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6.1 General Design Guidance

Designing an effective roundabout requires striking a balance between providing sufficient capacity to serve existing and future traffic demand and creating an environment that is going to allow for safe and efficient travel for all users. Finding this balance requires the designer to know the environment that they are working in, the physical constraints, the composition and quantity of expected users, and knowledge of the surrounding roadway system. Each of these factors plays a role in determining the size, shape, and purpose for the roundabout. This section describes the fundamental principles guiding roundabout design and looks at various geometric elements, providing considerations to achieve a balanced design.

Fundamental Design Principles

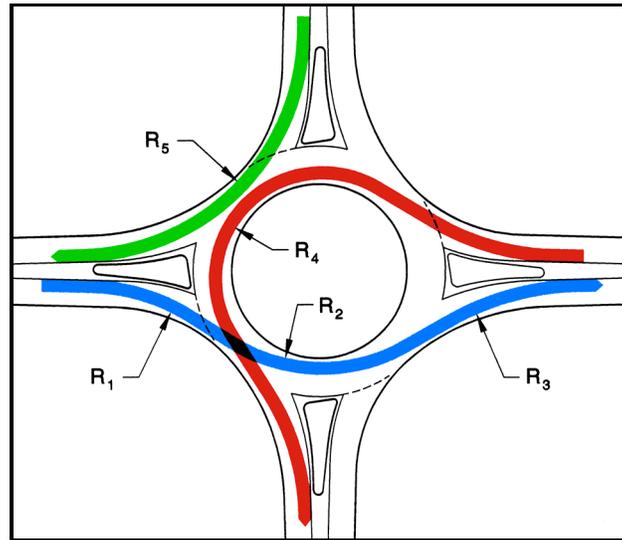
Fundamentally, the principles of roundabout design are no different than other roadways and intersection types. The designer must consider the context of the project and provide suitable geometry and traffic control devices according to established engineering tools and design standards. These considerations include design speed, design vehicle, lane numbers, lane arrangements, user types, and physical environment. However, some of the geometric features and operational objectives are implemented slightly different for roundabouts than for other intersection forms. These fundamental principles are discussed below.

Design Speeds

One of the most critical design objectives is achieving appropriate vehicular speed through the roundabout. Roundabouts operate most safely when their geometry forces traffic to enter, circulate, and exit at slow speeds. Generally, design speeds should be between 15 and 30 miles per hour. The fastest path allowed by the geometry determines the design speed of a roundabout. This is the smoothest, flattest path possible for a single vehicle, in the absence of other traffic and ignoring all lane markings. The fastest path is drawn for a vehicle traversing through the entry, around the central island, and out the exit.

The fastest paths must be drawn for all approaches and all movements, including left-turn movements (which generally represent the slowest of the fastest paths) and right-turn movements (which may be faster than the through movement paths at some roundabouts). Exhibit 6-1 illustrates the five critical path radii that must be checked at each approach.

Exhibit 6-1
Vehicle Path Radii at a Roundabout

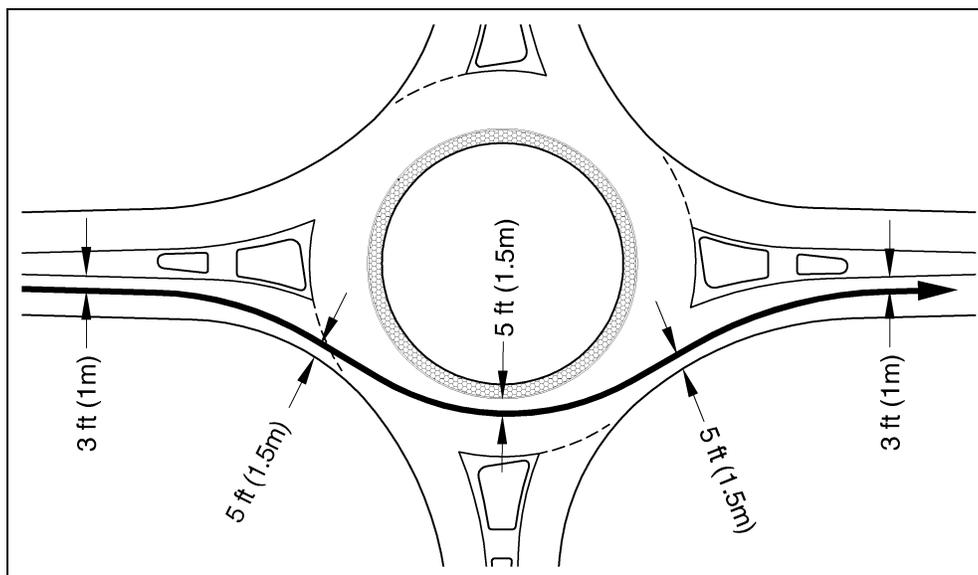


The fastest path is drawn assuming a vehicles starts at the left-hand edge of the approach lane, moves to the right side as it enters the roundabouts, cuts to the left side of the circulatory roadway, then moves back to the right side at the exit, and completes its move at the left-hand side of the departure lane. The centerline of the vehicle path is drawn using the following minimum offset distances:

- 5 ft (1.5 m) from concrete curbs,
- 5 ft (1.5 m) from roadway centerline, and
- 3 ft (1.0 m) from striped edge lines or lane.

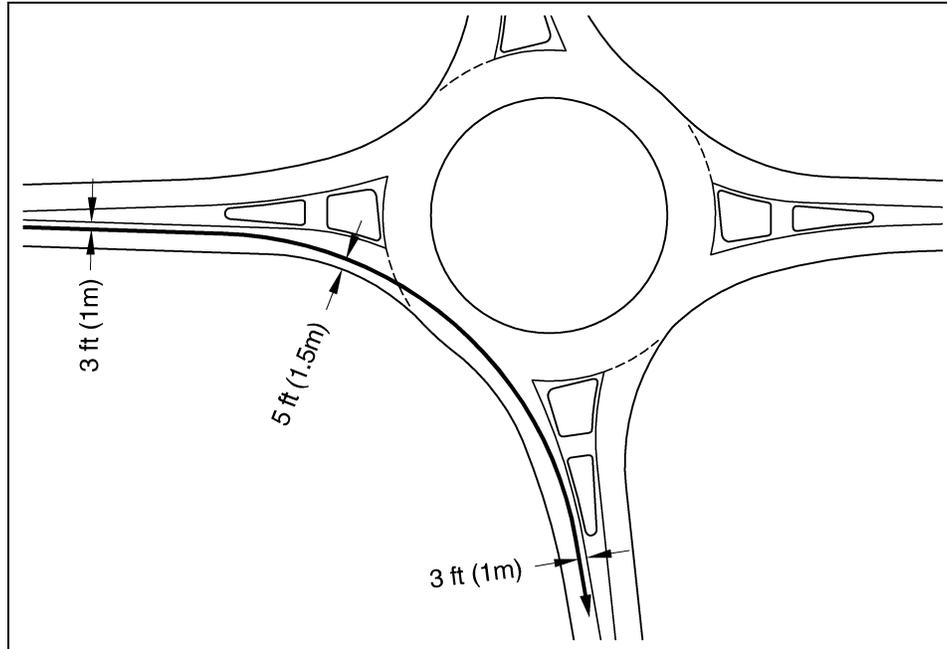
Exhibit 6-2 illustrates the construction of the fastest vehicle path for a through movement at a typical single-lane roundabout.

Exhibit 6-2
Fastest Vehicular Paths at a Single-Lane Roundabout



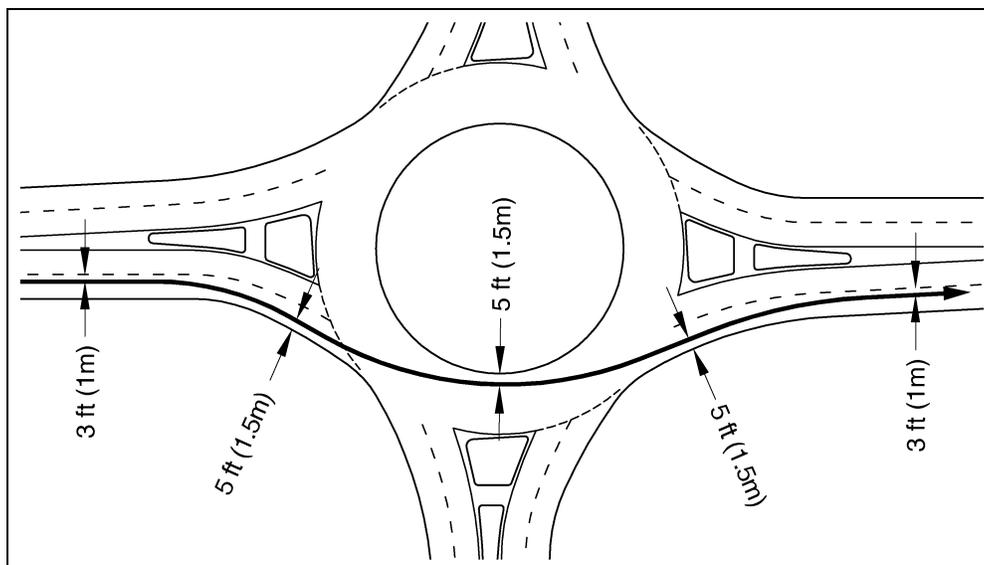
In some cases the right-turn path may be faster than the through movement path. Thus, the right-turn fastest path should be drawn carefully using the same principles and offsets described above. Exhibit 6-3 shows a sample right-turn path.

Exhibit 6-3
Fastest Vehicular Paths for a Critical Right-Turn Movement



At double-lane roundabouts, the fastest path is drawn assuming the vehicle approaches in the right lane, cuts across into the left hand circulatory lane, and then exits into the right lane. Exhibit 6-4 illustrates the fastest path at a typical double-lane roundabout. Note that Exhibit 6-4 is consistent with the guidance in the FHWA Roundabout Guide. However, a potentially faster path can be drawn by assuming that the vehicle changes lanes on approach and/or on exit.

Exhibit 6-4
Fastest Vehicular Paths at a Double-Lane Roundabout



Once the fastest paths are drawn, the minimum radii along these paths are then measured, and the corresponding design speed is calculated according to the methodology in the AASHTO publication *A Policy on Geometric Design of Highways and Streets* (commonly referred to as the “Green Book”). The equation for the design speed with respect to horizontal curve radius is given below (please refer to the FHWA Roundabout Guide for the metric version).

Speed-Radius Relationship:
$$V = \sqrt{15R(e + f)}$$

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 (R_1 , R_3 , and R_5) and -0.02 for curves around the central island (R_2 and R_4). More details related to superelevation design are provided later in this chapter.

Values for side friction factor can be determined in accordance with AASHTO standards for curves at intersections (see 2001 AASHTO Exhibit 3-43). The coefficient of friction between a vehicle’s tires and the pavement varies with the vehicle’s speed. Using the appropriate friction factors corresponding to each speed, Exhibit 6-5 was developed to graphically show the speed-radius relationship for curves on both a +0.02 superelevation and -0.02 superelevation.

**Exhibit 6-5
Speed-Radius Relationship**

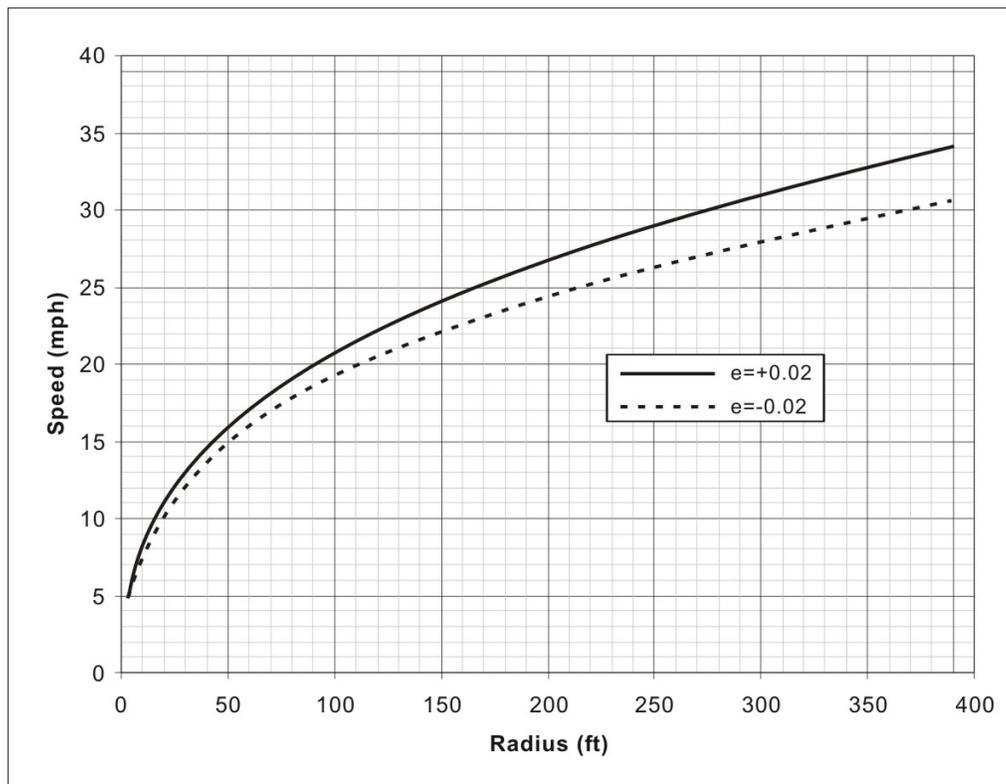


Exhibit 6-6 displays the maximum recommended design speeds for various roundabout categories.

**Exhibit 6-6
 Roundabout Design Speeds**

Site Category	Maximum Entry (R_1) Design Speed
Mini Roundabout	20 mph (32 km/h)
Urban Compact Roundabout	20 mph (32 km/h)
Urban Single-Lane Roundabout	25 mph (40 km/h)
Rural Single-Lane Roundabout	25 mph (40 km/h)
Urban Double-Lane Roundabout	25 mph (40 km/h)
Rural Double-Lane Roundabout	30 mph (48 km/h)

Speed Consistency

In addition to achieving the appropriate design speed for the fastest movements, the relative speeds between consecutive geometric elements should be minimized and the relative speeds between conflicting traffic streams should be minimized. This means that all fastest path radii (R_1 , R_2 , R_3 , R_4 , and R_5 from Exhibit 6-1) are determined at each approach and the corresponding design speeds are evaluated. Ideally, the relative differences between all speeds within the roundabout should be no more than 6 mph (10 km/h). However, it is often difficult to achieve this goal, particularly at roundabouts that must accommodate large trucks. In these cases, the maximum speed differential between movements should be no more than 12 mph (20 km/h).

The exit radius, R_3 , should not be less than R_1 or R_2 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. More guidance related to path overlap at multilane roundabouts is provided later in this section. At multilane roundabouts and single-lane roundabouts where no pedestrians are expected, it is acceptable for the design speed of the exit radius (R_3) to be slightly higher than 25 mph (40 km/h). Where pedestrians are present, tighter exit curvature may be necessary to ensure sufficiently low speeds at the downstream pedestrian crossing.

Some recent design philosophies have recommended relaxing the design speed guidelines for roundabout exits. These studies advocate large radii or even tangential geometry at exits to reduce vehicle-to-vehicle conflicts and ease the flow of traffic as it departs from the circulatory roadway. The basic principle behind this argument is that if entry and circulatory speeds are sufficiently low, vehicles will not be able to accelerate significantly on the exit; thus, the safety for pedestrians will not be compromised. However, at this time there is limited data relating pedestrian safety to exit geometry. Exits should therefore be designed with sufficient curvature to ensure even aggressive drivers cannot achieve excessive exits speeds. Overly tight exit geometry should also be avoided, particularly for multilane exits where tight radii can lead to

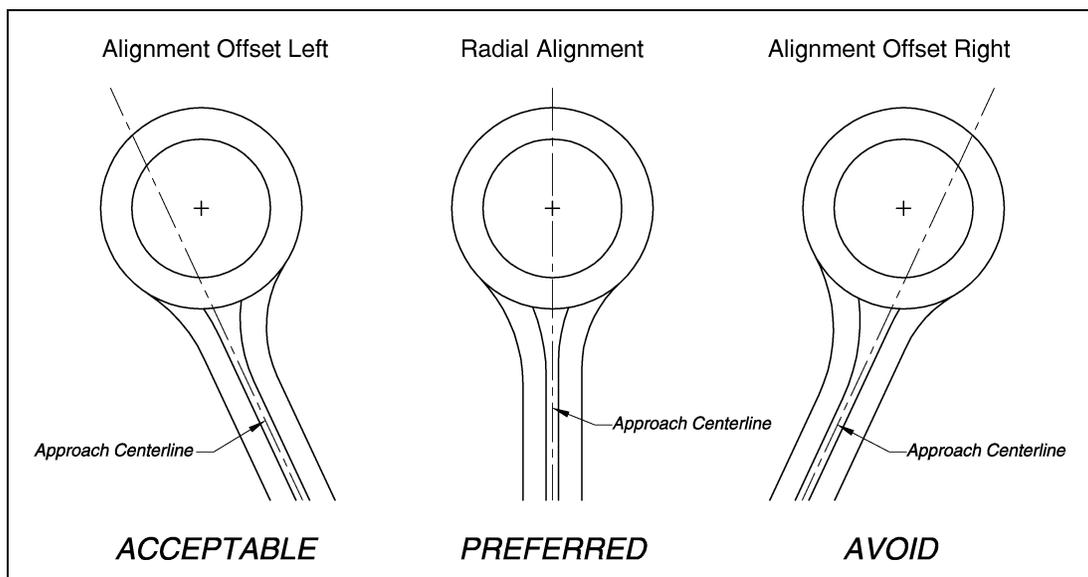
higher frequency of crashes. Thus, the design of exits should be a carefully balanced geometry to maximize safety for all users.

Once a preliminary geometric design for a roundabout has been developed, the fastest path radii and speeds should be summarized in a tabular format (a sample design speed summary table is provided later in Exhibit 6-13). This tabular summary should be provided along with the sketched fastest path diagrams for all conceptual and/or preliminary roundabout design plans submitted to KDOT and/or other governing agencies for review.

Approach Alignment

Ideally, the centerline of the roundabout approaches should align through the center of the roundabout. However, it is acceptable for the approach to be slightly offset to the left of the center point, as this alignment enhances the deflection of the entry path. If it is aligned too far to the left, however, an excessive tangential exit may occur, causing higher exit speeds. If the alignment of the entry is offset to the right, the approach geometry often does not provide enough deflection for the entering vehicles. Therefore, approach alignments offset to the right of the roundabout center should be avoided unless other geometric features are used to provide adequate speed reduction. Exhibit 6-7 illustrates the preferred approach alignment for roundabouts in general.

