inscribed circle diameter is determined by a number of design objectives. The designer often has to experiment with varying diameters before determining the optimal size at a given location.

For a single-lane roundabout, the minimum inscribed circle diameter is 30 m (100 ft) to accommodate a WB-15 (WB-50) vehicle.

At single-lane roundabouts, the size of the inscribed circle is largely dependent upon the turning requirements of the design vehicle. The diameter must be large enough to accommodate the design vehicle while maintaining adequate deflection curvature to ensure safe travel speeds for smaller vehicles. However, the circulatory roadway width, entry and exit widths, entry and exit radii, and entry and exit angles also play a significant role in accommodating the design vehicle and providing deflection. Careful selection of these geometric elements may allow a smaller inscribed circle diameter to be used in constrained locations. In general, the inscribed circle diameter should be a *minimum* of 30 m (100 ft) to accommodate a WB-15 (WB-50) design vehicle. Smaller roundabouts can be used for some local street or collector street intersections, where the design vehicle may be a bus or single-unit truck.

For a double-lane roundabout, the minimum inscribed circle diamter is 45 m (150 ft).

At double-lane roundabouts, accommodating the design vehicle is usually not a constraint. The size of the roundabout is usually determined either by the need to achieve deflection or by the need to fit the entries and exits around the circumference with reasonable entry and exit radii between them. Generally, the inscribed circle diameter of a double-lane roundabout should be a *minimum* of 45 m (150 ft).

In general, smaller inscribed diameters are better for overall safety because they help to maintain lower speeds. In high-speed environments, however, the design of the approach geometry is more critical than in low-speed environments. Larger inscribed diameters generally allow for the provision of better approach geometry, which leads to a decrease in vehicle approach speeds. Larger inscribed diameters also reduce the angle formed between entering and circulating vehicle paths, thereby reducing the relative speed between these vehicles and leading to reduced entering-circulating crash rates (2). Therefore, roundabouts in high-speed environments may require diameters that are somewhat larger than those recommended for low-speed environments. Very large diameters (greater than 60 m [200 ft]), however, should generally not be used because they will have high circulating speeds and more crashes with greater severity. Exhibit 6-19 provides recommended ranges of inscribed circle diameters for various site locations.

Exhibit 6-19. Recommended inscribed circle diameter ranges.

Site Category	Typical Design Vehicle	Inscribed Circle Diameter Range*
Mini-Roundabout	Single-Unit Truck	13–25m (45–80 ft)
Urban Compact	Single-Unit Truck/Bus	25–30m (80–100 ft)
Urban Single Lane	WB-15 (WB-50)	30–40m (100–130 ft)
Urban Double Lane	WB-15 (WB-50)	45–55m (150–180 ft)
Rural Single Lane	WB-20 (WB-67)	35–40m (115–130 ft)
Rural Double Lane	WB-20 (WB-67)	55–60m (180–200 ft)

* Assumes 90-degree angles between entries and no more than four legs.

6.3.2 Entry width

Entry width is the largest determinant of a roundabout's capacity. The capacity of an approach is not dependent merely on the number of entering lanes, but on the total width of the entry. In other words, the entry capacity increases steadily with incremental increases to the entry width. Therefore, the basic sizes of entries and circulatory roadways are generally described in terms of *width*, not number of lanes. Entries that are of sufficient width to accommodate multiple traffic streams (at least 6.0 m [20 ft]) are striped to designate separate lanes. However, the circulatory roadway is usually not striped, even when more than one lane of traffic is expected to circulate (for more details related to roadway markings, see Chapter 7).

Entry width is the largest determinant of a roundabout's capacity.

As shown in Exhibit 6-1, entry width is measured from the point where the yield line intersects the left edge of the traveled-way to the right edge of the traveled-way, along a line perpendicular to the right curb line. The width of each entry is dictated by the needs of the entering traffic stream. It is based on design traffic volumes and can be determined in terms of the number of entry lanes by using Chapter 4 of this guide. The circulatory roadway must be at least as wide as the widest entry and must maintain a constant width throughout.

Entry widths should be kept to a minimum to maximize safety while achieving capacity and performance objectives.

To maximize the roundabout's safety, entry widths should be kept to a minimum. The capacity requirements and performance objectives will dictate that each entry be a certain width, with a number of entry lanes. In addition, the turning requirements of the design vehicle may require that the entry be wider still. However, larger entry and circulatory widths increase crash frequency. Therefore, determining the entry width and circulatory roadway width involves a trade-off between capacity and safety. The design should provide the minimum width necessary for capacity and accommodation of the design vehicle in order to maintain the highest level of safety. Typical entry widths for single-lane entrances range from 4.3 to 4.9 m (14 to 16 ft); however, values higher or lower than this range may be required for site-specific design vehicle and speed requirements for critical vehicle paths.

When the capacity requirements can only be met by increasing the entry width, this can be done in two ways:

1. By adding a full lane upstream of the roundabout and maintaining parallel lanes through the entry geometry; or

2. By widening the approach gradually (flaring) through the entry geometry.

Exhibit 6-20 and Exhibit 6-21 illustrate these two widening options.

Exhibit 6-20. Approach widening by adding full lane.

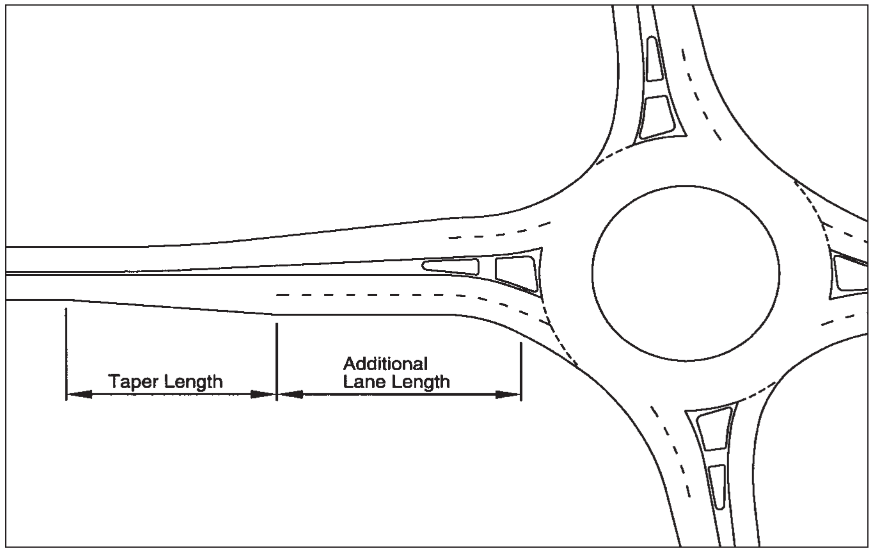
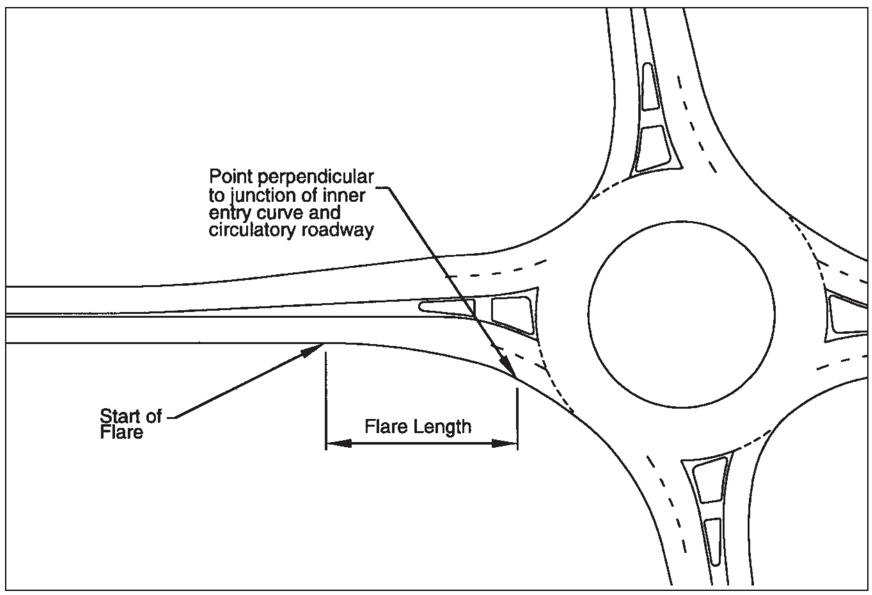


Exhibit 6-21. Approach widening by entry flaring.



Flare lengths should be at least 25 m in urban areas and 40 m in rural areas.

As discussed in Chapter 4, flaring is an effective means of increasing capacity without requiring as much right-of-way as a full lane addition. While increasing the length of flare increases capacity, it does not increase crash frequency. Consequently, the crash frequency for two approaches with the same entry width will be essentially the same, whether they have parallel entry lanes or flared entry designs. Entry widths should therefore be minimized and flare lengths maximized to achieve the desired capacity with minimal effect on crashes. Generally, flare lengths should be a minimum of 25 m (80 ft) in urban areas and 40 m (130 ft) in rural areas. However, if right-of-way is constrained, shorter lengths can be used with noticeable effects on capacity (see Chapter 4).

In some cases, a roundabout designed to accommodate design year traffic volumes, typically projected 20 years from the present, can result in substantially wider entries and circulatory roadway than needed in the earlier years of operation. Because safety will be significantly reduced by the increase in entry width, the designer may wish to consider a two-phase design solution. In this case, the first-phase design would provide the entry width requirements for near-term traffic volumes with the ability to easily expand the entries and circulatory roadway to accommodate future traffic volumes. The interim solution should be accomplished by first laying out the ultimate plan, then designing the first phase within the ultimate curb lines. The interim roundabout is often constructed with the ultimate inscribed circle diameter, but with a larger central island and splitter islands. At the time additional capacity is needed, the splitter and central islands can be reduced in size to provide additional widths at the entries, exits, and circulatory roadway.

Two-phase designs allow for small initial entry widths that can be easily expanded in the future when needed to accommodate greater traffic volumes.

6.3.3 Circulatory roadway width

The required width of the circulatory roadway is determined from the width of the entries and the turning requirements of the design vehicle. In general, it should always be at least as wide as the maximum entry width (up to 120 percent of the maximum entry width) and should remain constant throughout the roundabout (3).

6.3.3.1 Single-lane roundabouts

At single-lane roundabouts, the circulatory roadway should just accommodate the design vehicle. Appropriate vehicle-turning templates or a CAD-based computer program should be used to determine the swept path of the design vehicle through each of the turning movements. Usually the left-turn movement is the critical path for determining circulatory roadway width. In accordance with AASHTO policy, a minimum clearance of 0.6 m (2 ft) should be provided between the outside edge of the vehicle's tire track and the curb line. AASHTO Table III-19 (1994 edition) provides derived widths required for various radii for each standard design vehicle.

In some cases (particularly where the inscribed diameter is small or the design vehicle is large) the turning requirements of the design vehicle may dictate that the circulatory roadway be so wide that the amount of deflection necessary to slow passenger vehicles is compromised. In such cases, the circulatory roadway width can be reduced and a truck apron, placed behind a mountable curb on the central island, can be used to accommodate larger vehicles. However, truck aprons generally provide a lower level of operation than standard nonmountable islands. They are sometimes driven over by four-wheel drive automobiles, may surprise inattentive motorcyclists, and can cause load shifting on trucks. They should, therefore, be used only when there is no other means of providing adequate deflection while accommodating the design vehicle.

Truck aprons generally provide a lower level of operations, but may be needed to provide adequate deflection while still accommodating the design vehicle.

6.3.3.2 Double-lane roundabouts

At double-lane roundabouts, the circulatory roadway width is usually not governed by the design vehicle. The width required for one, two, or three vehicles, depending on the number of lanes at the widest entry, to travel simultaneously through the roundabout should be used to establish the circulatory roadway width. The combination of vehicle types to be accommodated side-by-side is dependent upon the specific traffic conditions at each site. If the entering traffic is predominantly passenger cars and single-unit trucks (AASHTO P and SU vehicles), where semi-trailer traffic is infrequent, it may be appropriate to design the width for two passenger vehicles or a passenger car and a single-unit truck side-by-side. If semi-trailer traffic is relatively frequent (greater than 10 percent), it may be necessary to provide sufficient width for the simultaneous passage of a semi-trailer in combination with a P or SU vehicle.

Exhibit 6-22 provides minimum recommended circulatory roadway widths for two-lane roundabouts where semi-trailer traffic is relatively infrequent.

Exhibit 6-22. Minimum circulatory lane widths for two-lane roundabouts.

Inscribed Circle Diameter	Minimum Circulatory Lane Width*	Central Island Diameter
45 m (150 ft)	9.8 m (32 ft)	25.4 m (86 ft)
50 m (165 ft)	9.3 m (31 ft)	31.4 m (103 ft)
55 m (180 ft)	9.1 m (30 ft)	36.8 m (120 ft)
60 m (200 ft)	9.1 m (30 ft)	41.8 m (140 ft)
65 m (215 ft)	8.7 m (29 ft)	47.6 m (157 ft)
70 m (230 ft)	8.7 m (29 ft)	52.6 m (172 ft)

* Based on 1994 AASHTO Table III-20, Case III(A) (4). Assumes infrequent semi-trailer use (typically less than 5 percent of the total traffic). Refer to AASHTO for cases with higher truck percentages.

6.3.4 Central island

The central island of a roundabout is the raised, nontraversable area encompassed by the circulatory roadway; this area may also include a traversable apron. The island is typically landscaped for aesthetic reasons and to enhance driver recognition of the roundabout upon approach. Central islands should always be raised, not depressed, as depressed islands are difficult for approaching drivers to recognize.

In general, the central island should be circular in shape. A circular-shaped central island with a constant-radius circulatory roadway helps promote constant speeds around the central island. Oval or irregular shapes, on the other hand, are more difficult to drive and can promote higher speeds on the straight sections and reduced speeds on the arcs of the oval. This speed differential may make it harder for entering vehicles to judge the speed and acceptability of gaps in the circulatory traffic stream. It can also be deceptive to circulating drivers, leading to more loss-of-control crashes. Noncircular central islands have the above disadvantages to a rapidly increasing degree as they get larger because circulating speeds are higher. Oval shapes are generally not such a problem if they are relatively small and speeds are low. Raindrop-shaped islands may be used in areas where certain movements do not exist, such as interchanges (see Chapter 8), or at locations where certain turning movements cannot be safely accommodated, such as roundabouts with one approach on a relatively steep grade.

As described in Section 6.2.1, the size of the central island plays a key role in determining the amount of deflection imposed on the through vehicle's path. However, its diameter is entirely dependent upon the inscribed circle diameter and the required circulatory roadway width (see Sections 6.3.1 and 6.3.3, respectively). Therefore, once the inscribed diameter, circulatory roadway width, and initial entry geometry have been established, the fastest vehicle path must be drawn though the layout, as described in Section 6.2.1.3, to determine if the central island size is adequate. If the fastest path exceeds the design speed, the central island size may need to be increased, thus increasing the overall inscribed circle diameter. There may be other methods for increasing deflection without increasing the inscribed diameter, such as offsetting the approach alignment to the left, reducing the entry width, or reducing the entry radius. These treatments, however, may preclude the ability to accommodate the design vehicle.

In cases where right-of-way, topography, or other constraints preclude the ability to expand the inscribed circle diameter, a mountable apron may be added to the outer edge of the central island. This provides additional paved area to allow the over-tracking of large semi-trailer vehicles on the central island without compromising the deflection for smaller vehicles. Exhibit 6-23 shows a typical central island with a traversable apron.

Where aprons are used, they should be designed so that they are traversable by trucks, but discourage passenger vehicles from using them. They should generally be 1 to 4 m (3 to 13 ft) wide and have a cross slope of 3 to 4 percent away from the central island. To discourage use by passenger vehicles, the outer edge of the apron should be raised a minimum of 30 mm (1.2 in) above the circulatory roadway surface (6). The apron should be constructed of colored and/or textured paving

Leeds, MD

Exhibit 6-23. Example of central island with a traversable apron.

materials to differentiate it from the circulatory roadway. Care must be taken to ensure that delivery trucks will not experience load shifting as their rear trailer wheels track across the apron.

Issues regarding landscaping and other treatments within the central island are discussed in Chapter 7.

In general, roundabouts in rural environments typically need larger central islands than urban roundabouts in order to enhance their visibility and to enable the design of better approach geometry (2).

6.3.5 Entry curves

As shown in Exhibit 6-1, the entry curves are the set of one or more curves along the right curb (or edge of pavement) of the entry roadway leading into the circulatory roadway. It should not be confused with the *entry path curve*, defined by the radius of the fastest vehicular travel path through the entry geometry (R_1 on Exhibit 6-12).

The entry radius is an important factor in determining the operation of a roundabout as it has significant impacts on both capacity and safety. The entry radius, in conjunction with the entry width, the circulatory roadway width, and the central island geometry, controls the amount of deflection imposed on a vehicle's entry path. Larger entry radii produce faster entry speeds and generally result in higher crash rates between entering and circulating vehicles. In contrast, the operational performance of roundabouts benefits from larger entry radii. As described in Chapter 4, British research has found that the capacity of an entry increases as its entry radius is increased (up to 20 m [65 ft], beyond which entry radius has little effect on capacity.

The entry curve is designed curvilinearly tangential to the outside edge of the circulatory roadway. Likewise, the projection of the inside (left) edge of the entry roadway should be curvilinearly tangential to the central island. Exhibit 6-24 shows a typical roundabout entrance geometry.

The primary objective in selecting a radius for the entry curve is to achieve the speed objectives, as described in Section 6.2.1. The entry radius should first produce an appropriate design speed on the fastest vehicular path. Second, it should desirably result in an entry path radius (R_1) equal to or less than the circulating path radius (R_2) (see Section 6.2.1.5).

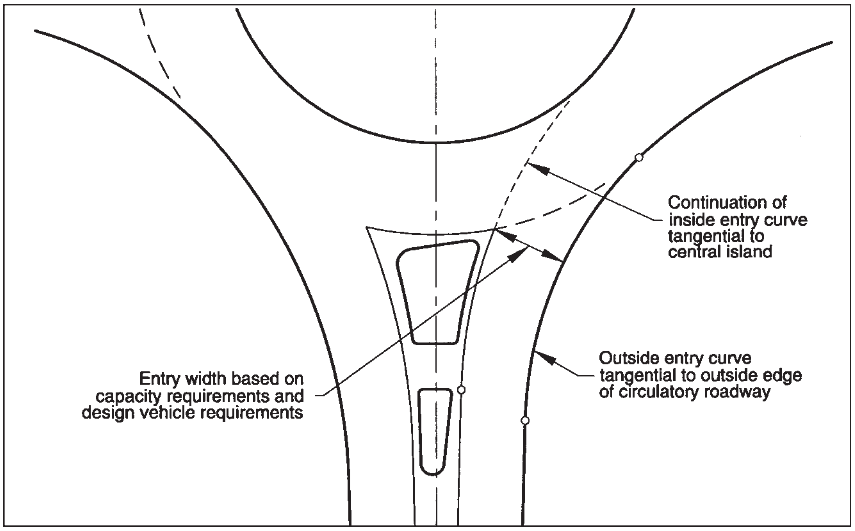


Exhibit 6-24. Single-lane roundabout entry design.

6.3.5.1 Entry curves at single-lane roundabouts

For single-lane roundabouts, it is relatively simple to achieve the entry speed objectives. With a single traffic stream entering and circulating, there is no conflict between traffic in adjacent lanes. Thus, the entry radius can be reduced or increased as necessary to produce the desired entry path radius. Provided sufficient clearance is given for the design vehicle, approaching vehicles will adjust their path accordingly and negotiate through the entry geometry into the circulatory roadway.

Entry radii at urban single-lane roundabouts typically range from 10 to 30 m (33 to 98 ft). Larger radii may be used, but it is important that the radii not be so large as to result in excessive entry speeds. At local street roundabouts, entry radii may be below 10 m (33 ft) if the design vehicle is small.

At rural and suburban locations, consideration should be given to the speed differential between the approaches and entries. If the difference is greater than 20 km/h (12 mph), it is desirable to introduce approach curves or some other speed reduction measures to reduce the speed of approaching traffic prior to the entry curvature. Further details on rural roundabout design are provided in Section 6.5.

6.3.5.2 Entry curves at double-lane roundabouts

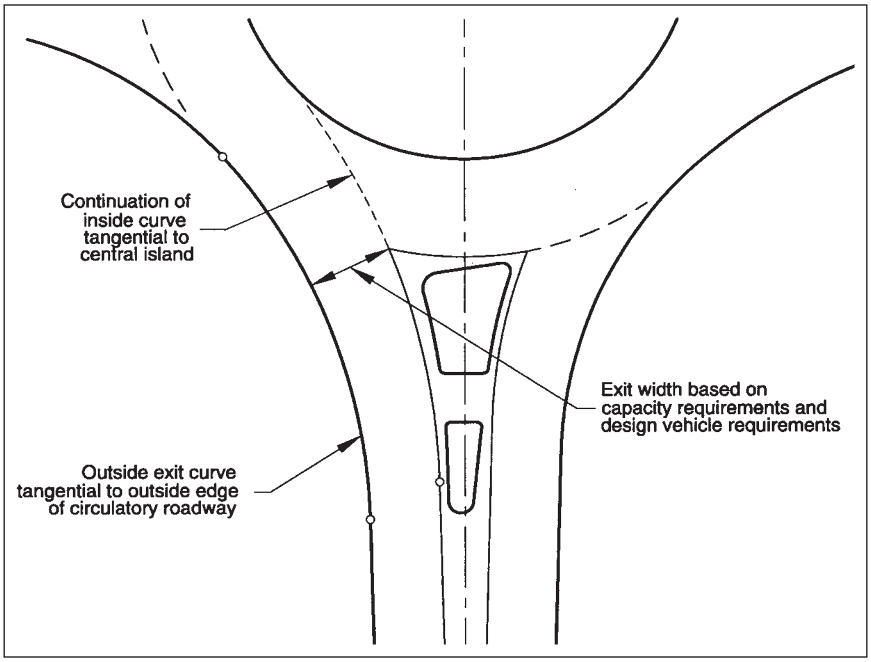
At double-lane roundabouts, the design of the entry curvature is more complicated. Overly small entry radii can result in conflicts between adjacent traffic streams. This conflict usually results in poor lane utilization of one or more lanes and significantly reduces the capacity of the approach. It can also degrade the safety performance as sideswipe crashes may increase. Techniques and guidelines for avoiding conflicts between adjacent entry lanes at double-lane roundabouts are provided in Section 6.4.

6.3.6 Exit curves

Exit curves usually have larger radii than entry curves to minimize the likelihood of congestion at the exits. This, however, is balanced by the need to maintain low speeds at the pedestrian crossing on exit. The exit curve should produce an *exit path radius* (R_3 in Exhibit 6-12) no smaller than the circulating path radius (R_2). If the exit path radius is smaller than the circulating path radius, vehicles will be traveling too fast to negotiate the exit geometry and may crash into the splitter island or into oncoming traffic in the adjacent approach lane. Likewise, the exit path radius should not be significantly greater than the circulating path radius to ensure low speeds at the downstream pedestrian crossing.

The exit curve is designed to be curvilinearly tangential to the outside edge of the circulatory roadway. Likewise, the projection of the inside (left) edge of the exit roadway should be curvilinearly tangential to the central island. Exhibit 6-25 shows a typical exit layout for a single-lane roundabout.

Exhibit 6-25. Single-lane roundabout exit design.



6.3.6.1 Exit curves at single-lane roundabouts

At single-lane roundabouts in urban environments, exits should be designed to enforce a curved exit path with a design speed below 40 km/h (25 mph) in order to maximize safety for pedestrians crossing the exiting traffic stream. Generally, exit radii should be no less than 15 m (50 ft). However, at locations with pedestrian activity and no large semi-trailer traffic, exit radii may be as low as 10 to 12 m (33 to 39 ft). This produces a very slow design speed to maximize safety and comfort for pedestrians. Such low exit radii should only be used in conjunction with similar or smaller entry radii on urban compact roundabouts with inscribed circle diameters below 35 m (115 ft).

In rural locations where there are few pedestrians, exit curvature may be designed with large radii, allowing vehicles to exit quickly and accelerate back to traveling speed. This, however, should not result in a straight path tangential to the central island because many locations that are rural today become urban in the future. Therefore, it is recommended that pedestrian activity be considered at all exits except where separate pedestrian facilities (paths, etc.) or other restrictions eliminate the likelihood of pedestrian activity in the foreseeable future.

6.3.6.2 Exit curves at double-lane roundabouts

As with the entries, the design of the exit curvature at double-lane roundabouts is more complicated than at single-lane roundabouts. Techniques and guidelines for avoiding conflicts between adjacent exit lanes at double-lane roundabouts are provided in Section 6.4.

6.3.7 Pedestrian crossing location and treatments

Pedestrian crossing locations must balance pedestrian convenience, pedestrian safety, and roundabout operations.

Pedestrian crossing locations at roundabouts are a balance among pedestrian convenience, pedestrian safety, and roundabout operations:

- *Pedestrian convenience*: Pedestrians want crossing locations as close to the intersection as possible to minimize out-of-direction travel. The further the crossing is from the roundabout, the more likely that pedestrians will choose a shorter route that may put them in greater danger.
- *Pedestrian safety*: Both crossing location and crossing distance are important. Crossing distance should be minimized to reduce exposure of pedestrian-vehicle conflicts. Pedestrian safety may also be compromised at a yield-line crosswalk because driver attention is directed to the left to look for gaps in the circulating traffic stream. Crosswalks should be located to take advantage of the splitter island; crosswalks located too far from the yield line require longer splitter islands. Crossings should also be located at distances away from the yield line measured in increments of approximate vehicle length to reduce the chance that vehicles will be queued across the crosswalk.

- *Roundabout operations*: Roundabout operations (primarily vehicular) can also be affected by crosswalk locations, particularly on the exit. A queuing analysis at the exit crosswalk may determine that a crosswalk location of more than one vehicle length away may be required to reduce to an acceptable level the risk of queuing into the circulatory roadway. Pedestrians may be able to distinguish exiting vehicles from circulating vehicles (both visually and audibly) at crosswalk locations further away from the roundabout, although this has not been confirmed by research.

With these issues in mind, pedestrian crossings should be designed as follows:

- The pedestrian refuge should be a minimum width of 1.8 m (6 ft) to adequately provide shelter for persons pushing a stroller or walking a bicycle (see Section 6.2.3).
- At single-lane roundabouts, the pedestrian crossing should be located one vehicle-length (7.5 m [25 ft]) away from the yield line. At double-lane roundabouts, the pedestrian crossing should be located one, two, or three car lengths (approximately 7.5 m, 15 m, or 22.5 m [25 ft, 50 ft, or 75 ft]) away from the yield line.
- The pedestrian refuge should be designed at street level, rather than elevated to the height of the splitter island. This eliminates the need for ramps within the refuge area, which can be cumbersome for wheelchairs.
- Ramps should be provided on each end of the crosswalk to connect the crosswalk to other crosswalks around the roundabout and to the sidewalk network.
- It is recommended that a detectable warning surface, as recommended in the Americans with Disabilities Act Accessibility Guidelines (ADAAG) §4.29 (Detectable Warnings), be applied to the surface of the refuge within the splitter island as shown in Exhibit 6-26. Note that the specific provision of the ADAAG requiring detectable warning surface at locations such as ramps and splitter islands (defined in the ADAAG as "hazardous vehicle areas") has been suspended until July 26, 2001 (ADAAG §4.29.5). Where used, a detectable warning surface shall meet the following requirements (7):
    - The detectable warning surface shall consist of raised truncated domes with a nominal diameter of 23 mm (0.9 in), a nominal height of 5 mm (0.2 in), and a nominal center-to-center spacing of 60 mm (2.35 in).
    - The detectable warning surface shall contrast visually with adjoining surfaces, either light-on-dark or dark-on-light. The material used to provide contrast shall be an integral part of the walking surface.
    - The detectable warning surface shall begin at the curb line and extend into the pedestrian refuge area a distance of 600 mm (24 in). This creates a minimum 600-mm (24-in) clear space between detectable warning surfaces for a minimum splitter island width of 1.8 m (6 ft) at the pedestrian crossing. This is a deviation from the requirements of (suspended) ADAAG §4.29.5, which requires a 915-mm (36-in) surface width. However, this deviation is necessary to enable visually impaired pedestrians to distinguish the two interfaces with vehicular traffic.

Detectable warning surfaces should be applied within the pedestrian refuge.

In urban areas, speed tables (flat-top road humps) could be considered for wheelchair users, provided that good geometric design has reduced absolute vehicle speeds to less than 20 km/h (12 mph) near the crossing. Pedestrian crossings across speed tables must have detectable warning material as described above to clearly delineate the edge of the street. Speed tables should generally be used only on streets with approach speeds of 55 km/h (35 mph) or less, as the introduction of a raised speed table in higher speed environments may increase the likelihood of single-vehicle crashes and is not consistent with the speed consistency philosophy presented in this document.

6.3.8 Splitter islands

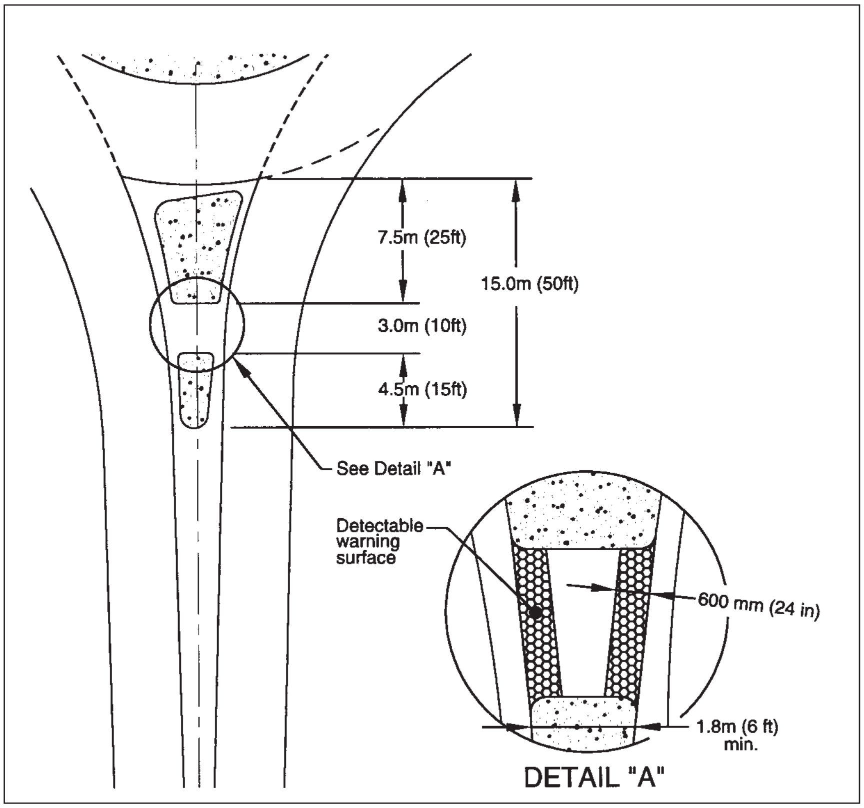
Splitter islands (also called *separator islands* or *median islands*) should be provided on all roundabouts, except those with very small diameters at which the splitter island would obstruct the visibility of the central island. Their purpose is to provide shelter for pedestrians (including wheelchairs, bicycles, and baby strollers), assist in controlling speeds, guide traffic into the roundabout, physically separate entering and exiting traffic streams, and deter wrong-way movements. Additionally, splitter islands can be used as a place for mounting signs (see Chapter 7).

Splitter islands perform multiple functions and should generally be provided.

The splitter island envelope is formed by the entry and exit curves on a leg, as shown previously in Exhibits 6-24 and 6-25. The total length of the island should generally be at least 15 m (50 ft) to provide sufficient protection for pedestrians and to alert approaching drivers to the roundabout geometry. Additionally, the splitter island should extend beyond the end of the exit curve to prevent exiting traffic from accidentally crossing into the path of approaching traffic.

Exhibit 6-26 shows the minimum dimensions for a splitter island at a single-lane roundabout, including the location of the pedestrian crossing as discussed in Section 6.3.7.

Exhibit 6-26. Minimum splitter island dimensions.

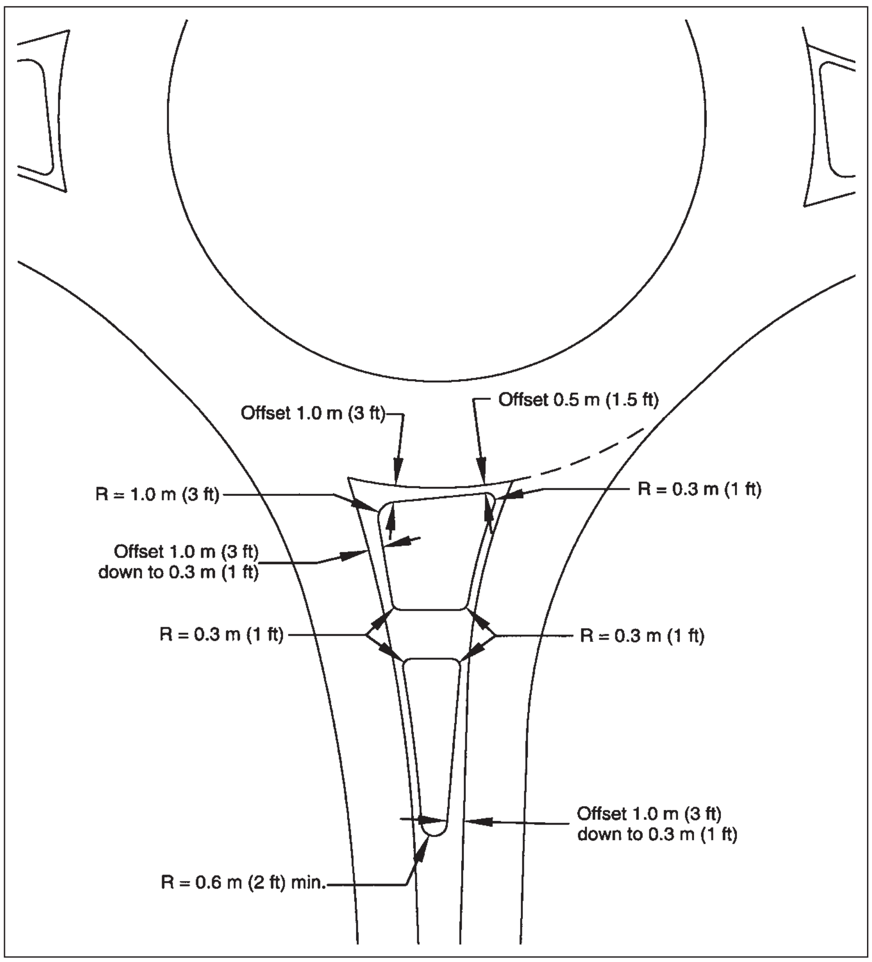


Larger splitter islands enhance safety, but require that the inscribed circle diameter be increased.

While Exhibit 6-26 provides minimum dimensions for splitter islands, there are benefits to providing larger islands. Increasing the splitter island width results in greater separation between the entering and exiting traffic streams of the same leg and increases the time for approaching drivers to distinguish between exiting and circulating vehicles. In this way, larger splitter islands can help reduce confusion for entering motorists. A recent study by the Queensland Department of Main Roads found that maximizing the width of splitter islands has a significant effect on minimizing entering/circulating vehicle crash rates (2). However, increasing the width of the splitter islands generally requires increasing the inscribed circle diameter. Thus, these safety benefits may be offset by higher construction cost and greater land impacts.

Standard AASHTO guidelines for island design should be followed for the splitter island. This includes using larger nose radii at approach corners to maximize island visibility and offsetting curb lines at the approach ends to create a funneling effect. The funneling treatment also aids in reducing speeds as vehicles approach the roundabout. Exhibit 6-27 shows minimum splitter island nose radii and offset dimensions from the entry and exit traveled ways.

Exhibit 6-27. Minimum splitter island nose radii and offsets.



6.3.9 Stopping sight distance

Stopping sight distance is the distance along a roadway required for a driver to perceive and react to an object in the roadway and to brake to a complete stop before reaching that object. Stopping sight distance should be provided at every point within a roundabout and on each entering and exiting approach.

National Cooperative Highway Research Program (NCHRP) Report 400, *Determination of Stopping Sight Distances* (8), recommends the formula given in Equation 6-2 for determining stopping sight distance (presented in metric units, followed by a conversion of the equation to U.S. customary units).

$$d = (0.278)(t)(V) + 0.039\frac{V^2}{a} \qquad \text{(6-2a, metric)}$$

where:
- d = stopping sight distance, m;
- t = perception-brake reaction time, assumed to be 2.5 s;
- V = initial speed, km/h; and
- a = driver deceleration, assumed to be 3.4 m/s².

$$d = (1.468)(t)(V) + 1.087\frac{V^2}{a}$$

where:
- d = stopping sight distance, ft;
- t = perception-brake reaction time, assumed to be 2.5 s;
- V = initial speed, mph; and
- a = driver deceleration, assumed to be 11.2 ft/s².

Exhibit 6-28 gives recommended stopping sight distances for design, as computed from the above equations.

Exhibit 6-28. Design values for stopping sight distances.

Speed (km/h)	Computed Distance* (m)	Speed (mph)	Computed Distance* (ft)
10	8.1	10	46.4
20	18.5	15	77.0
30	31.2	20	112.4
40	46.2	25	152.7
50	63.4	30	197.8
60	83.0	35	247.8
70	104.9	40	302.7
80	129.0	45	362.
90	155.5	50	427.2
100	184.2 *	55	496.7

Assumes 2.5 s perception-braking time, 3.4 m/s² (11.2 ft/s²) driver deceleration

Stopping sight distance should be measured using an assumed height of driver's eye of 1,080 mm (3.54 ft) and an assumed height of object of 600 mm (1.97 ft) in accordance with the recommendations to be adopted in the next AASHTO "Green Book" (8).

At least three critical types of locations should be checked for stopping sight distance.

At roundabouts, three critical types of locations should be checked at a minimum:

- Approach sight distance (Exhibit 6-29);
- Sight distance on circulatory roadway (Exhibit 6-30); and
- Sight distance to crosswalk on exit (Exhibit 6-31).

Forward sight distance at entry can also be checked; however, this will typically be satisfied by providing adequate stopping sight distance on the circulatory roadway itself.

Exhibit 6-29. Approach sight distance.

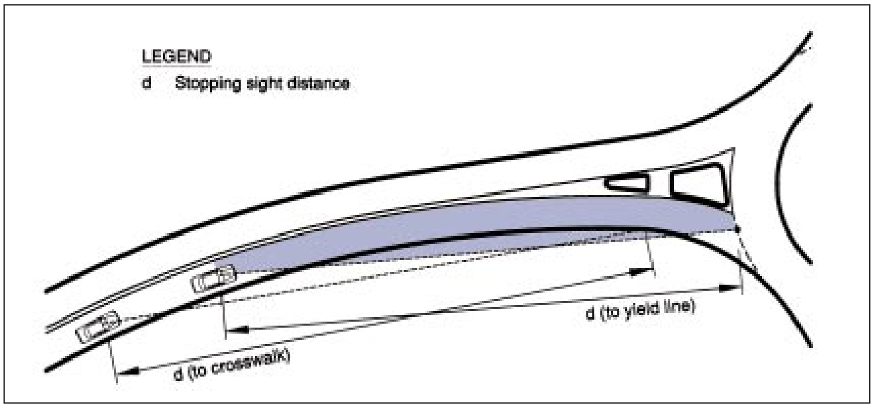
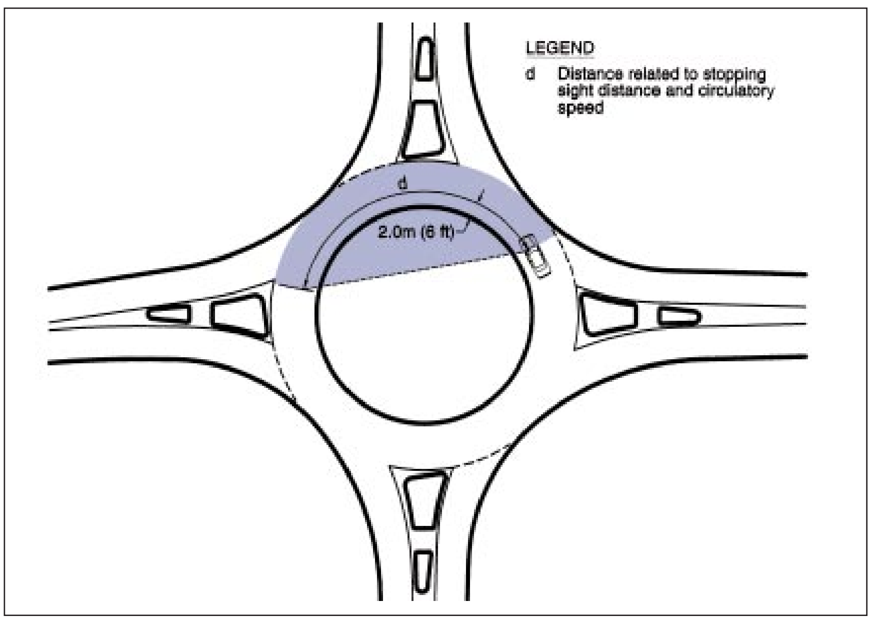


Exhibit 6-30. Sight distance on circulatory roadway.



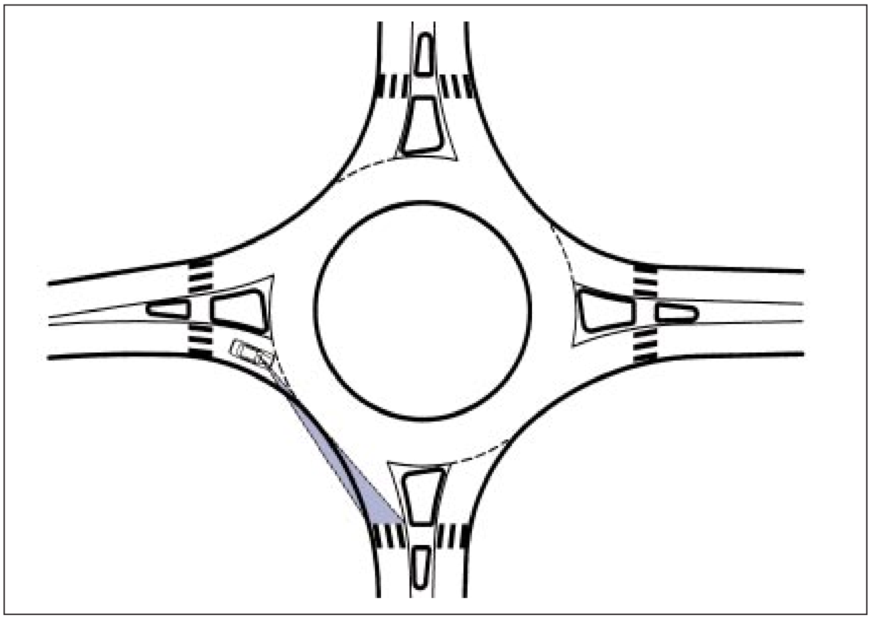


Exhibit 6-31. Sight distance to crosswalk on exit.

6.3.10 Intersection sight distance

Roundabout entries require adequate intersection sight distance.

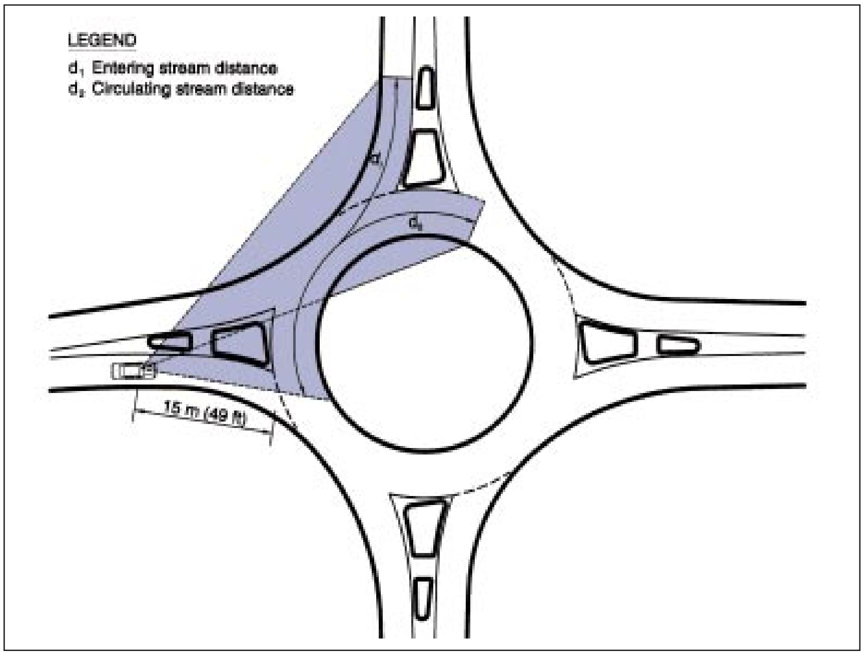
Intersection sight distance is the distance required for a driver without the right of way to perceive and react to the presence of conflicting vehicles. Intersection sight distance is achieved through the establishment of adequate sight lines that allow a driver to see and safely react to potentially conflicting vehicles. At roundabouts, the only locations requiring evaluation of intersection sight distance are the entries.

Intersection sight distance is traditionally measured through the determination of a *sight triangle*. This triangle is bounded by a length of roadway defining a limit away from the intersection on each of the two conflicting approaches and by a line connecting those two limits. For roundabouts, these "legs" should be assumed to follow the curvature of the roadway, and thus distances should be measured not as straight lines but as distances along the vehicular path.

Intersection sight distance should be measured using an assumed height of driver's eye of 1,080 mm (3.54 ft) and an assumed height of object of 1,080 mm (3.54 ft) in accordance with the recommendations to be adopted in the next AASHTO "Green Book" (4).

Exhibit 6-32 presents a diagram showing the method for determining intersection sight distance. As can be seen in the exhibit, the sight distance "triangle" has two conflicting approaches that must be checked independently. The following two subsections discuss the calculation of the length of each of the approaching sight limits.

Exhibit 6-32. Intersection sight distance



6.3.10.1 Length of approach leg of sight triangle

The length of the approach leg of the sight triangle should be limited to 15 m (49 ft). British research on sight distance determined that excessive intersection sight distance results in a higher frequency of crashes. This value, consistent with British and French practice, is intended to require vehicles to slow down prior to entering the roundabout, which allows them to focus on the pedestrian crossing prior to entry. If the approach leg of the sight triangle is greater than 15 m (49 ft), it may be advisable to add landscaping to restrict sight distance to the minimum requirements.

6.3.10.2 Length of conflicting leg of sight triangle

A vehicle approaching an entry to a roundabout faces conflicting vehicles within the circulatory roadway. The length of the conflicting leg is calculated using Equation 6-3:

$$b = 0.278(V_{major})(t_c) \qquad \text{(6-3a, metric)}$$

where: b = length of conflicting leg of sight triangle, m
V_{major} = design speed of conflicting movement, km/h, discussed below
t_c = critical gap for entering the major road, s, equal to 6.5 s

$$b = 1.468(V_{major})(t_c) \qquad \text{(6-3b, U.S. customary)}$$

where: b = length of conflicting leg of sight triangle, ft
V_{major} = design speed of conflicting movement, mph, discussed below
t_c = critical gap for entering the major road, s, equal to 6.5 s

Two conflicting traffic streams should be checked at each entry:

- *Entering stream*, comprised of vehicles from the immediate upstream entry. The speed for this movement can be approximated by taking the average of the entry path speed (path with radius R_1 from Exhibit 6-12) and the circulating path speed (path with radius R_2 from Exhibit 6-12).
- *Circulating stream*, comprised of vehicles that entered the roundabout prior to the immediate upstream entry. This speed can be approximated by taking the speed of left turning vehicles (path with radius R_4 from Exhibit 6-12).

The critical gap for entering the major road is based on the amount of time required for a vehicle to turn right while requiring the conflicting stream vehicle to slow no less than 70 percent of initial speed. This is based on research on critical gaps at stop-controlled intersections, adjusted for yield-controlled conditions (9). The critical gap value of 6.5 s given in Equation 6-3 is based on the critical gap required for passenger cars, which are assumed to be the most critical design vehicle for intersection sight distance. This assumption holds true for single-unit and combination truck speeds that are at least 10 km/h (6 mph) and 15 to 20 km/h (9 to 12 mph) slower than passenger cars, respectively.

Exhibit 6-33. Computed length of conflicting leg of intersection sight triangle.

Conflicting Approach Speed (km/h)	Computed Distance (m)	Conflicting Approach Speed (mph)	Computed Distance (ft)
20	36.1	10	95.4
25	45.2	15	143.0
30	54.2	20	190.1
35	63.2	25	238.6
40	72.3	30	286.3

In general, it is recommended to provide no more than the minimum required intersection sight distance on each approach. Excessive intersection sight distance can lead to higher vehicle speeds that reduce the safety of the intersection for all road users (vehicles, bicycles, pedestrians). Landscaping can be effective in restricting sight distance to the minimum requirements.

Providing more than the minimum required intersection sight distance can lead to higher speeds that reduce intersection safety.

Note that the stopping sight distance on the circulatory roadway (Exhibit 6-30) and the intersection sight distance to the circulating stream (Exhibit 6-32) imply restrictions on the height of the central island, including landscaping and other objects, within these zones. In the remaining central area of the central island, higher landscaping may serve to break the forward vista for through vehicles, thereby contributing to speed reduction. However, should errant vehicles encroach on the central island, Chapter 7 provides recommended maximum grades on the central island to minimize the probability of the vehicles rolling over, causing serious injury.

6.3.11 Vertical considerations

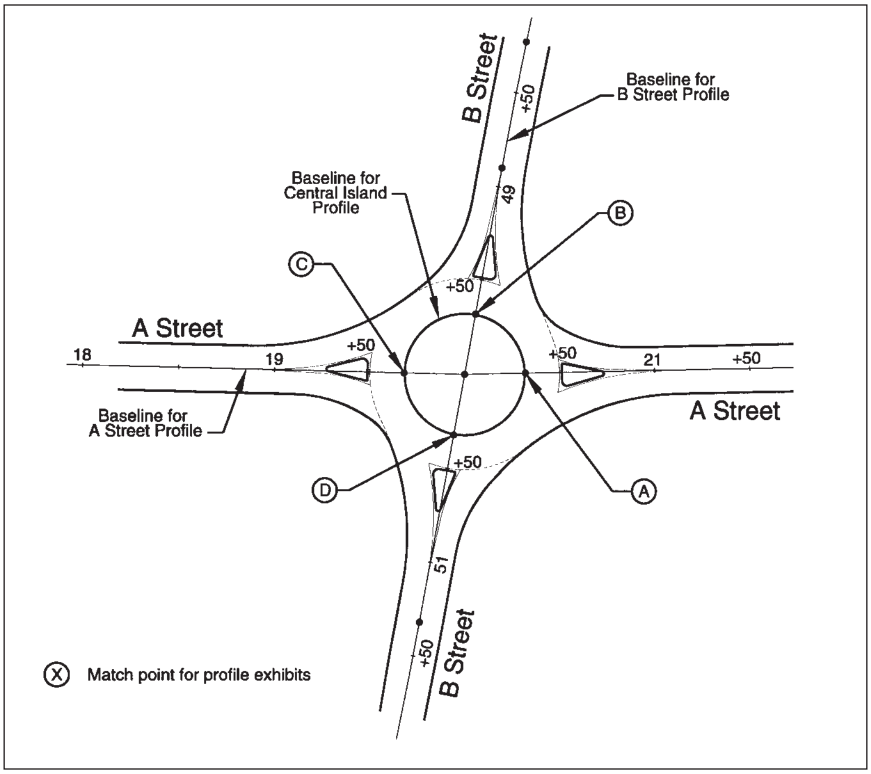
Elements of vertical alignment design for roundabouts include profiles, superelevation, approach grades, and drainage.

6.3.11.1 Profiles

The vertical design of a roundabout begins with the development of approach roadway and central island profiles. The development of each profile is an iterative process that involves tying the elevations of the approach roadway profiles into a smooth profile around the central island.

Generally, each approach profile should be designed to the point where the approach baseline intersects with the central island. A profile for the central island is then developed which passes through these four points (in the case of a four-legged roundabout). The approach roadway profiles are then readjusted as necessary to meet the central island profile. The shape of the central island profile is generally in the form of a sine curve. Examples of how the profile is developed can be found in Exhibits 6-34, 6-35, and 6-36, which consist of a sample plan, profiles on each approach, and a profile along the central island, respectively. Note that the four points where the approach roadway baseline intersects the central island baseline are identified on the central island profile.

Exhibit 6-34. Sample plan view.



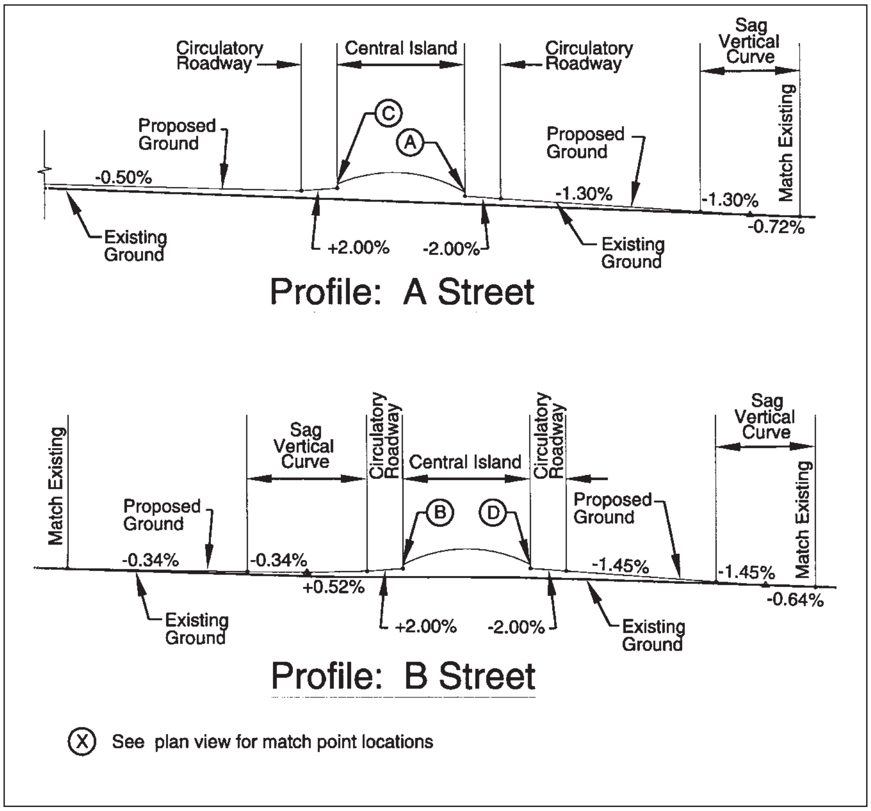


Exhibit 6-35. Sample approach profile.

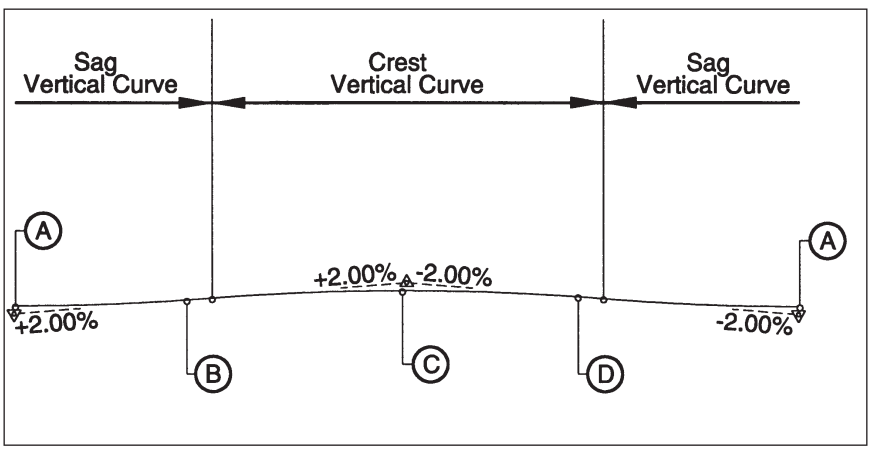


Exhibit 6-36. Sample central island profile.

6.3.11.2 Superelevation

Negative superelevation (- 2%) should generally be used for the circulatory roadway.

As a general practice, a cross slope of 2 percent away from the central island should be used for the circulatory roadway. This technique of sloping outward is recommended for four main reasons:

- It promotes safety by raising the elevation of the central island and improving its visibility;
- It promotes lower circulating speeds;
- It minimizes breaks in the cross slopes of the entrance and exit lanes; and
- It helps drain surface water to the outside of the roundabout (2, 6).

The outward cross slope design means vehicles making through and left-turn movements must negotiate the roundabout at negative superelevation. Excessive negative superelevation can result in an increase in single-vehicle crashes and loss-of-load incidents for trucks, particularly if speeds are high. However, in the intersection environment, drivers will generally expect to travel at slower speeds and will accept the higher side force caused by reasonable adverse superelevation (10).

Exhibit 6-37 provides a typical section across the circulatory roadway of a roundabout without a truck apron. Exhibit 6-38 provides a typical section for a roundabout with a truck apron. Where truck aprons are used, the slope of the apron should be 3 to 4 percent; greater slopes may increase the likelihood of loss-of-load incidents.

Exhibit 6-37. Typical circulatory roadway section.

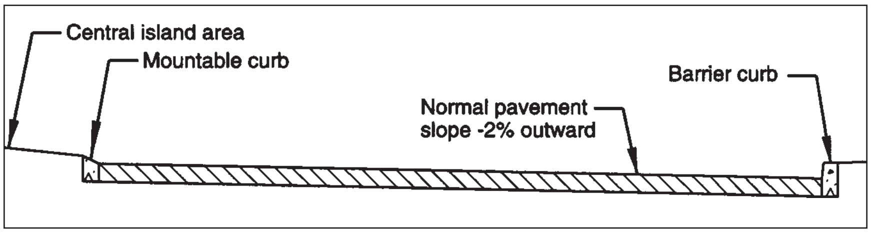
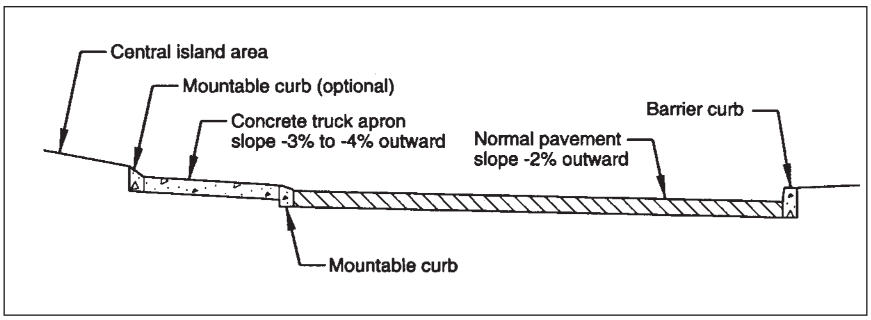


Exhibit 6-38. Typical section with a truck apron.



6.3.11.3 Locating roundabouts on grades

It is generally not desirable to locate roundabouts in locations where grades through the intersection are greater than four percent. The installation of roundabouts on roadways with grades lower than three percent is generally not problematic (6). At locations where a constant grade must be maintained through the intersection, the circulatory roadway may be constructed on a constant-slope plane. This means, for instance, that the cross slope may vary from +3 percent on the high side of the roundabout (sloped toward the central island) to -3 percent on the low side (sloped outward). Note that central island cross slopes will pass through level at a minimum of two locations for roundabouts constructed on a constant grade.

Avoid locating roundabouts in areas where grades through the intersection are greater than 4%.

Care must be taken when designing roundabouts on steep grades. On approach roadways with grades steeper than -4 percent, it is more difficult for entering drivers to slow or stop on the approach. At roundabouts on crest vertical curves with steep approaches, a driver's sight lines will be compromised, and the roundabout may violate driver expectancy. However, under the same conditions, other types of at-grade intersections often will not provide better solutions. Therefore, the roundabout should not necessarily be eliminated from consideration at such a location. Rather, the intersection should be relocated or the vertical profile modified, if possible.

6.3.11.4 Drainage

With the circulatory roadway sloping away from the central island, inlets will generally be placed on the outer curbline of the roundabout. However, inlets may be required along the central island for a roundabout designed on a constant grade through an intersection. As with any intersection, care should be taken to ensure that low points and inlets are not placed in crosswalks. If the central island is large enough, the designer may consider placing inlets in the central island.

6.3.12 Bicycle provisions

With regard to bicycle treatments, the designer should strive to provide bicyclists the choice of proceeding through the roundabout as either a vehicle or a pedestrian. In general, bicyclists are better served by treating them as vehicles. However, the best design provides both options to allow cyclists of varying degrees of skill to choose their more comfortable method of navigating the roundabout.

To accommodate bicyclists traveling as vehicles, bike lanes should be terminated in advance of the roundabout to encourage cyclists to mix with vehicle traffic. Under this treatment, it is recommended that bike lanes end 30 m (100 ft) upstream of the yield line to allow for merging with vehicles (11). This method is most successful at smaller roundabouts with speeds below 30 km/h (20 mph), where bicycle speeds can more closely match vehicle speeds.

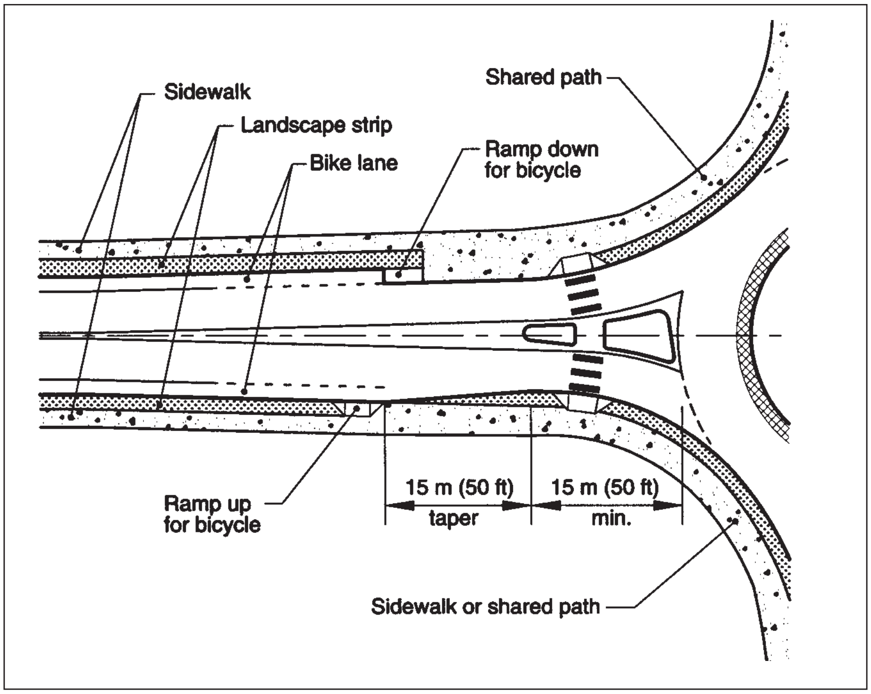
Terminate bicycle lanes prior to a roundabout.

To accommodate bicyclists who prefer not to use the circulatory roadway, a widened sidewalk or a shared bicycle/pedestrian path may be provided physically separated from the circulatory roadway (not as a bike lane within the circulatory

Ramps leading to a shared pathway can be used to accommodate bicyclists traveling as pedestrians.

roadway). Ramps or other suitable connections can then be provided between this sidewalk or path and the bike lanes, shoulders, or road surface on the approaching and departing roadways. The designer should exercise care in locating and designing the bicycle ramps so that they are not misconstrued by pedestrians as an unmarked pedestrian crossing. Nor should the exits from the roadway onto a shared path allow cyclists to enter the shared path at excessive speeds. Exhibit 6-39 illustrates a possible design of this treatment. The reader is encouraged to refer to the AASHTO *Guide for Development of Bicycle Facilities* (12) for a more detailed discussion of the design requirements for bicycle and shared-use path design.