**Exhibit 6-7
Approach Alignment Guidelines**



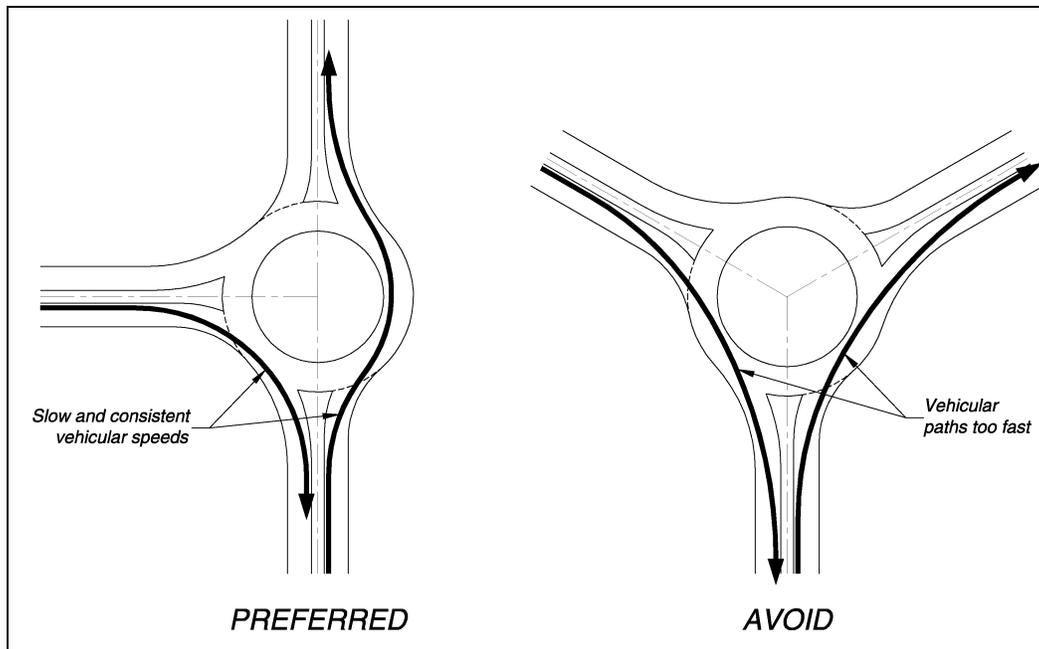
Angles Between Approaches

Similar to signalized and stop-controlled intersections, the angle between approach legs is an important design consideration. Although it is not necessary for opposing legs to align directly opposite one another (as it is for conventional intersections), it is generally preferable for the approaches to intersect at perpendicular or near-perpendicular intersection angles. If two approach legs intersect at an angle significantly less than or greater than 90 degrees, it will often result in excessive speeds for one or more right-turn movements. At the same time, left-turn movements from all approaches will be relatively low, resulting in a higher speed differential

than desired. Designing the approaches at perpendicular or near-perpendicular angles generally results in relatively slow and consistent speeds for all movements. Highly skewed intersection angles can often require significantly larger inscribed circle diameters to achieve the speed objectives.

Exhibit 6-8 illustrates the fastest paths at a roundabout with perpendicular approach angles versus a roundabout with obtuse approach angles.

Exhibit 6-8
Perpendicular Approach Angles versus Obtuse Approach Angles



As this figure implies, roundabout T-intersections should intersect as close to 90 degrees as possible. Y-shaped intersection alignments will typically result in higher speeds than desired and should therefore be avoided. Approaches that intersect at angles greater than approximately 105 degrees should generally be realigned by introducing curvature in advance of the roundabout to produce a more perpendicular intersection. For low speed urban roundabouts where large trucks are not present, it may be acceptable to allow larger intersection angles provided the entry curvature is sufficiently tight to ensure low entry speeds.

Design Vehicle

Roundabouts should be designed to accommodate the largest vehicle that can reasonably be anticipated. Because roundabouts are intentionally designed to slow traffic, narrow curb-to-curb widths and tight turning radii are used. However, if the widths and turning requirements are designed too tight, it can create difficulties for oversized vehicles. Large trucks and buses often dictate many of the roundabout's dimensions, particularly for single-lane roundabouts. Therefore, it is very important to determine the design vehicle at the start of the design and investigation process. Exhibit 6-9 illustrates one example roundabout that does not adequately accommodate a truck and one that does.

**Exhibit 6-9
Truck Accommodations at Roundabouts**



Example of roundabout not properly designed to accommodate large trucks



Example of roundabout designed properly for large trucks

Selecting the design vehicle is determined by considering the types of roadways involved, the area where the intersection is located, and the types and volume of vehicles using the intersection. For intersections in a residential environment, the design vehicle is often a school bus or fire truck. At urban collector or arterial intersections, the design vehicle is often a WB-50 (WB-15m) semi-trailer. For freeway ramp terminals and other intersections on state highway routes, the design vehicle is generally a WB-67 (WB-20m).

Typical design vehicles for various roadway types are given in Exhibit 6-10. The appropriate staff from KDOT and/or the governing local agencies should be consulted early in the design process to identify the design vehicle at each project location. Consideration should be given to the actual vehicle classification mix in addition to the adjacent land uses and facility classifications for the near term and future design years.

**Exhibit 6-10
Recommended Design Vehicles**

Intersection Type	Design Vehicle
State Highway Routes	WB-67 (WB-20m)
Ramp Terminal	WB-67 (WB-20m)
Other Rural	WB-50 (WB-15m)
Urban Major Streets	WB-50 (WB-15m)
Other Urban	Bus or Single Unit Truck

Vehicle turning path templates or CAD-based vehicle turning path simulation software should be used during the design process to establish the turning path requirements of the design vehicle.

Pedestrian Accommodations

As with any intersection form, providing safe and comfortable accommodations for pedestrians is a fundamental objective. At roundabouts, pedestrian crosswalks are set back from the entrance line approximately one to two vehicle lengths. This distance allows drivers to focus on pedestrians prior to arriving at the entrance line and focusing on other traffic. Refuge areas in the splitter islands enable pedestrians to cross the traffic streams in two stages, by first crossing the entrance lanes and then crossing the exit lanes. Exhibit 6-11 displays pedestrian crossings at an urban single-lane roundabout leg.

**Exhibit 6-11
Pedestrian Crossings at a Roundabout**



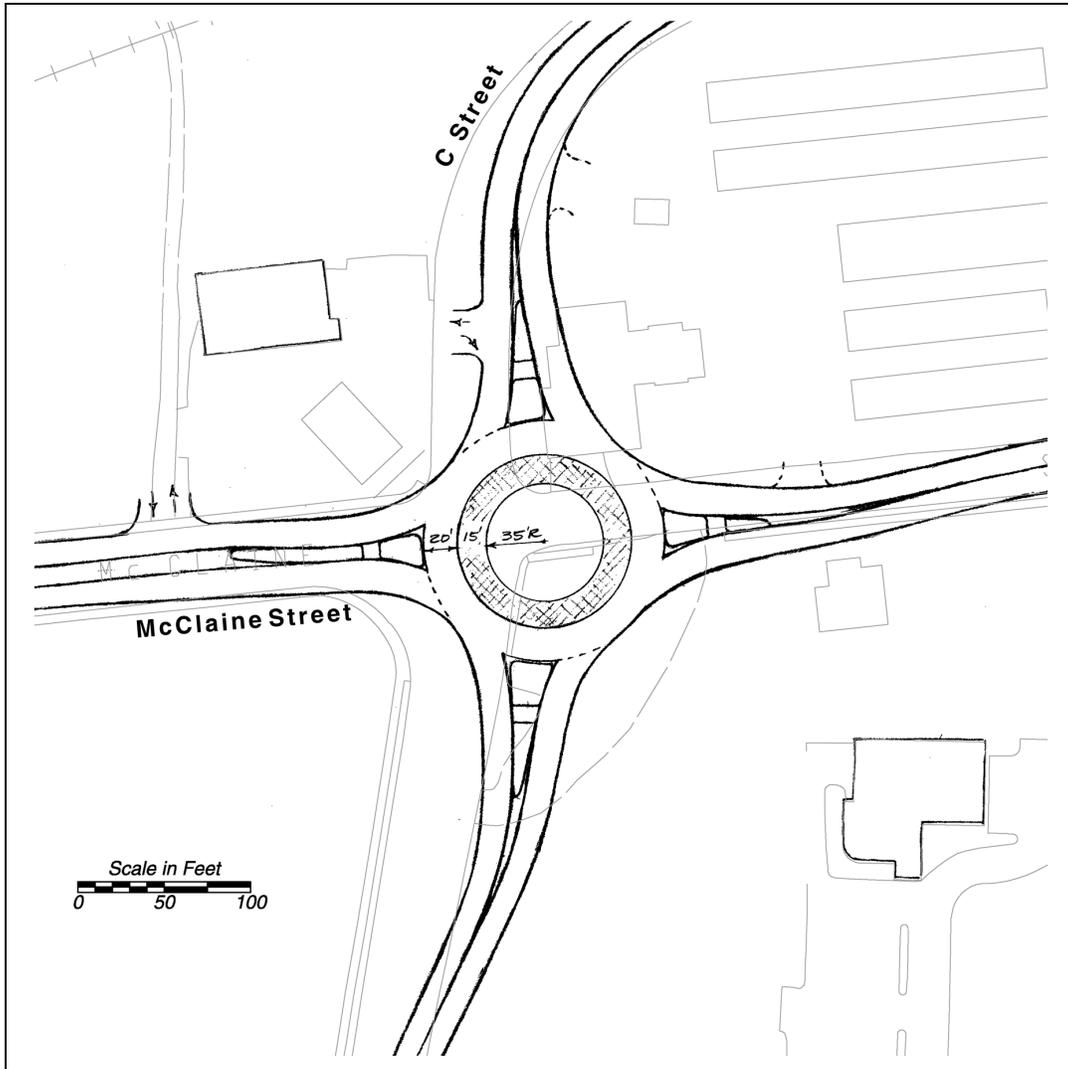
Roundabout Design Process

Roundabout design is an iterative process requiring the designer to consider operational and safety effects of the geometric elements. The recommended process for designing a roundabout is generally as follows:

1. Identify the intersection context and design vehicle. The intersection context includes identifying whether this is the first roundabout in an area and whether the site is new or a retrofit.
2. Perform operational analysis to determine the number of lanes required. In general, the number of entry lanes and exit lanes should be kept to the minimum necessary based on the design year traffic projections. For example, if the designer determines that a two-lane roundabout is required, he/she should then optimize each of the approaches to determine if the demand can be served for any of the approaches with just single-lane entries. It is also important to minimize the number of exit lanes, as exits are the most difficult for pedestrians to cross.

3. Prepare an initial roundabout layout at a sketch level. A scale of 1"=50' (1:500) is generally preferred for this sketch-level design. Exhibit 6-12 shows an example conceptual design sketch.

Exhibit 6-12
Example Roundabout Design Sketch



4. Check the design speeds of all movements at all legs of the roundabout. Watch out for entry speeds greater than 25 mph (40 km/h) or speed differentials of greater than 12 mph (20 km/h). Exhibit 6-13 displays an example design speed summary.

**Exhibit 6-13
Sample Roundabout Design Speeds Summary Table**

Approach	Curve	Radius (feet)	Speed (mph)	Relative Speed Difference* (mph)
Northbound C Street	R1	140	23	8
	R2	115	20	5
	R3	150	24	9
	R4	55	15	-
	R5	120	22	7
Southbound C Street	R1	150	24	9
	R2	125	21	6
	R3	175	25	10
	R4	55	15	-
	R5	110	21	6
Eastbound McClaine Street	R1	115	22	7
	R2	115	20	5
	R3	150	24	9
	R4	55	15	-
	R5	100	20	5
Westbound McClaine Street	R1	125	22	7
	R2	115	20	5
	R3	165	25	10
	R4	55	15	-
	R5	130	23	8

* Relative difference is from minimum speed within roundabout (typically, R4 speed).

5. If necessary, revise the sketched geometry to meet design speed and speed consistency objectives. Then check the design speeds of the revised design and continue to refine the geometry as necessary.
6. Check the design vehicle turning movement paths at each leg.
7. Revise the sketch if needed to accommodate the design vehicle. It may require using a larger diameter roundabout in order to meet the speed objectives and accommodate the design vehicle.
8. Re-analyze the operational performance if necessary to reflect the geometric parameters. Note that this may not be necessary for intersections with a volume-to-capacity ratio of less than approximately 0.50.
9. Prepare and evaluate alternative roundabout layouts following the same process above. You may test different inscribed diameters or different approach alignments to determine the optimal design.

Elements of Design

Guidelines for designing each element of a roundabout geometry are described in the remainder of this section.

Number of Entering/Exiting/Circulating Lanes

One of the first considerations in the initial design stages of a roundabout project is determining the number of entering/exiting lanes on each approach to the roundabout. Increases in entry width for additional travel lanes on an approach have a direct effect in increasing capacity. However, with an increased number of lanes come additional conflicts that are not present with single-lane roundabouts. International crash models indicate that increasing from a single to a multilane roundabout increases the potential for injury crashes. Additional entering/exiting lanes also increase the number of conflicts for pedestrians, as pedestrians are required to travel a greater distance across an approach and have increased exposure to vehicular traffic. Pedestrians are especially vulnerable on roundabout exits where drivers are beginning to accelerate.

In general, the number of entering/circulating/exiting lanes should be limited to the minimum number required for capacity considerations. It may be possible on multilane roundabouts to provide single lane entries and exits on low volume approaches where additional lanes are not required.

Inscribed Circle Diameter

The inscribed circle diameter is the distance across the circle inscribed by the outer curb (or edge) of the circulatory roadway. It is the sum of the central island diameter and twice the circulatory roadway width. 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.

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 approach 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, 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, reducing the relative speed between these vehicles and leading to reduced entering-circulating crash rates. Therefore, roundabouts in high-speed environments may require diameters that are somewhat larger than those recommended for low-speed environments.

Exhibit 6-14 provides recommended ranges of inscribed circle diameters for various site locations.

Exhibit 6-14
Recommended Inscribed Circle Diameter Ranges

Site Category	Typical Design Vehicle	Inscribed Circle Diameter Range*
Mini-Roundabout	Single-Unit Truck	50 – 90 ft (15 – 27 m)
Urban Compact	Single-Unit Truck/Bus	90 – 120 ft (27 – 37 m)
Urban Single Lane	WB-50 (WB-15m)	120 – 150 ft (37 – 46 m)
Urban Double Lane	WB-50 (WB-15m)	150 – 220 ft (46 – 67 m)
Rural Single Lane	WB-67 (WB-20m)	130 – 200 ft (40 – 61 m)
Rural Double Lane	WB-67 (WB-20m)	175 – 250 ft (53 – 76 m)

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

Entry Design

One of the primary ingredients in the safety performance of a roundabout is the low operating speed associated with roundabout operation. Low operating speeds provide drivers the opportunity to react to conflicts and reduce the likelihood of loss of control crashes associated with navigating the geometric elements of the intersection. The entry design is a critical element of the overall design, as the geometric elements of the entry are most often the controlling factor to govern vehicle speeds. However, vehicular speeds are not the only consideration at the entry. At multilane roundabouts, the design must also provide appropriate alignment of vehicles at the entrance line to prevent sideswipe and angle collisions associated with overlapping natural vehicle paths. Other design considerations at the entry include accommodating the design vehicle (typically WB-50 [WB-15m] or WB-67 [WB-20m] trucks) and providing a safe environment for pedestrians.

To maximize the roundabout's safety, entry widths should be kept to a minimum. The capacity requirements and performance objectives will determine the number of entry lanes for each approach. 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 balancing between capacity and safety considerations. 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 14 to 18 ft (4.2 to 5.5 m); however, values slightly higher or lower than this range may be required for site-specific design vehicles and speed requirements for critical vehicle paths.

Entry radii at urban single-lane roundabouts typically range from 35 to 100 ft (10 to 30 m). 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 and traffic circles (typically mini-roundabouts, and urban compact roundabouts), entry radii may be below 35 ft (10 m) if the design vehicle is small.

At multilane roundabouts, the design of entry curves is more complicated due to considerations for side-by-side traffic streams entering the roundabout. Detailed guidelines for multilane entries are provided later in this chapter.

Ideally, the design should accommodate each of these considerations. However, in some circumstances, right-of-way or other constraints may limit the size, shape, or alignment of the roundabout and its approaches. These geometric limitations may make it difficult to provide both ideal speed control and ideal natural vehicle paths. Therefore, the designer may need to try several different alignments to find the one that best balances these design considerations.

Circulatory Roadway

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 and should remain constant throughout the roundabout.

Single-lane roundabouts

At single-lane roundabouts, the circulatory roadway should just accommodate the design vehicle, exclusive of the trailer for large trucks. 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. A minimum clearance of 2 ft (600 mm) should be provided between the outside edge of the vehicle's tire track and the curb line.

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. Truck aprons should be used only when there is no other means of providing adequate deflection while accommodating the design vehicle. The width of the truck apron should be determined based upon vehicle-turning templates or a CAD based computer program to accommodate the swept path of the design vehicle for each of the various movements. There is no standard width for a truck apron. However, the designer should re-evaluate the design to ensure that the proper size and geometric features are being provided if an apron is less than 2 ft (600 mm) or greater than 14 ft (4.2 m) in width. In some situations, a very small or very large truck apron may be an indicator that other geometric features are being compromised in the design.

Multilane roundabouts

At multilane roundabouts, the circulatory roadway width is usually not governed by the design vehicle. The width required for 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. In many urban locations, it may be a bus or single-unit truck in combination with a passenger vehicle. If large semi-trailers are relatively infrequent, it is often appropriate to design the circulatory roadway such that these large trucks sweep across both lanes within the circulatory roadway. However, if large trucks are relatively frequent, it may be necessary to accommodate a semi-trailer in combination with a passenger vehicle. The appropriate staff from KDOT and/or other governing agencies should be consulted early in the design process to determine the choice of vehicle types to be accommodated side-by-side.

Exhibit 6-15 displays an example of the swept paths of two vehicles circulating side-by-side through a roundabout geometry. In this case, the roundabout was located on a predominantly recreational route and was designed to accommodate two motor home vehicles with boat trailers circulating side-by-side.

Exhibit 6-15
Example Design: Circulatory Roadway Accommodates Side-by-Side Motorhomes with Boat Trailers.

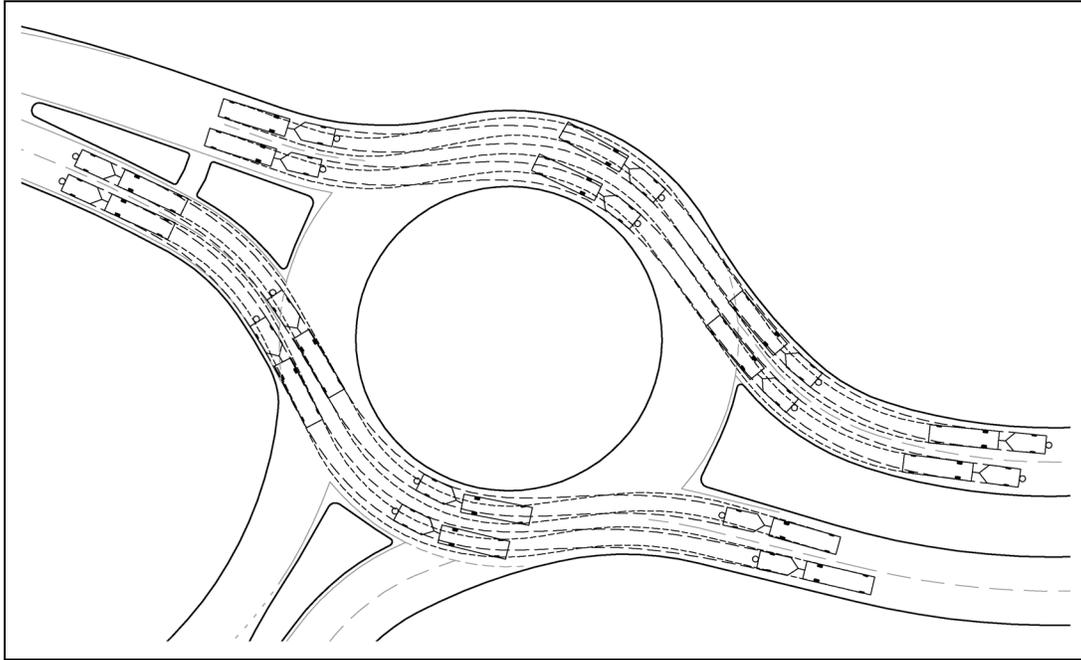


Exhibit 6-16 provides minimum recommended circulatory roadway widths for two-lane roundabouts where semi-trailer traffic is relatively infrequent.

Exhibit 6-16
Minimum Circulatory Lane Widths for Two-Lane Roundabouts.

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

* Based on 2001 AASHTO Exhibit 3-55, Case III(A). Assumes infrequent semi-trailer use.

Exits

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 Figure 6-1) 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 are maintained at the pedestrian crossing.

Right-Turn Bypass Lanes

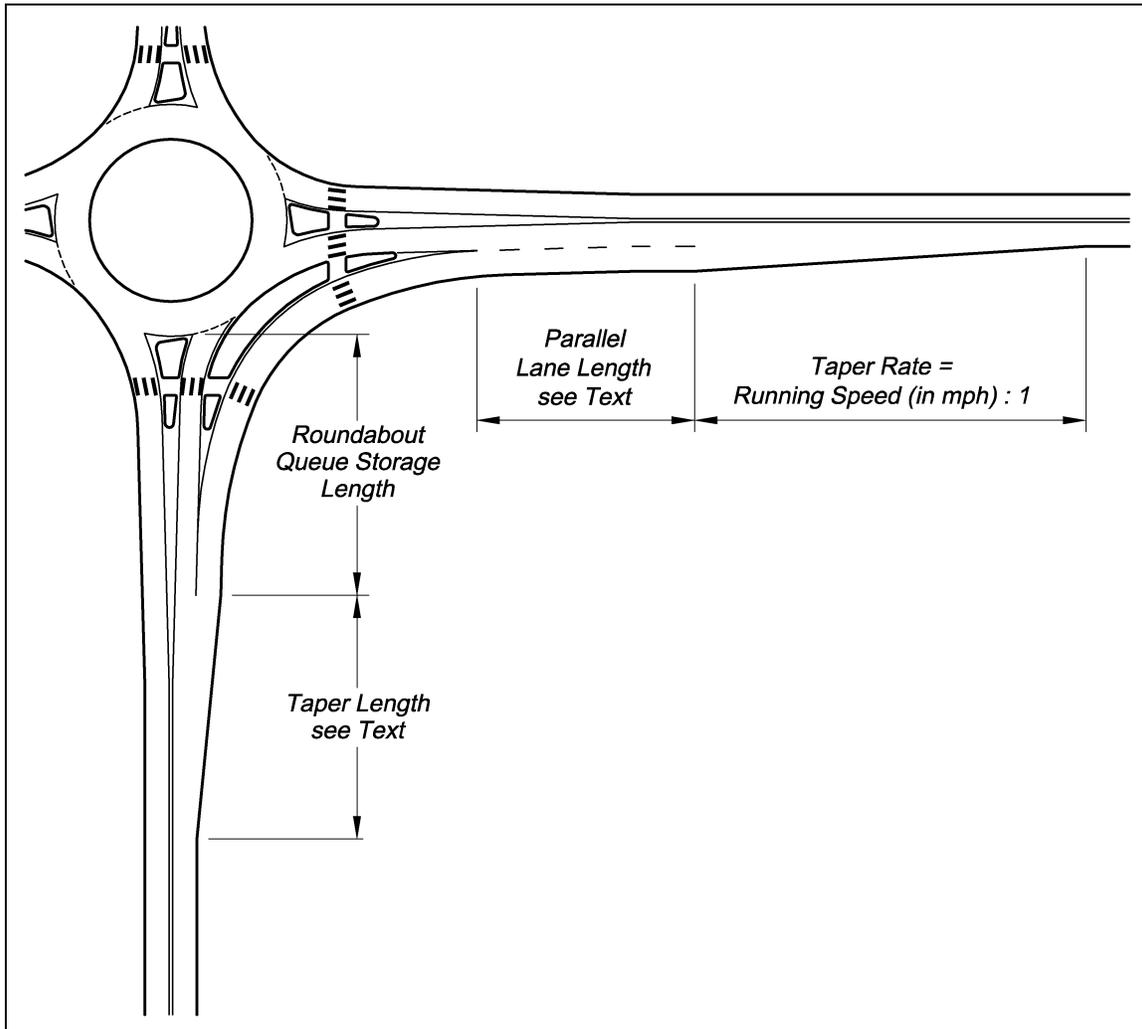
Right-turn bypass lanes (or *right-turn slip lanes*) are useful in providing additional capacity on approaches with high right-turn vehicular volumes. These lanes can effectively remove right turning vehicles from entering the roundabout, thus increasing the capacity of the intersection as a whole. However, right-turn bypass lanes should be used with caution and implemented only where applicable due to capacity or operational considerations. Bypass lanes introduce additional vehicular conflicts on the exits from the roundabout due to the required merge. They also further complicate the task of navigating the roundabout for visually impaired pedestrians due to the additional vehicle conflicts and increased exposure due to the longer crossing distance.

In general, right-turn bypass lanes should be carefully evaluated 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 also increase the risk of collisions with pedestrians. However, in some situations, providing a right-turn bypass lane may prevent the need for a multilane roundabout. Thus, the potential adverse safety effects created by the free-flow bypass lane may be offset by the safety benefits of maintaining single-lane entries within the roundabout.

The design speed of the right-turn bypass lanes should be consistent with the design speed of the roundabout. In other words, the speed of vehicles within the right-turn bypass lane should be comparable to the speed of vehicles entering, circulating, and exiting the roundabout. Thus, the fundamental roundabout design speeds shown in Exhibit 6-6 should also govern the design of the right-turn bypass lane.

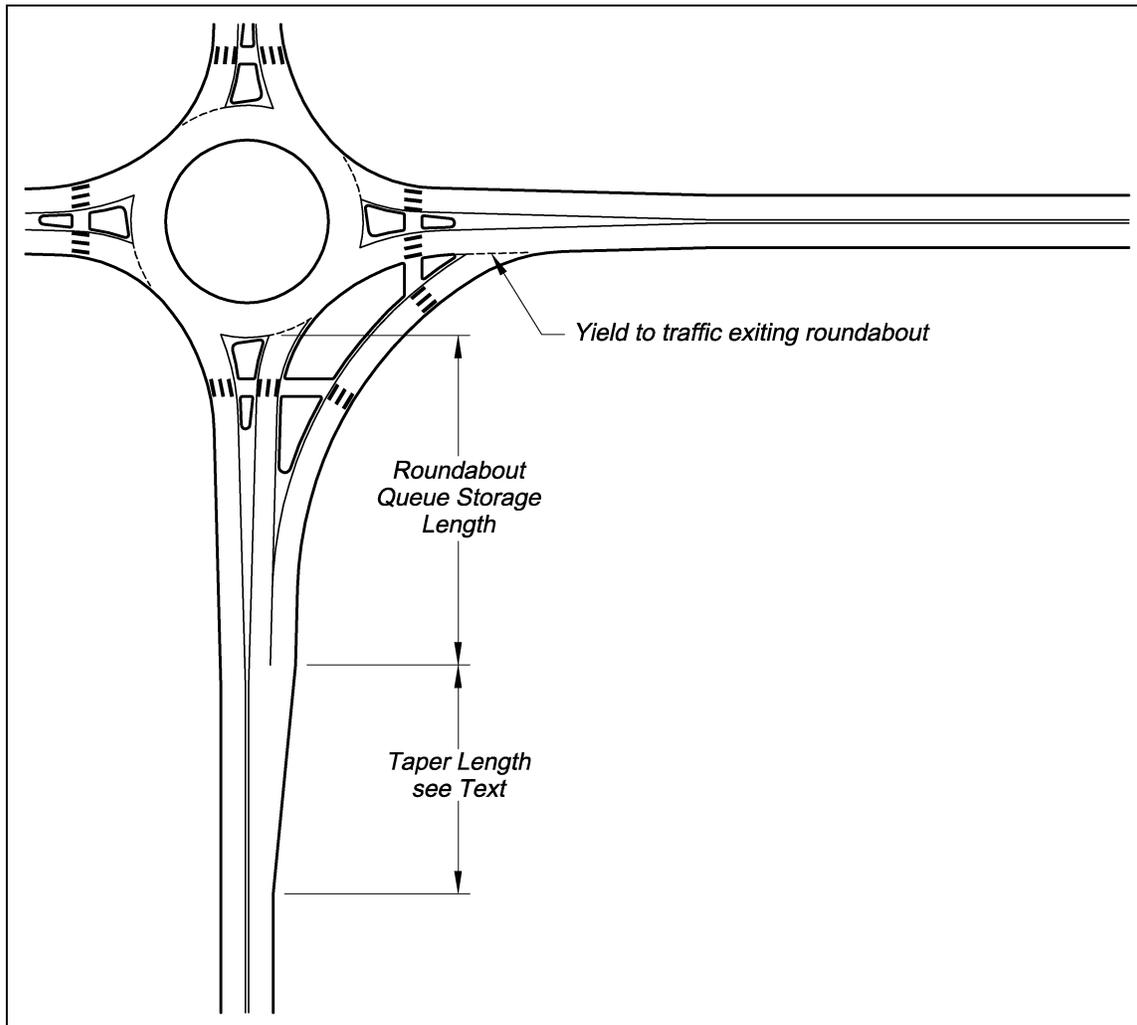
There are two design options for right-turn bypass lanes. The first option, shown in Exhibit 6-17, is to carry the bypass lane parallel to the adjacent exit roadway, and then merge it into the main exit lane from the roundabout. Under this option, the bypass lane should be carried alongside the main roadway for a sufficient distance to allow vehicles in the bypass lane and vehicles exiting the roundabout to achieve similar speeds and safely merge. This distance should be at least long enough to allow proper advance placement of warning signs for a typical lane reduction, based on MUTCD guidelines. The bypass lane is then merged at a taper rate of the design speed (in mph) to one.

Exhibit 6-17
Right-Turn Bypass Configuration



The second design option for a right-turn bypass lane, shown in Exhibit 6-18, is to provide a yield-controlled entrance onto the adjacent exit roadway. This option generally requires less widening and right-of-way downstream of the roundabout than the first. It is also generally more amenable to bicyclists, as they do not have to cross free-flowing traffic from the bypass lane. However, it often requires more right-of-way at the corner with this design option to achieve adequate speed reduction for the right-turn movement while providing pedestrian refuge areas. Consideration should also be given for the intersection angle at the yield point between the bypass traffic stream and traffic stream exiting the roundabout. If the intersection angle at the yield point is too small, it may be difficult for drivers (particularly older drivers) to perceive and react to conflicting vehicles from the roundabout.

Exhibit 6-18
Right-Turn Bypass Configuration



The design of the approach taper for the right-turn bypass lane is developed in a manner similar to right-turn lanes at signalized and stop-controlled intersections. The bay taper, which guides motorists into the right-turn lane, should be developed along the right edge of traveled way. The appropriate length of the taper is per AASHTO, based on KDOT design guidelines for right-turn deceleration lanes at typical intersections (see KDOT Standard Drawings). Shorter taper distances may be acceptable in urban environments or locations with topographic or right-of-way constraints.

The length of the right-turn bypass lane should be designed, at a minimum, to accommodate the 95th-percentile queue at the roundabout entrance without blocking the entrance to the right-turn bypass lane.

6.2 Guidance for Multilane Roundabouts

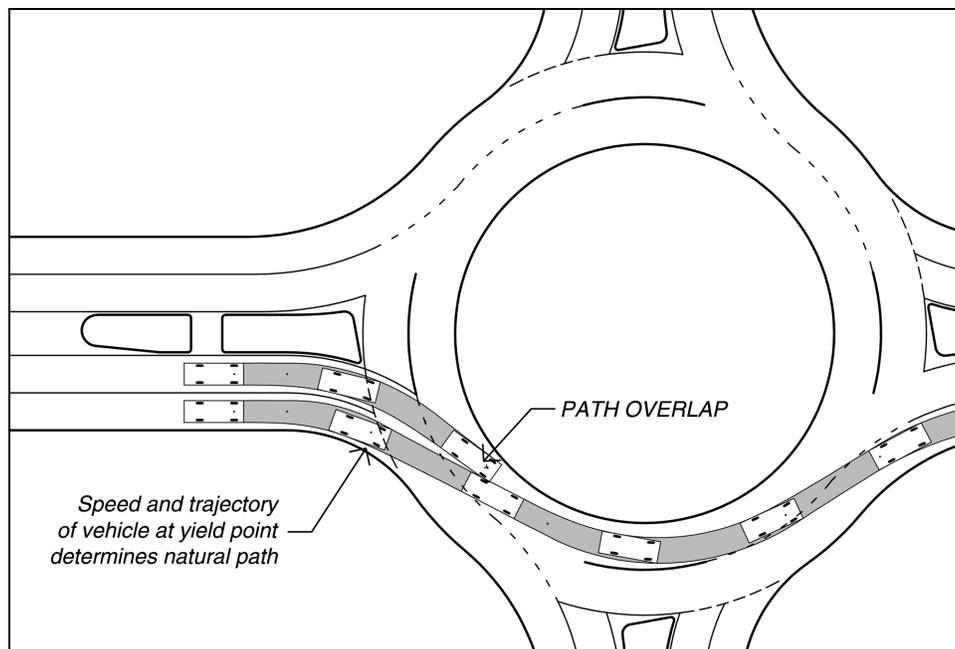
Designing multilane roundabouts is much more complex than single-lane roundabouts due to the additional conflicts present with multiple traffic streams entering, circulating, and exiting the roundabout in adjacent lanes. With single-lane roundabouts, the primary design objective is to ensure the fastest vehicular paths are sufficiently slow and relatively consistent. With multilane roundabouts, the designer must also consider the *natural paths* of vehicles. The natural path is the path a vehicle will naturally follow based on the speed and orientation imposed by the geometry. While the fastest path assumes a vehicle will intentionally cut across the lane markings to maximize speed, the natural path assumes there are other vehicles present and all vehicles will attempt to stay within the proper lane.

The natural path is drawn by assuming the vehicle stays within the center of the lane up to the entrance line. At the yield point, the vehicle will maintain its natural trajectory into the circulatory roadway. The vehicle will then continue into the circulatory roadway and exit with no sudden changes in curvature or speed. If the roundabout geometry tends to lead vehicles into the wrong lane, this can result in operational or safety deficiencies.

Path overlap

Path overlap occurs when the natural paths of vehicles in adjacent lanes overlap or cross one another. It occurs most commonly at entries, where the geometry of the right-hand lane tends to lead vehicles into the left-hand circulatory lane. Exhibit 6-19 illustrates an example of path overlap at a multilane roundabout entry.

Exhibit 6-19
Path Overlap

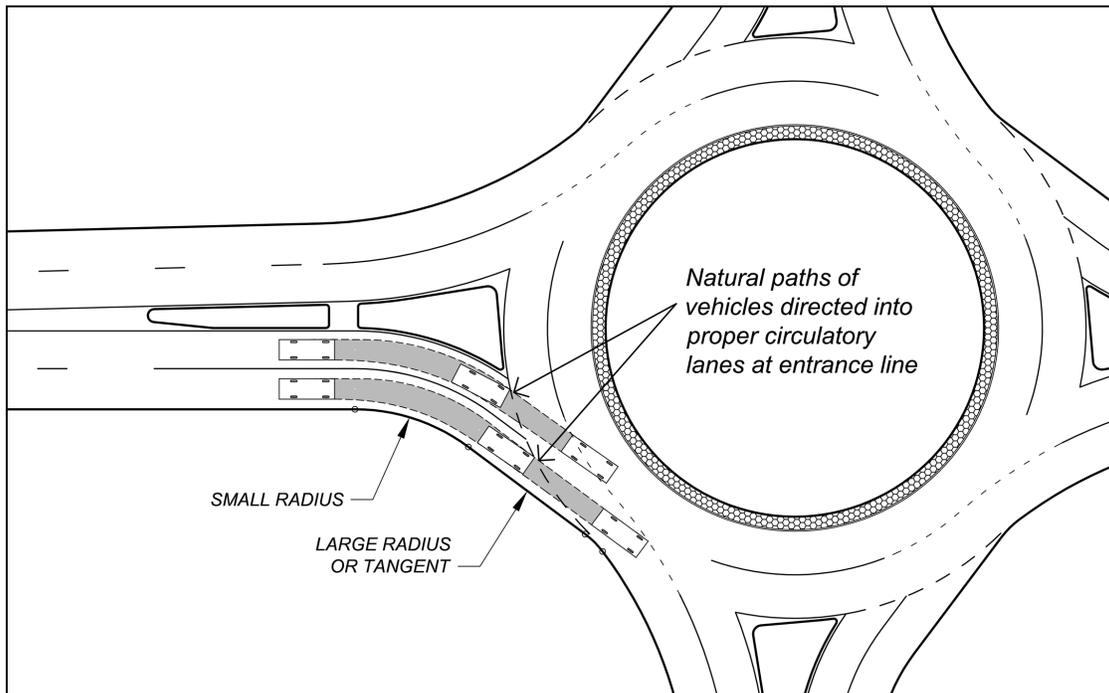


In the design shown in Exhibit 6-19, the geometry consists of a tight-radius entry curve located tangential to the outside edge of the circulatory roadway. At the entrance line, vehicles in the right-hand lane are oriented toward the inside lane of the circulatory roadway. If vehicles follow this natural path, they will cut off vehicles in the left lane, which must make a sharp turn within the circulatory roadway to avoid the central island.

Multilane Entry Design Technique

The preferred design technique for multilane entries is illustrated in Exhibit 6-20.