Exhibit 6-39. Possible provisions for bicycles.



6.3.13 Sidewalk treatments

Set back sidewalks 1.5 m (5 ft) from the circulatory roadway where possible.

Where possible, sidewalks should be set back from the edge of the circulatory roadway in order to discourage pedestrians from crossing to the central island, particularly when an apron is present or a monument on the central island. Equally important, the design should help pedestrians with visual impairments to recognize that they should not attempt to cross streets from corner to corner but at designated crossing points. To achieve these goals, the sidewalk should be designed so that pedestrians will be able to clearly find the intended path to the crosswalks. A recommended set back distance of 1.5 m (5 ft) (minimum 0.6 m [2 ft]) should be used, and the area between the sidewalk and curb can be planted with low shrubs or grass (see Chapter 7). Exhibit 6-40 shows this technique.

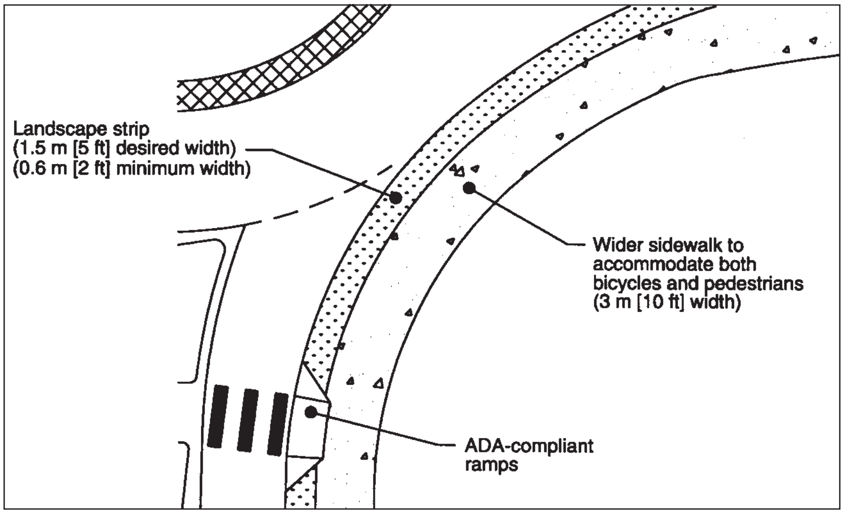


Exhibit 6-40. Sidewalk treatments.

6.3.14 Parking considerations and bus stop locations

Parking or stopping in the circulatory roadway is not conducive to proper roundabout operations and should be prohibited. Parking on entries and exits should also be set back as far as possible so as not to hinder roundabout operations or to impair the visibility of pedestrians. AASHTO recommends that parking should end at least 6.1 m (20 ft) from the crosswalk of an intersection (4). Curb extensions or “bulb-outs” can be used to clearly mark the limit of permitted parking and reduce the width of the entries and exits.

For safety and operational reasons, bus stops should be located as far away from entries and exits as possible, and never in the circulatory roadway.

- *Near-side stops*: If a bus stop is to be provided on the near side of a roundabout, it should be located far enough away from the splitter island so that a vehicle overtaking a stationary bus is in no danger of being forced into the splitter island, especially if the bus starts to pull away from the stop. If an approach has only one lane and capacity is not an issue on that entry, the bus stop could be located at the pedestrian crossing in the lane of traffic. This is not recommended for entries with more than one lane, because vehicles in the lane next to the bus may not see pedestrians.
- *Far-side stops*: Bus stops on the far side of a roundabout should be constructed with pull-outs to minimize queuing into the roundabout. These stops should be located beyond the pedestrian crossing to improve visibility of pedestrians to other exiting vehicles.

6.3.15 Right-turn bypass lanes

Right-turn bypass lanes can be used in locations with minimal pedestrian and bicycle activity to improve capacity when heavy right-turning traffic exists.

In general, right-turn bypass lanes (or *right-turn slip lanes*) should be avoided, especially in urban areas with bicycle and pedestrian activity. The entries and exits of bypass lanes can increase conflicts with bicyclists. The generally higher speeds of bypass lanes and the lower expectation of drivers to stop increases the risk of collisions with pedestrians. However, in locations with minimal pedestrian and bicycle activity, right-turn bypass lanes can be used to improve capacity where there is heavy right turning traffic.

The provision of a right-turn bypass lane allows right-turning traffic to bypass the roundabout, providing additional capacity for the through and left-turn movements at the approach. They are most beneficial when the demand of an approach exceeds its capacity and a significant proportion of the traffic is turning right. However, it is important to consider the reversal of traffic patterns during the opposite peak time period. In some cases, the use of a right-turn bypass lane can avoid the need to build an additional entry lane and thus a larger roundabout. To determine if a right-turn bypass lane should be used, the capacity and delay calculations in Chapter 4 should be performed. Right-turn bypass lanes can also be used in locations where the geometry for right turns is too tight to allow trucks to turn within the roundabout.

Exhibit 6-41 shows an example of a right-turn bypass lane.

Exhibit 6-41. Example of right-turn bypass lane.

There are two design options for right-turn bypass lanes. The first option, shown in Exhibit 6-42, is to carry the bypass lane parallel to the adjacent exit roadway, and then merge it into the main exit lane. Under this option, the bypass lane should be carried alongside the main roadway for a sufficient distance to allow vehicles in the bypass lane and vehicles exiting the roundabout to accelerate to comparable speeds. The bypass lane is then merged at a taper rate according to AASHTO guidelines for the appropriate design speed. The second design option for a right-turn bypass lane, shown in Exhibit 6-43, is to provide a yield-controlled entrance onto the adjacent exit roadway. The first option provides better operational performance than the second does. However, the second option generally requires less construction and right-of-way than the first.

Right-turn bypass lanes can merge back into the main exit roadway or provide a yield-controlled entrance onto the main exit roadway.

The option of providing yield control on a bypass lane is generally better for both bicyclists and pedestrians and is recommended as the preferred option in urban areas where pedestrians and bicyclists are prevalent. Acceleration lanes can be problematic for bicyclists because they end up being to the left of accelerating motor vehicles. In addition, yield control at the end of a bypass lane tends to slow motorists down, whereas an acceleration lane at the end of a bypass lane tends to promote higher speeds.

The radius of the right-turn bypass lane should not be significantly larger than the radius of the fastest entry path provided at the roundabout. This will ensure vehicle speeds on the bypass lane are similar to speeds through the roundabout, resulting in safe merging of the two roadways. Providing a small radius also provides greater safety for pedestrians who must cross the right-turn slip lane.

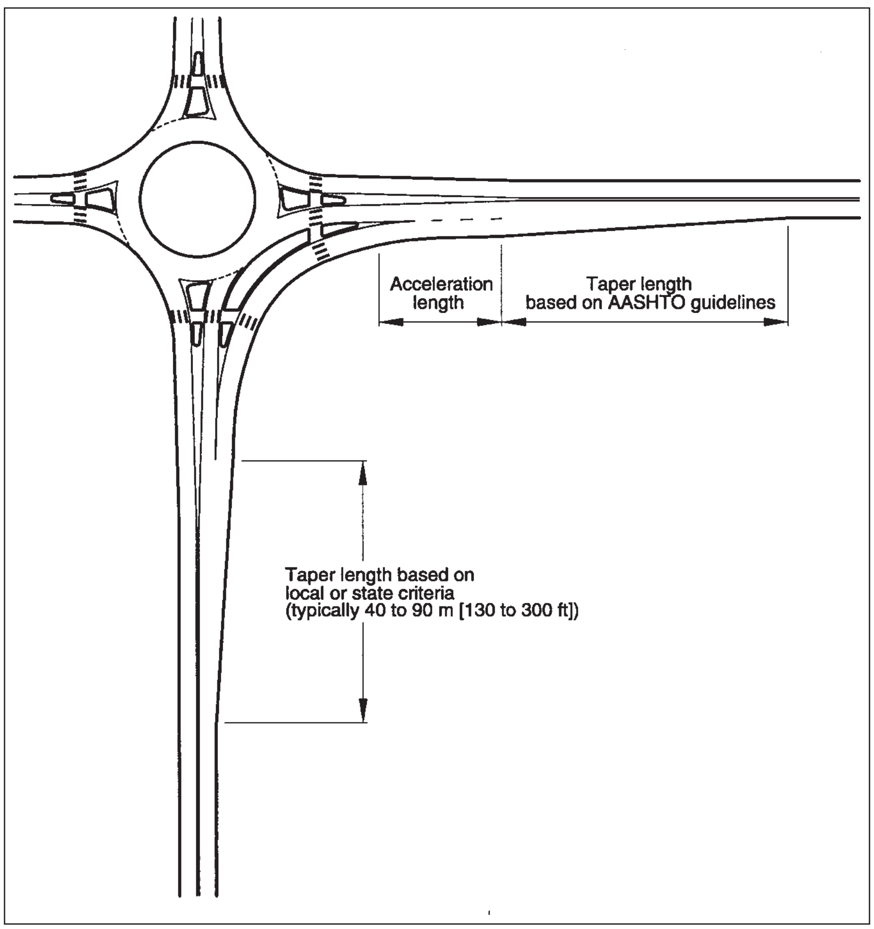
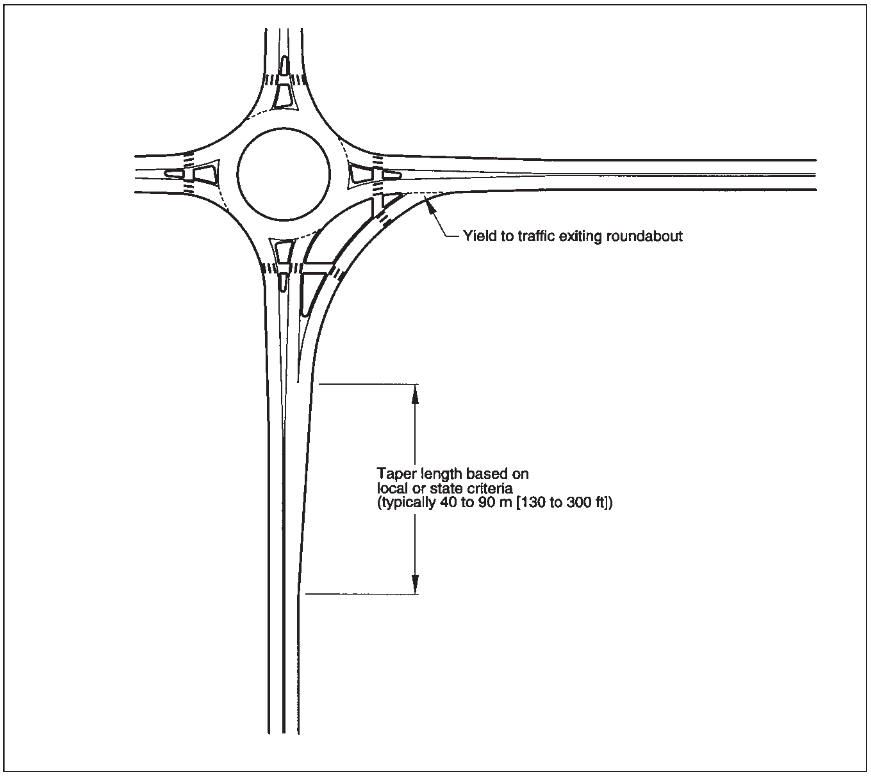


Exhibit 6-42. Configuration of right-turn bypass lane with acceleration lane.

Exhibit 6-43. Configuration of right-turn bypass with yield at exit leg.



6.4 Double-Lane Roundabouts

While the fundamental principles described above apply to double-lane roundabouts as well as single-lane roundabouts, designing the geometry of double-lane roundabouts is more complicated. Because multiple traffic streams may enter, circulate through, and exit the roundabout side-by-side, consideration must be given to how these adjacent traffic streams interact with each other. Vehicles in adjacent entry lanes must be able to negotiate the roundabout geometry without competing for the same space. Otherwise, operational and/or safety deficiencies can occur.

6.4.1 The natural vehicle path

As discussed in Section 6.2.1, the fastest path through the roundabout is drawn to ensure the geometry imposes sufficient curvature to achieve a safe design speed. This path is drawn assuming the roundabout is vacant of all other traffic and the vehicle cuts across adjacent travel lanes, ignoring all lane markings. In addition to evaluating the fastest path, at double-lane roundabouts the designer must also evaluate the *natural* vehicle paths. This is the path an approaching vehicle will naturally take, assuming there is traffic in all approach lanes, through the roundabout geometry.

As two traffic streams approach the roundabout in adjacent lanes, they will be forced to stay in their lanes up to the yield line. At the yield point, vehicles will continue along their natural trajectory into the circulatory roadway, then curve around the central island, and curve again into the opposite exit roadway. The speed and orientation of the vehicle at the yield line determines its natural path. If the natural path of one lane interferes or overlaps with the natural path of the adjacent lane, the roundabout will not operate as safely or efficiently as possible.

The key principle in drawing the natural path is to remember that drivers cannot change the direction of their vehicle instantaneously. Neither can they change their speed instantaneously. This means that the natural path does not have sudden changes in curvature; it has transitions between tangents and curves and between consecutive reversing curves. Secondly, it means that consecutive curves should be of similar radius. If a second curve has a significantly smaller radius than the first curve, the driver will be traveling too fast to negotiate the turn and may lose control of the vehicle. If the radius of one curve is drawn significantly smaller than the radius of the previous curve, the path should be adjusted.

To identify the natural path of a given design, it may be advisable to sketch the natural paths over the geometric layout, rather than use a computer drafting program or manual drafting equipment. In sketching the path, the designer will naturally draw transitions between consecutive curves and tangents, similar to the way a driver would negotiate an automobile. Freehand sketching also enables the designer to feel how changes in one curve affect the radius and orientation of the next curve. In general, the sketch technique allows the designer to quickly obtain a smooth, natural path through the geometry that may be more difficult to obtain using a computer.

Exhibit 6-44 illustrates a sketched natural path of a vehicle through a typical double-lane roundabout.

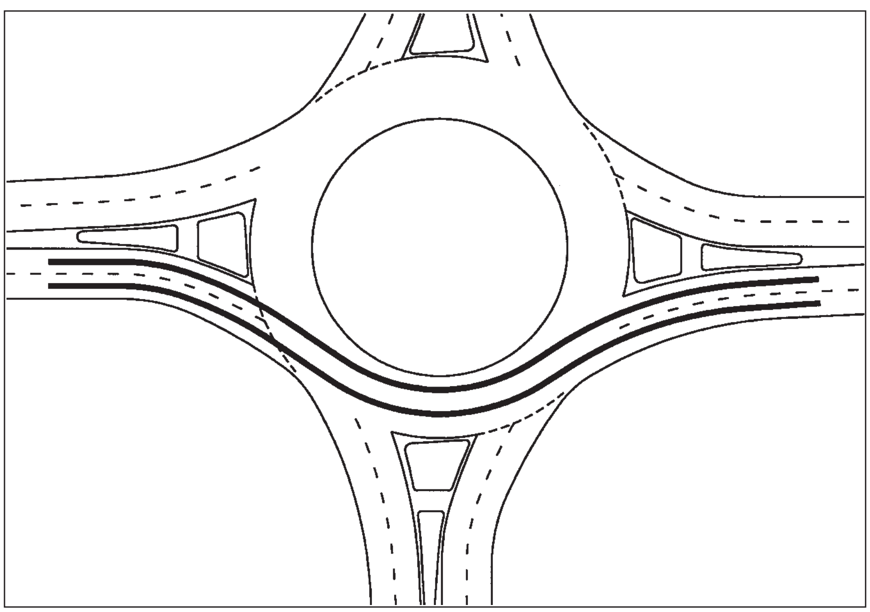
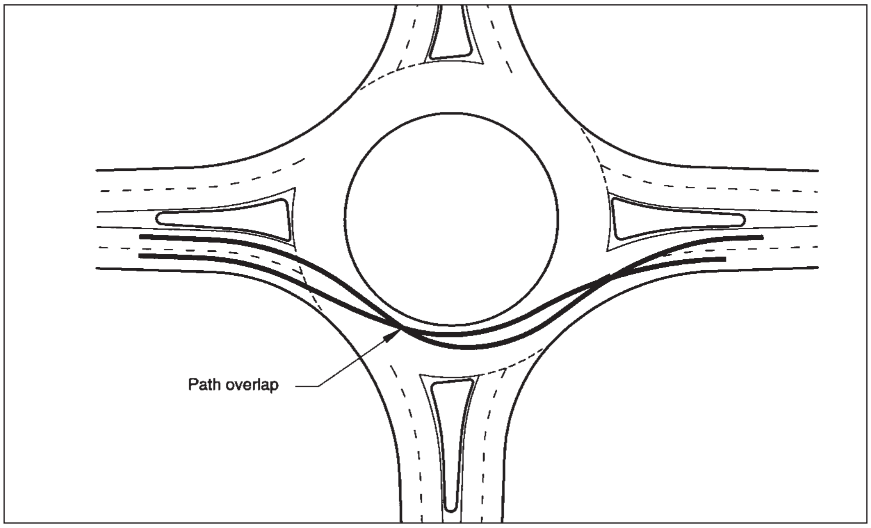


Exhibit 6-44. Sketched natural paths through a double-lane roundabout.

6.4.2 Vehicle path overlap

Vehicle path overlap occurs when the natural path through the roundabout of one traffic stream overlaps the path of another. This can happen to varying degrees. It can reduce capacity, as vehicles will avoid using one or more of the entry lanes. It can also create safety problems, as the potential for sideswipe and single-vehicle crashes is increased. The most common type of path overlap is where vehicles in the left lane on entry are cut off by vehicles in the right lane, as shown in Exhibit 6-45.

Exhibit 6-45. Path overlap at a double-lane roundabout.



6.4.3 Design method to avoid path overlap

Achieving a reasonably low design speed at a double-lane roundabout while avoiding vehicle path overlap can be difficult because of conflicting interaction between the various geometric parameters. Providing small entry radii can produce low entry speeds, but often leads to path overlap on the entry, as vehicles will cut across lanes to avoid running into the central island. Likewise, providing small exit radii can aid in keeping circulating speeds low, but may result in path overlap at the exits.

6.4.3.1 Entry curves

At double-lane entries, the designer needs to balance the need to control entry speed with the need to minimize path overlap. This can be done a variety of ways that will vary significantly depending on site-specific conditions, and it is thus inappropriate to specify a single method for designing double-lane roundabouts. Regardless of the specific design method employed, the designer should maintain the overall design principles of speed control and speed consistency presented in Section 6.2.

One method to avoid path overlap on entry is to start with an inner entry curve that is curvilinearly tangential to the central island and then draw parallel alignments to determine the position of the outside edge of each entry lane. These curves can range from 30 to 60 m (100 to 200 ft) in urban environments and 40 to 80 m (130 to 260 ft) in rural environments. These curves should extend approximately 30 m (100 ft) to provide clear indication of the curvature to the driver. The designer should check the critical vehicle paths to ensure that speeds are sufficiently low and consistent between vehicle streams. The designer should also ensure that the portion of the splitter island in front of the crosswalk meets AASHTO recommendations for minimum size. Exhibit 6-46 demonstrates this method of design.

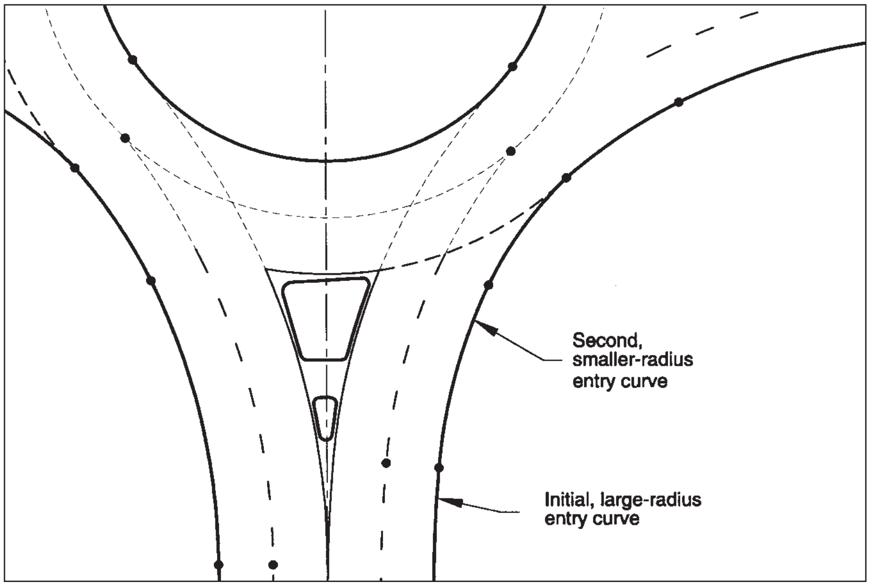


Exhibit 6-46. One method of entry design to avoid path overlap at double-lane roundabouts.

Another method to reduce entry speeds and avoid path overlap is to use a small-radius (generally 15 to 30 m [50 to 100 ft]) curve approximately 10 to 15 m (30 to 50 ft) upstream of the yield line. A second, larger-radius curve (or even a tangent) is then fitted between the first curve and the edge of the circulatory roadway. In this way, vehicles will still be slowed by the small-radius approach curve, and they will be directed along a path that is tangential to the central island at the time they reach the yield line. Exhibit 6-47 demonstrates this alternate method of design.

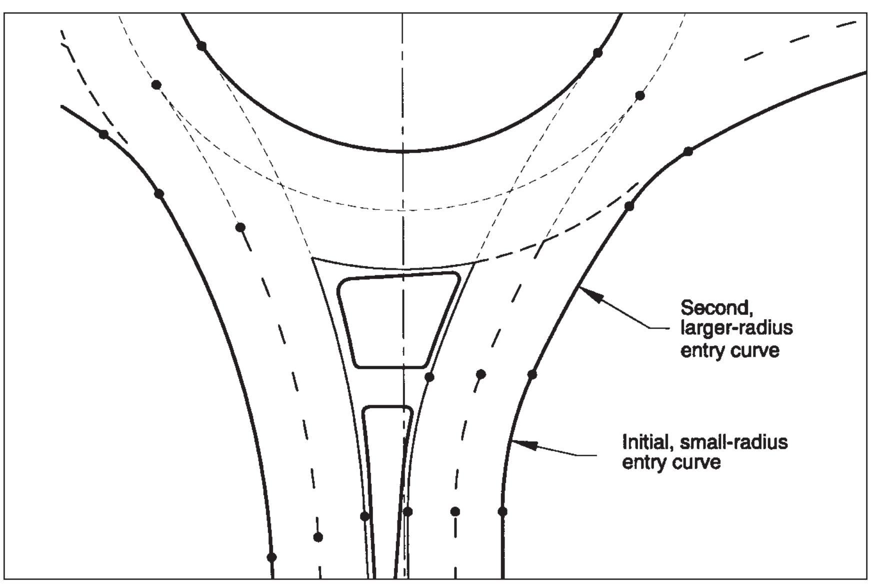


Exhibit 6-47. Alternate method of entry design to avoid path overlap at double-lane roundabouts.

As in the case of single-lane roundabouts, it is a primary objective to ensure that the entry path radius along the fastest path is not substantially larger than the circulating path radius. Referring to Exhibit 6-12, it is desirable for R_1 to be less than or approximately equal to R_2. At double-lane roundabouts, however, R_1 should not be excessively small. If R_1 is too small, vehicle path overlap may result, reducing the operational efficiency and increasing potential for crashes. Values for R_1 in the range of 40 to 70 m (130 to 230 ft) are generally preferable. This results in a design speed of 35 to 45 km/h (22 to 28 mph).

The entry path radius, R_1, is controlled by the offset between the right curb line on the entry roadway and the curb line of the central island (on the driver's left). If the initial layout produces an entry path radius above the preferred design speed, one way to reduce it is to gradually shift the approach to the left to increase the offset; however, this may increased adjacent exit speeds. Another method to reduce the entry path radius is to move the initial, small-radius entry curve closer to the circulatory roadway. This will decrease the length of the second, larger-radius curve and increase the deflection for entering traffic. However, care must be taken to ensure this adjustment does not produce overlapping natural paths.

6.4.3.2 Exit curves

To avoid path overlap on the exit, it is important that the exit radius at a double-lane roundabout not be too small. At single-lane roundabouts, it is acceptable to use a minimal exit radius in order to control exit speeds and maximize pedestrian safety. However, the same is not necessarily true at double-lane roundabouts. If the exit radius is too small, traffic on the inside of the circulatory roadway will tend to exit into the outside exit lane on a more comfortable turning radius.

At double-lane roundabouts in urban environments, the principle for maximizing pedestrian safety is to reduce vehicle speeds prior to the yield and maintain similar (or slightly lower) speeds within the circulatory roadway. At the exit points, traffic will still be traveling slowly, as there is insufficient distance to accelerate significantly. If the entry and circulating path radii (R_1 and R_2, as shown on Exhibit 6-12) are each 50 m (165 ft), exit speeds will generally be below 40 km/h (25 mph) regardless of the exit radius.

To achieve exit speeds slower than 40 km/h (25 mph), as is often desirable in environments with significant pedestrian activity, it may be necessary to tighten the exit radius. This may improve safety for pedestrians at the possible expense of increased vehicle-vehicle collisions.

6.5 Rural Roundabouts

Roundabouts located on rural roads often have special design considerations because approach speeds are higher than urban or local streets and drivers generally do not expect to encounter speed interruptions. The primary safety concern in rural locations is to make drivers aware of the roundabout with ample distance to comfortably decelerate to the appropriate speed. This section provides design guidelines for providing additional speed-reduction measures on rural roundabout approaches.

6.5.1 Visibility

Perhaps the most important element affecting safety at rural intersections is the visibility of the intersection itself. Roundabouts are no different from stop-controlled or signalized intersections in this respect except for the presence of curbing along roadways that are typically not curbed. Therefore, although the number and severity of multiple-vehicle collisions at roundabouts may decrease (as discussed previously), the number of single-vehicle crashes may increase. This potential can be minimized with attention to proper visibility of the roundabout and its approaches.

Roundabout visibility is a key design element at rural locations.

Where possible, the geometric alignment of approach roadways should be constructed to maximize the visibility of the central island and the general shape of the roundabout. Where adequate visibility cannot be provided solely through geometric alignment, additional treatments (signing, pavement markings, advanced warning beacons, etc.) should be considered (see Chapter 7). Note that many of these treatments are similar to those that would be applied to rural stop-controlled or signalized intersections.

6.5.2 Curbing

On an open rural highway, changes in the roadway's cross-section can be an effective means to help approaching drivers recognize the need to reduce their speed. Rural highways typically have no outside curbs with wide paved or gravel shoulders. Narrow shoulder widths and curbs on the outside edges of pavement, on the other hand, generally give drivers a sense they are entering a more urbanized setting, causing them to naturally slow down. Thus, consideration should be given to reducing shoulder widths and introducing curbs when installing a roundabout on an open rural highway.

Curbs should be provided at all rural roundabouts.

Curbs help to improve delineation and to prevent "corner cutting," which helps to ensure low speeds. In this way, curbs help to confine vehicles to the intended design path. The designer should carefully consider all likely design vehicles, including farm equipment, when setting curb locations. Little research has been performed to date regarding the length of curbing required in advance of a rural roundabout. In general, it may be desirable to extend the curbing from the approach for at least the length of the required deceleration distance to the roundabout.

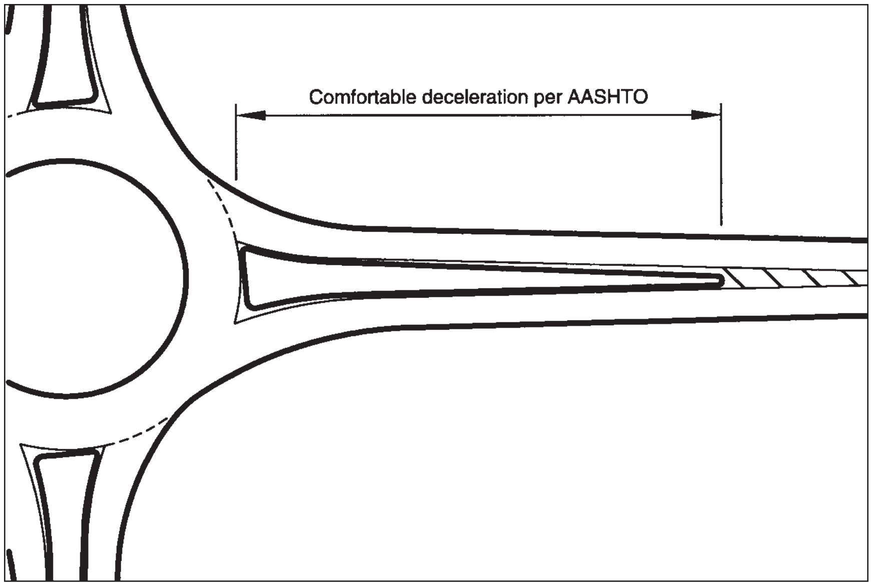
6.5.3 Splitter islands

Another effective cross-section treatment to reduce approach speeds is to use longer splitter islands on the approaches (10). Splitter islands should generally be extended upstream of the yield bar to the point at which entering drivers are expected to begin decelerating comfortably. A minimum length of 60 m (200 ft) is recommended (10). Exhibit 6-48 provides a diagram of such a splitter island design. The length of the splitter island may differ depending upon the approach speed. The AASHTO recommendations for required braking distance with an alert driver should be applied to determine the ideal splitter island length for rural roundabout approaches.

Extended splitter islands are recommended at rural locations.

A further speed-reduction technique is the use of landscaping on the extended splitter island and roadside to create a "tunnel" effect. If such a technique is used, the stopping and intersection sight distance requirements (sections 6.3.9 and 6.3.10) will dictate the maximum extent of such landscaping.

Exhibit 6-48. Extended splitter island treatment.



6.5.4 Approach curves

Roundabouts on high-speed roads (speeds of 80 km/h [50 mph] or higher), despite extra signing efforts, may not be expected by approaching drivers, resulting in erratic behavior and an increase in single-vehicle crashes. Good design encourages drivers to slow down before reaching the roundabout, and this can be most effectively achieved through a combination of geometric design and other design treatments (see Chapter 7). Where approach speeds are high, speed consistency on the approach needs to be addressed to avoid forcing all of the reduction in speed to be completed through the curvature at the roundabout.

The radius of an approach curve (and subsequent vehicular speeds) has a direct impact on the frequency of crashes at a roundabout. A study in Queensland, Australia, has shown that decreasing the radius of an approach curve generally decreases the approaching rear-end vehicle crash rate and the entering-circulating and exiting-circulating vehicle crash rates (see Chapter 5). On the other hand, decreasing the radius of an approach curve may increase the single-vehicle crash rate on the curve, particularly when the required side-friction for the vehicle to maintain its path is too high. This may encourage drivers to cut across lanes and increase sideswipe crash rates on the approach curve (2).

One method to achieve speed reduction that reduces crashes at the roundabout while minimizing single-vehicle crashes is the use of successive curves on approaches. The study in Queensland, Australia, found that by limiting the change in 85th-percentile speed on successive geometric elements to 20 km/h (12 mph), the crash rate was reduced. It was found that the use of successive reverse curves prior to the roundabout approach curve reduced the single-vehicle crash rate and the sideswipe crash rate on the approach. It is recommended that approach speeds immediately prior to the entry curves of the roundabout be limited to 60 km/h (37 mph) to minimize high-speed rear-end and entering-circulating vehicle crashes.

Exhibit 6-49 shows a typical rural roundabout design with a succession of three curves prior to the yield line. As shown in the exhibit, these approach curves should be successively smaller radii in order to minimize the reduction in design speed between successive curves. The aforementioned Queensland study found that shifting the approaching roadway laterally by 7 m (23 ft) usually enables adequate curvature to be obtained while keeping the curve lengths to a minimum. If the lateral shift is too small, drivers are more likely to cut into the adjacent lane (2).

A series of progressively sharper curves on a high-speed roundabout approach helps slow traffic to an appropriate entry speed.