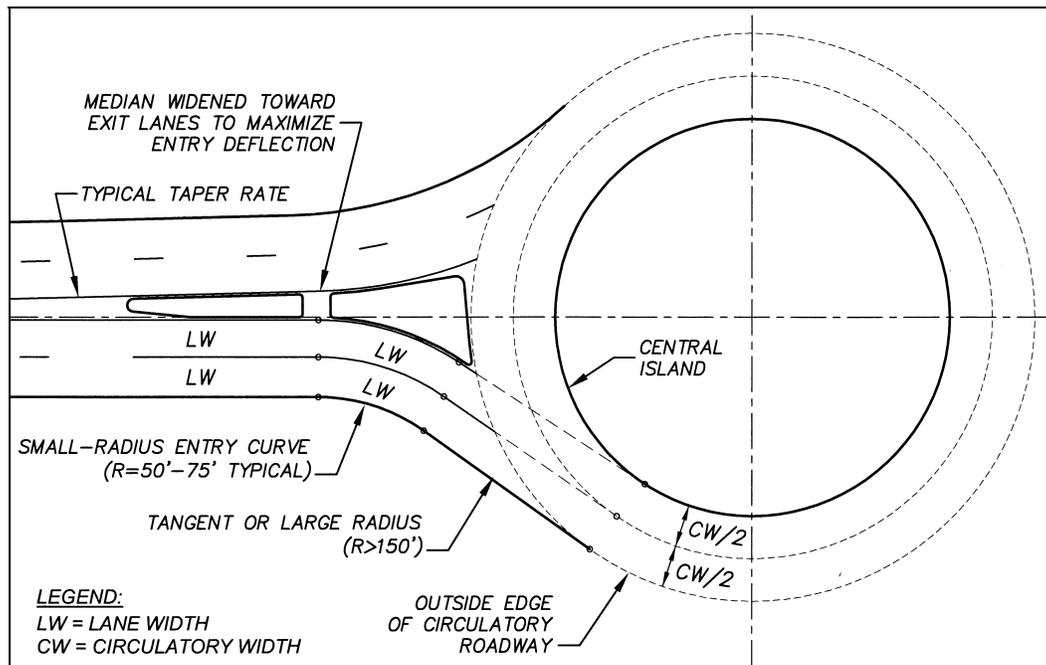
Exhibit 6-20
Design Technique to Avoid Path Overlap at Entry



As shown in Exhibit 6-20, the design consists of small-radius entry curve set back from the edge of the circulatory roadway. A short section of tangent is provided between the entry curve and the circulatory roadway to ensure vehicles are directed into the proper circulatory lane at the entrance line.

Typically, the entry curve radius is approximately 50 to 100 ft (15 to 30 m) and set back approximately 10 to 20 ft (3 to 6 m) from the edge of the circulatory roadway. A tangent or large-radius (greater than 150 ft [45 m]) curve is then fitted between the entry curve and the outside edge of the circulatory roadway. Exhibit 6-21 illustrates the entry design technique in greater detail.

Exhibit 6-21
Multilane Entry Design Details



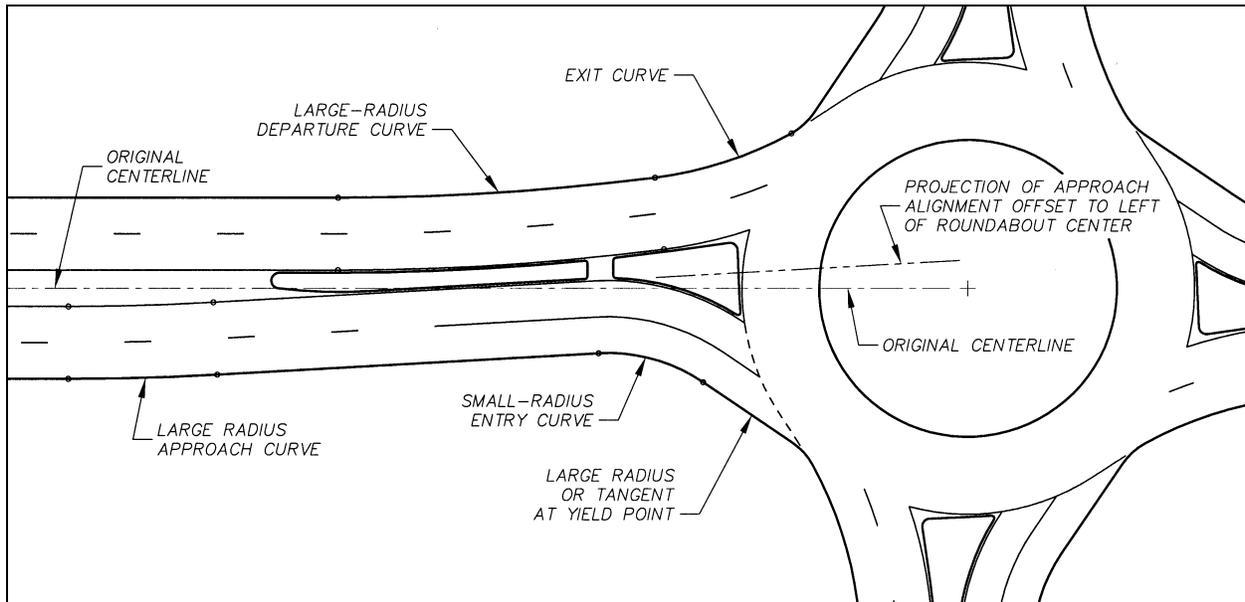
The primary objective of this design technique is to locate the entry curve at the optimal placement so that the projection of the inside entry lane at the entrance line forms a line tangential to the central island, as shown in Exhibit 6-21. Care should be taken in determining the optimal location of the entry curve. If it is located too close to the circulatory roadway, it can result in path overlap issues. However, if it is located too far away from the circulatory roadway, it can result in inadequate deflection (i.e. entry speeds too fast).

Design Techniques to Increase Entry Deflection

Designing multilane roundabouts without path overlap issues while achieving adequate deflection to control entry speeds can be difficult. The same measures that improve path overlap issues generally result in increased fastest path speeds. When the entry speed of a multilane roundabout is too fast, one technique for reducing the entry speed without creating path overlap is to increase the inscribed circle diameter of the roundabout. Often the inscribed circle of a double-lane roundabout must be 175 to 200 ft (53 to 60 m) in diameter, or more, to achieve a satisfactory entry design. However, increasing the diameter will result in slightly faster circulatory speeds. Therefore, care should be exercised to balance the entry speeds and circulatory speeds.

In cases where right-of-way or other physical constraints restrict the size of a multilane roundabout, the technique shown in Exhibit 6-22 may be used.

Exhibit 6-22
Approach Offset to Increase Entry Deflection



In the design shown in Exhibit 6-22, the entry deflection is enhanced by shifting the approach alignment slightly towards the left of the roundabout center. This technique of offsetting the approach alignment left of the roundabout center is effective at increasing entry deflection. However, it also reduces the deflection of the exit on the same leg. In general, it is important to maintain a level of deflection at exits to keep speeds relatively low within the pedestrian crosswalk location. Therefore, the distance of the approach offset from the roundabout center should generally be kept to a minimum to maximize safety for pedestrians.

6.3 Grading and Drainage Considerations

Chapter 6.3.11 of the FHWA publication, *Roundabouts: An Informational Guide*, provides guidance on the development of the vertical profile and location of drainage structures. Roundabouts should be generally designed to slope away from the central island with drainage inlets located on the outer curb line. This will help to raise the elevation of the central island and increase its conspicuity and visibility.

The slope of the circulatory roadway should prevent water from collecting or pooling around the central island. This will help to minimize icing on the circulatory roadway or on the approaches to the roundabout. For large roundabouts, additional drainage inlets may be required within the central island to help minimize the amount of runoff from the central island on to the circulatory roadway. As with any intersection, reasonable care should be taken to avoid low points and inlets placed in the crosswalks.

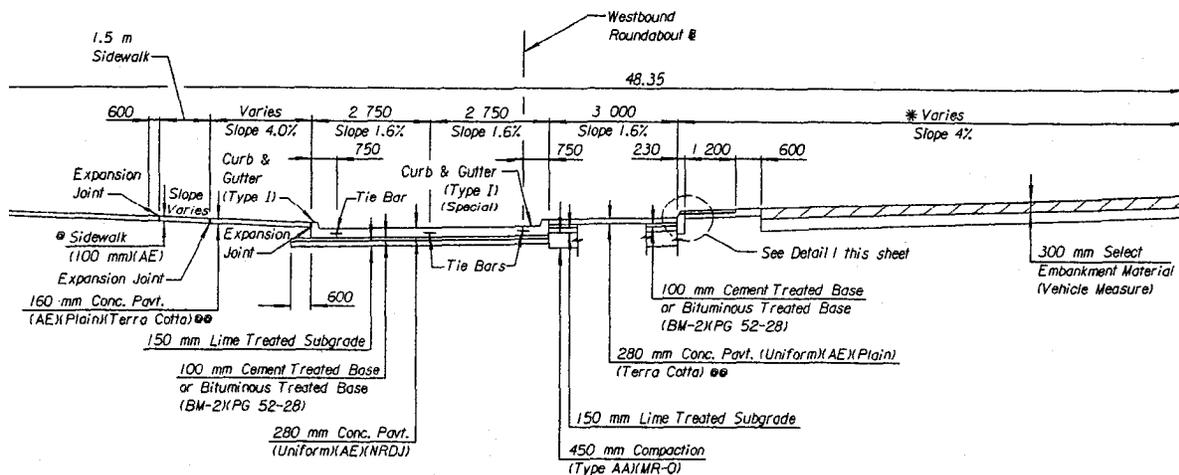
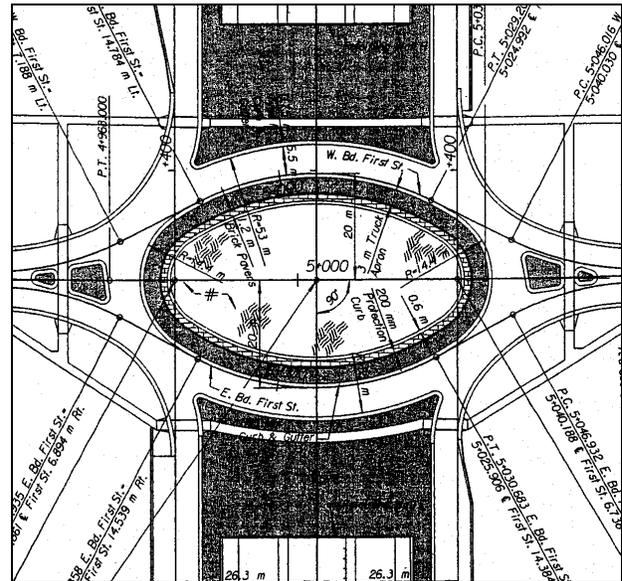
6.4 Curb and Pavement Design

Summary of Current Practices

In order to review current design practices related to curb and pavement design on roundabout projects in Kansas, five projects were reviewed based on plans provided by KDOT and the City of Overland Park. These projects are as follows:

I-135 at Broadway and Main Streets, Newton

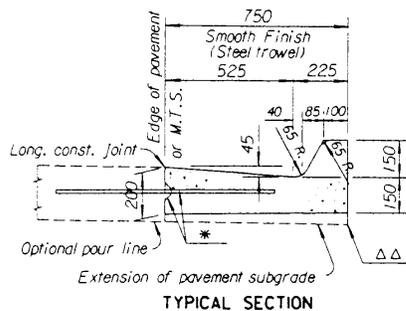
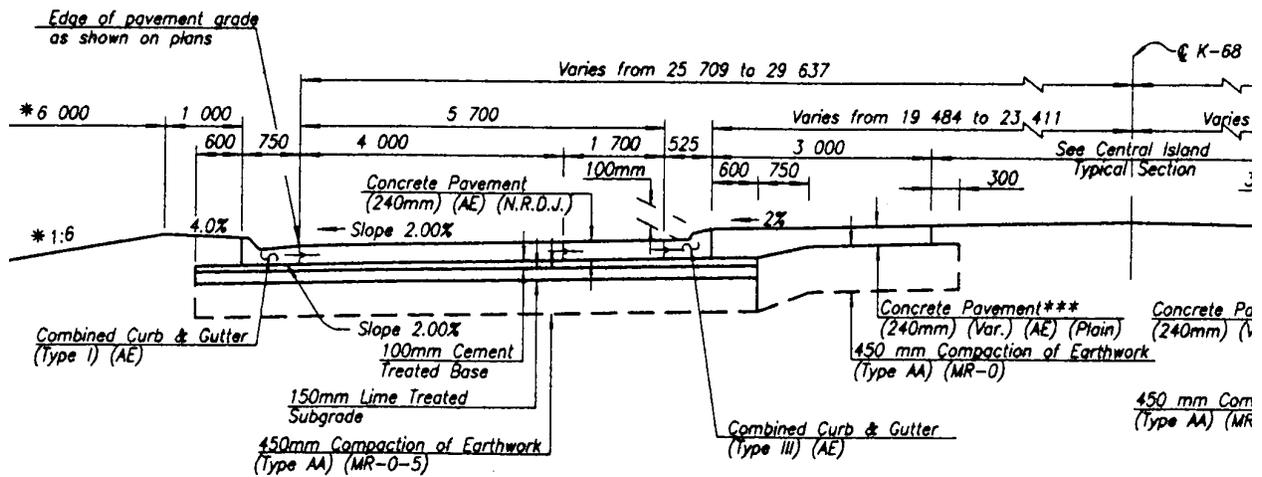
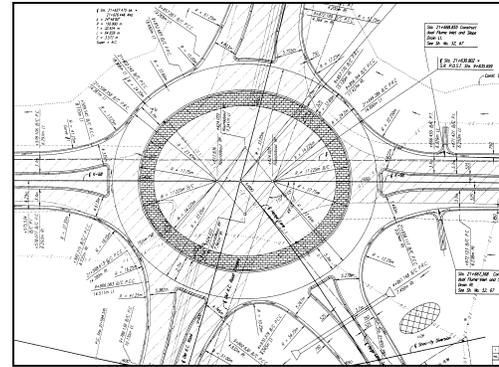
The two roundabouts in Newton are located at adjacent interchanges on I-135. One-way ramps on each side of the highway form four legs of the roundabouts with the cross street forming the other two. Both roundabouts experience significant truck traffic. The elliptical roundabouts are approximately 230 ft (70 m) east/west and 164 ft (50 m) north/south in diameter. All approach lanes and the circulatory roadway are single lane. The circulatory roadway is 16.4 ft (5.0 m) wide plus a 10 ft (3.0 m) truck apron. Pavement is concrete, with KDOT Type I curbs on the outside and inside edges of the circulatory roadway. An additional curb is provided inside the truck apron. Type I curbs are also used around the splitter islands.



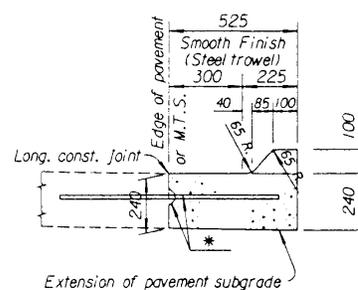
Design by: Burns and McDonnell, 2000.

K-68 & Old Kansas City Road, Miami County

This roundabout is elliptical with five legs and is located in a primarily rural area. The diameter of the roundabout is between 151 ft (46 m) and 190 ft (58 m). All approach lanes are single lane, as is the circulatory roadway. The circulatory roadway is 18.7 ft (5.7 m) wide with a 10 ft (3.0-m) truck apron. Pavement is 9.5 in (240 mm) concrete, with a KDOT Type I curb on the outside edge and a Type III curb around the inner circle and the splitter islands.



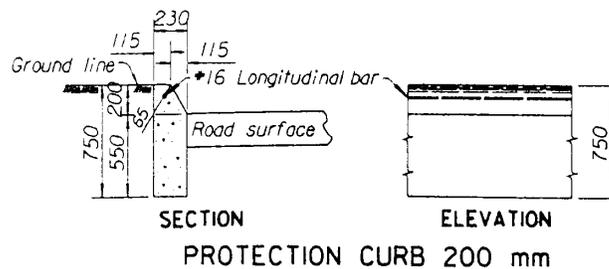
TYPICAL SECTION



TYPICAL SECTION

COMBINED CURB & GUTTER - TYPE I (750 mm WIDTH) COMBINED CURB & GUTTER - TYPE III (525 mm WIDTH)

Note: Use Class "A" Concrete (AE) throughout.
 All exposed edges shall be finished with an edging tool.
 Place a 25 mm premoulded Expansion Joint Filler (nonextruding, Type B) at a spacing not to exceed 75 m.

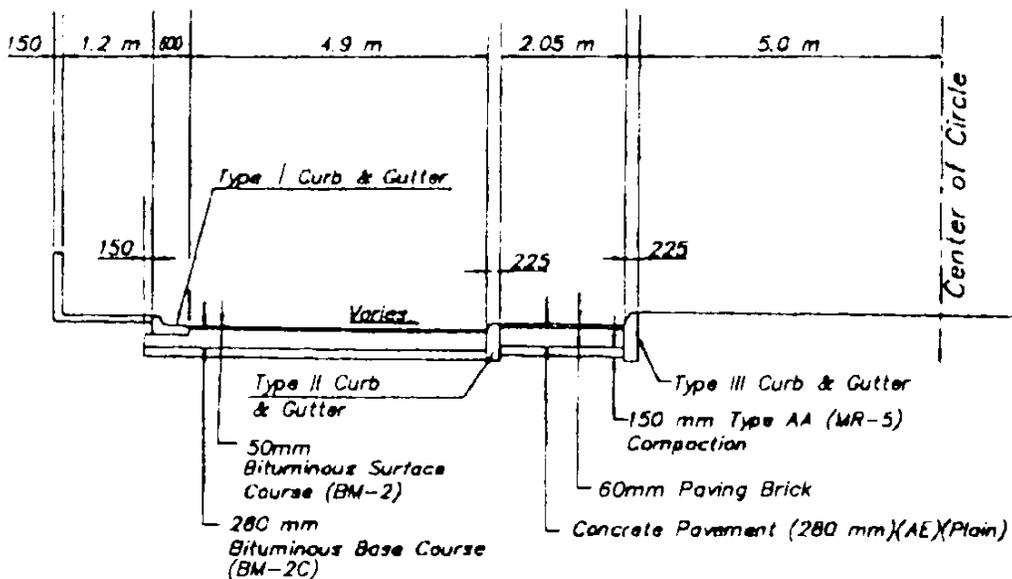
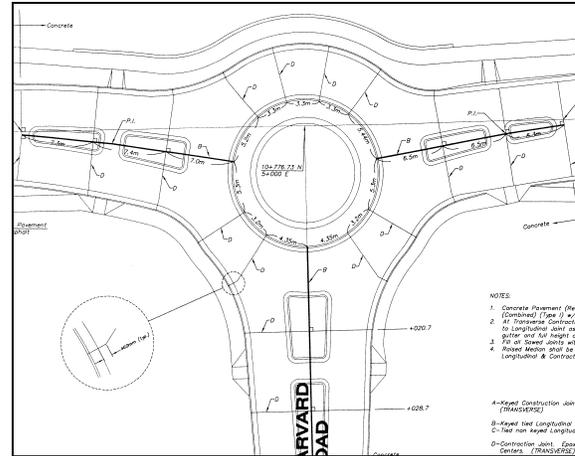


SECTION ELEVATION
 PROTECTION CURB 200 mm

Design by: Professional Engineering Consultants, P.A., 2001.

Harvard Road and Monterey Way, Lawrence

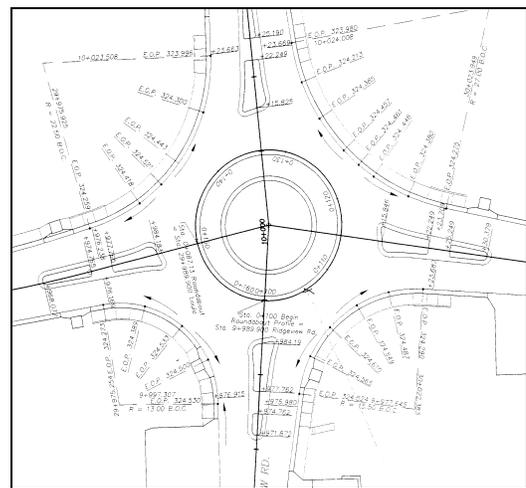
Harvard Road and Monterey Way form a “tee” intersection of two local collector streets in a residential area. The diameter of the roundabout is 85.3 ft (26 m). All approach lanes are single lane, as is the circulatory roadway. The circulatory roadway is 16 ft (4.9 m) wide with an 8.2 ft (2.5 m) truck apron. Contradictory information is provided in the plans about the type of curb and gutter utilized. The pavement in the roundabout is asphalt, with an 11 in (280 mm) base and 2-in (50 mm) surface course.

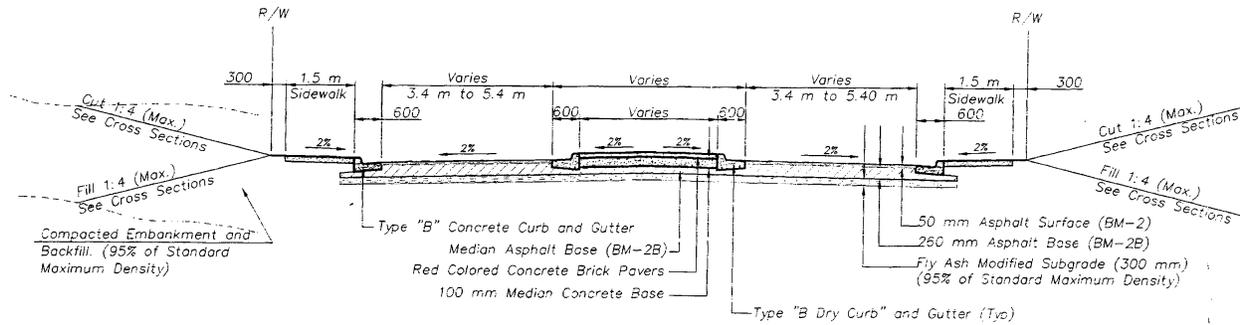


Design by: E.B.H. & Associates, 1998.

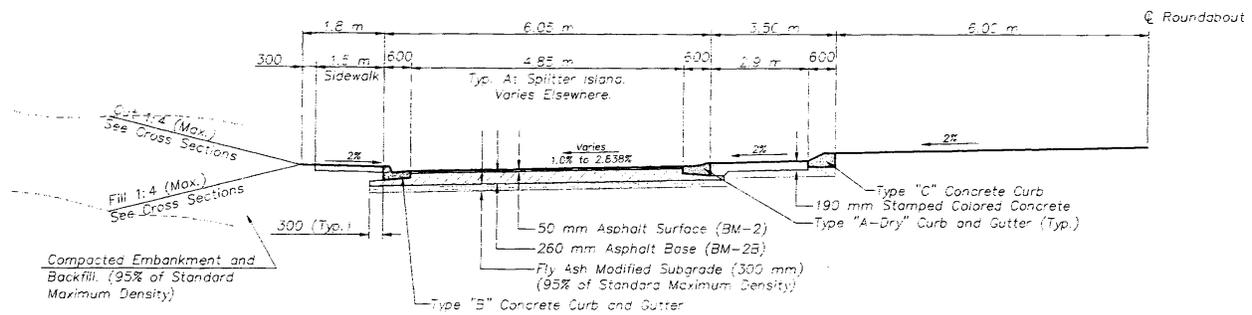
Ridgeview Road and Loula Street, Olathe

The Ridgeview Road and Loula Street roundabout has a circular shape with a 100 ft (30 m) inscribed circle diameter. All approach lanes are single lane, as is the circulatory roadway. The circulatory roadway is 16 ft (4.85 m) wide with a 9.5 ft (2.9 m) truck apron. The design utilizes Type “B” concrete curb and gutter along the outside edge of the approaches and along the outside of the circulatory roadway. Type “B Dry Curb” and gutter are used along edge of the splitter islands, with Type “A-Dry” curb and gutter along the inside edge of the circulatory roadway. The pavement for this roundabout is a 2 in (50 mm) asphalt surface with a 10.25 in (260 mm) asphalt base.





TYPICAL SECTION AT SPLITTER ISLAND
 (Not to Scale)

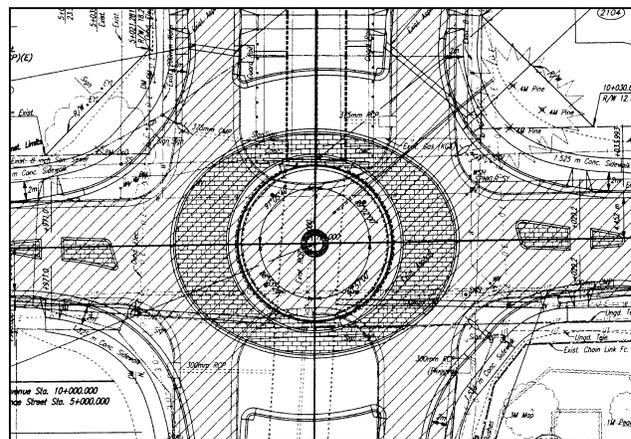


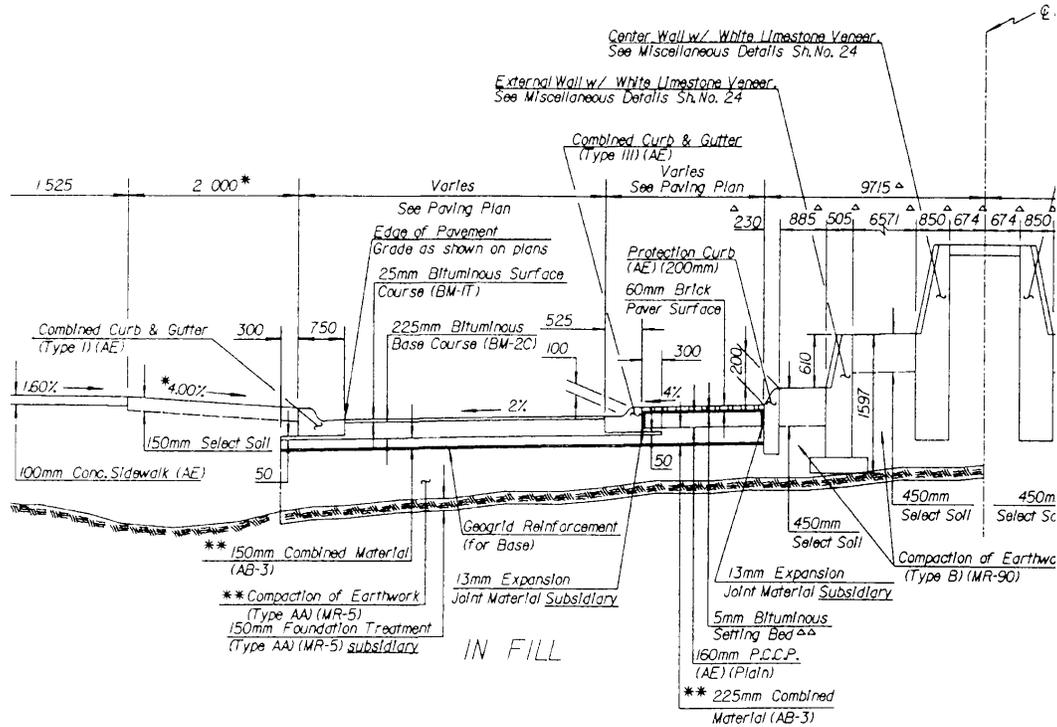
LOULA AND RIDGEVIEW SECTION – ROUNDABOUT
 (Not to Scale)

Design by: Olsson Associates, 2002

23rd Street and Severance Street, Hutchinson

Twenty Third Street and Severance Street are both minor arterial streets. Severance Street has a large drainage channel that runs between the north and southbound lanes, resulting in a median that is approximately 55.8 ft (17 m) wide. The roundabout is elliptical, with a diameter of approximately 145 ft (44 m) east-west and 125 ft (38 m) north-south. All approaches are single lane, as is the circulatory roadway. The circulatory roadway is approximately 23 ft (7 m) in width. A truck apron is provided, varying in width from about 6.5 ft (2 m) to about 16.4 ft (5 m). The outside curb around the roundabout is a KDOT Type I; the inside curb is a KDOT Type III. The curb around the splitter island is a 9-in (230-mm) wide KDOT protection curb, modified to 6 in (150 mm) in height. The pavement in the roundabout is asphalt, with a 9-in (225-mm) base and 1-in (25-mm) surface course.

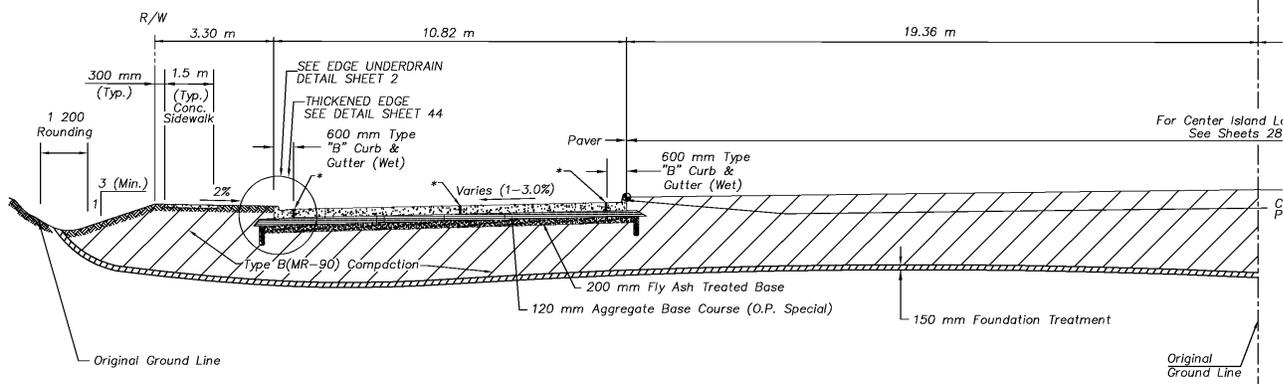
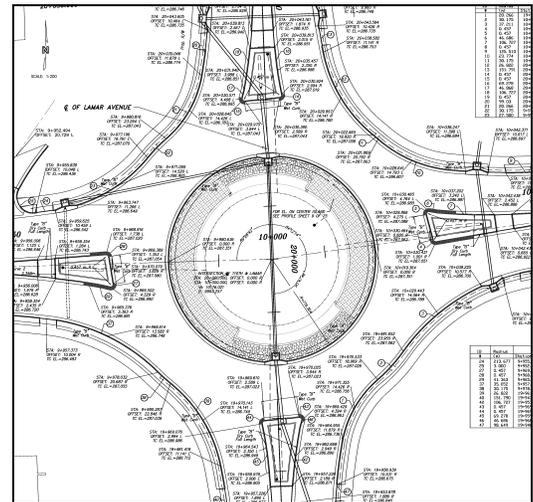


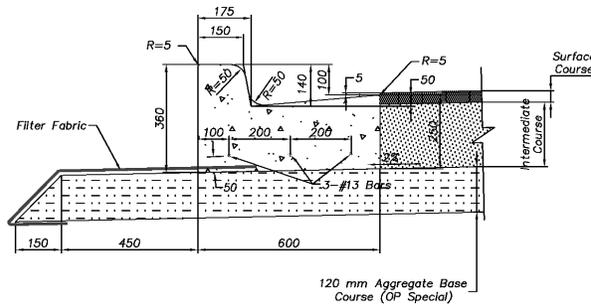


Design by: Professional Engineering Consultants, P.A., 2000.

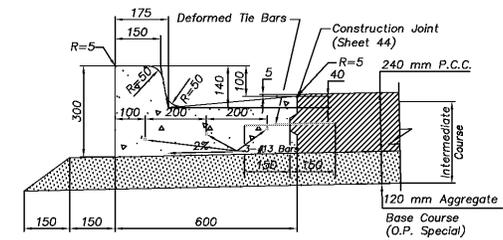
110th Street and Lamar Avenue, Overland Park

Lamar Avenue is a collector street, while 110th Street serves an adjacent business park and the Overland Park convention center. All approaches are two lanes, with a two lane circulatory roadway. The roundabout is 197 ft (60 m) in diameter with a 36-ft (11-m) circulating roadway. The roundabout was designed to be constructed as either 9.5-in (240-mm) concrete pavement or asphalt with an 8-in (205-mm) base course and a 2-in (50-mm) surface course. Ultimately the roundabout was constructed as concrete. The inner and outer curbs around the roundabout as well as around the splitter islands are Overland Park Type B curbs. The Type B curb has a curb height of 5.5 in (140 mm).

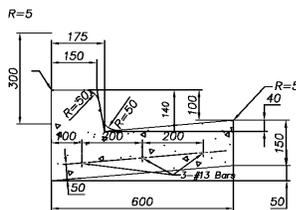




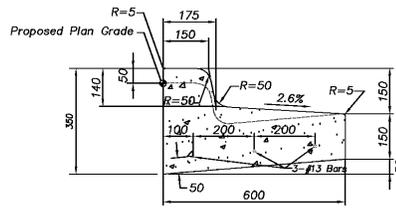
Type "B" Curb with O.P. Special Base Course
See Sheet 3 for Edge Drain Details



Type "B" Modified Curb with Concrete Pavement O.P. Special Base Course

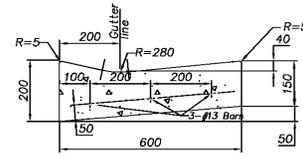


Standard Type "B" Curb



Type "B - Dry" Curb

NOTE: In transitions, water shall flow from the gutter of Type "B" curb to the lip of Type "B-Dry" curb at 0.5% min. slope.



Standard Type "C" Curb*

Design by: Olsson Associates, 2001.

Discussion

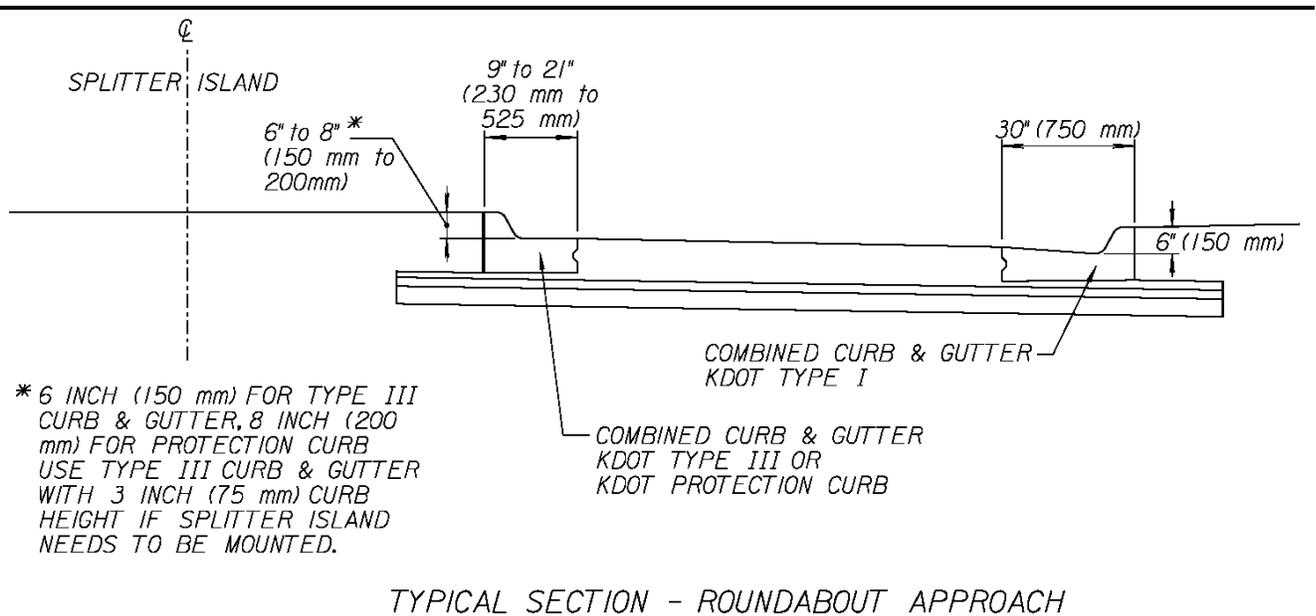
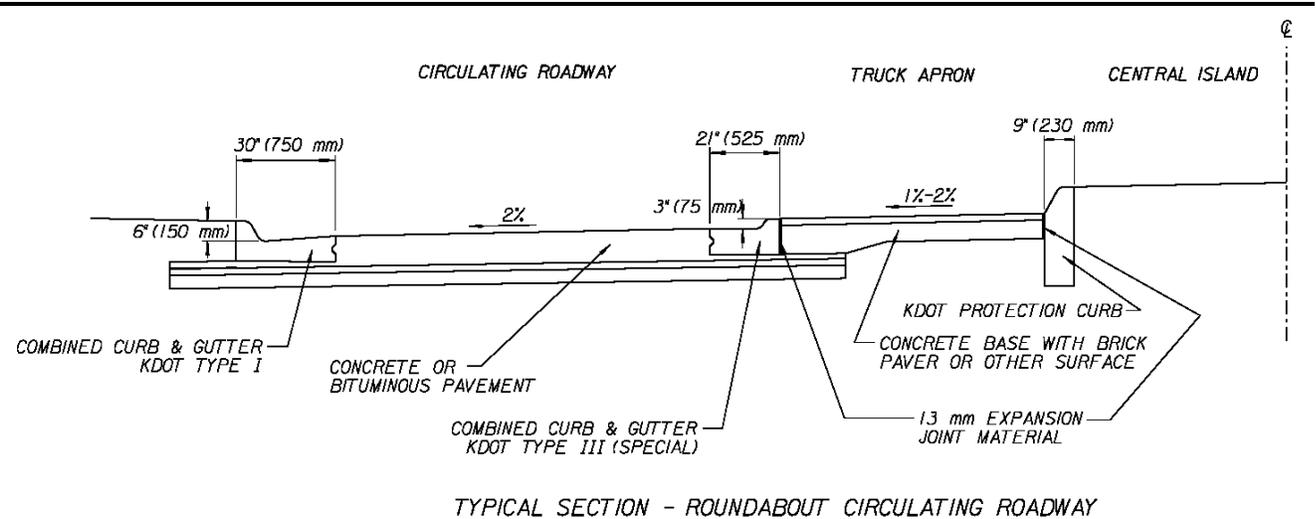
Curb Types

Generally, the curb and gutter type around the outside edges of all of the roundabouts are a KDOT Type I or similar. This type has a curb height of 6 in (150 mm). Around the central island the majority of the designs either used the Type I or Type III curb and gutter. The Type III is similar to Type I, but is 1.75 ft (525 mm) wide, as opposed to 2.5 ft (750 mm). Generally, this was a "dry" type curb, with the exception of the Overland Park roundabout, where a "wet" type curb was used to capture runoff from the central island. Heights of these curbs varied from 4 to 6 in (100 to 150 mm). Around the splitter islands, the KDOT Type III or Protection curb were utilized which generally have a curb height of 6 to 8 in (150 to 200 mm). In those cases where a curb was provided on the inside of the truck apron, generally an 8-in (200-mm) protection curb was utilized.