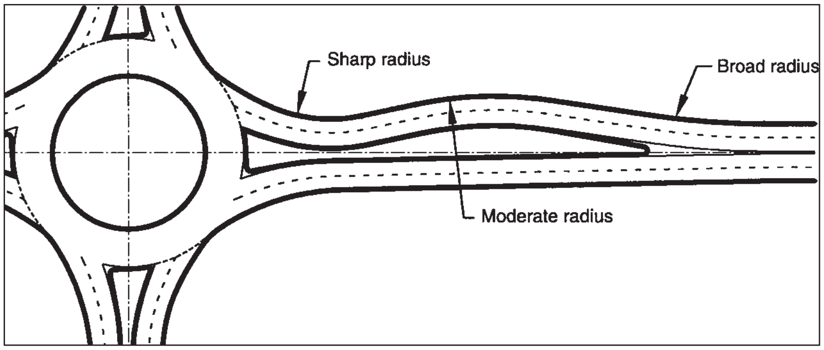


Exhibit 6-49. Use of successive curves on high speed approaches.

Equations 6-4 and 6-5 can be used to estimate the operating speed of two-lane rural roads as a function of degree of curvature. Equation 6-6 can be used similarly for four-lane rural roads (13).

Two-lane rural roads:

$$V_{85} = 103.66 - 1.95D, D \geq 3° \qquad (6\text{-}4)$$

$$V_{85} = 97.9, D < 3° \qquad (6\text{-}5)$$

where: V_{85} = 85th-percentile speed, km/h (1 km/h = 0.621 mph); and
D = degree of curvature, degrees = 1746.38 / R
R = radius of curve, m

Four-lane rural roads:

$$V_{85} = 103.66 - 1.95D \qquad (6\text{-}6)$$

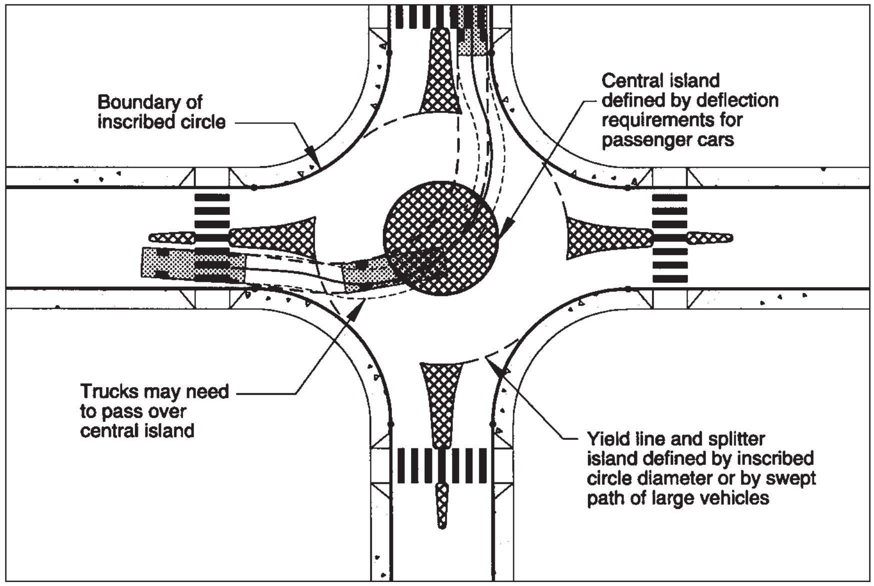
where: V_{85} = 85th-percentile speed, km/h (1 km/h = 0.621 mph); and
D = degree of curvature, degrees = 1746.38 / R
R = radius of curve, m

6.6 Mini-Roundabouts

As discussed in Chapter 1, a mini-roundabout is an intersection design alternative that can be used in place of stop control or signalization at physically constrained intersections to help improve safety problems and excessive delays at minor approaches. Mini-roundabouts are not traffic calming devices but rather are a form of roundabout intersection. Exhibit 6-50 presents an example of a mini-roundabout.

Mini-roundabouts are not recommended where approach speeds are greater than 50 km/h (30 mph), nor in locations with high U-turning volumes.

Exhibit 6-50. Example of a mini-roundabout.



Mini-roundabouts should only be considered in areas where all approaching roadways have an 85th-percentile speed of less than 50 km/h (30 mph). In addition, mini-roundabouts are not recommended in locations in which high U-turn traffic is expected, such as at the ends of street segments with access restrictions. Mini-roundabouts are not well suited for high volumes of trucks, as trucks will occupy most of the intersection when turning.

The central island of a mini-roundabout should be clear and conspicuous.

The design of the central island of a mini-roundabout is defined primarily by the requirement to achieve speed reduction for passenger cars. As discussed previously in Section 6.2, speed reduction for entering vehicles and speed consistency with circulating vehicles are important. Therefore, the location and size of the central island are dictated by the inside of the swept paths of passenger cars that is needed to achieve a maximum recommended entry speed of 25 km/h (15 mph). The central island of a mini-roundabout is typically a minimum of 4 m (13 ft) in diameter and is fully mountable by large trucks and buses. Composed of asphalt, concrete, or other paving material, the central island should be domed at a height of 25 to 30 mm per 1 m diameter (0.3 to 0.36 in per 1 ft diameter), with a maximum height of 125 mm (5 in) (14). Although fully mountable and relatively small, it is essential that the central island be clear and conspicuous (14, 15). Chapter 7 provides a sample signing and striping planing plan for mini-roundabout.

The outer swept path of passenger cars and large vehicles is typically used to define the location of the yield line and boundary of each splitter island with the circulatory roadway. Given the small size of a mini-roundabout, the outer swept path of large vehicles may not be coincident with the inscribed circle of the roundabout, which is defined by the outer curbs. Therefore, the splitter islands and yield line may extend into the inscribed circle for some approach geometries. On the other hand, for very small mini-roundabouts, such as the one shown in Exhibit 6-50, all turning trucks will pass directly over the central island while not encroaching on the circulating roadway to the left which may have opposing traffic. In these cases, the yield line and splitter island should be set coincident with the inscribed

6.7 References

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15. Brilon, W., and L. Bondzio. *Untersuchung von Mini-Kreisverkehrsplaetzen (Investigation of Mini-Roundabouts)*. Ruhr-University Bochum, Germany, 1999.

7

Traffic Design and Landscaping

Chapter 7 Traffic Design and Landscaping

This chapter presents guidelines on the design of traffic elements, illumination, and landscaping associated with roundabouts. The design of these elements is critical in achieving the desired operational and safety features of a roundabout, as well as the desired visibility and aesthetics. This chapter is divided into the following sections:

- Signing;
- Pavement Markings;
- Illumination;
- Work Zone Traffic Control; and
- Landscaping.

Signing, striping, illumination, and landscaping are the critical finishing touches for an effectively functioning roundabout.

7.1 Signing

The overall concept for roundabout signing is similar to general intersection signing. Proper regulatory control, advance warning, and directional guidance are required to avoid driver expectancy related problems. Signs should be located where they have maximum visibility for road users but a minimal likelihood of even momentarily obscuring pedestrians as well as motorcyclists and bicyclists, who are the most vulnerable of all roundabout users. Signing needs are different for urban and rural applications and for different categories of roundabouts.

7.1.1 Relationship with the *Manual on Uniform Traffic Control Devices*

The *Manual on Uniform Traffic Control Devices for Streets and Highways* (MUTCD) (1) and *Standard Highway Signs* (2), as well as local applicable standards, govern the design and placement of signs. To the extent possible, this guide has been prepared in accordance with the 1988 edition of the MUTCD. However, roundabouts present a number of new signing issues that are not addressed in the 1988 edition. For this reason, a number of new signs or uses for existing signs have been introduced that are under consideration for inclusion in the next edition of the MUTCD. Until such signs or uses are formally adopted, these recommendations should be considered provisional and are subject to MUTCD Section 1A-6, "Manual Changes, Interpretations and Authority to Experiment."

The following signs and applications recommended below are subject to these conditions:

- Use of YIELD signs on more than one approach to an intersection (Section 7.1.2.1);
- Long chevron plate (Section 7.1.2.2);
- Roundabout Ahead sign (Section 7.1.3.1);
- Advance diagrammatic guide signs (Section 7.1.4.1); and
- Exit guide signs (Section 7.1.4.2).

7.1.2 Regulatory signs

A number of regulatory signs are appropriate for roundabouts and are described below.

7.1.2.1 YIELD sign

YIELD signs are required on all approaches.

A YIELD sign (R1-2), shown in Exhibit 7-1, is required at the entrance to the roundabout. For single-lane approaches, one YIELD sign placed on the right side is sufficient, although a second YIELD sign mounted in the splitter island on the left side of the approach may be used. For approaches with more than one lane, the designer should place YIELD signs on both the left and right sides of the approach. This practice is consistent with the recommendations of the MUTCD on the location of STOP and YIELD signs on single-lane and multilane approaches (MUTCD, §2B-9). To prevent circulating vehicles from yielding unnecessarily, the face of the yield sign should not be visible from the circulatory roadway. YIELD signs may also be used at the entrance to crosswalks on both the entry and exit legs of an approach. However, the designer should not use both YIELD signs and Pedestrian Crossing signs (see Section 7.1.3.5) to mark a pedestrian crossing, as the yield signs at the roundabout entrance may be obscured.

Exhibit 7-1. YIELD sign (R1-2).

7.1.2.2 ONE WAY sign

ONE WAY signs establish the direction of traffic flow within the roundabout.

ONE WAY signs (R6-1R) may be used in the central island opposite the entrances. An example is shown in Exhibit 7-2. The ONE WAY sign may be supplemented with chevron signs to emphasize the direction of travel within the circulatory roadway (see Section 7.1.3.4).

At roundabouts with one-way streets on one or more approaches, the use of a regulatory ONE WAY sign may be confusing. In these cases, a Large Arrow warning sign (see Section 7.1.3.3) may be used.

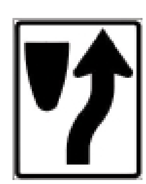
Exhibit 7-2. ONE WAY sign (R6-1R).

7.1.2.3 KEEP RIGHT sign

KEEP RIGHT signs (R4-7 or text variations R4-7a and R4-7b) should be used at the nose of all nonmountable splitter islands. This sign is shown in Exhibit 7-3.

For small splitter islands, a Type 1 object marker may be substituted for the KEEP RIGHT sign. This may reduce sign clutter and improve the visibility of the YIELD sign.

Exhibit 7-3. KEEP RIGHT sign (R4-7).



7.1.2.4 Lane-use control signs

Lane-use control signs are generally not recommended.

For roundabouts with multiple entry lanes, it can often be confusing for unfamiliar drivers to know which lanes to use for the various left, through, and right movements. There is no international consensus on the effectiveness of lane-use signs and/or pavement markings.

The designation of lanes on entry to a roundabout is directly related to a number of factors:

- *Traffic volume balance*. Roundabouts with especially heavy left- or right-turning traffic may require more than one lane to handle the expected demand (see Chapter 4).
- *Exit lane requirements*. In general, the number of exit lanes provided should be the minimum required to handle the expected exit volume. This may not correspond with the number of entry lanes on the opposite side of the roundabout that would use the exit as through vehicles (see Chapter 4).
- The rules of the road. Drivers have a reasonable expectation that multiple through lanes entering a roundabout will have an equal number of receiving lanes on exit on the far side of the roundabout (see Chapter 2).

Lane-use control signs are generally not required where the number of receiving lanes for through vehicles on exit matches the number of entry lanes, as shown in Exhibit 7-4. Lane-use control signs should be used only for the following conditions:

- Where only a single exit lane is provided to receive two lanes of vehicles making through movements, lane-use designations should be made to indicate that an entry lane drops as a turning movement (see Exhibit 7-4). This does not include cases where an approach is flared from one to two lanes at the roundabout.
- Where left- or right-turning traffic demand dictates the need for more than one left-turn lane or more than one right-turn lane for capacity reasons (see Exhibit 7-5).

The use of a left-turn-only lane designation as shown in the exhibits may be initially confusing to drivers. This type of designation has worked successfully in other countries, and there is no evidence to suggest that it will not work in the United States. However, given the general unfamiliarity of roundabouts to drivers in the United States at this time, it is recommended that double-lane roundabouts be designed to avoid the use of lane-use control signs wherever possible, at least until drivers become more accustomed to driving roundabouts.

Exhibit 7-4. Lane-use control signing for roundabouts with double-lane entries.

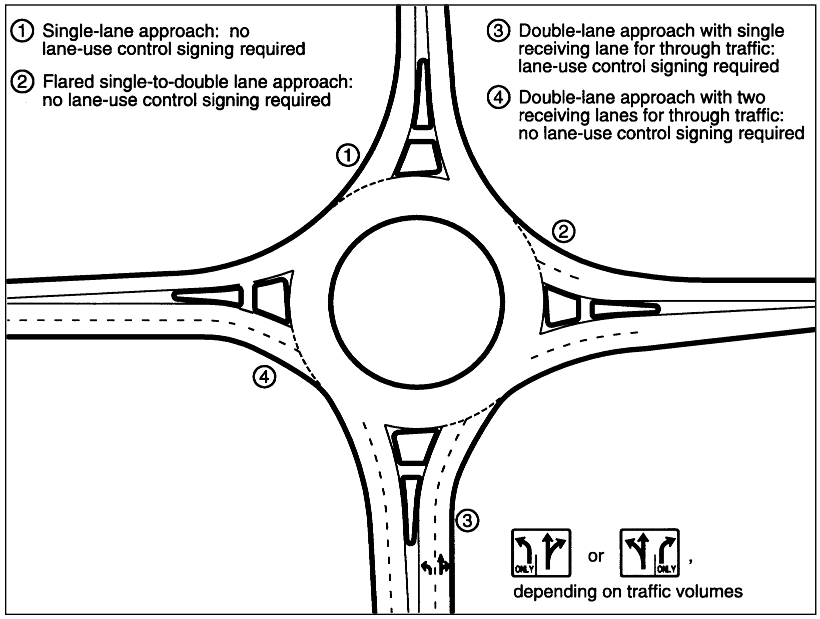
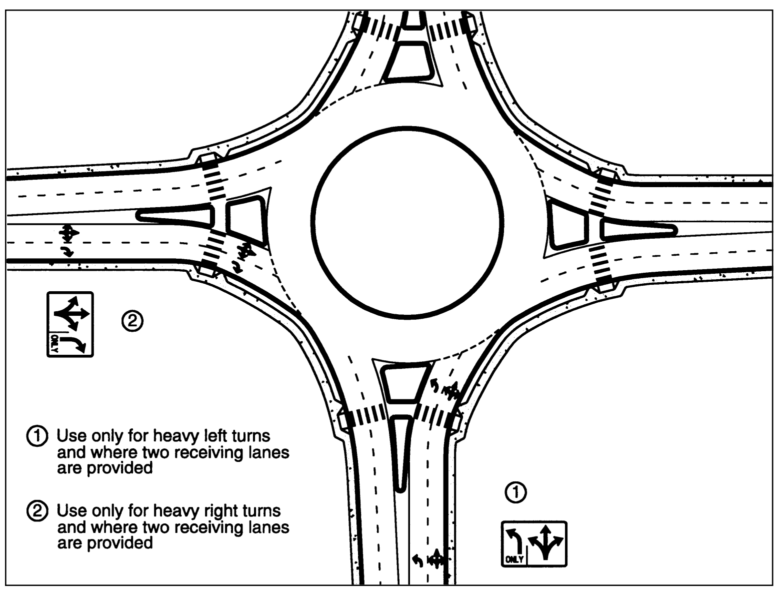


Exhibit 7-5. Lane-use control signing for roundabouts with heavy turning traffic.



7.1.3 Warning signs

A number of warning signs are appropriate for roundabouts and are described below. The amount of warning a motorist needs is related to the intersection setting and the vehicular speeds on approach roadways. The specific placement of warning signs is governed by the applicable sections of the MUTCD.

7.1.3.1 Circular Intersection sign

A Circular Intersection sign (W2-6) may be installed on each approach in advance of the roundabout. This sign, given in Exhibit 7-6, is proposed as part of the next edition of the MUTCD. When used, it is recommended that this sign be modified to reflect the number and alignment of approaches.

Exhibit 7-6. Circular Intersection sign (W2-6).

It is also recommended that an advisory speed plate (W13-1) be used with this sign, as shown in Exhibit 7-7. The speed given on the advisory speed plate should be no higher than the design speed of the circulatory roadway, as determined in Chapter 6.

Exhibit 7-7. Advisory speed plate (W13-1).

An alternative to the Circular Intersection sign, called a Roundabout Ahead sign, has been proposed and is shown in Exhibit 7-8. The rationale for this sign is given in Appendix C. At a minimum it is recommended that the Roundabout Ahead sign be used in place of the Circular Intersection sign at mini-roundabouts (see Section 7.1.7).

Exhibit 7-8. Roundabout Ahead sign.

7.1.3.2 YIELD AHEAD sign

YIELD AHEAD signs warn drivers of the upcoming YIELD sign.

A YIELD AHEAD sign (W3-2 or W3-2a) should be used on all approaches to a roundabout in advance of the yield sign. These signs provide drivers with advance warning that a YIELD sign is approaching. The preferred symbolic form of this sign is shown in Exhibit 7-9.

Exhibit 7-9. YIELD AHEAD sign (W3-2a).

7.1.3.3 Large Arrow sign

A Large Arrow sign with a single arrow pointing to the right (W1-6) should be used in the central island opposite the entrances, unless a regulatory ONE-WAY sign has been used. The Large Arrow sign is shown in Exhibit 7-10.

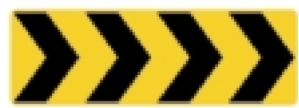
Exhibit 7-10. Large Arrow sign (W1-6).

7.1.3.4 Chevron Plate

Chevron plates can be especially useful for nighttime visibility for sites without illumination.

The Large Arrow may be supplemented or replaced by a long chevron board (W1-8a, as proposed in the next edition of the MUTCD) to emphasize the direction of travel within the circulatory roadway.

Exhibit 7-11. Chevron plate (W1-8a).



7.1.3.5 Pedestrian Crossing

Pedestrian Crossing signs (W11-2a) may be used at pedestrian crossings within a roundabout at both entries and exits. Pedestrian Crossing signs should be used at all pedestrian crossings at double-lane entries, double-lane exits, and right-turn bypass lanes. This sign is shown in Exhibit 7-12.

The use of Pedestrian Crossing signs is dependent on the specific laws of the governing state. If the crosswalk at a roundabout is not considered to be part of the intersection and is instead considered a marked midblock crossing, Pedestrian Crossing signs are required. Where installed, Pedestrian Crossing signs should be located in such a way to not obstruct view of the YIELD sign.

Exhibit 7-12. Pedestrian Crossing sign (W11-2a).

7.1.4 Guide signs

Guide signs are important in providing drivers with proper navigational information. This is especially true at roundabouts where out-of-direction travel may disorient unfamiliar drivers. A number of guide signs are appropriate for roundabouts and are described below.

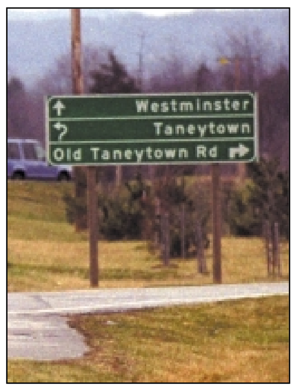
7.1.4.1 Advance destination guide signs

Advance destination guide signs should be used in all rural locations and in urban/suburban areas where appropriate. The sign should be either a destination sign using text (D1-3) or using diagrams. Examples of both are shown in Exhibit 7-13. Diagrammatic signs are preferred because they reinforce the form and shape of the approaching intersection and make it clear to the driver how they are expected to navigate the intersection. Advance destination guide signs are not necessary at local street roundabouts or in urban settings where the majority of traffic tends to be familiar with the site.

The circular shape in a diagrammatic sign provides an important visual cue to all users of the roundabout.

Exhibit 7-13. Examples of advance destination guide signs.

Leeds, MD



Taneytown, MD

Diagrammatic Style (Preferred)

Lothian, MD

Long Beach, CA

7.1.4.2 Exit guide signs

Exit guide signs reduce the potential for disorientation.

Exit guide signs (D1-1) are recommended to designate the destinations of each exit from the roundabout. These signs are conventional intersection direction signs or directional route marker assemblies and can be placed either on the right-hand side of the roundabout exit or in the splitter island. An example is shown in Exhibit 7-14.

Exhibit 7-14. Exit guide sign (D1-1).

7.1.4.3 Route confirmation signs

For roundabouts involving the intersection of one or more numbered routes, route confirmation assemblies should be installed directly after the roundabout exit. These provide drivers with reassurance that they have selected the correct exit at the roundabout. These assemblies should be located no more than 30 m (100 ft) beyond the intersection in urban areas and 60 m (200 ft) beyond the intersection in rural areas.

7.1.5 Urban signing considerations

The designer needs to balance the need for adequate signing with the tendency to use too many signs.

The amount of signing required at individual locations is largely based on engineering judgment. However, in practice, the designer can usually use fewer and smaller signs in urban settings than in rural settings. This is true because drivers are generally traveling at lower vehicular speeds and have higher levels of familiarity at urban intersections. Therefore, in many urban settings the advance destination guide signs can be eliminated. However, some indication of street names should be included in the form of exit guide signs or standard street name signs. Another consideration in urban settings is the use of minimum amounts of signing to avoid sign clutter. A sample signing plan for an urban application is shown in Exhibit 7-15.

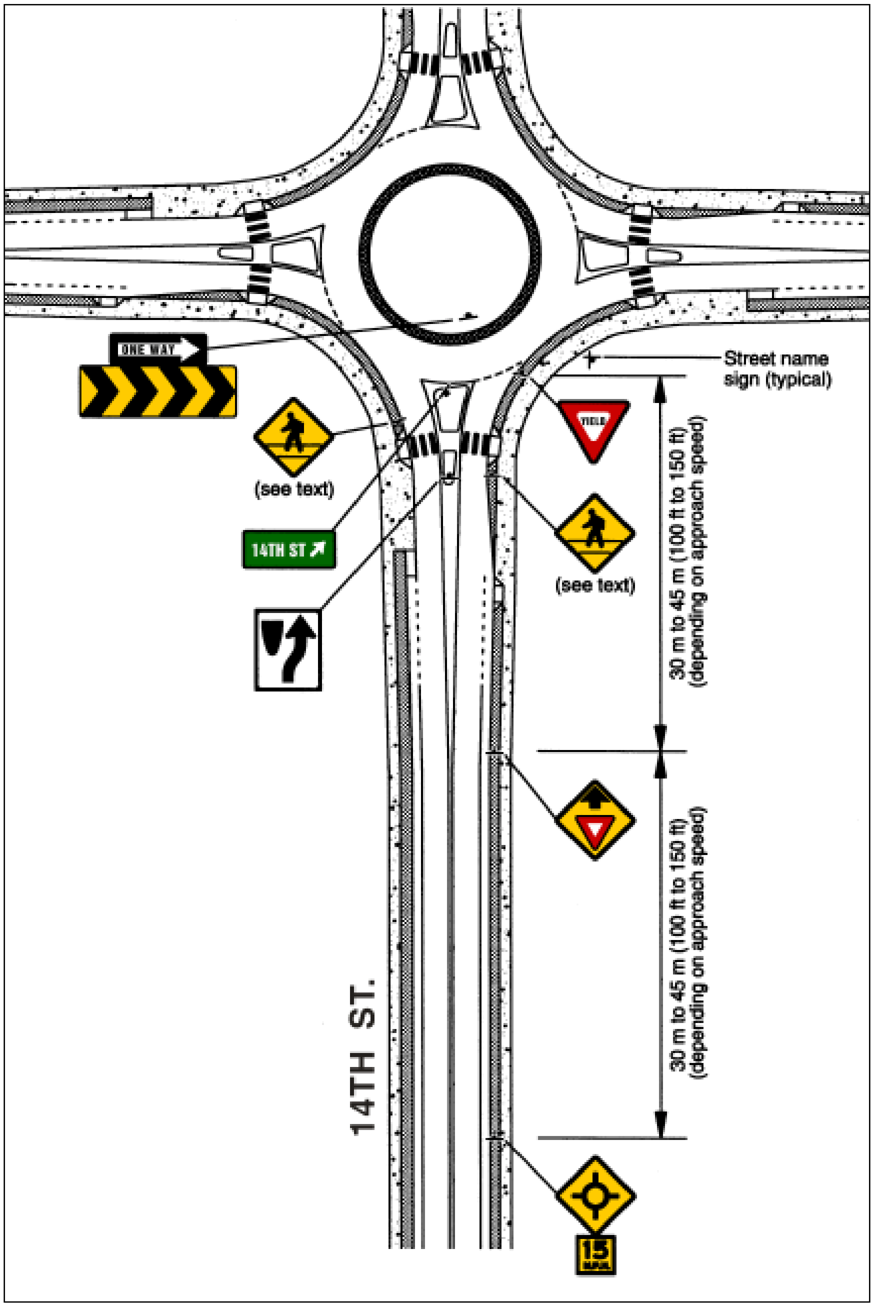


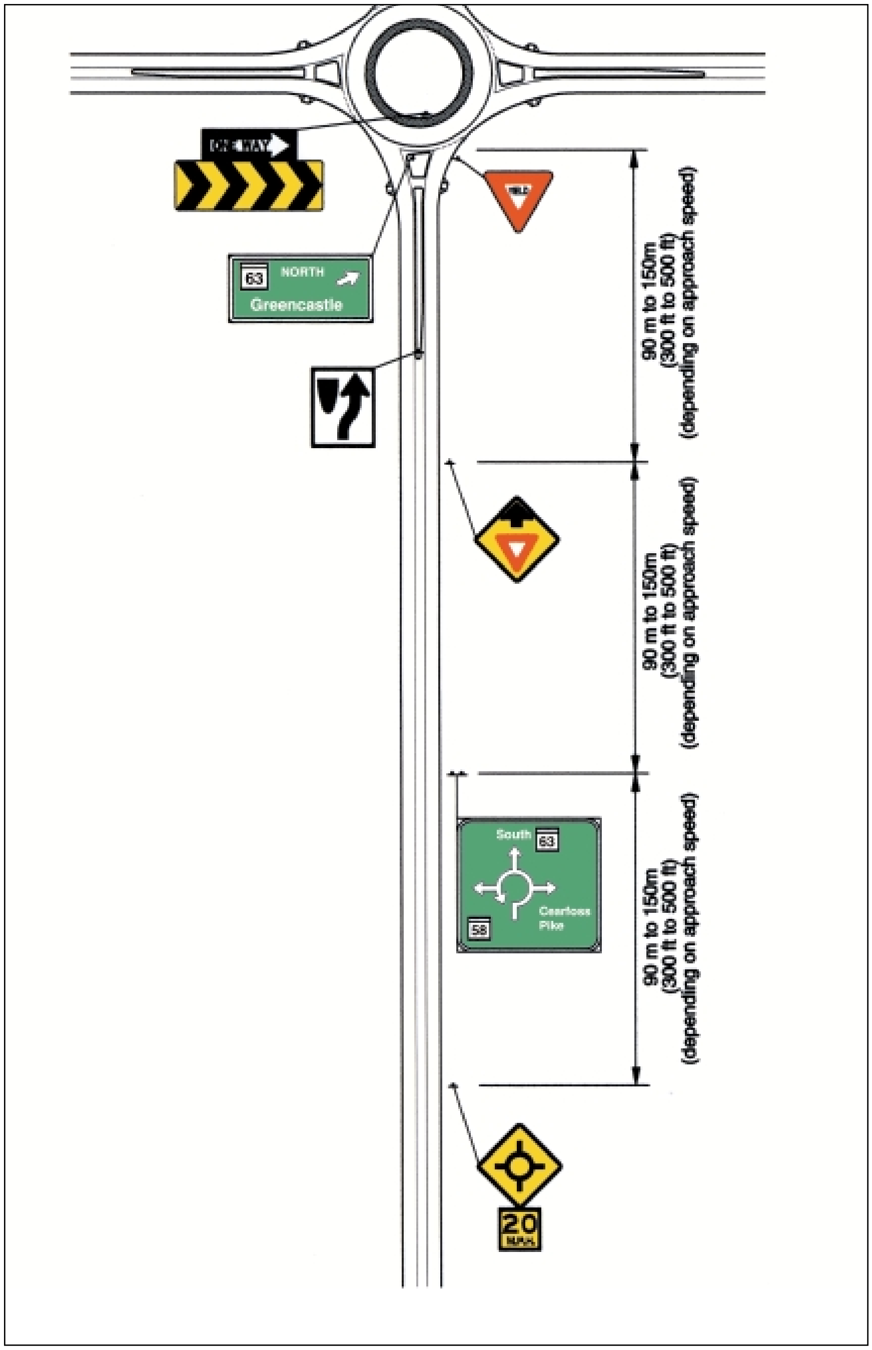
Exhibit 7-15. Sample signing plan for an urban roundabout.

7.1.6 Rural and suburban signing considerations

Rural signing needs to be more conspicuous than urban signing due to higher approach speeds.

Rural and suburban conditions are characterized by higher approach speeds. Route guidance tends to be focused more on destinations and numbered routes rather than street names. A sample signing plan for a rural application is shown in Exhibit 7-16.

Exhibit 7-16. Sample signing plan for a rural roundabout.



In cases where high speeds are expected (in excess of 80 km/h [50 mph]) and the normal signage and geometric features are not expected to produce the desired reduction in vehicle speeds, the following measures may also be considered (examples of some of these treatments are given in Exhibit 7-17):

These speed reduction treatments can apply to all intersection types, not just roundabouts.

- Large advance warning signs;
- Addition of hazard identification beacons to approach signing;
- Use of rumble strips in advance of the roundabout;
- Pavement marking across pavement; and
- Use of speed warning signs. These can be triggered by speeds exceeding an acceptable threshold.

Exhibit 7-17. Examples of speed reduction treatments.

Warning beacons. *Leeds, MD*

Rumble strips. *Cearfoss, MD*

Speed warning signs. *Leeds, MD*

7.1.7 Mini-roundabout signing considerations

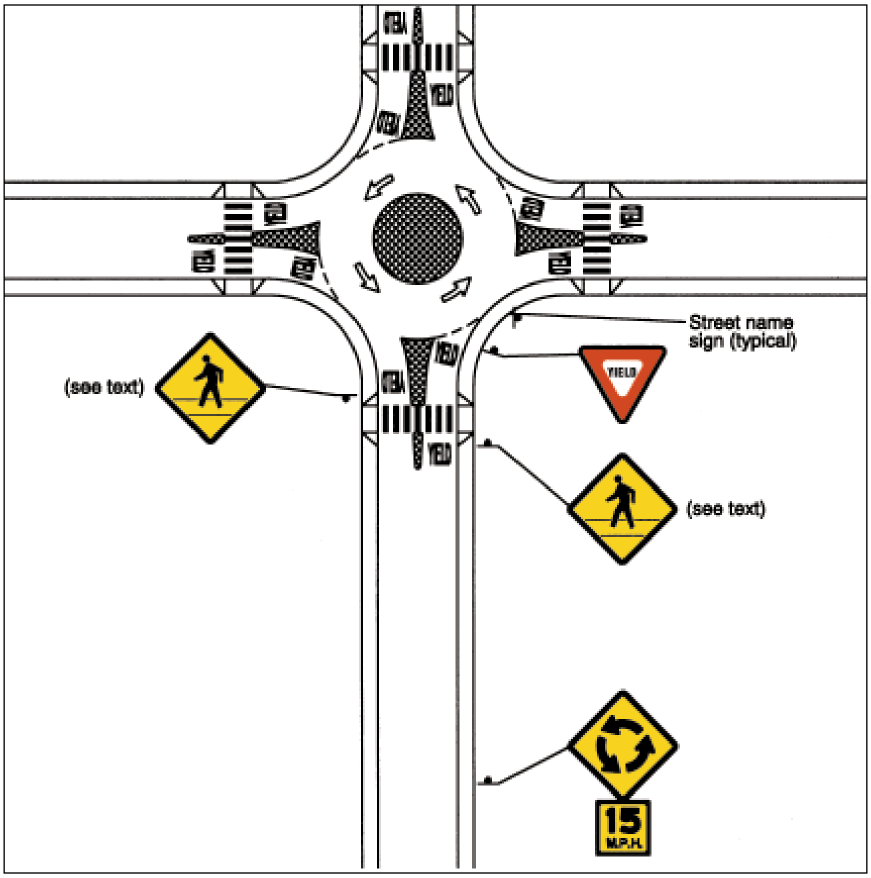
Due to their small size and unique features, mini-roundabouts require a somewhat different signing treatment than the larger urban roundabouts. The principal differences in signing at mini-roundabouts as compared to other urban roundabouts are the following:

- The central island is fully mountable. Therefore, no ONE WAY signs, Large Arrow signs, or chevrons can be located there. It is recommended that the direction of circulation be positively indicated through the use of pavement markings, as discussed in Section 7.2.4.
- The splitter islands are either painted or are fully mountable. Therefore, KEEP RIGHT signs are not appropriate for mini-roundabouts.

- Typically, advance directional guide signs and exit guide signs are unnecessary, given the size of the mini-roundabout and the nature of the approach roadways (generally low-speed local streets). However, standard street name signs (D3) should be used.
- The Roundabout Ahead warning sign discussed in Section 7.1.3.1 should be used on each approach in advance of the YIELD sign. The Circular Intersection warning gives no indication of the direction of circulation required at the mini-roundabout.

Exhibit 7-18 gives a sample signing plan for a mini-roundabout.

Exhibit 7-18. Sample signing plan for a mini-roundabout.



7.2 Pavement Markings

Typical pavement markings for roundabouts consist of delineating the entries and the circulatory roadway.

7.2.1 Relationship with the *Manual on Uniform Traffic Control Devices*

As with signing, the MUTCD (1) and applicable local standards govern the design and placement of pavement markings. Roundabouts present a number of new pavement marking issues that are not addressed in the 1988 edition of the MUTCD. For this reason, a number of new pavement markings or uses for existing pavement markings have been introduced that are under consideration for inclusion in the next edition of the MUTCD. Until such pavement markings or uses are formally adopted, these recommendations should be considered provisional and are subject to MUTCD Section 1A-6, "Manual Changes, Interpretations and Authority to Experiment."

The following pavement markings and applications recommended below are subject to these conditions:

- YIELD lines (Section (7.2.2.1); and
- Symbolic YIELD legend (Section 7.2.2.2).

7.2.2 Approach and entry pavement markings

Approach and entry pavement markings consist of yield lines, pavement word and symbol markings, and channelization markings. In addition, multilane approaches require special attention to pavement markings. The following sections discuss these in more detail.

7.2.2.1 Yield lines

Yield lines should be used to demarcate the entry approach from the circulatory roadway. Yield lines should be located along the inscribed circle at all roundabouts except mini-roundabouts (see Section 7.2.4). No yield lines should be placed to demarcate the exit from the circulatory roadway.

Yield lines provide a visual separation between the approach and the circulatory roadway.

The MUTCD currently provides no standard for yield lines. The recommended yield line pavement marking is a broken line treatment consisting of 400-mm (16-in) wide stripes with 1-m (3-ft) segments and 1-m (3-ft) gaps. This type of yield line is the simplest to install.

Alternatively, several European countries use a yield line marking consisting of a series of white triangles (known as "shark's teeth"). These markings tend to be more visible to approaching drivers. Exhibit 7-19 presents examples of broken line and "shark's teeth" yield line applications. The "shark's teeth" ahead of the broken line has been recommended for adoption in the next edition of the MUTCD.

"Shark's teeth" provide more visual "punch" but require a new template for installation.

Exhibit 7-19. Examples of yield lines.

Broken line. *Leeds, MD*

"Shark's teeth." *Lothian, MD*

7.2.2.2 Pavement word and symbol markings

Pavement word markings are less effective in rainy or especially snowy climates.

In some cases, the designer may want to consider pavement word or symbol markings to supplement the signing and yield line marking. This typically consists of the word YIELD painted on the entrance to the roundabout immediately prior to the yield line. These markings should conform to the standards given in the appropriate section of the MUTCD (§3B-20).

Alternatively, some European countries paint a symbolic yield sign upstream of the yield line. This treatment has the advantage of being symbolic; however, such a treatment has not seen widespread use in the United States to date.

7.2.2.3 Lane-use control markings

If lane-use control signing has been used to designate specific lane use on an approach with more than one lane, it is recommended that corresponding arrow legends be used within each lane. See Section 7.1.2.4 for more discussion of the use of lane-use controls.

7.2.2.4 Approach markings

Typically, pavement markings are provided around raised splitter islands and right-turn bypass islands to enhance driver recognition of the changing roadway. Channelization markings shall be yellow when to the left of the traffic stream and white when to the right of the traffic stream. For a roundabout splitter island, pavement markings shall be yellow adjacent to the entry and exit and white adjacent to the circulatory roadway. Exhibit 7-20 presents a recommended pavement marking plan for the channelization on a typical single-lane approach to a roundabout. Optionally, edge stripes may end at the points of the splitter islands, allowing the curbs themselves to provide edge delineation.

Raised pavement markers are useful supplements to pavement markings.

Raised pavement markers are generally recommended for supplementing pavement markings. These have the benefit of additional visibility at night and in inclement weather. However, they increase maintenance costs and can be troublesome in areas requiring frequent snow removal. In addition, raised pavement markers should not be used in the path of travel of bicycles.

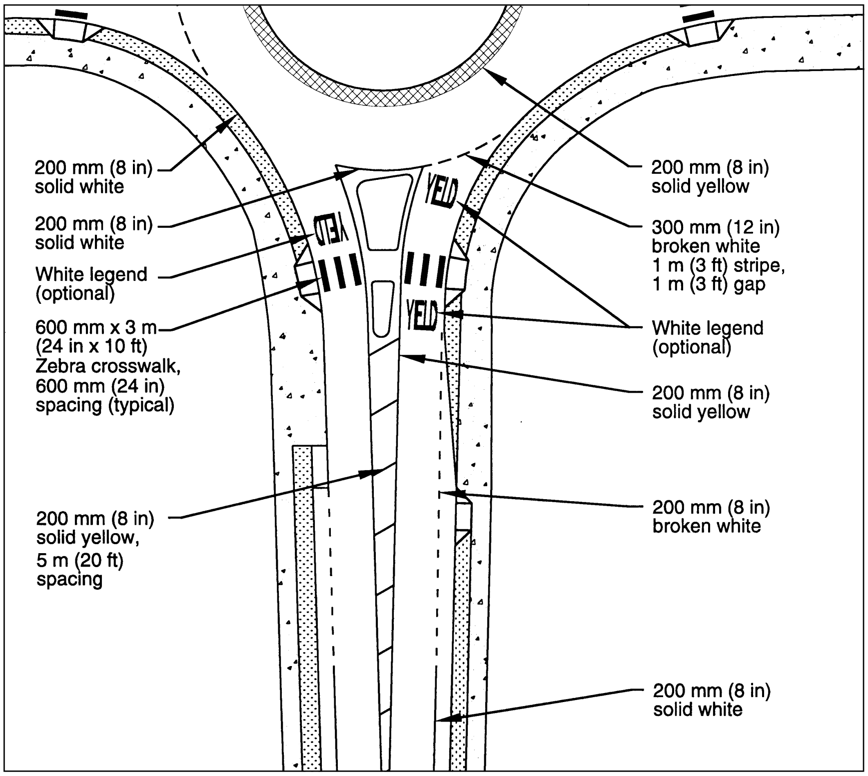


Exhibit 7-20. Approach pavement markings.

For small splitter islands (in area less than 7 m^2 [75 ft^2), the island may consist of pavement markings only. However, where possible, curbed splitter islands should be used.

7.2.2.5 Pedestrian crosswalk markings

Zebra crosswalks provide an important visual cue for drivers and pedestrians.

Pedestrian crosswalk markings should generally be installed at all pedestrian crossing locations within roundabouts in urban locations. Because the crosswalk at a roundabout is located away from the yield line, it is important to channelize pedestrians to the appropriate crossing location. These markings should not be construed as a safety device, as data from other countries suggest that the presence of markings has no appreciable effect on pedestrian safety. Rather, markings provide guidance for pedestrians in navigating a roundabout and provide a visual cue to drivers of where pedestrians may be within the roadway. The use of crosswalk markings in this manner is consistent with published recommendations (3). Marked crosswalks are generally not needed at locations where the crosswalk is distinguished from the roadway by visually contrasting pavement colors and textures.

A crosswalk marking using a series of lines parallel to the flow of traffic (known as a "zebra crosswalk") is recommended. These lines should be approximately 0.3 m to 0.6 m (12 in to 24 in) wide, spaced 0.3 m to 1.0 m (12 in to 36 in) apart, and span the width of the crosswalk (similar to the recommendations in MUTCD §3B-18). Crosswalk markings should be installed across both the entrance and exit of each leg and across any right turn bypass lanes. The crosswalk should be aligned with the ramps and pedestrian refuge in the splitter island and have markings that are generally perpendicular to the flow of vehicular traffic.

The zebra crosswalk has a number of advantages over the traditional transverse crosswalk marking in roundabout applications:

- Because the crosswalk at a roundabout is set back from the yield line, the zebra crosswalk provides a higher degree of visibility.
- The zebra crosswalk is distinct from traditional transverse crosswalk markings typically used at signalized intersections, thus alerting both drivers and pedestrians that this intersection is different from a signalized intersection.
- The zebra crosswalk is also less likely to be confused with the yield line than a transverse crosswalk.
- Although the initial cost is somewhat higher, the zebra crossing may require less maintenance due to the ability to space the markings to avoid vehicle tire tracks.

In rural locations where pedestrian activity is expected to be minimal, pedestrian crosswalk markings are optional. Pedestrian crosswalk markings should not be used at roundabouts without illumination (see Section 7.3 for an identification of these cases) because the headlights of vehicles may not be sufficient to illuminate a pedestrian in time to avoid a collision (4). Regardless of whether the crosswalk is marked, all roundabouts with any reasonable possibility of pedestrian activity should have geometric features to accommodate pedestrians as described in Chapter 6.

In addition to pavement markings, flashing warning lights mounted in the pavement and activated by a pedestrian push button or other method may be considered. These are not part of the current MUTCD and thus must be treated as an experimental traffic control device (see Section 7.2.1).

7.2.2.6 Bike lane markings

Bicycle striping treatments should be used when an existing (or proposed) bike lane is part of the roadway facility. Exhibit 7-20 shows a recommended treatment for bike lanes on an approach to a roundabout.

7.2.3 Circulatory roadway pavement markings

Circulatory pavement markings are generally not recommended.

In general, lane lines should not be striped within the circulatory roadway, regardless of the width of the circulatory roadway. Circulatory lane lines can be misleading in that they may provide drivers a false sense of security.

Bike lanes within the roundabout are not recommended.

In addition, bike lane markings within the circulatory roadway are not recommended. The additional width of a bike lane within the circulatory roadway increases vehicular speed and increases the probability of motor vehicle-cyclist crashes. Bicyclists should circulate with other vehicles, travel through the roundabout as a pedestrian on the sidewalk, or use a separate shared-use pedestrian and bicycle facility where provided.

7.2.4 Mini-roundabout pavement markings

Mini-roundabouts require pavement marking treatments that are somewhat different from other urban roundabouts. The following pavement marking treatments are recommended for mini-roundabouts.

- Pavement marking arrows should be provided in the circulatory roadway in front of each entry to indicate the direction of circulation. As noted in the discussion of signing treatments (Section 7.1.7), no signs can be placed in the fully mountable central island.
- At a minimum, the edges of the mountable central island and splitter islands should be painted to improve their visibility.

A sample pavement marking plan for a mini-roundabout is given in Exhibit 7-21.

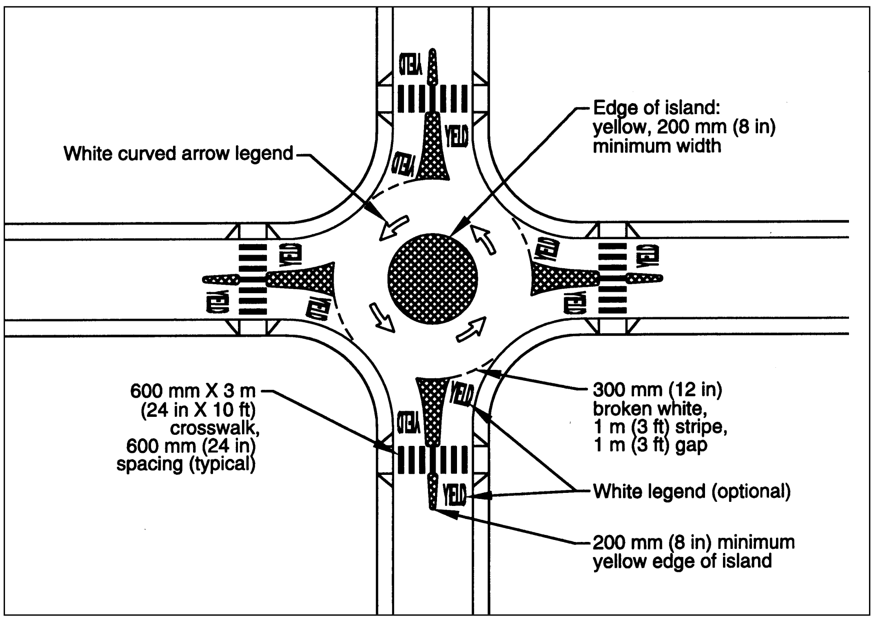


Exhibit 7-21. Sample pavement marking plan for a mini-roundabout.

7.3 Illumination

For a roundabout to operate satisfactorily, a driver must be able to enter the roundabout, move through the circulating traffic, and separate from the circulating stream in a safe and efficient manner. To accomplish this, a driver must be able to perceive the general layout and operation of the intersection in time to make the appropriate maneuvers. Adequate lighting should therefore be provided at all roundabouts. Exhibit 7-22 shows an example of an illuminated roundabout at night.

Exhibit 7-22. Illumination of a roundabout.

Loveland, CO

7.3.1 Need for illumination

The need for illumination varies somewhat based on the location in which the roundabout is located.

7.3.1.1 Urban conditions

In urban settings, illumination should be provided for the following reasons:

- Most if not all approaches are typically illuminated.
- Illumination is necessary to improve the visibility of pedestrians and bicyclists.

7.3.1.2 Suburban conditions

For roundabouts in suburban settings, illumination is recommended. For safety reasons, illumination is necessary when:

- One or more approaches are illuminated.
- An illuminated area in the vicinity can distract the driver's view.
- Heavy nighttime traffic is anticipated.

Continuity of illumination must be provided between illuminated areas and the roundabout itself (5). An unlit roundabout with one or more illuminated approaches is dangerous. This is because a driver approaching on an unlit approach will be attracted to the illuminated area(s) and may not see the roundabout.

7.3.1.3 Rural conditions

For rural roundabouts, illumination is recommended but not mandatory. If there is no power supply in the vicinity of the intersection, the provision of illumination can be costly. When lighting is not provided, the intersection should be well signed and marked so that it can be correctly perceived by day and night. The use of reflective pavement markers and retroreflective signs (including chevrons supplementing the ONE-WAY signs) should be used when lighting cannot be installed in a cost-effective manner.

Where illumination can be provided, any raised channelization or curbing should be illuminated. In general, a gradual illumination transition zone of approximately 80 m (260 ft) should be provided beyond the final trajectory changes at each exit (5). This helps drivers adapt their vision from the illuminated environment of the roundabout back into the dark environment of the exiting roadway, which takes approximately 1 to 2 seconds. In addition, no short-distance dark areas should be allowed between two consecutive illuminated areas (5).

7.3.2 Standards and recommended practices

The following standards and recommended practices should be consulted in completing the lighting plan:

- AASHTO, *An Information Guide for Roadway Lighting* (6). This is the basic guide for highway lighting. It includes information on warranting conditions and design criteria.
- AASHTO, *Standard Specifications for Structural Supports for Highway Signs, Luminaires and Traffic Signals* (7). This specification contains the strength requirements of the poles and bracket arms for various wind loads, as well as the frangibility requirements. All luminaire supports, poles, and bracket arms must comply with these specifications.
- IES RP-8: *The American National Standard Practice for Roadway Lighting* (8). This Recommended Practice, published by the Illuminating Engineering Society, provides standards for average-maintained illuminance, luminance, and small target visibility, as well as uniformity of lighting. Recommended illumination levels for streets with various classifications and in various areas are given in Exhibit 7-23.

Exhibit 7-23. Recommended street illumination levels.

Street Classification	Area Classification	Average Maintained Illuminance Values	Illuminance Uniformity Ratio (Average to Minimum)
Arterial	Commercial Intermediate Residential	17 lx (1.7 fc) 13 lx (1.3 fc) 9 lx (0.9 fc)	3 to 1
Collector	Commercial Intermediate Residential	12 lx (1.2 fc) 9 lx (0.9 fc) 6 lx (0.6 fc)	4 to 1
Local	Commercial Intermediate Residential	9 lx (0.9 fc) 7 lx (0.7 fc) 4 lx (0.4 fc)	6 to 1

Definitions:

Commercial — A business area of a municipality where ordinarily there are many pedestrians during night hours. This definition applies to densely developed business areas outside, as well as within, the central part of a municipality. The area contains land use which attracts a relatively heavy volume of nighttime vehicular and/or pedestrian traffic on a frequent basis.

Intermediate — Those areas of a municipality often with moderately heavy nighttime pedestrian activity such as in blocks having libraries, community recreation centers, large apartment buildings, industrial buildings, or neighborhood retail stores.

Residential — A residential development, or a mixture of residential and small commercial establishments, with few pedestrians at night.

Note: Values in table assume typical asphalt roadway surface (pavement classification R2 or R3). Consult the IES document for other pavement surfaces.

Source: Illuminating Engineering Society RP-8 (8)

7.3.3 General recommendations

The primary goal of illumination is to ensure perception of the approach and mutual visibility among the various categories of users. To achieve this, the following features are recommended:

- The overall illumination of the roundabout should be approximately equal to the sum of the illumination levels of the intersecting roadways. If the approaching roadways have been designed to the illumination levels given in Exhibit 7-23, this may result in illumination levels at the roundabout ranging from 9 lx (0.8 fc) for roundabouts at the intersection of local streets in residential areas to 36 lx (3.4 fc) for roundabouts at the intersection of arterials in commercial areas. Local illumination standards should also be considered when establishing the illumination at the roundabout to ensure that the lighting is consistent.
- Good illumination should be provided on the approach nose of the splitter islands, at all conflict areas where traffic is entering the circulating stream, and at all places where the traffic streams separate to exit the roundabout.

Lighting from the central island causes vehicles to be backlit and thus less visible.

- It is preferable to light the roundabout from the outside in towards the center. This improves the visibility of the central island and the visibility of circulating vehicles to vehicles approaching to the roundabout. Ground-level lighting within the central island that shines upwards towards objects in the central island can improve their visibility.

- Special consideration should be given to lighting pedestrian crossing and bicycle merging areas.

7.3.4 Clear zone requirements

As discussed in Chapter 5, the proportion of single-vehicle crashes at roundabouts is high compared to other intersection types. This is because roundabouts consist of a number of relatively small-radii horizontal curves for each traveled path through the roundabout. Drivers travel on these curves with quite high values of side friction, particularly at roundabouts in higher speed areas. Single-vehicle crashes, which predominantly involve out-of-control vehicles, increase with an increased amount of side friction.

Because of the relatively high number of out-of-control vehicles, it is desirable to have adequate amounts of clear zone where there are no roadside hazards on each side of the roadway. Lighting supports and other poles should not be placed within small splitter islands or on the right-hand perimeter just downstream of an exit point. Lighting poles should be avoided in central islands when the island diameter is less than 20 m (65 ft).

The reader should refer to the AASHTO *Roadside Design Guide* for a more detailed discussion of clear zone requirements (9).

7.4 Work Zone Traffic Control

During the construction of a roundabout it is essential that the intended travel path be clearly identified. This may be accomplished through pavement markings, signing, delineation, channelizing devices, and guidance from police and/or construction personnel, depending on the size and complexity of the roundabout. Care should be taken to minimize the channelizing devices so that the motorist, bicyclist, and pedestrian has a clear indication of the required travel path. Each installation should be evaluated separately, as a definitive guideline for the installation of roundabouts is beyond the scope of this guide. Refer to Part 6 of the MUTCD for requirements regarding work zone traffic control.

7.4.1 Pavement markings

The pavement markings used in work zones should be the same layout and dimension as those used for the final installation. Because of the confusion of a work area and the change in traffic patterns, additional pavement markings may be used to clearly show the intended direction of travel. In some cases when pavement markings cannot be placed, channelizing devices should be used to establish the travel path.

7.4.2 Signing

Construction signing for a roundabout should follow the MUTCD standard.

The signing in work zones should consist of all necessary signing for the efficient movement of traffic through the work area, preconstruction signing advising the public of the planned construction, and any regulatory and warning signs necessary for the movement of traffic outside of the immediate work area. The permanent roundabout signing should be installed where practicable during the first construction stage so that it is available when the roundabout is operable. Permanent signing that cannot be installed initially should be placed on temporary supports in the proposed location until permanent installation can be completed.

7.4.3 Lighting

Permanent lighting, as described in Section 7.3, should be used to light the work area. If lighting will not be used, pavement markings, as described in Section 7.2, should be used.

7.4.4 Construction staging

Construction staging should be considered during the siting of the roundabout, especially if it must be built under traffic.

As is the case with any construction project, before any work can begin, all traffic control devices should be installed as indicated in the traffic control plan or recommended typical details. This traffic control shall remain in place as long as it applies and then be removed when the message no longer applies to the condition.

Prior to work that would change the traffic patterns to that of a roundabout, certain peripheral items may be completed. This would include permanent signing (covered), lighting, and some pavement markings. These items, if installed prior to the construction of the central island and splitter islands, would expedite the opening of the roundabout and provide additional safety during construction.

When work has commenced on the installation of the roundabout, it is desirable that it be completed as soon as possible to minimize the time the public is faced with an unfinished layout or where the traffic priority may not be obvious. If possible, all work, including the installation of splitter islands and striping, should be done before the roundabout is open to traffic.

If it is necessary to leave a roundabout in an uncompleted state overnight, the splitter islands should be constructed before the central island. Any portion of the roundabout that is not completed should be marked, delineated, and signed in such a way as to clearly outline the intended travel path. Pavement markings that do not conform to the intended travel path should be removed.

It is highly desirable to detour traffic for construction of a roundabout. This will significantly reduce the construction time and cost and will increase the safety of the construction personnel. If it is not possible to detour all approaches, detour as many approaches as possible and stage the remainder of the construction as follows:

1. Install and cover proposed signing.
2. Construct outside widening if applicable.
3. Reconstruct approaches if applicable.

4. Construct splitter islands and delineate the central island. At this point the signs should be uncovered and the intersection should operate as a roundabout.
5. Finish construction of the central island.

7.4.5 Public education

It is important to educate the public whenever there is a change in traffic patterns. It is especially important for a roundabout because a roundabout will be new to most motorists. The techniques discussed in Chapter 2 can be applied during the construction period. The following are some specific suggestions to help alleviate initial driver confusion.

Public education during construction is as important as the public education effort during the planning process.

- Hold public meetings prior to construction;
- Prepare news releases/handouts detailing what the motorist can expect before, during, and after construction;
- Install variable message signs before and during construction;
- Use Travelers Advisory Radio immediately prior to and during construction to disseminate information on "How to drive," etc.; and
- Install signing during and after construction that warns of changed traffic patterns.

7.5 Landscaping

This section provides an overview of the use of landscaping in the design of a roundabout.

7.5.1 Advantages

Landscaping in the central island, in splitter islands (where appropriate), and along the approaches can benefit both public safety and community enhancement.

Landscaping is one of the distinguishing features that gives roundabouts an aesthetic advantage over traditional intersections.

The landscaping of the roundabout and approaches should:

- Make the central island more conspicuous;
- Improve the aesthetics of the area while complementing surrounding streetscapes as much as possible;
- Minimize introducing hazards to the intersection, such as trees, poles, walls, guide rail, statues, or large rocks;
- Avoid obscuring the form of the roundabout or the signing to the driver;
- Maintain adequate sight distances, as discussed in Chapter 6;
- Clearly indicate to the driver that they cannot pass straight through the intersection;
- Discourage pedestrian traffic through the central island; and
- Help blind and visually impaired pedestrians locate sidewalks and crosswalks.

7.5.2 Central island landscaping

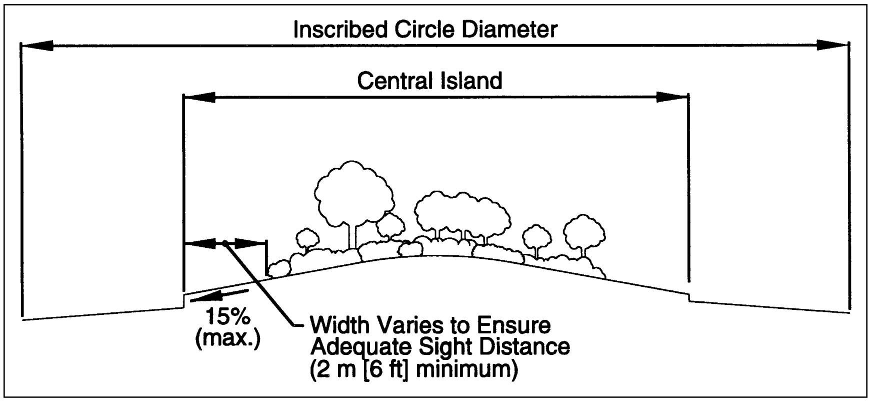
The central island landscaping can enhance the safety of the intersection by making the intersection a focal point and by lowering speeds. Plant material should be selected so that sight distance (discussed in Chapter 6) is maintained, including consideration of future maintenance requirements to ensure adequate sight distance for the life of the project. Large, fixed landscaping (trees, rocks, etc.) should be avoided in areas vulnerable to vehicle runoff. In northern areas, the salt tolerance of any plant material should be considered, as well as snow storage and removal practices. In addition, landscaping that requires watering may increase the likelihood of wet and potentially slippery pavement. Exhibit 7-24 shows the recommended placement of landscaping within the central island.

The slope of the central island should not exceed 6:1 per the requirements of the AASHTO *Roadside Design Guide* (9).

Avoid items in the central island that might tempt people to take a closer look.

Where truck aprons are used in conjunction with a streetscape project, the pavement should be consistent with other streetscape elements. However, the material used for the apron should be different than the material used for the sidewalks so that pedestrians are not encouraged to cross the circulatory roadway. Street furniture that may attract pedestrian traffic to the central island, such as benches or monuments with small text, must be avoided. If fountains or monuments are being considered for the central island, they must be designed in a way that will enable proper viewing from the perimeter of the roundabout. In addition, they must be located and designed to minimize the possibility of impact from an errant vehicle.

Exhibit 7-24. Landscaping of the central island.



7.5.3 Splitter island and approach landscaping

In general, unless the splitter islands are very large or long, they should not contain trees, planters, or light poles. Care must be taken with the landscaping to avoid obstructing sight distance, as the splitter islands are usually located within the critical sight triangles (see Chapter 6).

Landscaping on the approaches to the roundabout can enhance safety by making the intersection a focal point and by reducing the perception of a high-speed through traffic movement. Plant material in the splitter islands (where appropriate) and on the right and left side of the approaches can help to create a funneling effect and induce a decrease in speeds approaching the roundabout. Landscaping in the corner radii will help to channelize pedestrians to the crosswalk areas and discourage pedestrians from crossing to the central island.

7.5.4 Maintenance

A realistic maintenance program should be considered in the design of the landscape features of a roundabout. It may be unrealistic to expect a typical highway agency to maintain a complex planting plan. Formal agreements may be struck with local civic groups and garden clubs for maintenance where possible. Liability issues should be considered in writing these agreements. Where there is no interest in maintaining the proposed enhancements, the landscape design should consist of simple plant materials or hardscape items that require little or no maintenance.

Ensure that whatever landscaping is installed, it will be maintained.

7.6 References

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2. Federal Highway Administration (FHWA). *Standard Highway Signs*. Washington, D.C.: FHWA, 1979.
3. Smith, S.A., and R.L. Knoblauch. "Guidelines for the Installation of Crosswalk Markings." In *Transportation Research Record 1141*. Transportation Research Board, National Research Council, Washington, D.C., 1987.
4. Herms, B.F. "Some Visual Aspects of Pedestrian Crosswalks." In *Proceedings, 22nd California Street and Highway Conference*, Institute of Transportation and Traffic Engineering, University of California, Los Angeles, January 1970.
5. Centre d'Etudes sur les Réseaux les Transports, l'Urbanisme et les constructions publiques (CERTU). *L'Éclairage des Carrefours à Sens Giratoire (The Illumination of Roundabout Intersections)*. Lyon, France: CERTU, 1991.
6. American Association of State Highway and Transportation Officials (AASHTO). *An Information Guide for Roadway Lighting*. Washington, D.C.: AASHTO, 1985.
7. American Association of State Highway and Transportation Officials (AASHTO). *Standard Specifications for Structural Supports for Highway Signs, Luminaires and Traffic Signals*. Washington, D.C.: AASHTO, 1994.
8. Illuminating Engineering Society (IES). *American National Standard Practice for Roadway Lighting*. Standard RP-8. December 1982.
9. American Association of State Highway and Transportation Officials (AASHTO). *Roadside Design Guide*. Washington, D.C.: AASHTO, 1989.

8 System Considerations

Chapter 8 System Considerations

This chapter considers roundabouts as they relate to other elements of the transportation system, including other intersections.

Roundabouts have been considered as isolated intersections in most other international roundabout guides and publications. However, roundabouts may need to fit into a network of intersections, with the traffic control functions of a roundabout supporting the function of nearby intersections and vice versa. The purpose of this chapter is to provide some guidance on potentially difficult, but not uncommon, circumstances or constraints.

Many countries whose initial design and driver experience was with isolated roundabouts have since extended their application to transportation system design and operation. This chapter addresses the appropriate use of roundabouts in a roadway network context and the benefits obtained. Since the design of each roundabout should generally follow the principles of isolated roundabout design, the discussion is at a conceptual and operational level and generally complements the planning of isolated roundabouts discussed in Chapter 3. In many cases, site-specific issues will determine the appropriate roundabout design elements.

To establish some fundamental understanding for subsequent discussion, three design issues at an isolated roundabout are presented. First, this chapter will describe the requirements and effects of signal control of one or more legs of a roundabout, as well as the entire roundabout. It is noted that fully signalized roundabouts are not desirable. Next, modified designs that incorporate at-grade rail crossings are discussed. It is noted that intersections with rail lines passing through them or near them are not desirable. However, these situations do occur and would then need to be analyzed.

Building upon this understanding, the next sections address design and performance of two closely spaced roundabouts and the specific application to roundabout interchanges. This is followed by issues pertaining to the use of roundabouts on an arterial or network that may include or replace coordinated signalized intersections. Finally, the role of microscopic simulation models in assisting with analysis of these system effects is reviewed.

8.1 Traffic Signals at Roundabouts

Although yield control of entries is the default at roundabouts, when necessary, traffic circles and roundabouts have been signalized by metering one or more entries, or signalizing the circulatory roadway at each entry. Roundabouts should never be planned for metering or signalization. However, unexpected demand may dictate the need after installation. Each of these will be discussed in turn. In the first case, entrance metering can be implemented at the entrance or some distance upstream.

8.1.1 Metered entrance

Roundabouts should not be planned for metering or signalization unless unexpected demand dictates this need after installation.

Roundabouts operate effectively only when there are sufficient longer and acceptable gaps between vehicles in the circulatory lanes. If there is a heavy movement of circulating drivers, then entering drivers at the next downstream entry may not be able to enter. This situation occurs most commonly during the peak periods, and the performance of the roundabout can be greatly improved with entrance metering.

The concept of entrance metering at roundabouts is similar to ramp metering on freeways. A convenient sign is a changeable one that reads "Stop on red signal" and shows the usual yield sign for a roundabout otherwise. The sign would also include a yellow and red signal above the sign. The operation of the sign would be to show drivers the roundabout sign, display the yellow light and the sign "Stop on red signal," and finally display the red light and the same text sign. This would cause entering vehicles to stop and allow the vehicles at the downstream entrance to proceed. A queue length detector on the downstream entrance may be used to indicate to the signal controller when the metering should be activated and deactivated. Once on the circulatory roadway, vehicles are not stopped from leaving the roundabout.

8.1.2 Nearby vehicular and pedestrian signals

Nearby intersections or pedestrian crossing signals can also meter traffic, but not as effectively as direct entrance metering.