It is generally recommended that a 6-in (150-mm) high curb be used around the outside of the roundabout, the central island and the splitter islands, as one of the important elements of these features is to force deflection in vehicles traveling through the roundabout. If the curb is considered to be mountable by drivers, this effect is lessened. The barrier curb on the approach and in the splitter island also provides better protection for the pedestrian. However, most roundabouts must also be designed to accommodate large trucks. In this case, it is recommended that a 3-in (75-mm) curb height be used, as necessary, on the splitter islands, truck apron, or central islands. On occasion, trucks may also need to mount the outside curb; curb height will also need to be a consideration in these cases. Cross slopes on the circulating roadway are recommended to be 2 percent. On the truck apron, it is recommended that the cross slope be 1 to 2 percent to help prevent load shifting in trucks.

Exhibit 6-23 illustrates the recommended typical sections through the roundabout and the approach lanes.

Exhibit 6-23
Circulatory Roadway and Approach Typical Sections



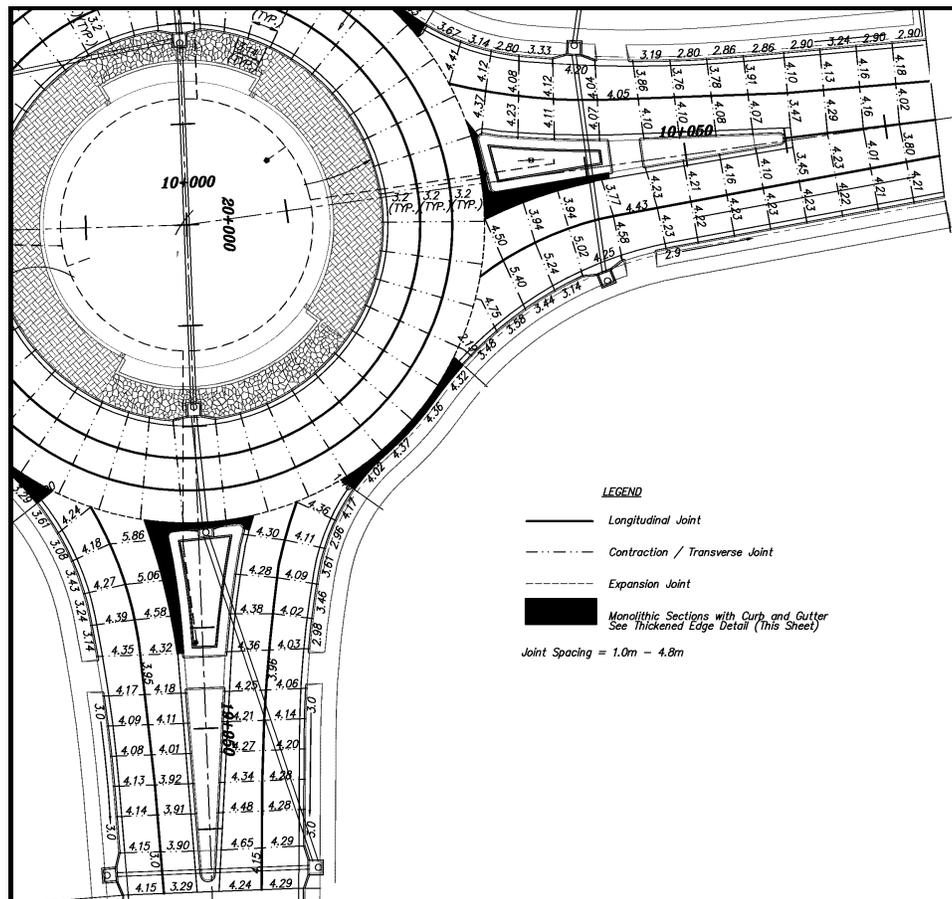
Pavement Type

Both asphalt and concrete pavements were used in the roundabouts reviewed. This is unusual nationally and internationally, where the vast majority of roundabouts are constructed using asphalt. The decision whether to utilize asphalt or concrete will depend on local preferences and the pavement type of the approach roadways. Concrete generally has a longer design life and holds up better under truck traffic. However, national experience has been that rutting has not been a problem with well-constructed asphalt pavement. Constructability is also a consideration in choosing pavement type. Generally, if the roundabout is to be constructed under traffic,

asphalt pavement will need to be used. For the truck apron, all of the projects utilized concrete pavement, generally 11 in (280 mm) in depth, or concrete pavement with a brick paver surface. Other options for the truck apron would include using large (4 in [100 mm]) river rocks embedded in concrete that can be traversed by trucks but are uncomfortable for smaller vehicles or pedestrians. A geogrid type material can also be used to provide a more landscaped type appearance but hold up to occasional encroachment by large trucks. The material used for the truck apron should be selected so as to not look like the sidewalk. This will help to keep pedestrians off the truck apron and central island. If the truck apron is constructed under traffic, high early strength concrete should be used to minimize the amount of down time for the intersection.

If concrete pavement is used, joint patterns should be concentric and radial to the circulating roadway within the roundabout. Ideally the joints should not conflict with pavement markings within the roundabout, although concrete panel sizes may control this. On multilane roundabouts, circumferential joints within the circulating roadway should follow the lane edges. Jointing and dowel details should generally utilize KDOT standards RD651 and RD682. Additional information and publications regarding jointing is available from the American Concrete Paving Association (www.pavement.com). Examples of jointing plans are shown below in Exhibit 6-24.

Exhibit 6-24
Example Jointing Plans



6.5 Pedestrian and Bicycle Considerations

As discussed in the FHWA publication, *Roundabouts: An Informational Guide*, pedestrian crossings at roundabouts should balance pedestrian convenience, pedestrian safety, and roundabout operations. To strike this balance, several geometric elements should be considered when designing pedestrian facilities at a roundabout as described below.

General Design Considerations for Pedestrian Crossings:

- Location of the pedestrian crossing
- Crossing alignment
- Splitter islands / pedestrian refuge design
- Providing for visually impaired pedestrians
- Discouraging pedestrians from crossing to the central island
- Multi-modal sidewalk usage

Exhibit 6-25
Roundabout Pedestrian Accommodations



Selection of the Pedestrian Crossing Location

The FHWA Roundabout Guide provides detailed discussion on considerations in the selection of the pedestrian crossing location. These considerations include minimizing the crossing distance, taking advantage of the splitter island as a pedestrian refuge, minimizing out of direction travel for pedestrians, and minimizing impacts to the roundabout operations. Crossings should be located behind the entrance line in increments of approximate vehicle lengths to reduce the

chance of a vehicle being queued across the crosswalk. The crossing should be oriented perpendicular to the direction of traffic to minimize pedestrian exposure time and reduce uncertainty for visually impaired pedestrians regarding crossing alignment.

It is recommended that pedestrian crossings be located one vehicle length, 25 ft (7.5 m) away from the entrance line at both single-lane and multilane roundabouts. This distance is thought to provide the optimal balance of pedestrian safety and convenience by minimizing out of direction travel and utilizing the geometric features of the roundabout to provide slow vehicle speeds in the crossing areas. As the distance from the entrance line increases, the slowing effects of the roundabout geometry may be diminished resulting in greater vehicle speeds, especially upon the exit. This crossing location also provides a greater degree of consistency with other intersection forms, by keeping the crosswalk close to the intersection, which may increase the conspicuity of the crossing to motorists that are not familiar with driving at roundabouts.

Pedestrian crossings should be marked using a series of lines parallel to the flow of traffic (also known as a “zebra crosswalk”) to identify the location of pedestrian activity.

Curb Ramps and Crossing Alignment

Curb ramps should be provided at each end of the crosswalk to connect the crosswalk to the sidewalk and other crosswalks around the roundabout. Curb ramps should be aligned with the crossing to guide pedestrians in the proper direction. Pedestrian crossings should be provided in a straight continuous alignment across the entire intersection approach. Crossings that curve or change alignment at the pedestrian refuge should be avoided. A straight alignment allows a visually impaired pedestrian to cross the approach and find the opposite curb ramp without the need to change direction.

Pedestrian refuge areas within the splitter island 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 may be cumbersome for wheelchairs. However, detectable warning surfaces should be used to indicate when the pedestrian reaches and exits the splitter island.

Exhibit 6-26 Pedestrian Crossing Illustrations



At a single lane roundabout, pedestrian crossings should be placed one vehicle length away from the entrance line as shown in the photo at left.

Pedestrian crossings should be provided in a straight alignment with the surface of the pedestrian refuge at street level.



Place curb ramps in line with the pedestrian crossing to properly guide pedestrians across the approach. A curb ramp such as the one shown in the photo *should be avoided*, as it directs pedestrians into the path of vehicles traveling on the circulatory roadway instead of in the direction of the striped crossing.

Curvilinear pedestrian crossings should also be avoided.



Curb ramps should be centered on the pedestrian crossing.

Avoid placing drainage structures in the crossing area. Drainage inlets such as the one shown in the photo at left may pose a potential hazard for visually impaired pedestrians. In this case the curb ramp had to be offset to the right side of the crossing to avoid the inlet.

Provisions for Visually Impaired Pedestrians

At roundabouts and other intersections, pedestrians with visual impairments are presented with travel challenges that are not experienced by sighted pedestrians. These challenges can be broken down into two general categories: way-finding and gap detection. The following section discusses design treatments and current requirements for assisting visually impaired pedestrians with detecting and navigating the crossing. Additional research is needed to adequately address the issue of the ability for visually impaired pedestrians to detect acceptable gaps in traffic, which is beyond the scope of this guide.

The crossing of a roundabout for visually impaired pedestrians consists of the following tasks (Ref. 1):

1. Finding the beginning of the crosswalk;
2. Establishing directional alignment for the crossing;
3. Deciding when to initiate the crossing;
4. Maintaining proper direction and monitoring traffic movements while crossing;
5. Finding the beginning of the splitter island;
6. Finding the end of the splitter island;
7. Finding the end of the crosswalk.

Each of the above tasks can be aided through the geometric design of the roundabout with exception to Task 3: Deciding when to initiate the crossing. Tactile surfaces placed at the ramps, crosswalks, and splitter islands can be used to help a blind pedestrian to identify each of the geometric elements associated with accomplishing Tasks 1, and 5 through 7. Maintaining a consistent alignment of the pedestrian ramp and the crosswalk across the entire approach can help visually impaired pedestrians with Tasks 2 and 4.

The 3rd task, deciding when to initiate the crossing, is much more complex, as it requires a visually impaired pedestrian to distinguish between the circulating traffic and entering/exiting vehicles. Current research efforts are in progress attempting to address this issue.

The National Institute of Health/National Eye Institute is sponsoring a research effort headed by Western Michigan University. This study is designed to improve the mobility of blind, or otherwise visually impaired, individuals by making intersections more accessible. Roundabout research is being conducted to examine the ability of a blind person to judge sufficient gaps in traffic in comparison to sighted individuals. The study also evaluates the response of drivers at roundabouts to the presence of pedestrians with and without mobility devices.

Other forthcoming NCHRP research is planned to examine the navigational issues of visually impaired pedestrians at roundabouts and identify geometric design issues to help optimize the location of pedestrian facilities. This research may also identify ITS or technology issues related to the use of such devices as pedestrian signals.

Title II of the Americans with Disabilities Act (ADA) requires that new and altered facilities constructed by, on behalf of, or for the use of state and local government entities be designed and constructed to be readily accessible to and usable by individuals with disabilities (28 CFR 35.151). The Americans with Disabilities Act Accessibility Guidelines (ADAAG, 1991) were developed under the umbrella of the ADA to provide guidelines for making facilities accessible to people with disabilities. The ADAAG require that a detectable warning surface be applied to the surface of the curb ramps and within the refuge of a splitter island (defined in the ADAAG as “hazardous vehicle areas”) to provide tactile cues to individuals with visual impairments.

Detectable warnings consist of a surface of truncated domes built in or applied to walking surfaces that provides a distinctive surface detectable by cane or underfoot. This surface works to alert visually impaired pedestrians of the presence of the vehicular travel way, and provides physical cues to assist pedestrians in detecting the boundary from sidewalk to street where curb ramps and blended transitions are devoid of other tactile cues typically provided by a curb face. The current ADAAG require the use of detectable warnings on the entire surface of the curb ramp (excluding the side flares).

Exhibit 6-27
Example Pedestrian Crossing with Detectable Warnings



This crosswalk design incorporates the use of truncated dome detectable warning surfaces into the curb ramps and splitter island to facilitate navigation by a visually impaired pedestrian.

Additional tactile devices (distinct from detectable warning surfaces) are also provided along the outside edge and along the center of the crossing to aid the pedestrian in detecting the edges of the crossing and maintaining the proper direction across the intersection.

Within the refuge area of the splitter island, the FHWA Roundabout Guide recommends that a detectable warning surface be applied as shown in Exhibit 6-27. The detectable warning surface shall begin at the curb line and extend into the pedestrian refuge area a distance of 24 in (610 mm). This creates a minimum clear space of 24 in (610 mm) between the detectable warning surfaces for a minimum splitter island width of 6 ft (1.8 m) at the pedestrian crossing. This is consistent with the KDOT standard drawings for *Auxiliary Details For Sidewalks & Steps* and is necessary to enable visually impaired pedestrians to distinguish where the refuge begins and ends from the adjacent roadway where the minimum refuge width of 6 ft (1.8 m) is provided. Exhibit 6-28 provides a summary of the ADAAG requirements for detectable warning surfaces.

**Exhibit 6-28
Requirements for Detectable Warning Surfaces***

Legislation	Americans with Disabilities Act Accessibility Guidelines (ADAAG)	Draft Guidelines on Accessible Public Rights-of-Way
Applicability	Required under existing regulations	These guidelines are in the rulemaking process and are therefore <i>not</i> enforceable. These guidelines are ultimately intended to be incorporated into the ADAAG, however the recommendations listed below are subject to revision prior to the issuance of a final rule.
Type	Raised truncated domes	Raised truncated domes aligned in a square grid pattern
Dome Size	A nominal diameter of 0.9 in (23 mm), A nominal height of 0.2 in (5 mm).	A base diameter of 0.9 in (23 mm) minimum to 1.4 in (36 mm) maximum A top diameter of 50% of the base diameter minimum to 65% of the base diameter maximum A height of 0.2 in (5 mm).
Dome Spacing	A nominal center-to-center spacing of 2.35 in (60 mm).	A center-to-center spacing of 1.6 in (41 mm) minimum and 2.4 in (61 mm) maximum, A base-to-base spacing of 0.65 in (16 mm) minimum, measured between the most adjacent domes on square grid.
Contrast	Detectable warning surfaces shall contrast visually with adjacent walking surfaces either light-on-dark, or dark-on-light. The material used to provide contrast shall be an integral part of the walking surface.	Detectable warning surfaces shall contrast visually with adjacent walking surfaces either light-on-dark, or dark-on-light.
Size	At curb ramps: The detectable warning shall extend the full width and depth of the curb ramp. Within Splitter Island: boundary between the (curbs) shall be defined by a continuous detectable warning which is 36 in (915 mm) wide, beginning at the curb line.	At curb ramps, landings, or blended transitions connecting to a crosswalk: Detectable warning surfaces shall extend 24 in (610 mm) minimum in the direction of travel and the full width of the curb ramp, landing, or blended transition. The detectable warning surface shall be located so that the edge nearest the curb line is 6 in (150 mm) minimum and 8 in (205 mm) maximum from the curb line. Within Splitter Island: The detectable warning surface shall begin at the curb line and extend into the pedestrian refuge a minimum of 24 in (600 mm). Detectable warnings shall be separated by a 24 in (610 mm) minimum length of walkway without detectable warnings

*Reflects requirements current as of September 2003

Other recent recommendations offer similar guidance to that of the FHWA Roundabout Guide for detectable surfaces within the refuge area of a splitter island. The *Draft Guidelines on Accessible Public Rights-of-Way* (June 14, 2002), developed by the Access Board, issued a similar recommendation for use of a width of 24 in (610 mm) for detectable warning surfaces. This is consistent with the existing ADAAG requirements for truncated dome detectable warning surfaces at transit platforms. The draft public right-of-way guidelines are based upon the recommendations of the Public Rights of Way Access Advisory Committee as published in the report *Building a True Community*. For detectable warning surfaces, both the U.S. Access Board and FHWA are encouraging the use of the new (recommended) design pattern and application over the original ADAAG requirements (Ref. 5).

Ongoing research is being conducted to improve accessibility for visually impaired pedestrians at roundabouts. This research is required to develop the information necessary for jurisdictions to determine where roundabouts may be appropriate and what design features are required for people with disabilities. Until specific standards or guidelines are adopted, such as the Public Right of Way Accessibility Guidelines, 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.

Non-Typical Pedestrian Treatments

While the detectable warning surfaces required by the ADAAG assist pedestrians in locating the crossing and pedestrian refuge area, blind or other visually impaired pedestrians may require further assistance in navigating a roundabout. For example, a motorized volume that is too heavy at times to provide a sufficient number of gaps acceptable for pedestrians may warrant consideration of an indicator that provides visual or audible cues to assist people with visual disabilities and increase the conspicuity of the crossing to motorists.

Other potential treatments to help reduce the difficulties faced by pedestrians include: narrow entry widths, raised speed tables with detectable warnings, detectable surfaces that direct visually impaired pedestrians to the crossing location, and in-pavement markers with yellow flashing lights to alert drivers of crossing pedestrians (Ref. 6). While not typical, treatments such as these may be implemented if a traffic study identifies the need for additional pedestrian accommodations. At this time there is limited data relating pedestrian safety at roundabouts to implementation of non-typical pedestrian indicators or other treatments. Therefore, implementation of non-typical pedestrian treatments should be evaluated on a case-by-case basis.

Where consideration is given to pedestrian activated indicators near a roundabout, the crossing location should be determined based on an analysis of the interaction between the roundabout and signal to minimize operational impacts and minimize the likelihood of exiting vehicle queues extending into the roundabout.

Speed tables, where considered, should ensure that adequate geometric design is provided to reduce absolute vehicle speeds to less than 12 mph (20 km/h) near the crossing. In addition, speed tables should generally be used only on streets with approach speeds of 35 mph (55 km/h) or less, as the introduction of a raised speed table in higher speed environments may increase the likelihood of single-vehicle crashes.