Another method of metering is the use, with appropriate timing, of a nearby upstream signalized intersection or a signalized pedestrian crossing on the subject approach road. Unlike pure entry metering, such controls may stop vehicles from entering and leaving the roundabout, so expected queue lengths on the roundabout exits between the metering signal and the circulatory roadway should be compared with the proposed queuing space.

Because of additional objectives and constraints, metering by upstream signals is generally not as effective as direct entrance metering. However, a signalized pedestrian crossing may be desirable on its own merits. More than one entrance can be metered, and the analyst needs to identify operational states and evaluate each one separately to provide a weighted aggregate performance measure.

When disabled pedestrians and/or school children are present at a high-volume site, a pedestrian-actuated traffic signal could be placed 20 to 50 m (65 to 165 ft) from the yield line. This longer distance than at an unsignalized crossing may be required because the vehicle queues downstream of the roundabout exit will be longer. The trade-offs for any increased distance requirement are increased walking distances and higher exiting vehicle speeds. An analysis of signal timing will be needed to minimize queuing of vehicles into the roundabouts.

8.1.3 Full signalization of the circulatory roadway

Full signalization of the circulatory roadway requires careful coordination and vehicle progression.

Full signalization that includes control of circulating traffic at junctions with major entrances is possible at large-diameter multilane traffic circles or rotaries that have adequate storage space on the circulatory roadway. The double-lane roundabout dimensions resulting from the design criteria recommended in this guide may preclude such possibilities. As stated previously, full signalization should in any case only be considered as a retrofit alternative resulting from unanticipated traffic demands. Other feasible alternatives should also be considered, such as flaring critical approaches, along with the associated widening of the circulatory roadway; converting a large-diameter rotary to a more compact modern roundabout form; or converting to a conventional signalized intersection. This guide recommends that signalizing roundabouts to improve capacity be considered only when it is the most cost-effective solution.

Traffic signals at fully signalized rotaries should be timed carefully to prevent queuing on the circulatory roadway by ensuring adequate traffic progression of circulating traffic and especially critical movements. Introducing continuous or part-time signals on the circulatory roadway requires careful design of geometry, signs, lane markings, and signal timing settings, and literature on this specific topic should be consulted (1, 2).

8.2 At-Grade Rail Crossings

Locating any intersection near an at-grade railroad crossing is generally discouraged. However, roundabouts are sometimes used near railroad-highway at-grade crossings. Rail transit, including stations, have successfully been incorporated into the medians of approach roadways to a roundabout, with the tracks passing through the central island. In such situations, the roundabout either operates partially during train passage, or is completely closed to allow the guided vehicles or trains to pass through. The treatment of at-grade rail crossings should follow primarily the recommendations of the *Manual on Uniform Traffic Control Devices* (MUTCD) (3). Another relevant reference is the *FHWA Railroad-Highway Grade Crossing Handbook* (4).

There are essentially two ways in which rails can interact with a roundabout, as shown in Exhibit 8-1:

- Through the center; or
- Across one leg in close proximity to the roundabout.

In either case, traffic must not be forced to stop on the tracks. A new intersection should not be designed with railroad tracks passing through the center of it. However, on occasions, the rail line passes through an existing intersection area. The traffic engineer might be faced with a decision whether to change the intersection type to a roundabout or to grade-separate the crossing.

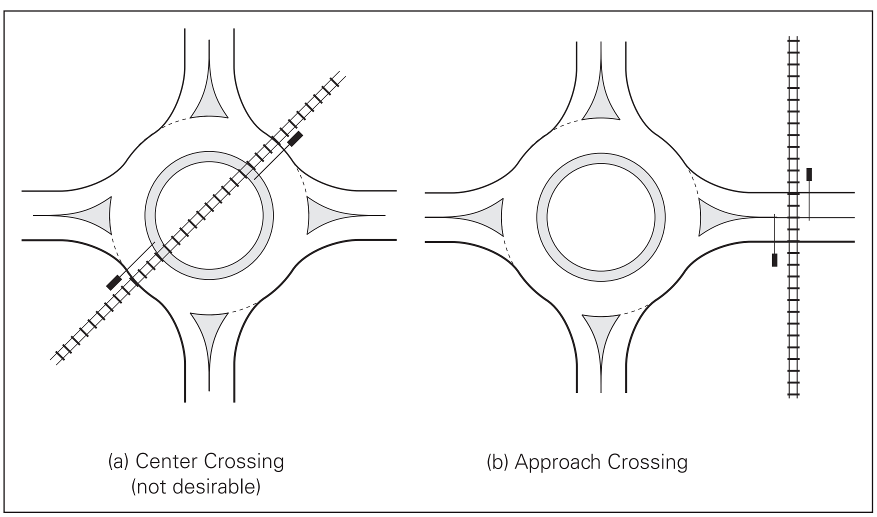
A gated rail crossing through the center of a roundabout can be accommodated in two ways. The first method is to prevent all vehicular traffic from entering the roundabout. The second method is to prevent traffic from crossing the tracks while still allowing some movements to occur. This latter method will have lower delays and queues, but it may be more confusing and less safe.

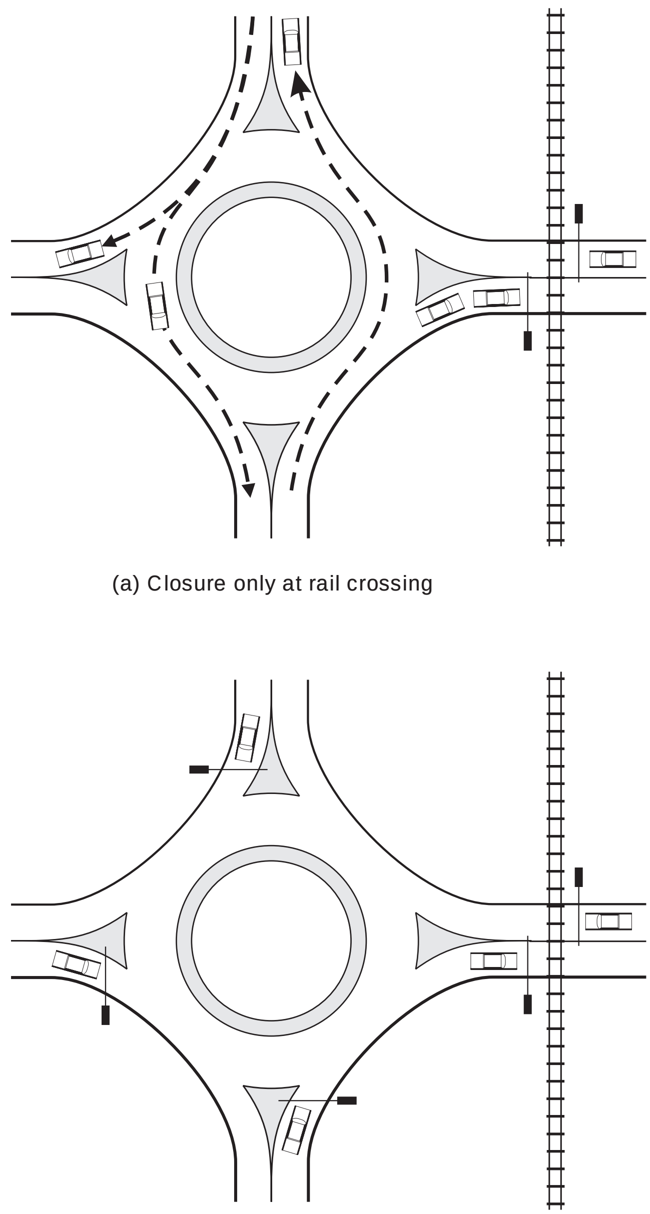
A gated rail crossing adjacent to a roundabout can be accommodated in two ways, as shown in Exhibit 8-2:

Closing only the leg with the rail crossing may work if queues are not anticipated to back into the circulatory roadway.

- *Method A: Closure only at rail crossing.* This method prohibits vehicles from crossing the rails but still allows vehicles to enter and leave the circulatory roadway. This method allows for many of the movements through the roundabout to continue to run free, if a queue does not build to the point of impeding circulation within the roundabout. A queuing analysis should be performed using the expected volume crossing the rails and the expected duration of rail crossing to determine the likelihood that this blockage will occur. In general, this method works better than Method B if there is sufficient separation between the roundabout and the rail crossing. If blockage is anticipated, the designer should choose Method B.
- *Method B: Closure at rail crossing and at most entries to the roundabout.* This method closes all entries to the roundabout except for the entry nearest the rail crossing. This allows any vehicles in the roundabout to clear prior to the arrival of the train. In addition, a gate needs to be provided on the approach to the rail crossing exiting the roundabout to protect against possible U-turns in the roundabout. This causes increased queuing on all approaches but is generally safer than Method A when there is insufficient storage capacity between the roundabout and rail crossing.

Exhibit 8-1. Rail crossing treatments at roundabouts.





(a) Closure only at rail crossing

(b) Closure at rail crossing and at most entries to roundabout

Exhibit 8-2. Methods for accommodating a rail crossing adjacent to a roundabout.

8.3 Closely Spaced Roundabouts

It is sometimes desirable to consider the operation of two or more roundabouts in close proximity to each other. In these cases, the expected queue lengths at each roundabout become important. Exhibit 8-3 presents an example of closely spaced T-intersections. The designer should compute the 95th-percentile queues for each approach to check that sufficient queuing space is provided for vehicles between the roundabouts. If there is insufficient space, then drivers will occasionally queue into the upstream roundabout and may cause it to lock.

Exhibit 8-3. Example of closely spaced offset T-intersection with roundabouts.

France (5)

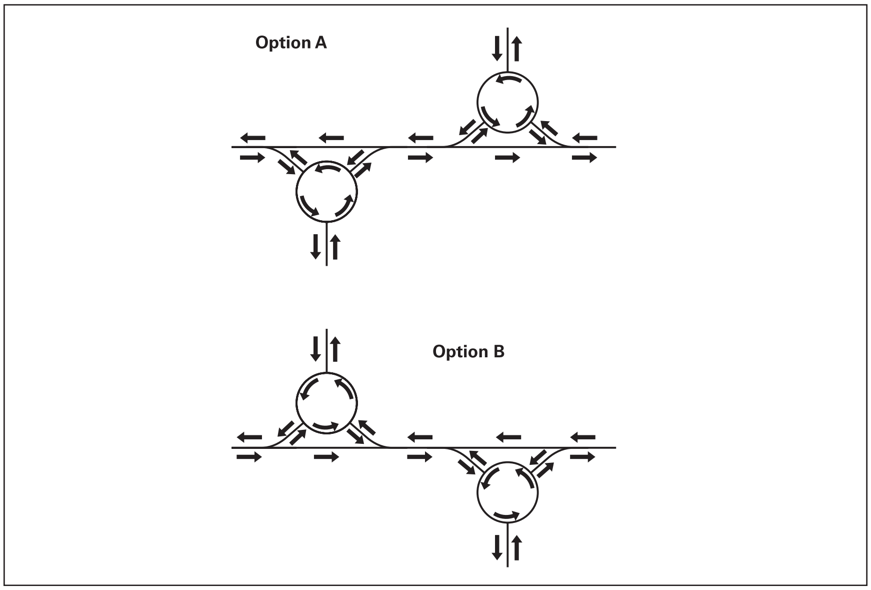
Closely spaced roundabouts may have a traffic calming effect on the major road.

Closely spaced roundabouts may improve safety by "calming" the traffic on the major road. Drivers may be reluctant to accelerate to the expected speed on the arterial if they are also required to slow again for the next close roundabout. This may benefit nearby residents.

When roundabouts are used at offset T-intersections, there is an opportunity to bypass one through lane direction on the major road at each roundabout. Exhibit 8-4 presents sketches of through bypass lanes for the two basic types of offset T-intersection configurations. In both cases, through traffic in each direction needs to negotiate only one roundabout, and capacity is therefore typically improved. The weaving section should be analyzed both for capacity and for safety through an evaluation of the relative speeds of the weaving vehicles.

Exhibit 8-4. Through bypass lanes at staggered T-intersections.

Option A (roundabout precedes bypass) is preferred.



Of the two arrangements shown in Exhibit 8-4, Option A (roundabout precedes bypass) is preferred. The roundabout offers a visual cue to drivers to slow in Arrangement A and encourages slower (and therefore safer) driving through the two roundabouts. If Option B (bypass precedes roundabout) is used, the merges and diverges could occur at higher speeds. It may be appropriate in this case to omit the bypass lane and pass all through traffic through both roundabouts. Another advantage of Option A is that there would be less queuing of traffic on the road space between the roundabouts.

Note that when conventional T-intersections are used, Option A is less preferable than Option B due to the need to provide interior storage space for left turns in Option A. Therefore, roundabouts may be a satisfactory solution for cases like Option A.

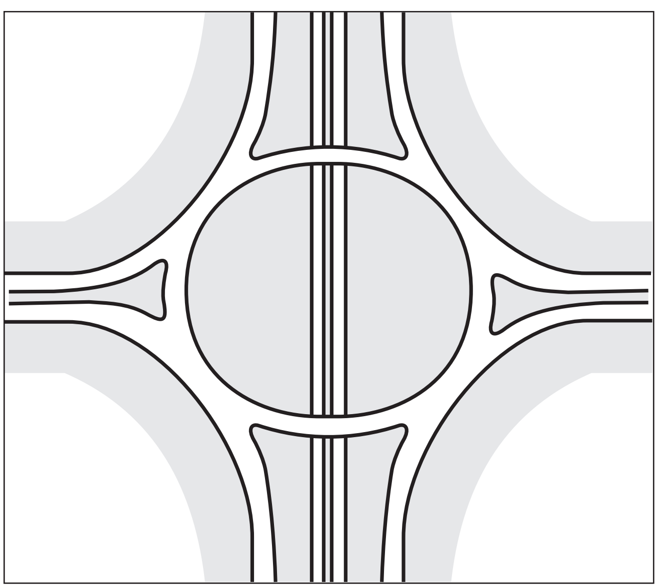
8.4 Roundabout Interchanges

Freeway ramp junctions with arterial roads are potential candidates for roundabout intersection treatment. This is especially so if the subject interchange typically has a high proportion of left-turn flows from the off-ramps and to the on-ramps during certain peak periods, combined with limited queue storage space on the bridge crossing, off-ramps, or arterial approaches. In such circumstances, roundabouts operating within their capacity are particularly amenable to solving these problems when compared with other forms of intersection control.

8.4.1 Two-bridge roundabout interchange

There are two basic types of roundabout interchanges. The first is a large diameter roundabout centered over or under a freeway. The ramps connect directly into the roundabout, as do the legs from the crossroad. This is shown in Exhibit 8-5.

Exhibit 8-5. Two-bridge roundabout interchange.



Source: Based on (6)

The freeway may go either over or under the circulatory roadway.

This type of interchange requires two bridges. If the roundabout is above the freeway as shown in Exhibit 8-5, then the bridges may be curved. Alternatively, if the freeway goes over the roundabout then up to four bridges may be required. The number of bridges will depend on the optimum span of the type of structure compared with the inscribed diameter of the roundabout island and on whether the one bridge is used for both freeway directions or whether there is one bridge for each direction. The road cross-section will also influence the design decision. Exhibit 8-6 shows an example from the United Kingdom. The designer should decide if the expected speeds of vehicles at larger roundabouts are acceptable.

Exhibit 8-6. Examples of two-bridge roundabout interchanges.

A50/Heron Cross, United Kingdom (mirrored to show right-hand-side driving)

8.4.2 One-bridge roundabout interchange

The second basic type uses a roundabout at each side of the freeway and is a specific application of closely spaced roundabouts discussed in the previous section. A bridge is used for the crossroad over the freeway or for a freeway to cross over the minor road. Again, two bridges may be used when the freeway crosses over the minor road.

One-bridge roundabout interchanges have been successfully used to defer the need for bridge widening.

This interchange form has been used successfully in some cases to defer the need to widen bridges. Unlike signalized ramps that may require exclusive left-turn lanes across the bridge and extra queue storage, this type of roundabout interchange exhibits very little queuing between the intersections since these movements are almost unopposed. Therefore, the approach lanes across the bridge can be minimized.

The actual roundabouts can have two different shapes or configurations. The first configuration is a conventional one with circular central islands. This type of configuration is recommended when it is desirable to allow U-turns at each roundabout or to provide access to legs other than the cross street and ramps. Examples from the United Kingdom and France are shown in Exhibit 8-7.

Exhibit 8-7. Examples of one-bridge roundabout interchanges with circular central islands.

France

Exhibit 8-7 (continued). Examples of one-bridge roundabout interchanges with circular central islands.

Raindrop central islands make wrong-way movements more difficult, but require navigating two roundabouts to make a U-turn.

The second configuration uses raindrop-shaped central islands that preclude some turns at the roundabout. This configuration is best used when ramps (and not frontage roads) intersect at the roundabout. A raindrop central island can be considered to be a circular shape blocked at one end. In this configuration, a driver wanting to make a U-turn has to drive around both raindrop-shaped central islands. This configuration has an additional advantage in that it makes wrong-way turns into the off-ramps more difficult. On the other hand, drivers do not have to yield when approaching from the connecting roadway between the two roundabouts. If the roundabout is designed poorly, drivers may be traveling faster than they should to negotiate the next roundabout safely. The designer should analyze relative speeds to evaluate this alternative. On balance, if the length of the connecting road is short, this design may offer safety advantages. Exhibit 8-8 provides an example of this type of interchange configuration.

Exhibit 8-8. One-bridge roundabout interchange with raindrop-shaped central islands.

Interstate 70/Avon Road, Avon, CO

8.4.3 Analysis of roundabout interchanges

The traffic performance evaluation of the roundabout interchange is the same as for a single conventional roundabout. The maximum entry capacity is dependent on the circulatory flow and the geometry of the roundabouts. The evaluation process is included in Chapter 4.

Roundabouts produce more random headways on ramps than signalized intersections, resulting in smoother merging behavior on the freeway.

The benefits and costs associated with this type of interchange also follow those for a single roundabout. A potential benefit of roundabout interchanges is that the queue length on the off-ramps may be less than at a signalized intersection. In almost all cases, if the roundabout would operate below capacity, the performance of the on-ramp is likely to be better than if the interchange is signalized. The headway between vehicles leaving the roundabout along the on-ramp is more random than when signalized intersections are used. This more random ramp traffic allows for smoother merging behavior on the freeway and a slightly higher performance at the freeway merge area compared with platooned ramp traffic from a signalized intersection.

The traffic at any entry is the same for both configurations. The entry capacity is the same and the circulating flow is the same for the large single roundabout (Exhibit 8-6) and for the second configuration of the two teardrop roundabout system (Exhibit 8-8). Note that the raindrop form may be considered and analyzed as a single large roundabout as in the circular roundabout interchange, but with a "pinched" waistline across or under one bridge rather than two. The relative performance of these systems will only be affected by the geometry of the roundabouts and islands. The system with the two circular roundabouts will have a slightly different performance depending upon the number of U-turns.

8.4.4 Geometric design parameters

The design parameters are not restrained by any requirement here. They are only constrained by the physical space available to the designer and the configuration selected. The raindrop form can be useful if grades are a design issue since they remove a potential cross-slope constraint on the missing circulatory road segments.

If there are more roads intersecting with the interchange than the single cross road, then two independent circular roundabouts are likely to be the best solution.

8.5 Roundabouts in an Arterial Network

In order to understand how roundabouts operate within a roadway system, it is important to understand their fundamental arrival and departure characteristics and how they may interact with other intersections. Exhibit 8-9 gives an example of a series of roundabouts along an arterial street.

Avon Road, Avon, CO

Exhibit 8-9. Roundabouts in an arterial network.

The Avon Road network consists of five roundabouts (all pictured)—two at the interchange ramp terminals and three along the arterial south of the freeway.

8.5.1 Platooned arrivals on roundabout approaches

Signalized intersections close to roundabouts produce gaps in traffic that can be used by minor street traffic to enter the major street.

The performance of a roundabout is affected by its proximity to signalized intersections. If a signalized intersection is very close to the roundabout, it causes vehicles to enter the roundabout in closely spaced platoons; more importantly, it results in regular periods when no vehicles enter. These latter periods provide an excellent opportunity for traffic on the next downstream entry to enter. Since the critical gap is larger than the follow-up time, a roundabout becomes more efficient when the vehicles are handled as packets of vehicles rather than as isolated vehicles.

When the signalized intersection is some distance from the roundabout, then the vehicles' arrival patterns have fewer closely spaced platoons. Platoons tend to disperse as they move down the road. The performance of a roundabout will be reduced under these circumstances when compared with a close upstream signal. If arrival speeds are moderate, then few longer gaps allow more drivers to enter a roundabout than a larger number of shorter gaps. If arrival speeds are low, then there are more opportunities for priority-sharing (where entering and circulating vehicles alternate) and priority-reversals (where the circulating vehicles tend to yield to entering vehicles) between entering and circulating traffic streams, and the influence of platoon dispersal is not as marked.

8.5.2 Roundabout departure pattern

Traffic leaving a roundabout tends to be more random than if another type of intersection control were used. A roundabout may therefore affect the performance of other unsignalized intersections or driveways more than if the intersection was signalized. However, as this traffic travels further along the road downstream of the roundabout, the faster vehicles catch up to the slower vehicles and the proportion of platooning increases.

In the case of a well-defined platoon from an upstream signalized intersection arriving at a downstream unsignalized intersection just after a well-defined platoon arrives from the other direction, it may be difficult for the minor street drivers at this unsignalized intersection to enter the link. If, on the other hand, one of these signalized intersections were to be replaced by a roundabout, then the effect of the random traffic from the roundabout might be relatively advantageous. Under these conditions, more dispersed platoons (or random) traffic could assist drivers entering along the link at the unsignalized intersection.

Even one circulating vehicle in a roundabout will result in a platoon breaking down.

If a roundabout is used in a network of coordinated signalized intersections, then it may be difficult to maintain the closely packed platoons required. If a tightly packed platoon approached a roundabout, it could proceed through the roundabout as long as there was no circulating traffic or traffic upstream from the left. Only one circulating vehicle would result in the platoon breaking down. Hence, the use of roundabouts in a coordinated signalized network needs to be evaluated carefully. One possibility for operating roundabouts within a signal network is to signalize the major approaches of the roundabout and coordinate them with adjacent upstream and downstream signalized intersections.

Another circumstance in which a roundabout may be advantageous is as an alternative to signal control at a critical signalized intersection within a coordinated network. Such intersections are the bottlenecks and usually determine the required cycle length, or are placed at a signal system boundary to operate in isolated actuated mode to minimize their effect on the rest of the surrounding system. If a roundabout can be designed to operate within its capacity, it may allow a lowering of the system cycle length with resultant benefits to delays and queues at other intersections.

Because roundabouts accommodate U-turns more easily than do signals, they may also be useful as an access management tool. Left-turn exits from driveways onto an arterial which may currently experience long delays and require two-stage left-turn movements could be replaced with a simpler right turn, followed by a U-turn at the next roundabout.

Roundabouts as an access management tool.

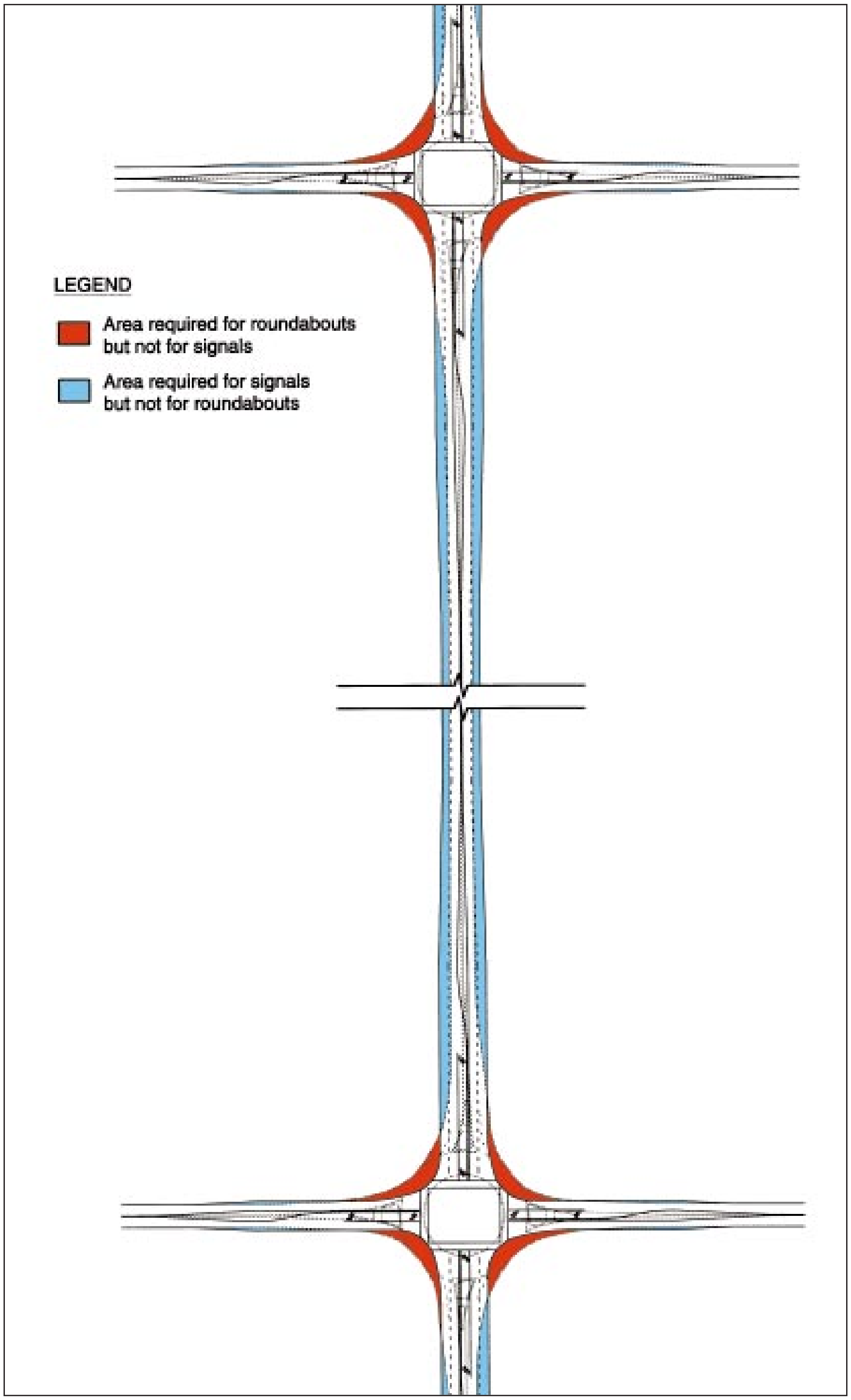
8.5.3 Wide nodes and narrow roads

The ultimate manifestation of roundabouts in a system context is to use them in lieu of signalized intersections. Some European cities such as Nantes, France, and some Australian cities have implemented such a policy. It is generally recognized that intersections (or nodes), not road segments (or links), are typically the bottlenecks in urban roadway networks. A focus on maximizing intersection capacity rather than widening streets may therefore be appropriate. Efficient, signalized intersections, however, usually require that exclusive turn lanes be provided, with sufficient storage to avoid queue spillback into through lanes and adjacent intersections. In contrast, roundabouts may require more right-of-way at the nodes, but this may be offset by not requiring as many basic lanes on the approaches, relative to signalized arterials. This concept is demonstrated in Exhibit 8-10.

Roundabouts may require more right-of-way at intersections, but may also allow fewer lanes (and less right-of-way) between intersections.

Analysis tools, such as those provided in Chapter 4, should be used to evaluate the arterial or network. These may be supplemented by appropriate use of microscopic simulation models as discussed next. Supplemental techniques to increase the capacity of critical approaches may be considered if necessary, such as bypass lanes, flaring of approaches and tapering of exits, and signalization of some roundabout approaches.

Exhibit 8-10. Wide nodes and narrow roads.



8.6 Microscopic Simulation

Microscopic simulation of traffic has become a valuable aid in assessing the system performance of traffic flows on networks, as recognized by the *Highway Capacity Manual 2000* (7). Analysis of many of the treatments discussed in this chapter may benefit from the use of appropriate simulation models used in conjunction with analytic models of isolated roundabouts discussed in Chapter 4. These effects include more realistic modeling of arrival and departure profiles, time-varying traffic patterns, measurement of delay, spatial extent and interaction of queues, fuel consumption, emissions, and noise. However, the user must carefully select the appropriate models and calibrate the model for a particular use, either against field data, or other validated analytic models. It would also be advisable to check with others to see if there have been any problems associated with the use of the model.

8.6.1 How to use simulation

Microscopic simulation models are numerous and new ones are being developed, while existing models are upgraded frequently. Each model may have particular strengths and weaknesses. Therefore, when selecting a model, analysts should consider the following:

- Should a simulation model be used, or is an isolated analytic roundabout model sufficient?
- What are the model input requirements, are they sufficient, and how can they be provided or estimated?
- What outputs does the model provide in animated, graphical, or tabular form?
- What special features of the model are pertinent to the problem being addressed?
- Does the user manual for the simulation model specifically address modeling a roundabout?
- How sensitive is the model to various geometric parameters?
- Is there literature on the validation of this model for evaluating roundabouts?
- Is there sufficient information available on the microscopic processes being used by the model such as car following, gap acceptance, lane changing, or steering? (The availability of animation can assist in exposing model logic.)
- Are relevant past project examples available?

When a simulation model is used, the analyst is advised to use the results to make relative comparisons of the differences between results from changing conditions, and not to conclude that the absolute values found from the model are equivalent to field results. It is also advisable to perform a sensitivity analysis by changing selected parameters over a range and comparing the results. If a particular parameter is found

Simulation results are best used for relative comparisons, rather than relying on absolute values produced by the model.

to affect the outcomes significantly, then more attention should be paid to accurate representation and calibration of this parameter. Finally, the analyst should check differences in results from using different random number seeds. If the differences are large, then the simulation time should be increased substantially.

8.6.2 Examples of simulation models

Five commercially available microscopic simulation models are CORSIM, Integration, Simtraffic, Paramics, and VISSIM. The first three are North American models; Paramics is from Scotland, and VISSIM is from Germany. The following sections present a brief overview of each model. Since software packages (and simulation models in particular) are in constant development, the user is encouraged to consult the most current information available on each model.

Exhibit 8-11. Summary of simulation models for roundabout analysis.

Name	Scope	Notes (1999 versions)
CORSIM	Urban streets, freeways	FHWA has been investigating modifications that may be required for CORSIM to adequately model controls such as stop and yield control at roundabouts through gap acceptance logic. In this research, roundabouts have been coded as a circle of four yield-controlled T-intersections. The effect of upstream signals on each approach and their relative offsets has also been reported (8).
Integration	Urban streets, freeways	Integration has documented gap acceptance logic for permitted movements at signal-, yield-, and stop-controlled intersections. As with CORSIM, Integration requires coding a roundabout simply as a series of short links and nodes with yield control on the entrances.
Simtraffic	Urban streets	Simtraffic is a simulation model closely tied to the signal timing software package Synchro. Simtraffic has the capability to model unsignalized intersections and thus may be suitable for modeling roundabouts. However, no publications to date have demonstrated the accuracy of Simtraffic in modeling roundabout operations.
Paramics	Urban streets, freeways	Paramics has been used in the United Kingdom and internationally for a wide range of simulation projects. It has been specifically compared with ARCADY in evaluating roundabouts (9). The model has a coding feature to automatically code a roundabout intersection at a generic node, which may then be edited. The model has been used in the United Kingdom for a number of actual roundabout evaluations. The model specifically employs a steering logic on the circulatory roadway to track a vehicle from an entry vector to a target exit vector (10).
VISSIM	Urban streets, transit networks	VISSIM is widely used in Germany for modeling urban road and transit networks, including roundabouts. Roundabout examples are provided with the software, including explicit modeling of transit and pedestrians. Modeling a roundabout requires detailed coding of link connectors, control, and gap acceptance parameters (11).

8.7 References

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Glossary

85th-percentile speed—a speed value obtained from a set of field-measured speeds where only 15 percent of the observed speeds are greater (source: HCM 2000).

A

AADT—see *average annual daily traffic.*

AASHO—American Association of State Highway Officials. Predecessor to *AASHTO.*

AASHTO—American Association of State Highway and Transportation Officials.

accessible—describes a site, building, facility, or portion thereof that complies with the Americans with Disabilities Act Accessibility Guidelines (source: ADAAG).

accessible route—a continuous, unobstructed path connecting all accessible elements and spaces of a building or facility. Exterior accessible routes may include parking access aisles, curb ramps, crosswalks at vehicular ways, walks, ramps, and lifts (source: ADAAG).

accident—see *crash.*

ADA—Americans with Disabilities Act.

ADAAG—Americans with Disabilities Act Accessibility Guidelines.

all-way stop control—all approaches at the intersections have stop signs where all drivers must come to a complete stop. The decision to proceed is based in part on the rules of the road, which suggest that the driver on the right has the right-of-way, and also on the traffic conditions of the other approaches (source: HCM 2000).

angle, entry—see *entry angle.*

approach—the portion of a roadway leading into a *roundabout.*

approach capacity—the capacity provided at the *yield line* during a specified period of time.

approach curvature—a series of progressively sharper curves used on an *approach* to slow traffic to a safe speed prior to reaching the *yield line.*

approach road half-width—term used in the United Kingdom regression models. The approach half width is measured at a point in the approach upstream from any *entry flare*, from the median line or median curb to the nearside curb along a line perpendicular to the curb. See also *approach width.* (source: UK Geometric Design of Roundabouts)

approach speed—the posted or 85th-percentile speed on an *approach* prior to any geometric or signing treatments designed to slow speeds.

approach width—the width of the roadway used by approaching traffic upstream of any changes in width associated with the roundabout. The *approach* width is typically no more than half the total roadway width.

apron—the mountable portion of the *central island* adjacent to the *circulatory roadway.* Used in smaller roundabouts to accommodate the wheel tracking of large vehicles.

average annual daily traffic—the total volume passing a point or segment of a highway facility in both directions for one year divided by the number of days in the year (source: HCM 2000).

average effective flare length—term used in the United Kingdom regression models. Defined by a geometric construct and is approximately equivalent to the length of flare that can be effectively used by vehicles. (source: UK Geometric Design of Roundabouts)

AWSC—see *all-way stop control.*

B

back of queue—the distance between the yield line of a roundabout and the farthest reach of an upstream queue, expressed as a number of vehicles. The vehicles previously stopped at the front of the queue may be moving (adapted from HCM 2000).

benefit-cost analysis—a method of economic evaluation that uses the *benefit-cost ratio* as the measure of effectiveness.

benefit-cost ratio—the difference in benefits between an alternative and the no-build scenario, divided by the difference in costs between the alternative and the no-build scenario. See also *incremental benefit-cost ratio.*

bulb-out—see *curb extension.*

C

capacity—the maximum sustainable flow rate at which persons or vehicles can be reasonably expected to traverse a point or uniform segment of a lane or roadway during a specified time period under a given roadway, geometric, traffic, environmental, and control conditions. Usually expressed as vehicles per hour, passenger cars per hour, or persons per hour (source: HCM 2000).

capacity, approach—see *approach capacity.*

capacity, roundabout—see *roundabout capacity.*

capital recovery factor—a factor that converts a present value cost into an annualized cost over a period of *n* years using an assumed discount rate of *i* percent.

central island—the raised area in the center of a *roundabout* around which traffic circulates.

CFR—Code of Federal Regulations.

channelization—the separation or regulation of conflicting traffic movements into definite paths of travel by traffic islands or pavement marking to facilitate the safe and orderly movements of both vehicles and pedestrians (source: 1994 AASHTO Green Book).

circle, inscribed—see *inscribed circle.*

circular intersection—an intersection that vehicles traverse by circulating around a *central island.*

circulating flow—see *circulating volume.*

circulating path radius—the minimum radius on the fastest through path around the *central island.*

circulating traffic—vehicles located on the *circulatory roadway.*

circulating volume—the total volume in a given period of time on the *circulatory roadway* immediately prior to an entrance.

circulatory roadway—the curved path used by vehicles to travel in a counterclockwise fashion around the *central island.*

circulatory roadway width—the width between the outer edge of the *circulatory roadway* and the central island, not including the width of any *apron.*

circulating speed—the speed vehicles travel at while on the *circulatory roadway.*

community enhancement roundabout—a *roundabout* used for aesthetic or community enhancement reasons, rather than as a solution to traffic problems. When used, often located in commercial and civic districts.

conflict point—a location where the paths of two vehicles, or a vehicle and a bicycle or pedestrian, merge, diverge, cross, or queue behind each other.

conflict, crossing—see *crossing conflict.*

conflict, diverge—see *diverge conflict.*

conflict, merge—see *merge conflict.*

conflict, queuing—see *queuing conflict.*

conflicting flows—the two paths that merge, diverge, cross, or queue behind each other at a *conflict point.*

control delay—delay experienced by vehicles at an intersection due to movements at slower speeds and stops on approaches as vehicles move up in the queue.

crash—a collision between a vehicle and another vehicle, a pedestrian, a bicycle, or a fixed object.

crash frequency—the average number of crashes at a location per period of time.

crash rate—the number of crashes at a location or on a roadway segment, divided by the number of vehicles entering the location or by the length of the segment.

CRF—see *capital recovery factor.*

crossing conflict—the intersection of two traffic streams, including pedestrians. Crossing conflicts are the most severe type of conflict.

curb extension—the construction of curbing such that the width of a street is reduced. Often used to provide space for parking or a bus stop or to reduce pedestrian crossing distances.

curb ramp—a short ramp cutting through a curb or built up to it (source: ADAAG).

curvature, approach—see *approach curvature.*

D

D factor—the proportion of the two-way traffic assigned to the peak direction.

deflection—the change in trajectory of a vehicle imposed by geometric features of the roadway.

degree of saturation—see *volume-to-capacity ratio.*

delay—additional travel time experienced by a driver, passenger, or pedestrian beyond what would reasonably be desired for a given trip.

delay, control—see *control delay.*

delay, geometric—see *geometric delay.*

demand flow—the number of vehicles or persons that would like to use a roadway facility during a specified period of time.

departure width—the width of the roadway used by departing traffic downstream of any changes in width associated with the *roundabout.* The departure width is typically no more than half the total roadway width.

design user—any user (motorized or nonmotorized) that can be reasonably be anticipated to use a facility.

design vehicle—the largest vehicle that can reasonably be anticipated to use a facility.

detectable warning surface—a standardized surface feature built in or applied to walking surfaces or other elements to warn visually impaired people of hazards on a circulation path (source: ADAAG).

diameter, inscribed circle—see *inscribed circle diameter.*

distance, set-back—see *set-back distance.*

diverge conflict—the separation of two traffic streams, typically the least severe of all conflicts.

double-lane roundabout—a *roundabout* that has at least one entry with two lanes, and a *circulatory roadway* that can accommodate more than one vehicle traveling side-by-side.

downstream—the direction toward which traffic is flowing (source: HCM 2000).

E

entering traffic—vehicles located on a *roundabout* entrance.

entering volume—the total volume in a given period of time on an entrance to a roundabout.

entry angle—term used in the United Kingdom regression models. It serves as a geometric proxy for the conflict angle between entering and circulating streams and is determined through a geometric construct. (source: UK Geometric Design of Roundabouts)

entry flare—the widening of an approach to multiple lanes to provide additional capacity at the *yield line* and storage.

entry flow—see *entering volume.*

entry path curvature—term used in the United Kingdom to describe a measure of the amount of entry *deflection* to the right imposed on vehicles at the entry to a roundabout. (source: UK Geometric Design of Roundabouts)

entry path radius—the minimum radius on the fastest through path prior to the yield line.

entry radius—the minimum radius of curvature of the outside curb at the entry.

entry speed—the speed a vehicle is traveling at as it crosses the *yield line.*

entry width—the width of the entry where it meets the *inscribed circle,* measured perpendicularly from the right edge of the entry to the intersection point of the left edge line and the inscribed circle.

entry, perpendicular—see *perpendicular entry.*

exit path radius—the minimum radius on the fastest through path into the exit.

exit radius—the minimum radius of curvature of the outside curb at the exit.

exit width—the width of the exit where it meets the *inscribed circle*, measured perpendicularly from the right edge of the exit to the intersection point of the left edge line and the *inscribed circle.*

exiting traffic—vehicles departing a *roundabout* by a particular exit.

extended splitter island—see *splitter island, extended.*

F

FHWA—Federal Highway Administration.

flare—see *entry flare.*

flare, entry—see *entry flare.*

flow, circulating—*see circulating volume.*

flow, demand—see *demand flow.*

flow, entry—see *entry volume.*

flows, conflicting—see *conflicting flows.*

G

geometric delay—the delay caused by the alignment of the lane or the path taken by the vehicle on a roadway or through an intersection.

geometric design—a term used in this document to describe the design of horizontal and vertical alignment and cross-sectional elements of a roadway.

give way—term used in the United Kingdom and Australia for *yield.*

"give way" rule—rule adopted in the United Kingdom in November 1966 which required that all vehicles entering a roundabout *give way*, or *yield*, to circulating vehicles.

H

HCM—Highway Capacity Manual.

I

IES—Illuminating Engineers Society.

incremental benefit-cost ratio—the difference in benefits between two alternatives, divided by the difference in costs between the two alternatives. See also *benefit-cost ratio.*

inscribed circle—the circle forming the outer edge of the *circulatory roadway.*

inscribed circle diameter—the basic parameter used to define the size of a *roundabout*, measured between the outer edges of the *circulatory roadway.* It is the diameter of the largest circle that can be inscribed within the outline of the *intersection.*

interchange—a grade-separated junction of two roadways, where movement from one roadway to the other is provided for.

intersection—an at-grade junction of two or more roadways.

intersection sight distance—the distance required for a driver without the right-of-way to perceive and react to the presence of conflicting vehicles.

island, central—see *central island.*

island, median—see *splitter island.*

island, separator—see *splitter island.*

island, splitter—see *splitter island.*

ITE—Institute of Transportation Engineers.

K

K factor—the proportion of the AADT assigned to the design hour.

L

left-turn path radius—the minimum radius on the fastest path of the conflicting left-turn movement.

level of service—a qualitative measure describing operational conditions within a traffic stream, generally described in terms of service measures such as speed and travel time, freedom to maneuver, traffic interruptions, comfort, and convenience.

line, yield—see *yield line.*

locking—stoppage of traffic on the *circulatory roadway* caused by queuing backing into the *roundabout* from one of the exits, resulting in traffic being unable to enter or circulate.

LOS—see *level of service.*

M

maximum service volume—the maximum hourly rate at which vehicles, bicycles, or persons can be reasonably expected to traverse a point or uniform section of a roadway during an hour under specific assumed conditions while maintaining a designated level of service. (source: HCM 2000)

measures of effectiveness—a quantitative parameter whose value is an indicator of the performance of a transportation facility or service from the perspective of the users of the facility or service.

median island—see *splitter island.*

merge conflict—the joining of two traffic streams.

mini-roundabout—small roundabouts used in low-speed urban environments. The *central island* is fully *mountable*, and the *splitter islands* are either painted or *mountable.*

model, crash prediction—see *crash prediction model.*

modern roundabout—a term used to distinguish newer *circular intersections* conforming to the characteristics of *roundabouts* from older-style *rotaries* and *traffic circles.*

m.o.e.—see *measures of effectiveness.*

mountable—used to describe geometric features that can be driven upon by vehicles without damage, but not intended to be in the normal path of traffic.

multilane roundabout—a *roundabout* that has at least one entry with two or more lanes, and a *circulatory roadway* that can accommodate more than one vehicle traveling side-by-side.

MUTCD—Manual on Uniform Traffic Control Devices.

N

neighborhood traffic circle—a *circular intersection* constructed at the intersection of two local streets for *traffic calming* and/or aesthetic purposes. They are generally not channelized, may be uncontrolled or stop-controlled, and may allow left turns to occur left (clockwise) of the *central island.*

nonconforming traffic circle—see *traffic circle.*

nontraversable—see *raised.*

O

O&M costs—operations and maintenance costs.

P

peak hour factor—the hourly volume during the maximum-volume hour of the day divided by the peak 15-minute flow rate within the peak hour; a measure of traffic demand fluctuation within the peak hour.

pedestrian refuge—an at-grade opening within a median island that allows pedestrians to safely wait for an acceptable gap in traffic.

perpendicular entry—an *entry angle* of 70 degrees or more.

PHF—see *peak hour factor.*

platoon—a group of vehicles or pedestrians traveling together as a group, either voluntarily or involuntarily because of signal control, geometrics, or other factors.

point, conflict—see *conflict point.*

priority—the assignment of *right-of-way* to a particular traffic stream or movement.

progression, signal—see *signal progression.*

Q

queue—a line of vehicles, bicycles, or persons waiting to be served by the system in which the flow rate from the front of the queue determines the average speed within the queue. Slowly moving vehicles or persons joining the rear of the queue are usually considered a part of the queue. The internal queue dynamics may involve a series of starts and stops. (source: HCM 2000)

queuing conflict—a conflict that arises within a traffic stream between a lead vehicle and a following vehicle, when the lead vehicle must come to a stop.

R

radius, circulating path—see *circulating path radius.*

radius, entry—see *entry radius.*

radius, entry path—see *entry path radius.*

radius, exit—see *exit radius.*

radius, exit path—see *exit path radius.*

radius, left-turn path—see *left-turn path radius.*

radius, right-turn path—see *right-turn path radius.*

raised—used to describe geometric features with a sharp elevation change that are not intended to be driven upon by vehicles at any time.

ramp, wheelchair—see *wheelchair ramp.*

refuge, pedestrian—see *pedestrian refuge.*

right-of-way—(1) an intersection user that has *priority* over other users. (2) Land owned by a public agency for transportation uses.

right-turn bypass lane—a lane provided adjacent to, but separated from, the *circulatory roadway*, that allows right-turning movements to bypass the *roundabout.* Also known as a *right-turn slip lane.*

right-turn path radius—the minimum radius on the fastest path of a right-turning vehicle.

right-turn slip lane—see *right-turn bypass lane.*

roadway, circulatory—see *circulatory roadway.*

rotary—a term used particularly in the Eastern U.S. to describe an older-style *circular intersection* that does not have one or more of the characteristics of a *roundabout.* They often have large diameters, often in excess of 100 m (300 ft), allowing high travel speeds on the *circulatory roadway.* Also known as a *traffic circle.*

roundabout—a *circular intersection* with yield control of all entering traffic, channelized approaches, counter-clockwise circulation, and appropriate geometric curvature to ensure that travel speeds on the *circulatory roadway* are typically less than 50 km/h (30 mph).

roundabout capacity—the maximum number of entering vehicles that can be reasonably expected to be served by a *roundabout* during a specified period of time.

roundabout, community enhancement—see *community enhancement roundabout.*

roundabout, modern—see *modern roundabout.*

roundabout, multilane—see *multilane roundabout.*

roundabout, rural double-lane—see *rural double-lane roundabout.*

roundabout, rural single-lane—see *rural single-lane roundabout.*

roundabout, single lane—see *single-lane roundabout.*

roundabout, urban compact—see *urban compact roundabout.*

roundabout, urban single-lane—see *urban single-lane roundabout.*

rural double-lane roundabout—a *roundabout* located in a rural area that has at least one entry with two lanes, and a *circulatory roadway* that can accommodate more than one vehicle traveling side-by-side. They incorporate *approach curvature* to slow *entering traffic* to a safe speed.

rural single-lane roundabout—a *roundabout* located in a rural area that has single lanes on all entries and one circulatory lane. This form typically has larger diameters and more tangential exits than urban forms.

S

separator island—see *median island.*

service volume—the hourly rate at which vehicles, bicycles, or persons can be reasonably expected to traverse a point or uniform section of a roadway during an hour under specific assumed conditions. See also *maximum service volume.* (Adapted from HCM 2000)

set-back distance—the distance between the edge of the circulatory roadway and the sidewalk.

sharpness of flare—a measure of the rate at which extra width is developed in the *entry flare*. (source: UK Geometric Design of Roundabouts)

sight distance, intersection—see *intersection sight distance.*

sight distance, stopping—see *stopping sight distance.*

sight triangle—an area required to be free of obstructions to enable visibility between conflicting movements.

signal progression—the use of coordinated traffic signals along a roadway in order to minimize stops and delay to through traffic on the major road.

single-lane roundabout—a *roundabout* that has single lanes on all entries and one circulatory lane.

speed table—an extended, flat-top road hump sometimes used at pedestrian crossings to slow traffic and to provide a better visual indication of the crosswalk location.

speed, approach—see *approach speed.*

speed, circulating—see *circulating speed.*

speed, entry—see *entry speed.*

splitter island—a raised or painted area on an approach used to separate entering from exiting traffic, deflect and slow entering traffic, and provide storage space for pedestrians crossing that intersection approach in two stages. Also known as a *median island* or a *separator island.*

splitter island, extended—a raised splitter island that begins some distance upstream of the pedestrian crossing to separate entering and exiting traffic. A design feature of rural roundabouts.

stopping sight distance—the distance along a roadway required for a driver to perceive and react to an object in the roadway and to brake to a complete stop before reaching that object.

T

traffic calming—geometric treatments used to slow traffic speeds or to discourage the use of a roadway by nonlocal traffic.

traffic circle—a *circular intersection* that does not have one or more of the characteristics of a *roundabout.* Also known as a *rotary.*

traffic circle, neighborhood—see *neighborhood traffic circle.*

traffic circle, nonconforming—see *traffic circle.*

traffic design—a term used in this document to describe the design of traffic control devices, including signing, pavement markings, and construction traffic control.

traffic, circulating—see *circulating traffic.*

traffic, entering—see *entering traffic.*

truck apron—see *apron.*

two-stage crossing—a process in which pedestrians cross a roadway by crossing one direction of traffic at a time, waiting in a *pedestrian refuge* between the two traffic streams if necessary before completing the crossing.

two-way stop-control—stop signs are present on the approach(es) of the minor street. Drivers on the minor street or drivers turning left from the major street wait for a gap in the major street traffic in order to complete a maneuver.

TWSC—see *two-way stop control.*

U

U-turn—a turning movement at an *intersection* in which a vehicle departs the intersection using the same roadway it used to enter the intersection.

upstream—the direction from which traffic is flowing (source: HCM 2000).

urban compact roundabout—a small *roundabout* with a raised *central island* and *splitter islands,* with perpendicular approaches that require vehicles to make a distinct right turn into the *circulatory roadway.*

urban double-lane roundabout—an urban *roundabout* with at least one entry with two lanes, and a *circulatory roadway* that can accommodate more than one vehicle traveling side-by-side. They have similar speed characteristics as *urban single-lane roundabouts.*

urban single-lane roundabout—a *roundabout* with single lane entries on all legs and one circulatory lane. Entries are less perpendicular than the *urban compact roundabout,* allowing somewhat higher speeds with higher capacities.

UVC—Uniform Vehicle Code.

V

vehicle, design—see *design vehicle.*

volume, circulating—see *circulating volume.*

volume, entering—see *entering volume.*

volume, service—see *service volume.*

volume-to-capacity ratio—the ratio of flow rate to capacity for a transportation facility.

W

wheelchair ramp—see *curb ramp*.

width, approach—see *approach width*.

width, circulatory roadway—see *circulatory roadway width.*

width, departure—see *departure width.*

width, entry—see *entry width.*

width, exit—see *exit width.*

Y

yield—an intersection control in which controlled traffic must stop only if higher *priority* traffic is present.

yield line—a pavement marking used to mark the point of entry from an approach into the *circulatory roadway* and generally marked along the *inscribed circle.* If necessary, *entering traffic* must yield to *circulating traffic* before crossing this line into the circulatory roadway.

Z

zebra crossing—a crossing marked by transverse white stripes where vehicles are required to yield to pedestrians.

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Maryland DOT. "Modern Roundabouts."

Appendix A Operational Analysis Formulas

This appendix presents the assumptions used to develop the graphs and charts in the operational analysis presented in Chapter 4.

A.1 Single-Lane Roundabout

A.1.1 Equations

$$\begin{aligned} Q_e &= k(F - f_c Q_c), \quad & f_c Q_c \le F \\ &= 0, & f_c Q_c > F \end{aligned} \qquad \text{(A-1)}$$

where: Q_e = entry capacity, pce/h
Q_c = circulating flow, pce/h

$$k = 1 - 0.00347(\phi - 30) - 0.978\left(\frac{1}{r} - 0.05\right) \qquad \text{(A-2)}$$

$$F = 303x_2 \qquad \text{(A-3)}$$

$$f_c = 0.210t_D(1 + 0.2x_2) \qquad \text{(A-4)}$$

$$t_D = 1 + \frac{0.5}{1 + \exp\left(\frac{D - 60}{10}\right)} \qquad \text{(A-5)}$$

$$x_2 = v + \frac{e - v}{1 + 2S} \qquad \text{(A-6)}$$

$$S = \frac{1.6(e - v)}{l'} \qquad \text{(A-7)}$$

where: e = entry width, m
v = approach half width, m
l' = effective flare length, m
S = sharpness of flare, m/m
D = inscribed circle diameter, m
ϕ = entry angle, degrees
r = entry radius, m

A.1.2 Parameter assumptions

For design purposes, when $e = v$ then l' is effectively zero. However, setting $l' = 0$ results in S being undefined. Therefore a non-zero value of l' has been selected. When $e = v$, any non-zero value of l' results in $S = 0$ and $x_2 = v$.

D = 40 m
r_e = 20 m
ϕ = 30 degrees
v = 4 m
e = 4 m
l' = 40 m

$$S = \frac{1.6(e-v)}{l'} = \frac{1.6(4-4)}{40} = 0$$

$$t_D = 1 + \frac{0.5}{1+\exp\left(\frac{D-60}{10}\right)} = 1.4404$$

$$x_2 = v + \frac{e-v}{1+2S} = 4 + \frac{4-4}{1+2(0)} = 4$$

$$F = 303x_2 = 303(4) = 1212$$

$$f_c = 0.210t_D(1+0.2x_2) = 0.5447$$

$$k = 1 - 0.00347(\phi - 30) - 0.978\left(\frac{1}{r} - 0.05\right) = 1$$

A.1.3 Final equation

$$Q_e = 1212 - 0.5447Q_c \quad \text{(A-8)}$$

A.2 Double-Lane Roundabout

A.2.1 Equations

See Section A.1.1.

A.2.2 Parameter assumptions

For design purposes, when $e = v$ then l' is effectively zero. However, setting $l' = 0$ results in S being undefined. Therefore a non-zero value of l' has been selected. When $e = v$, any non-zero value of l' results in $S = 0$ and $x_2 = v$.

D = 55 m
r_e = 20 m
ϕ = 30 degrees
v = 8 m
e = 8 m
l' = 40 m

$$S = \frac{1.6(e-v)}{l'} = \frac{1.6(8-8)}{40} = 0$$

$$t_D = 1 + \frac{0.5}{1+\exp\left(\frac{D-60}{10}\right)} = 1.3112$$

$$x_2 = v + \frac{e-v}{1+2S} = 8 + \frac{8-8}{1+2(0)} = 8$$

$$F = 303x_2 = 303(8) = 2424$$

$$f_c = 0.210t_D(1+0.2x_2) = 0.7159$$

$$k = 1 - 0.00347(\phi - 30) - 0.978\left(\frac{1}{r} - 0.05\right) = 1$$

A.2.3 Final equation

$$Q_e = 2424 - 0.7159Q_c \quad \text{(A-9)}$$

A.3 Urban Compact Roundabout

The capacity curve for the urban compact roundabout is based on the capacity curves developed for roundabouts in Germany with single-lane entries and a single-lane circulatory roadway. This equation, developed by Brilon, Wu, and Bondzio is as follows:

$$Q_e = 1218 - 0.74Q_c \quad \text{(A-10)}$$

where: Q_e = entry capacity, pce/h
Q_c = circulating flow, pce/h

A.4 Short Lanes

The effect of short lanes (flare) on capacity has been documented by Wu (3). Page 321 of Wu's paper states that for a right flared approach,

$$k_{f,\,right} = \frac{1}{\sqrt[n_{F,\,right}+1]{(x_L + x_T)^{n_{F,\,right}+1} + x_R^{n_{F,\,right}+1}}} \quad \text{(A-11)}$$

Dropping some subscripts,

$$k = \frac{1}{\sqrt[n+1]{(x_{LT})^{n+1} + (x_R)^{n+1}}} \quad \text{(A-12)}$$

Noting that the capacities of each lane are the same and that the flows are the same (that is, the entries are constantly fed with vehicles), this gives:

$$k = \frac{1}{x\ \sqrt[n+1]{2}} \quad \text{(A-13)}$$

with $x_{LT} = x_R$. Capacity q_{max} is then

$$q_{max} = k \quad q_i \quad \text{(A-14)}$$

where q_i is flow in lane *i* and $q_1 = q_2$

$$q_{max} = \frac{2q}{x\ \sqrt[n+1]{2}} \quad \text{(A-15)}$$

q_{max2} is the capacity of a two-lane roundabout, the capacity of each entry lane is $q_{max2}/2$ and this is equal to the flow, *q*, divided by the degree of saturation, *x*.

$$q_{max} = \frac{q_{max\,2}}{\sqrt[n+1]{2}} \quad \text{(A-16)}$$

The results of Equation A-16 can be compared with the results from the British equations. The TRL equations are listed above. The results are listed for four circulating flow conditions: 500 veh/h, 1000 veh/h, 1500 veh/h, and 2000 veh/h.

Exhibit A-1. Tabular comparison of TRL and Wu short-lane methodologies.

	Q_c = 500 veh/h		Q_c=1000 veh/h		Q_c=1500 veh/h		Q_c=2000 veh/h	
n	**TRL**	**Wu**	**TRL**	**Wu**	**TRL**	**Wu**	**TRL**	**Wu**
0	940	940	668	668	395	395	123	123
1	1447	1461	1151	1208	855	955	559	702
2	1636	1640	1321	1356	1006	1072	691	787
3	1737	1737	1411	1436	1086	1135	761	834
4	1799	1799	1468	1487	1136	1175	805	864
5	1841	1841	1506	1522	1170	1203	835	884
6	1872	1871	1534	1547	1195	1223	857	899
7	1896	1895	1555	1566	1214	1238	873	910
8	1914	1913	1571	1581	1229	1250	886	919
9	1929	1928	1585	1594	1240	1260	896	926
10	1941	1940	1596	1604	1250	1268	905	932
11	1951	1950	1605	1612	1258	1274	912	936
12	1960	1959	1612	1619	1265	1280	918	941
13	1967	1966	1619	1626	1271	1285	923	944
14	1974	1973	1625	1631	1276	1289	928	947
15	1979	1978	1630	1636	1281	1293	931	950
16	1984	1983	1635	1640	1285	1296	935	952
17	1989	1988	1639	1644	1288	1299	938	955
18	1993	1992	1642	1647	1292	1302	941	957
19	1996	1996	1645	1650	1294	1304	943	958
20	2000 2066	1999 2066	1648 1708	1653 1708	1297 1350	1306 1350	946 992	960 992

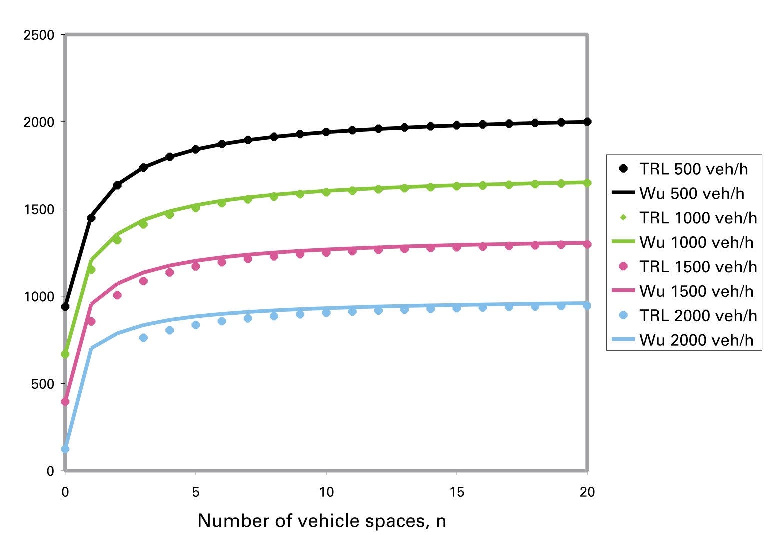


Exhibit A-2. Graphical comparison of TRL and Wu short-lane methodologies.

A.5 References

1. Kimber, R.M. *The traffic capacity of roundabouts.* TRRL Laboratory Report LR 942. Crowthorne, England: Transport and Road Research Laboratory, 1980.
2. Brilon , W., N. Wu, and L. Bondzio. "Unsignalized Intersections in Germany – A State of the Art 1997." In *Proceedings of the Third International Symposium on Intersections without Traffic Signals* (ed: M. Kyte), Portland, Oregon, U.S.A. University of Idaho, 1997.
3. Wu, N. "Capacity of shared/short lanes at unsignalized intersections." In *Proceedings of the Third International Symposium on Intersections without Traffic Signals* (ed: M. Kyte), Portland, Oregon, U.S.A. University of Idaho, 1997.

Appendix B Example Roundabout Designs

The purpose of this Appendix is to provide examples for each of the six roundabout categories. Exhibit B-1 lists typical inscribed circle diameter ranges for each roundabout category. Note that the flared-entry roundabout uses the same range of inscribed circle diameters as the double-lane roundabouts. Note that the dimensions of roundabouts may vary considerably within each category, depending on site-specific characteristics, including number of legs, approach angles, design vehicle requirements, and so on. Refer to Chapter 6 for more discussion of specific dimensions.

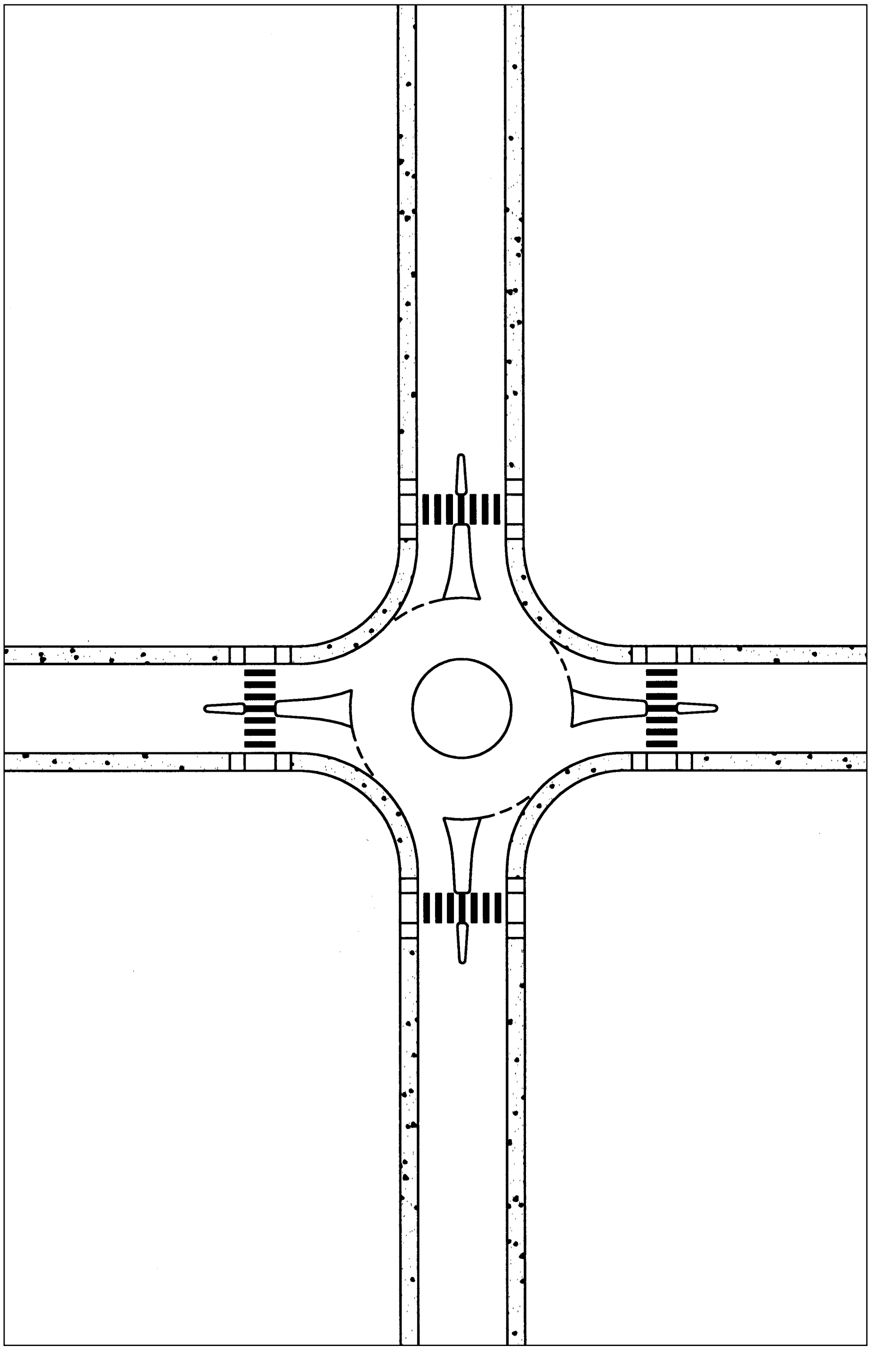
Exhibit B-1. Typical inscribed circle diameter ranges by roundabout category.