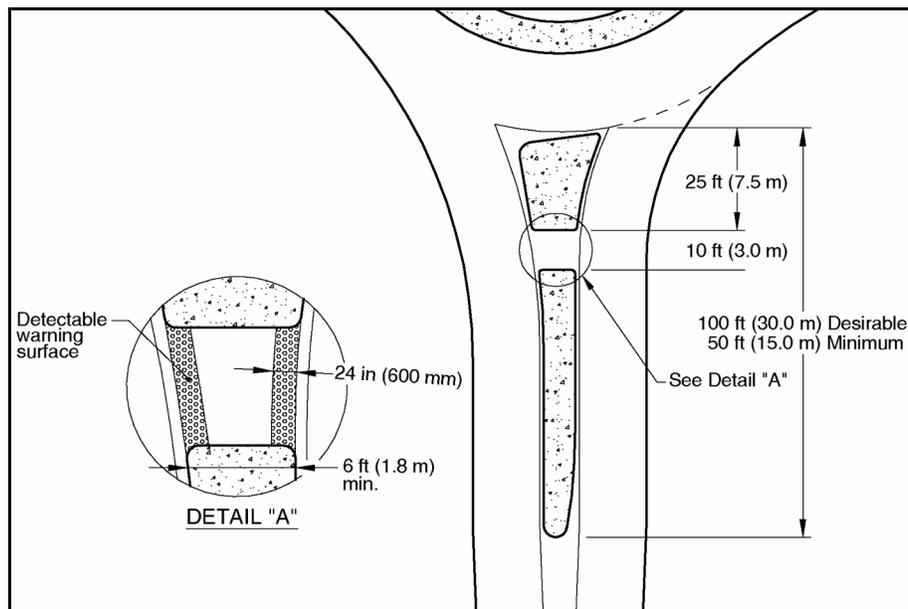
Splitter Islands

Splitter islands should be constructed on all roundabouts, except those with very small diameters at which the splitter island would obstruct the visibility of the central island. Splitter islands serve to separate and guide entering and exiting traffic, provide shelter for pedestrians (including wheelchairs, bicycles, and baby strollers), assist in controlling vehicle speeds, deter wrong way movements, and provide a place to mount signs.

The splitter island envelope is formed by the entry and exit curves on an approach. The extension of these curves should be tangent to the outside edge of the central island. The total length of a splitter island should generally be a minimum of 50 ft (15 m), although 100 ft (30 m) is desirable, 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. The minimum width of the splitter island is 6 ft (1.8 m), measured at the pedestrian crossing as shown in Exhibit 6-29.

Exhibit 6-29 shows the minimum dimensions for a splitter island at a single lane roundabout, including the location of the pedestrian crossing and location of detectable warning surfaces within the pedestrian refuge area.

Exhibit 6-29
Minimum Splitter Island Dimensions



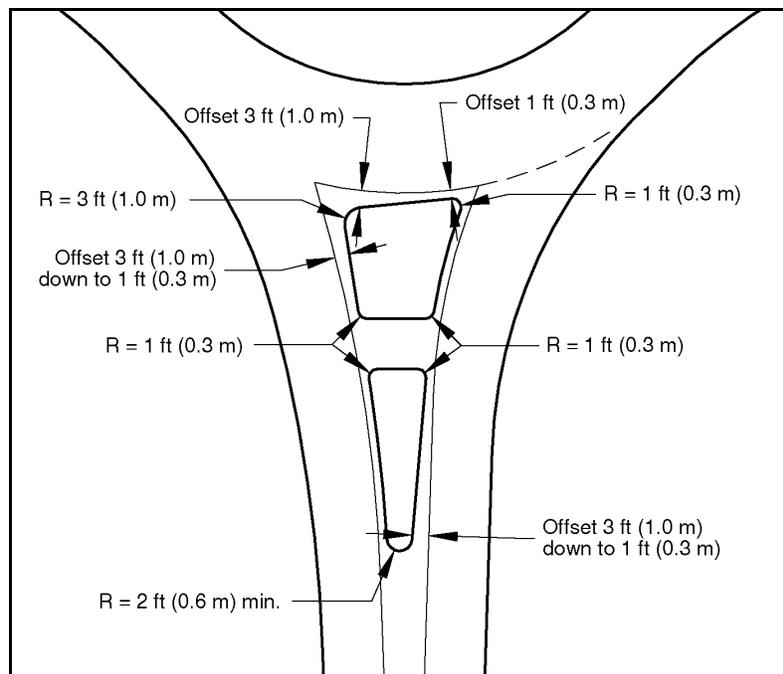
While Exhibit 6-29 provides minimum dimensions for splitter islands, there are benefits to providing larger islands. Longer splitter islands may be appropriate on facilities where vehicle speeds are sufficiently high in relation to the operating speed of the roundabout. The increased splitter island length provides additional warning to drivers of the impending intersection and need for speed reductions.

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. However, care should be taken when designing islands with larger widths to ensure that adequate deflection and speed reduction objectives are being achieved. Increases in the splitter island width generally require increasing the inscribed circle diameter and thus may have higher construction costs 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 6-30 shows the minimum splitter island nose radii and offset dimensions from the entry and exit traveled way.

Exhibit 6-30
Minimum Splitter Island Nose Radii and Offsets

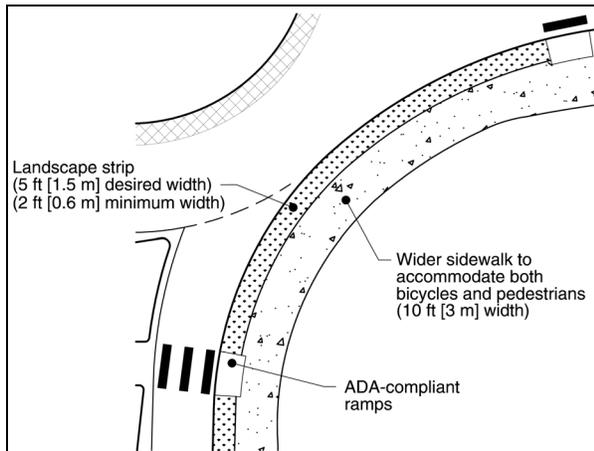


Sidewalk Considerations

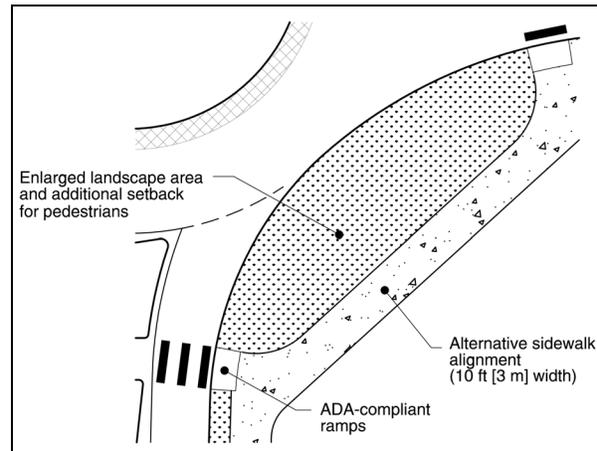
In order to deter pedestrians from crossing to the central island, sidewalks should be set back from the circulatory roadway. A setback distance of 5 ft (1.5 m) is recommended (minimum of 2 ft [0.6 m]) where possible. The area between the sidewalk and circulatory roadway can be planted with grass or low shrubbery to provide a visual barrier. Exhibits 6-31 through 6-33 show examples of this type of treatment.

In areas where sidewalk set back is not possible, bollards, or other barriers may be appropriate to guide pedestrians to the appropriate crossing location and prevent crossing to the central island.

**Exhibit 6-31
Sidewalk Treatments**



**Exhibit 6-32
Alternative Sidewalk Treatment**



**Exhibit 6-33
Example Sidewalk Setback at Roundabouts**



Landscaped planter strips set back the sidewalk from the adjacent roadway. This helps to define the sidewalk area and discourage pedestrians from crossing the roadway at locations other than the striped and/or signed crossing.

Providing sidewalk setback may also help visually impaired pedestrians to distinguish the location of the sidewalk and find the appropriate crossing locations.

In this photo, the break in the manicured grass planter strip, combined with the pedestrian crossing sign, help to heighten the conspicuity of the crossing to motorists, especially in the instance where sunlight glare on the concrete road surface may decrease the visibility of the crosswalk striping.

Sidewalk Considerations in Urban Areas

In urban areas, additional consideration may be required for pedestrian facilities, especially sidewalks, to provide for pedestrian mobility and encourage retail activity. The sidewalk width required adjacent to the roundabout is dependent on a number of factors. While, the level of pedestrian activity may be the first consideration, the sidewalk width may also be dependant on the nature of the adjacent business activity in the immediate vicinity of the roundabout. Larger densities of retail stores, restaurants, or entertainment attractions may elicit the need for wider sidewalks. Wider sidewalks accommodate window shoppers, allow for limited outdoor seating at restaurants, and also provide space for public street furniture such as benches or public art.

Exhibit 6-34
Example Pedestrian Features in Urban Areas



In urban areas with high pedestrian activity, consideration may be given to providing additional pedestrian features such as small plazas in the corner areas between the approach legs of the roundabout as shown in the photo. Open space, such as this, allow for increased pedestrian activity without overcrowding. It also allows space for pieces of public art to further accentuate the intersection.

In this example a vertical face of 18 in (450 mm) was provided on the roundabout side of the sidewalk edge and tapered down to match the curb height at the edge of the roadway. This structure was carefully designed to prevent impeding sight distance, but yet to help define the pedestrian space, protect the landscaping, and most importantly to prevent pedestrians from entering the circulatory roadway or crossing to the central island.

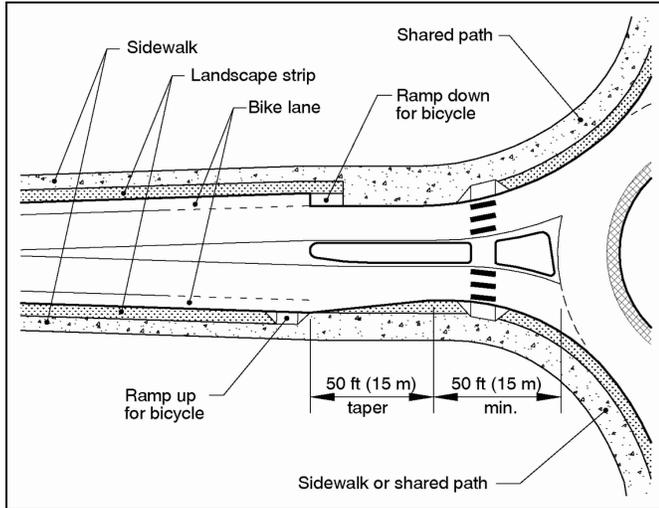
In some locations, where right-of-way is available, additional open space such as shown in Exhibit 6-34 may be provided to enhance the aesthetics of the intersection and increase the freedom of movement for non-motorized users. As with any roundabout, the overall design should ensure that adequate sight distance is provided to make pedestrians visible to motorists. This is especially true in urban areas where the location of landscaping, street furniture, or signs could obstruct the view of pedestrians.

Bicycle Provisions

Bike lanes should be terminated in advance of a roundabout to encourage cyclists to mix with vehicle traffic and navigate the roundabout as a vehicle. Bicycle riders uncomfortable with riding through the roundabout may choose to dismount and circulate around the roundabout as a pedestrian using the provided sidewalks and crossings. It is recommended that bike lanes end 100 ft (30 m) upstream of the entrance line to allow for merging with vehicles.

To accommodate bicyclists who prefer not to use the circulatory roadway, a widened sidewalk or shared bicycle/pedestrian path may be used provided it is physically separated from the circulatory roadway. Ramps or other suitable connections can then be provided between this sidewalk or path and the bike lanes, shoulder, or road surface on the approaching and departing roadways as shown in Exhibit 6-35. Care should be taken when locating and designing bicycle ramps to ensure that they are not misconstrued as an unmarked pedestrian crossing. The *AASHTO Guide for Development of Bicycle Facilities* provides further guidance on the design requirements for bicycle and shared-use path design.

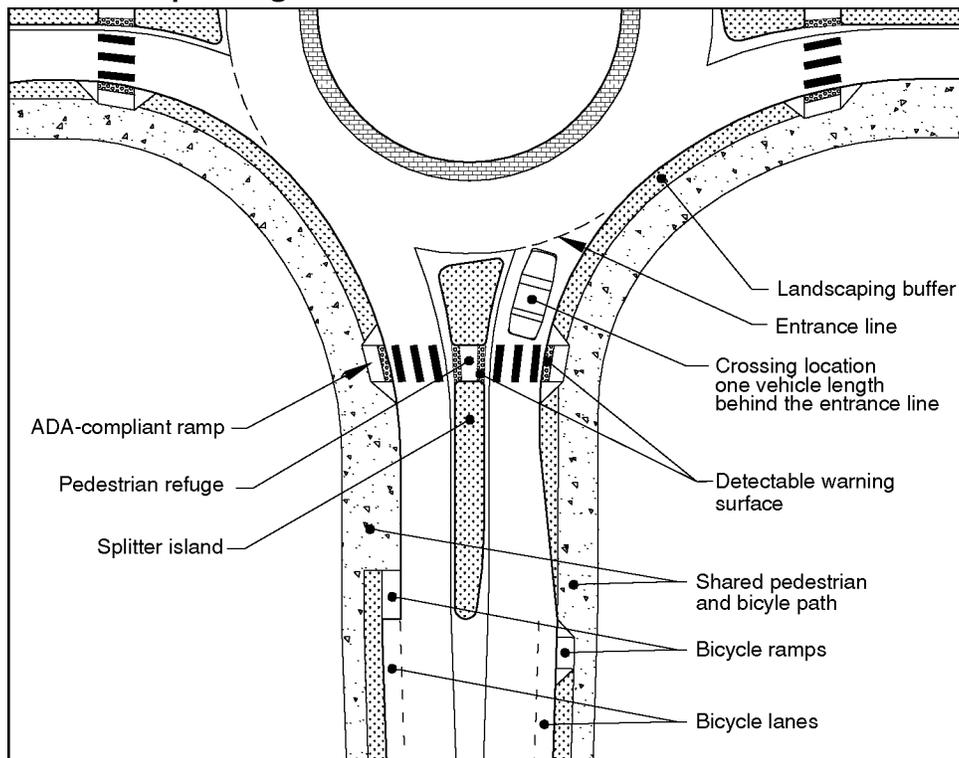
Exhibit 6-35
Possible Provisions for Bicycles



Example Pedestrian Facilities

Exhibit 6-36 provides a sample illustration of pedestrian and bicycle facilities for a single-lane roundabout in an urban or suburban setting. This figure incorporates the various design considerations discussed in Section 6.5. Specific dimensions and design considerations for individual elements are provided throughout Section 6.5 of this guide and in the FHWA publication *Roundabouts: An Informational Guide*.

Exhibit 6-36
Sample Single-Lane Roundabout Pedestrian Facilities



6.6 Sight Distance

As with all roadways, adequate stopping sight distance must be provided at all locations within the roundabout and on the approaches to avoid objects and other vehicles in the road. Intersection sight distance must also be provided at the entries to enable drivers to perceive vehicles from other approaches and safely enter the roundabout. The design speeds from the fastest path evaluation are used in the calculation of stopping sight distance and intersection sight distance requirements.

Stopping Sight Distance

At roundabouts, stopping sight distance should be checked at a minimum of three locations:

- Approach sight distance
- Sight distance on the circulatory roadway
- Sight distance to crosswalk on the immediate downstream exit

Exhibits 6-37 through 6-39 display the stopping sight distance requirements for roundabouts.

Exhibit 6-37
Approach Sight Distance

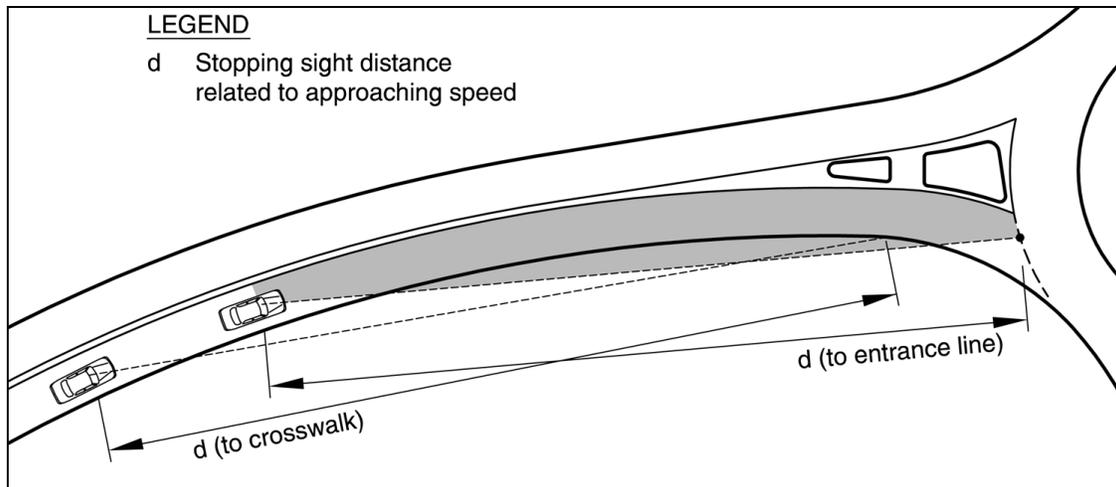


Exhibit 6-38
Sight Distance On Circulatory Roadway

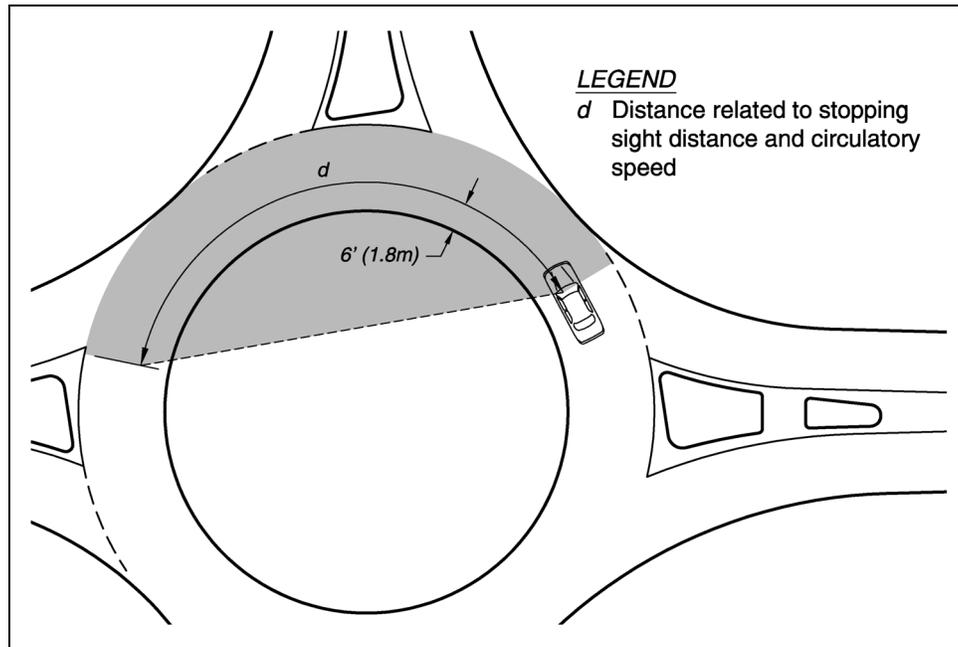
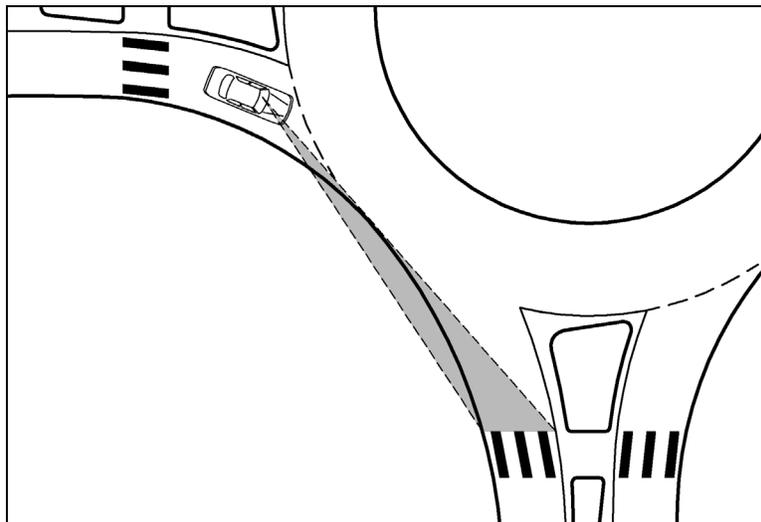


Exhibit 6-39
Sight Distance to Crosswalk on Exit



Stopping sight distance should be measured using an assumed drivers eye height of 3.5 ft (1,080 mm) and an assumed height of object of 2 ft (600 mm) in accordance with the fourth edition of the AASHTO publication, “A Policy on Geometric Design of Highways and Streets” (Green Book).