Site Category	Inscribed Circle Diameter Range
Mini-roundabout	13–25 m (45–80 ft)
Urban compact	25–30 m (80–100 ft)
Urban single lane	30–40 m (100–130 ft)
Urban double lane	45–55 m (150–180 ft)
Rural single lane	35–40 m (115–130 ft)
Rural double lane	55–60 m (180–200 ft)

The following pages show examples for each of the roundabout categories:

- Exhibit B-2: Typical mini-roundabout.
- Exhibit B-3: Typical urban compact roundabout.
- Exhibit B-4: Typical urban single-lane roundabout.
- Exhibit B-5: Typical urban double-lane roundabout.
- Exhibit B-6: Typical flared-entry roundabout.
- Exhibit B-7: Typical rural single-lane roundabout.
- Exhibit B-8: Typical rural double-lane roundabout.

Exhibit B-2. Example of a typical mini-roundabout.



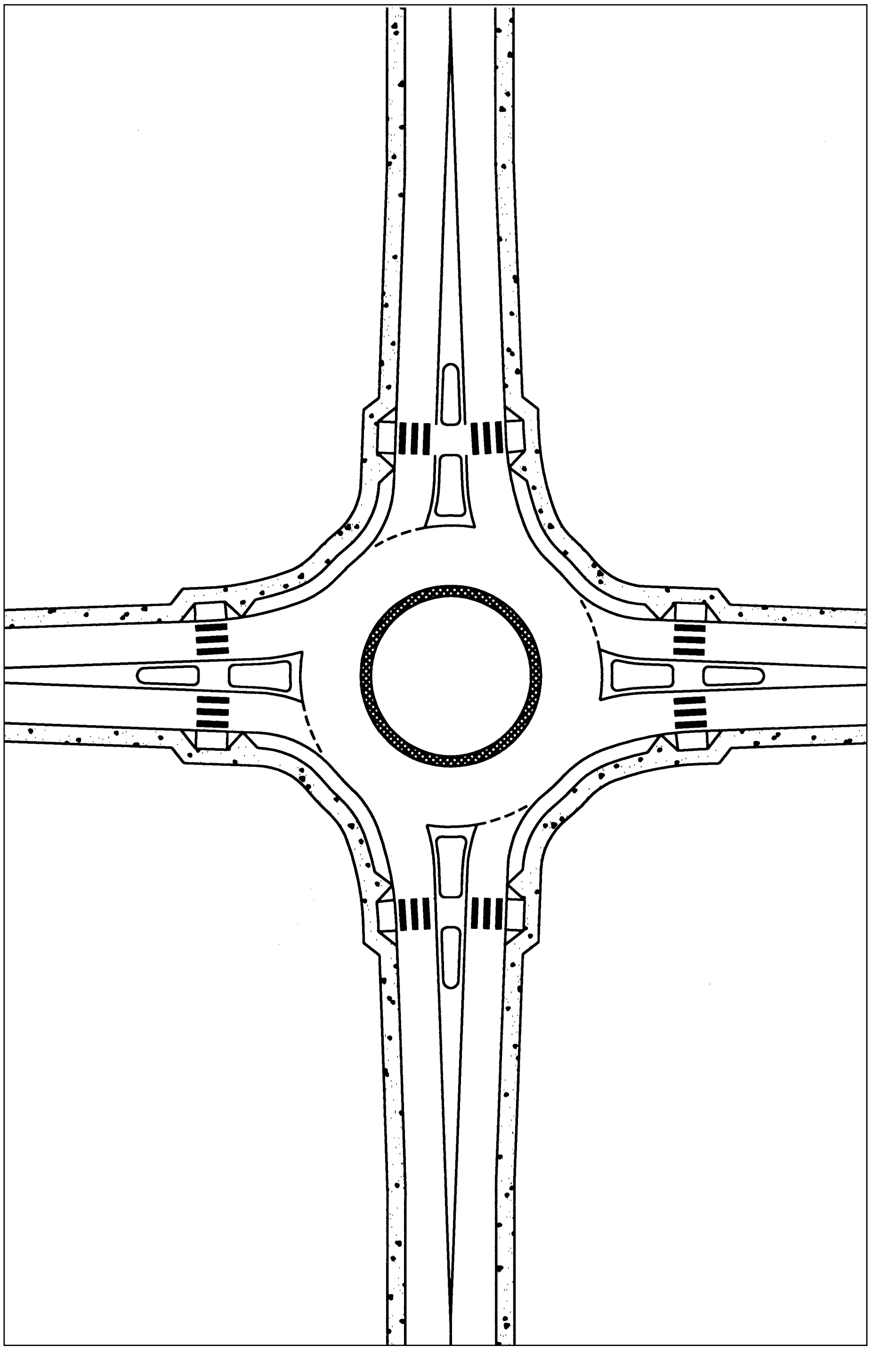
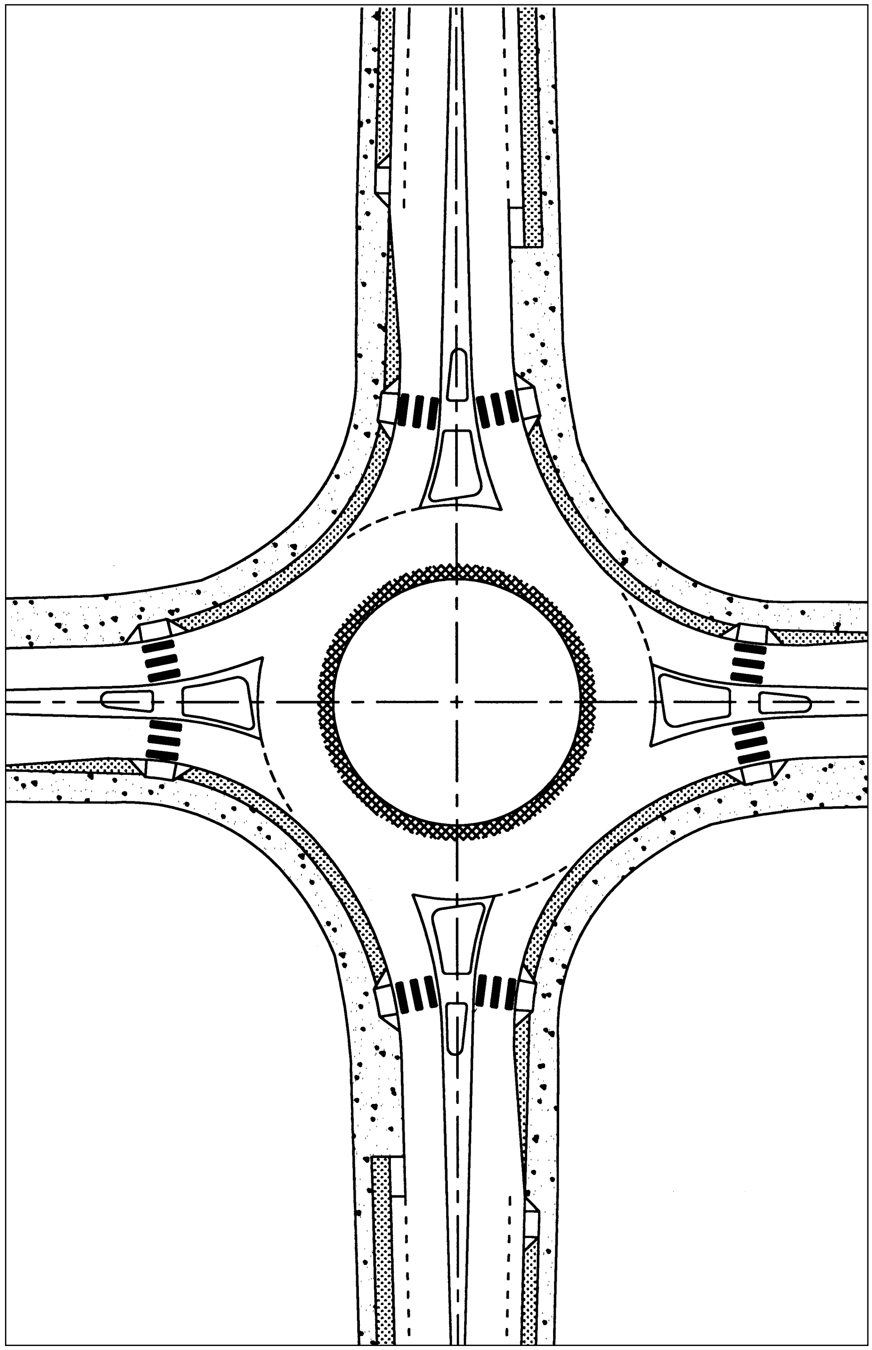


Exhibit B-3. Example of a typical urban compact roundabout.

Exhibit B-4. Example of a typical single-lane roundabout.



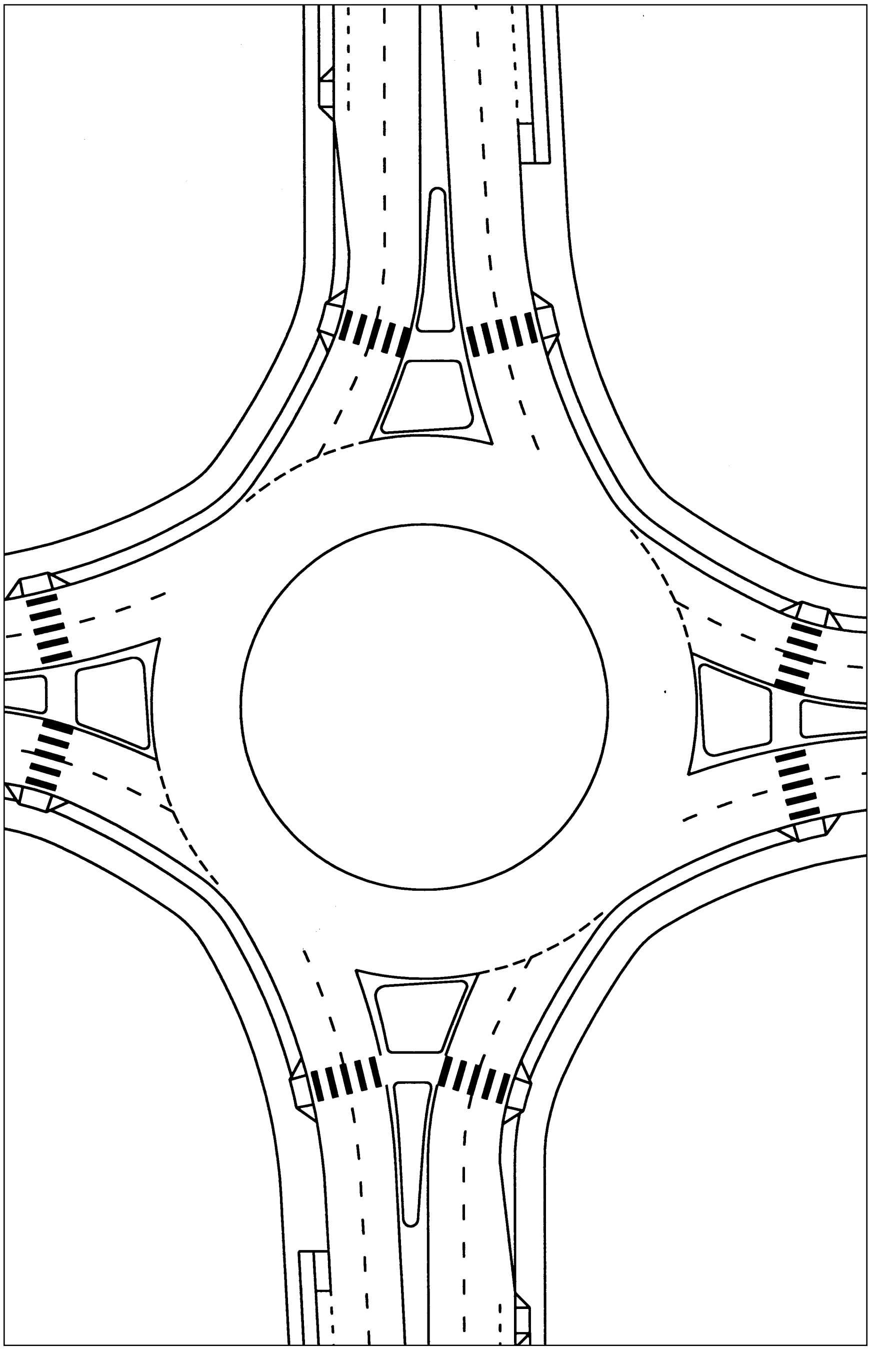
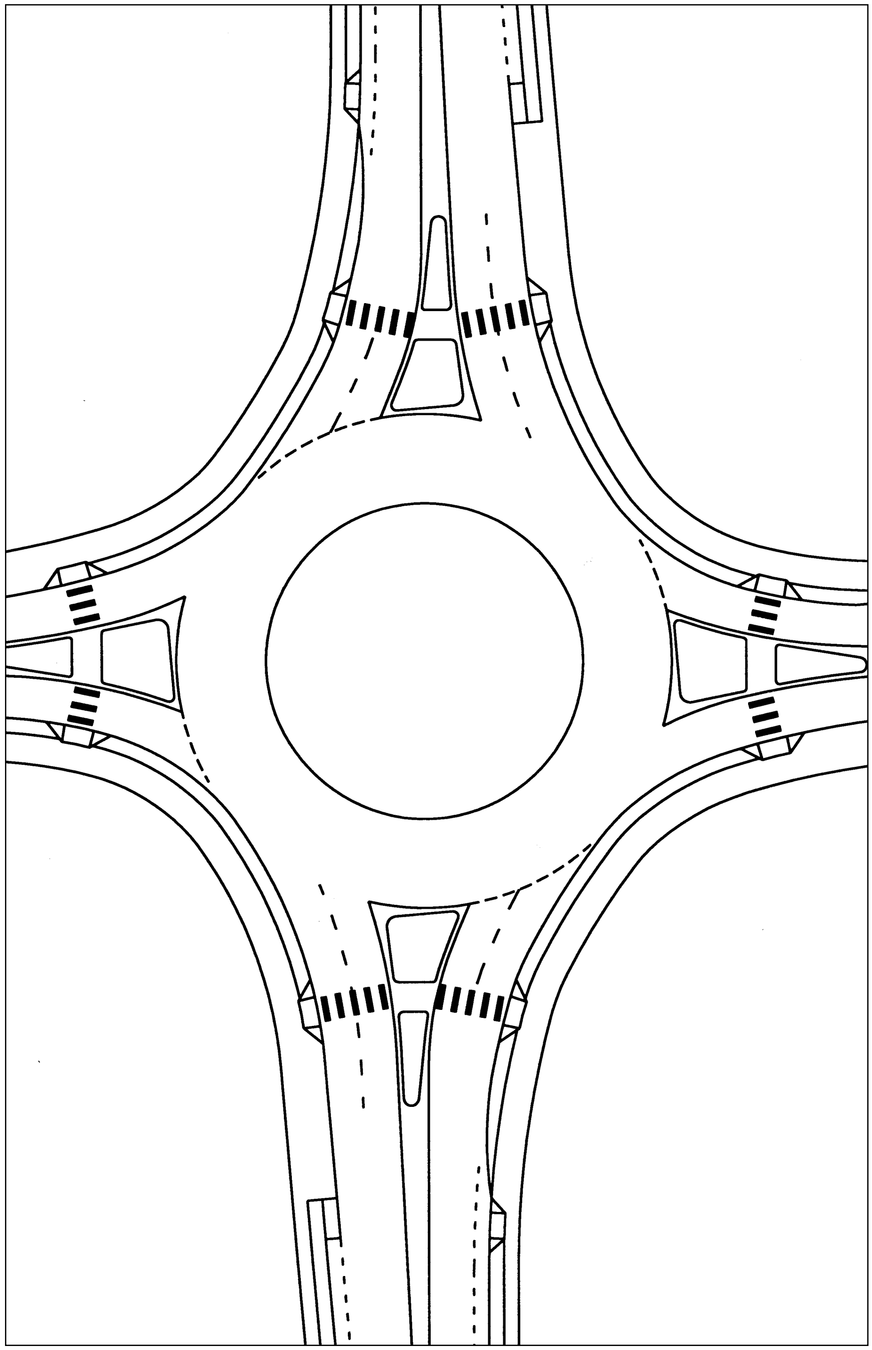


Exhibit B-5. Example of a typical urban double-lane roundabout.

Exhibit B-6. Example of a typical flared-entry roundabout.



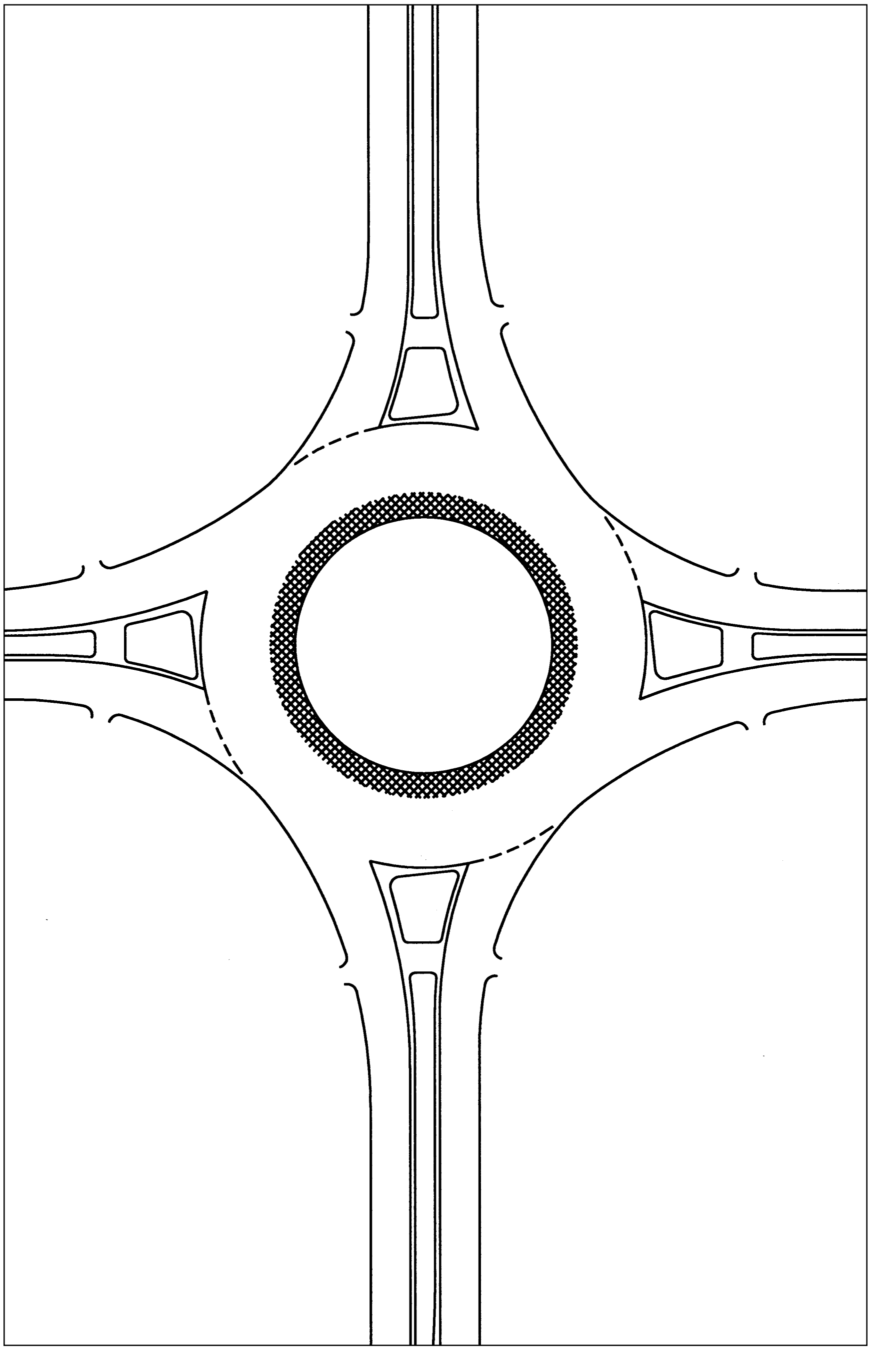
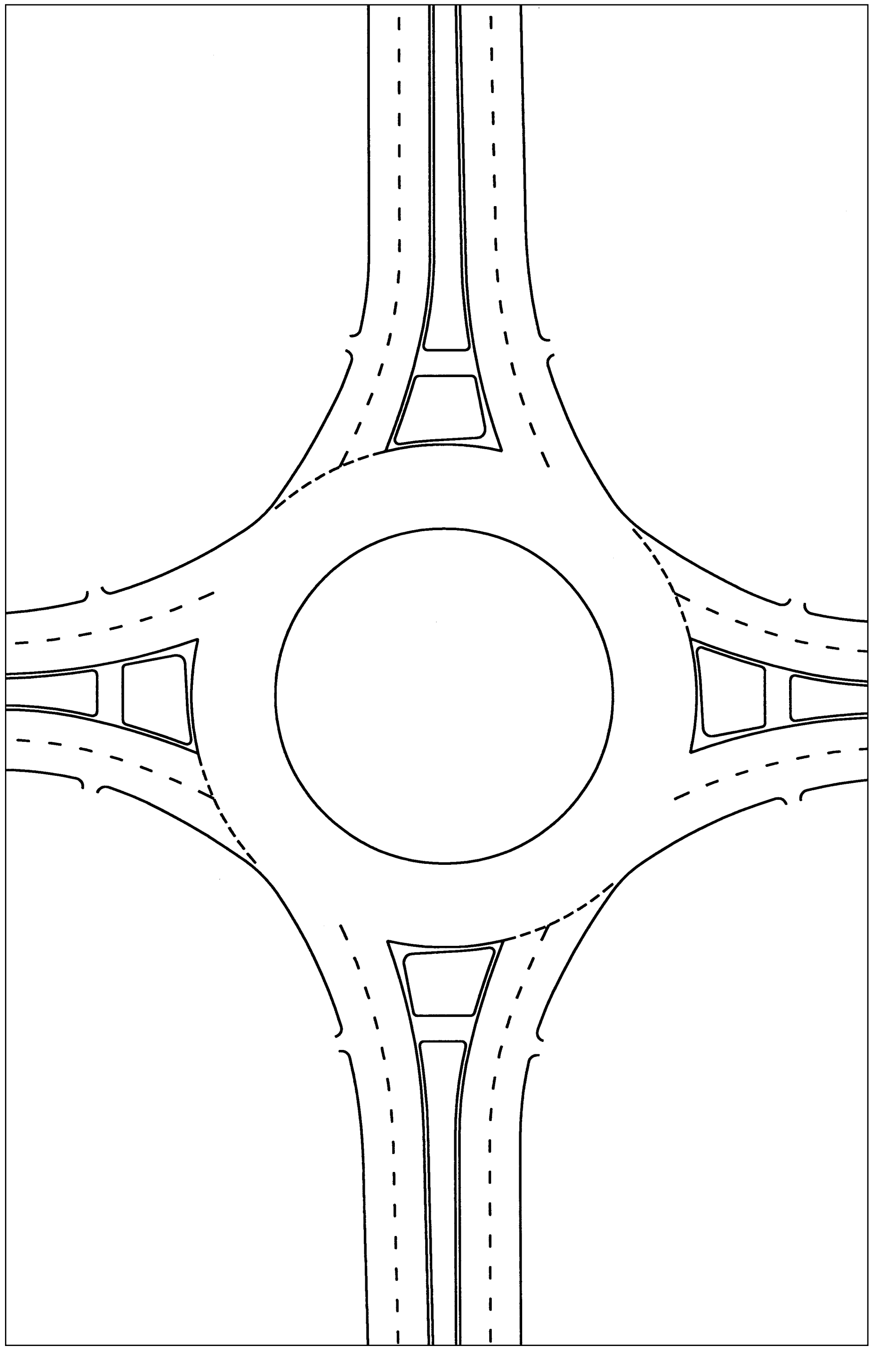


Exhibit B-7. Example of a typical rural single-lane roundabout.

Exhibit B-8. Example of a typical rural double-lane roundabout.



Appendix C MUTCD Recommendation

The purpose of this Appendix is to provide the rationale behind recommended deviations from the current (1988 edition) or proposed (2000 edition) *Manual on Uniform Traffic Control Devices* (MUTCD). The following devices are discussed:

- YIELD Sign
- Roundabout Ahead Sign

C.1 Yield Sign

The proposed use of the YIELD sign in the Guide is generally consistent with the MUTCD. However, the MUTCD contains language that generally discourages the use of YIELD signs for controlling the major flow at an intersection and the use of YIELD signs on more than one approach (MUTCD, §2B-8). This language predates the consideration of roundabouts and should be modified in the next edition of the MUTCD.

C.2 Roundabout Ahead Sign

As an alternative to the Circular Intersection sign, a Roundabout Ahead sign has been proposed. This sign, along with a supplemental advisory speed plate (W13-1), is shown in Exhibit C-1.

Exhibit C-1. Roundabout Ahead sign with advisory speed plate (W13-1).

This sign should be used on all approaches to a roundabout. The purpose of a Roundabout Ahead sign is to convey to a driver that the driver is approaching an intersection with the form of a roundabout. The intent of this sign is to be similar in function to the other intersection warning signs (e.g., CROSS ROAD (W2-1) signs), for example, which convey that the driver is approaching intersections of those forms. Unlike those signs, however, the Roundabout Ahead sign is recommended for all roundabouts, not just visually obscured locations.

C.2.1 Need

The 1988 edition of the MUTCD provides no sign related to roundabouts. The closest applicable sign is the YIELD AHEAD sign, either in word message or symbolic form (W3-2 or W3-2a, respectively). While this sign is necessary for indicating an upcoming traffic control device, it does not provide any information to the driver that the upcoming yield sign is for a roundabout. Driver behavior, lane assignments, and driver expectation are much different for roundabouts than for traditional yield-controlled locations (typically low-volume streets or right-turn bypass lanes). Identification that a roundabout is upcoming is particularly important for multilane approaches so that drivers can anticipate and move into the proper lane in advance of the roundabout. Therefore, some indication that a driver is approaching a roundabout is essential, especially given the relative rarity of roundabouts in the United States.

The National Committee on Uniform Traffic Control Devices (NCUTCD) has adopted the Circular Intersection sign shown in Exhibit C-2, and this sign is being considered for adoption by FHWA.

Exhibit C-2. Circular Intersection sign.

C.2.2 Existing Practice

Due to the lack of a standard Roundabout Ahead sign, jurisdictions in the U.S. have experimented with a variety of warning signs, sometimes with multiple variations within the same jurisdiction. Examples of these are shown in Exhibit C-3. As can be seen from the figure, the lack of standardization from jurisdiction to jurisdiction is evident.

Exhibit C-3. Sample of existing Roundabout Ahead signs in United States.

Bradenton Beach, FL (a)
Mary Esther, FL (b)
Mary Esther, FL (c)
Lisbon, MD (d)
Leeds, MD (e)
Lothian, MD (f)
Naples, FL (g)
West Boca Raton, FL (h)

Exhibit C-3 (continued).

(i) Santa Barbara, CA
(j) Tallahassee, FL
(k) Taneytown, MD
(l) Tavares, FL
(m) Vail, CO
(n) West Vail, CO

International practice varies from country to country but is generally more consistent than current U.S. practice. Sign shapes and coloration vary depending on the standards of that country, but the one consistent feature is a simple ring of arrows, oriented to the direction of traffic flow. Examples from the United Kingdom and Australia are given in Exhibit C-4.

United Kingdom　　Australia

Exhibit C-4. Sample of Roundabout Ahead signs used internationally.

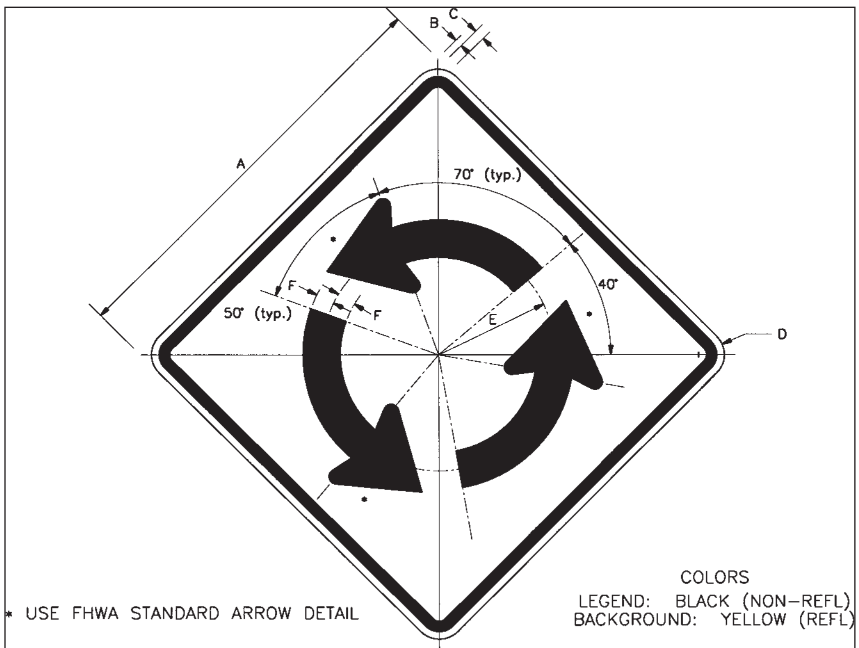
C.2.3 Recommendation

Based on a review of existing signs in the U.S. and current international practice, a recommended Roundabout Ahead sign was developed, as presented previously in Exhibit C-1 This sign is similar in concept to those shown in (b), (c), and (j) of Exhibit C-3 and is shown fully dimensioned in Exhibit C-5. This sign has been developed based on the following criteria:

- The recommended sign is symbolic, consistent with current MUTCD practice.
- The recommended sign uses the internationally recognized circular ring of arrows to represent a roundabout and is almost an exact mirror image of the sign used in Australia (Exhibit C-4).
- The recommended sign gives advanced notice of the proper direction of circulation. The NCUTCD-adopted sign in Exhibit C-2 does not convey this information and could give the driver the incorrect impression that the circulatory roadway is bidirectional.

- The recommended sign can be used for roundabouts with any number of legs, including intersections with one-way approaches. Many of the signs in Exhibit C-3 and the NCUTCD-recommended sign in Exhibit C-2 are unique to four-leg roundabouts with legs at right angles and would be inappropriate for roundabouts with three or five legs, for example.
- The recommended sign can be supplemented by an advisory speed plate. An advisory speed plate would not be appropriate for a YIELD AHEAD sign because of the need for the driver to proceed only when clear.
- The recommended sign is simple with no extraneous or distracting elements to confuse a driver. Some of the signs in Exhibit C-3 are perhaps too complex for higher speed environments.
- Mini-roundabouts cannot be easily signed to show the proper direction of circulation. The recommended sign provides guidance to the driver as to the proper direction of circulation.

Exhibit C-5. Dimensions of Roundabout Ahead sign.



DIMENSIONS IN MILLIMETERS					
A	B	C	D	E	F
900	16	22	56	250	40
1200	19	31	75	333	53

DIMENSIONS IN INCHES					
A	B	C	D	E	F
36	5/8	7/8	2 1/4	10	1 5/8
48	3/4	1 1/4	3	13 1/4	2 1/8