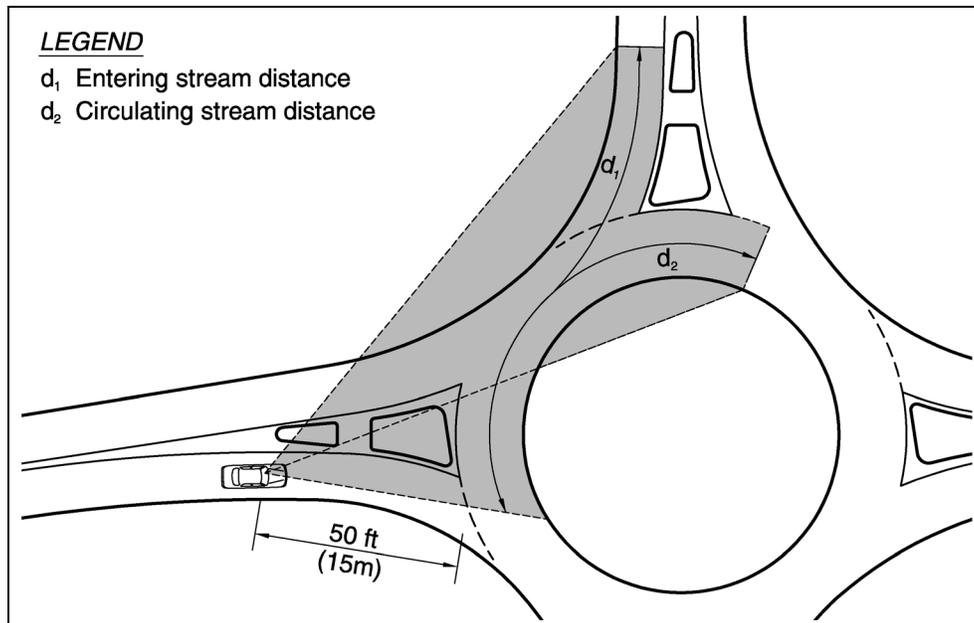
Equations and design values for determining the stopping sight distance required in Exhibit 6-37 through 6-39 are provided in section 6.3.9 of the FHWA publication, *Roundabouts: An Informational Guide*, and in the *Elements of Design* section of the AASHTO “Green Book”.

Intersection Sight Distance

Intersection sight distance is the distance required for a driver approaching the roundabout, without the right of way, to perceive and react to the presence of conflicting vehicles on the circulatory roadway and immediate upstream entry. At roundabouts, the only locations requiring evaluation of intersection sight distance are the entries.

The traditional method of using sight triangles to measure intersection sight distance is used. For roundabouts, the limits of the sight triangle are determined through the calculation of sight distance for the two independent conflicting traffic streams: the circulating stream and the entering stream on the immediate upstream entry. The sight distance required for each stream is measured along the curved vehicle path, *not* as a straight line. Exhibit 6-40 presents a diagram showing the method for determining intersection sight distance.

Exhibit 6-40
Intersection Sight Distance



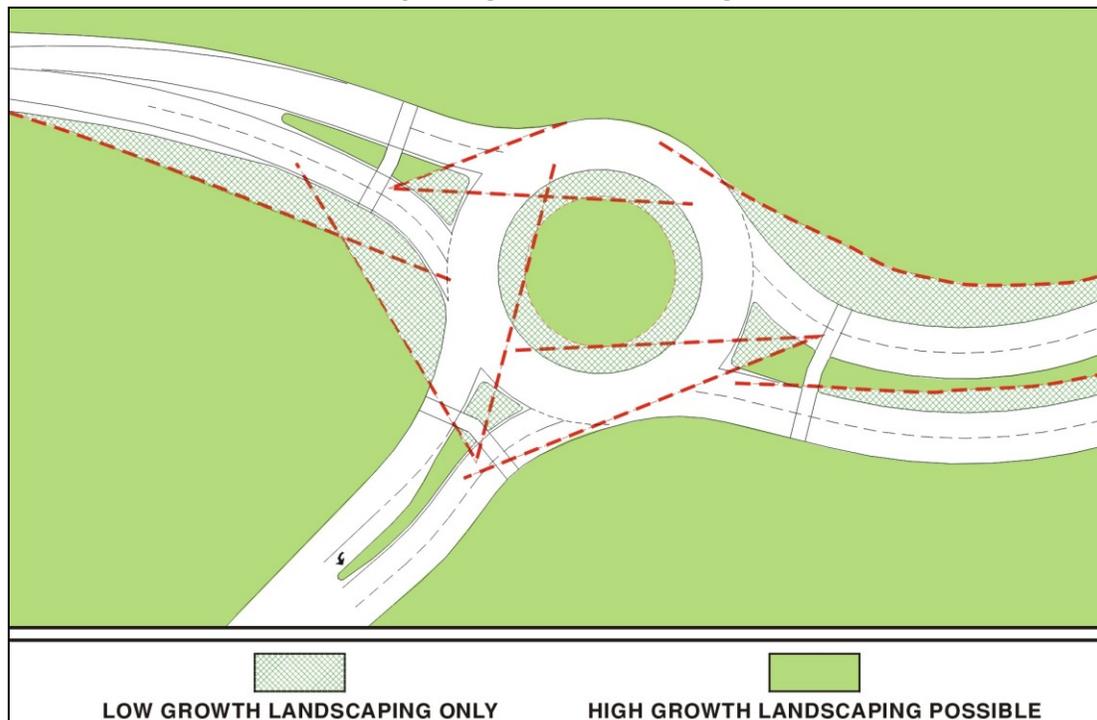
Intersection sight distance should be measured using an assumed drivers eye height of 3.5 ft (1,080 mm) and an assumed height of object of 3.5 ft (1,080 mm) in accordance with the fourth edition of the AASHTO publication, “A Policy on Geometric Design of Highways and Streets” (Green Book).

Equations and design values for determining the intersection sight distance components required in Exhibit 6-40 are provided in section 6.3.10 of the FHWA publication, “Roundabouts: An Informational Guide”. The equations are also provided in the *Intersections* section of the AASHTO “Green Book”. Calculations for intersection sight distance should assume a critical gap of 6.5 s, based on research of critical gaps at stop-controlled intersections, adjusted for yield-controlled conditions (Ref. 8). However, in locations where site distance may be constrained by adjacent topographic features or buildings, the critical gap may be reduced to 4.6 s. This value is consistent with the lower bound identified for roundabouts in the *Highway Capacity Manual* (HCM 2000). The designer can approximate the speeds for the entering stream by averaging the entry path speed and circulating path speed (paths with radius R_1 and R_2 respectively). Likewise,

the designer can approximate the speeds for the circulating stream by taking the speed of left-turning vehicles (path with radius R_L).

During design and review, roundabouts should be checked to ensure that adequate stopping and intersection sight distance is being provided. Checks for each approach should be overlaid onto a single drawing, as shown in Exhibit 6-41, to illustrate for all team members the clear vision areas for the intersection. This provides designers guidance on the appropriate locations for various types of landscaping or other treatments. The compiled drawing should be kept in the project file for future reference in the event landscaping or street furniture is contemplated after the project is completed. In general, it is recommended to provide no more than the minimum required intersection sight distance on each approach, as excessive intersection sight distance can lead to higher speeds that reduce intersection safety. Landscaping can be effective in restricting sight distance to the minimum.

Exhibit 6-41
Example Sight Distance Diagram



The hatched portions in Exhibit 6-41 are areas that should be clear of large obstructions that may hinder driver visibility. Objects such as low growth vegetation, poles, sign posts, and narrow trees may be acceptable within these areas provided that they do not significantly obstruct visibility of other vehicles, the splitter islands, the central island, or other key roundabout components. In the remaining areas (with solid shading), especially within the central island, taller landscaping may be used to break the forward view for through vehicles, thereby contributing to speed reductions and reducing oncoming headlight glare.

6.7 Landscaping Considerations

The use of landscaping at a roundabout is one of the distinguishing features that give roundabouts an aesthetic advantage over traditional intersections. The type and quantity of landscaping plantings or other material incorporated into the roundabout design may be dependant on both the site location and level of care available for maintenance. Exhibit 6-42 illustrates examples of landscaping installed at existing Kansas roundabouts.

Exhibit 6-42 Summary of Landscaping Schemes at Existing Kansas Roundabouts

Lawrence, Kansas – 24th Place at Inverness Drive



Topeka, Kansas – I-70 Ramps at Rice Road and Sycamore Drive



Olathe, Kansas – Sheridan Street at Clairborne Road



Olathe, Kansas – Sheridan Street at Rogers Road



Overland Park, Kansas – 110th Street at Lamar Avenue



**Manhattan, Kansas – Kimball Avenue at Grand Mere Parkway
(photo taken from central island)**



Manhattan, Kansas – Candlewood Drive at Gary Avenue



Maintenance Considerations

A realistic maintenance program should be developed when designing the landscaping features for any proposed roundabout. For KDOT maintained roundabouts, the landscaping should generally consist of simple, hearty plant materials or hardscape material that have minimal maintenance requirements. Plant selections should be appropriate for the climate to withstand both heat and cold depending on the season.

For roundabouts in urban areas, used as gateway treatments, or any other areas where more complex planting schemes are wanted, it may be desirable to seek out formal agreements with the local government entity, local civic groups, or garden clubs for maintenance where possible.

It is generally necessary for local governments to assume maintenance responsibilities for the roundabout landscaping to provide enhanced streetscapes for their communities. Where cross-jurisdictional or other agreements are formed, liability issues should be considered.

Planting such as grass, trees, and shrubs should be regularly trimmed or pruned to prevent obstruction of the sight triangles and to maintain the aesthetics of the intersection. Landscaping designs that require frequent watering may require installation of sprinkler systems. The design of the sprinkler system should minimize water runoff onto the circulatory roadway. Watering systems with a mist type spray head should be avoided as water spray onto windshields could create safety concerns.

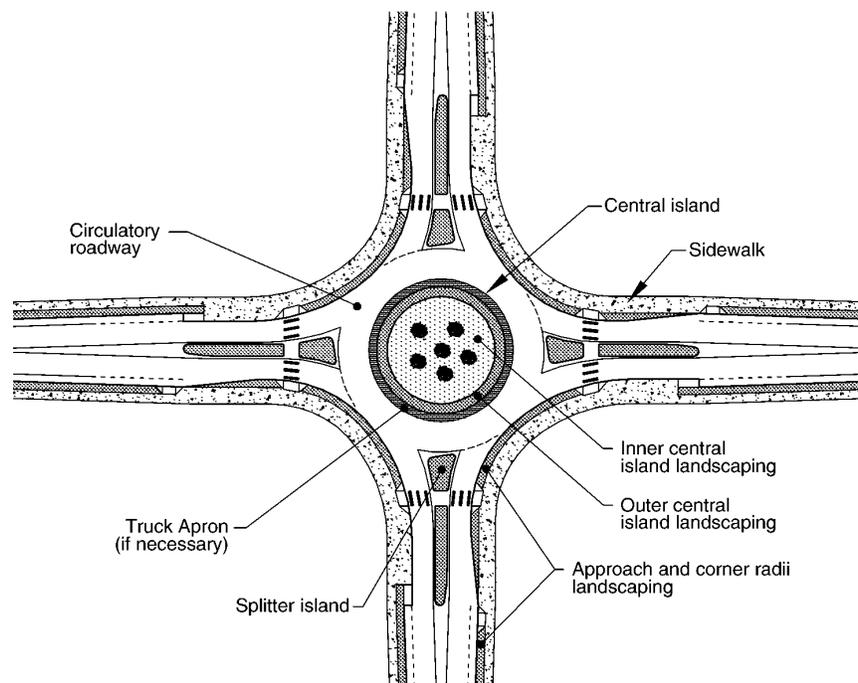
Sight Distance

As discussed in the previous section, sight distance requirements at the intersection dictate the size and types of landscaping materials appropriate for the various areas within and adjacent to the roundabout. Plants or hardscape materials should be placed to avoid obscuring the shape of the roundabout or the signing to the driver. Exhibit 6-41 in the previous section provides an example illustration of a sight distance diagram for a roundabout. Landscaping within the clear vision areas identified for the roundabout should be limited to a height of 2 ft (600 mm) to maintain adequate sight distance. Taller landscaping may be possible within the inner portion of the central island depending on the diameter of the inscribed circle.

Planting Zones

Exhibit 6-43 identifies the various planting areas at a typical roundabout.

Exhibit 6-43
Roundabout Planting Areas



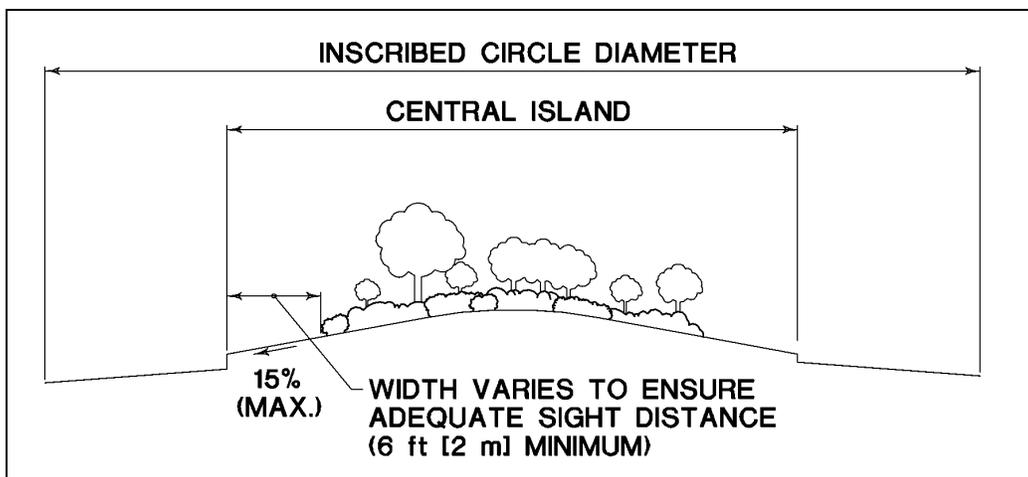
Central island landscaping

Landscaping within the central island provides enhancements to both aesthetics and safety for the intersection. The inner portion of the central island may be planted with trees, bushes and other large items. These plantings help to make the central island more conspicuous by creating a terminal vista in which the line of sight straight through the roundabout is partially obscured. This clearly indicates to the driver that they cannot pass straight through the intersection and helps to make the central island more visible at night with the vehicle headlights illuminating the landscaping.

The perimeter of the central island should be landscaped with low-lying shrubs, grass, or groundcover so that stopping sight distance requirements are maintained for vehicles within the circulatory roadway. This width may vary depending on the size of the roundabout, as shown in Exhibit 6-44. Many of the existing KDOT roundabouts have used bark, small rocks, and low growing plants to provide groundcover around the perimeter of the central island, and maintain sight distance. Large, fixed landscaping objects such as trees, poles, rocks, statues, or walls should be avoided in areas vulnerable to vehicle runoff. Shrubs and columnar growing species of trees may be appropriate within the inner portion of the central island. Consideration should be given to the size and shape of the mature plants. Trees with large canopies should be avoided within the central island. Large objects such as statues, monuments, and other art can often be desirable features and may be allowed in the central island provided that they are located outside the sight triangles and in areas unlikely to be struck by errant vehicles. The slope of the central island should not exceed 6:1 per the requirements of the AASHTO Roadside Design Guide (Ref. 9).

Landscaping within the central island should discourage pedestrian traffic to and through the central island. As such, the design of the central island should avoid use of street furniture such as benches or monuments with small text. Where truck aprons are used, the material or pattern used for the surface of the apron should be different from that used for the sidewalks so that pedestrians are not encouraged to cross the circulatory roadway, or perceive that the truck apron is a sidewalk.

Exhibit 6-44
Central Island Landscaping



Splitter island and approach landscaping

When designing landscaping for the splitter islands and along the outside edges of the approach, care should be taken to avoid obstructing sight distance, as splitter islands are usually located within the critical sight triangles. Landscaping should avoid obscuring the form of the roundabout or the signing to an approaching driver.

At existing Kansas roundabouts, splitter islands have often been constructed with either low-growth plant material or have been devoid of landscaping all together, simply using a patterned concrete or concrete paver surface. The size of the splitter island and location of the roundabout are determining factors in assessing whether or not to provide landscaping within the splitter islands.

Landscaping on the right and left side of the approaches and within the splitter islands (where appropriate) can help to create a funneling effect and induce a decrease in speeds approaching the roundabout. Landscaping on the outer edges of the approach and in the corner radii provide sidewalk setback which helps to channelize pedestrians to the crosswalk areas and discourage pedestrians from crossing to the central island.

For existing Kansas roundabouts, grass has typically been used along the outer edge of the roadway and within the corner radii between adjacent legs of the roundabout. Although other plants species may be used, grass typically blends in well with the surrounding streetscapes and requires little or no watering. The main maintenance requirement for planting grass is mowing, thus consideration may be given to dwarfed varieties such as “buffalo grass” which has a shorter height and requires less frequent maintenance.

Exhibit 6-45 Example Splitter Island Landscaping



Landscaping within the splitter islands and along the outer edge of the approach can help create a funneling effect to help decrease speeds prior to the roundabout.

Landscaping should be carefully placed as to not obstruct the sight distance requirements for the intersection. Trees within the splitter island may not be appropriate in all locations.



Grass or low growth plants can provide improved aesthetics within the splitter island area.

Consider the use of dwarfed plant varieties or horizontally growing ground cover type species to minimize maintenance requirements and preserve sight distance requirements.

Arid plant species may be appropriate within the splitter island to minimize watering requirements.

6.8 References

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2. Americans with Disabilities Act Accessibility Guidelines for Buildings and Facilities (ADAAG). 36 CFR Part 1191. As amended through January 1998.
3. Architectural and Transportation Barriers Compliance Board. Draft Guidelines for Public Rights of Way. (June 2002) Washington D.C.: U.S.
4. Building a True Community: Report of the Public Rights of Way Access Advisory Committee. (2001) Washington, D.C.: U.S. Architectural and Transportation Barriers Compliance Board.
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8. Harwood, D.W. et al. *NCHRP Report 383: Intersection Sight Distances*. National Cooperative Highway Research Program, Transportation Research Board, National Research Council. Washington D.C.: National Academy Press, 1997.
9. American Association of State Highway and Transportation Officials (AASHTO). Roadside Design Guide. Washington, D.C.: AASHTO, 1989.