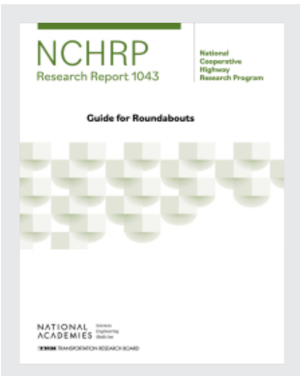

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP RESEARCH REPORT 1043

Guide for Roundabouts

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2023

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed, and implementable research is the most effective way to solve many problems facing state departments of transportation (DOTs) administrators and engineers. Often, highway problems are of local or regional interest and can best be studied by state DOTs individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation results in increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

Recognizing this need, the leadership of the American Association of State Highway and Transportation Officials (AASHTO) in 1962 initiated an objective national highway research program using modern scientific techniques—the National Cooperative Highway Research Program (NCHRP). NCHRP is supported on a continuing basis by funds from participating member states of AASHTO and receives the full cooperation and support of the Federal Highway Administration (FHWA), United States Department of Transportation, under Agreement No. 693JJ31950003.

The Transportation Research Board (TRB) of the National Academies of Sciences, Engineering, and Medicine was requested by AASHTO to administer the research program because of TRB's recognized objectivity and understanding of modern research practices. TRB is uniquely suited for this purpose for many reasons: TRB maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; TRB possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; TRB's relationship to the National Academies is an insurance of objectivity; and TRB maintains a full-time staff of specialists in highway transportation matters to bring the findings of research directly to those in a position to use them.

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NCHRP RESEARCH REPORT 1043

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This document was prepared under NCHRP Project 03-130, "Guide for Roundabouts." It provides guidance for planning, designing, and implementing roundabouts that is based on integrating user needs within the widest array of project contexts. It expands upon a performance-based approach centered on developing project solutions to best meet and balance each user's needs.

Kittelson & Associates, Inc. (Kittelson), served as the prime contractor. Brian Ray, Sunrise Transportation Strategies, LLC (formerly with Kittelson), served as the principal investigator. Lee Rodegerdts, Kittelson, initiated the project as principal investigator and continued to serve as a key author of *NCHRP Research Report 1043: Guide for Roundabouts* (guide) content. Julia Knudsen (Kittelson) managed the guide's development and provided invaluable project coordination. Michael Alston, Alek Pochowski, Krista Purser, Justin Bansen, Ed Myers, and Gene Hawkins completed the Kittelson team.

Subcontractors provided valuable contributions to research tasks and guide content: Mark Lenters and Jay VonAhsen of Kimley-Horn and Associates, Inc.; Janet Barlow and Beezy Bentzen of Accessible Design for the Blind, LLC; and Marcus Brewer of Texas A&M University, Texas Transportation Institute. Quality Counts, LLC, supported data collection for research tasks that informed guide content.

Guide development was supported by Ralph Bentley, Mindy Weber, Dimitryan Shadrin, Caleb Cox, and Anthea Fernandes of Kittelson. Andrew Ooms, Andy Duerr, Liz Byrom, Aditya Inamdar, Radu Nan, Margaret Kent, and Liz Flanagan (all of Kittelson) contributed to guide content, assisted with graphical information, and conducted early project tasks.

FOREWORD

By Amir N. Hanna
Staff Officer
Transportation Research Board

NCHRP Research Report 1043: Guide for Roundabouts provides information and guidance on all aspects of roundabouts and supersedes *NCHRP Report 672: Roundabouts: An Informational Guide—Second Edition*. The information contained in *NCHRP Research Report 1043* will help highway agencies and other organizations address relevant issues when considering the planning and implementation of roundabouts.

Since its publication in 2010, *NCHRP Report 672: Roundabouts: An Informational Guide—Second Edition* has served as a national guide on roundabout planning, analysis, design, and construction. However, in the years since *NCHRP Report 672* was published, technology has changed, substantial research on roundabouts has been performed, and many roundabouts have been constructed. The findings and experience gained from these developments have contributed to knowledge on implementing roundabouts. However, additional research was needed to address the gaps in available roundabout guidance and incorporate the information on new technologies, the findings of new and earlier research, and the lessons learned from constructed projects into a guide that provides updated information and guidance on all aspects of roundabouts. Under NCHRP Project 03-130, "Guide for Roundabouts," Kittelson & Associates, Inc., was tasked with developing a guide to supersede *NCHRP Report 672* and provide guidance on many aspects of roundabouts.

To accomplish this objective, the research team reviewed relevant literature, including national and state research and guidance documents and other sources; sought and incorporated practitioners' experiences; and conducted research on designing for trucks to assess roundabout design decisions for serving large trucks and research on designing for bicycles to better address bicycle treatments. The research team also synthesized information pertaining to roundabout design and implementation in the following areas: oversized/overweight trucks, retrofitting of existing roundabouts, mini-roundabouts, pedestrian crossings, traffic control devices, illumination, and economic impacts. Finally, the research team developed a comprehensive guide that integrates a performance-based design approach, incorporates research findings, and provides roundabout-specific guidance.

A conduct of research report summarizing the work performed to develop *NCHRP Research Report 1043* together with several appendices that provide further elaboration on the research are available as *NCHRP Web-Only Document 347: Background and Summary of a Guide for Roundabouts* from the National Academies Press website (nap.nationalacademies.org).

CONTENTS

PART IV Horizontal, Vertical, and Cross-Section Design

PART V Final Design and Implementation

Note: Photographs, figures, and tables in this report may have been converted from color to grayscale for printing. The electronic version of the report (posted on the web at nap.nationalacademies.org) retains the color versions.

PART I

Introduction to Roundabouts

PROJECT DEVELOPMENT PROCESS

Project Development Process	Part	Chapters
	Part I: Introduction to Roundabouts	Chapter 1: Introduction Chapter 2: Roundabout Characteristics and Applications
Planning	*Part II: Planning and Stakeholder Considerations*	Chapter 3: A Performance-Based Planning and Design Approach Chapter 4: User Considerations Chapter 5: Stakeholder Considerations Chapter 6: Intersection Control Evaluation
Identify and Evaluate Alternatives	*Part III: Roundabout Evaluation and Conceptual Design*	Chapter 7: Safety Performance Analysis Chapter 8: Operational Performance Analysis Chapter 9: Geometric Design Process and Performance Checks
Preliminary Design	*Part IV: Horizontal, Vertical, and Cross-Section Design*	Chapter 10: Horizontal Alignment and Design Chapter 11: Vertical Alignment and Cross-Section Design
Final Design Construction, Operations, and Maintenance	*Part V: Final Design and Implementation*	Chapter 12: Traffic Control Devices and Applications Chapter 13: Curb and Pavement Details Chapter 14: Illumination, Landscaping, and Artwork Chapter 15: Construction and Maintenance
Supplemental Appendix		Appendix: Design Performance Check Techniques

CHAPTER 1

Introduction

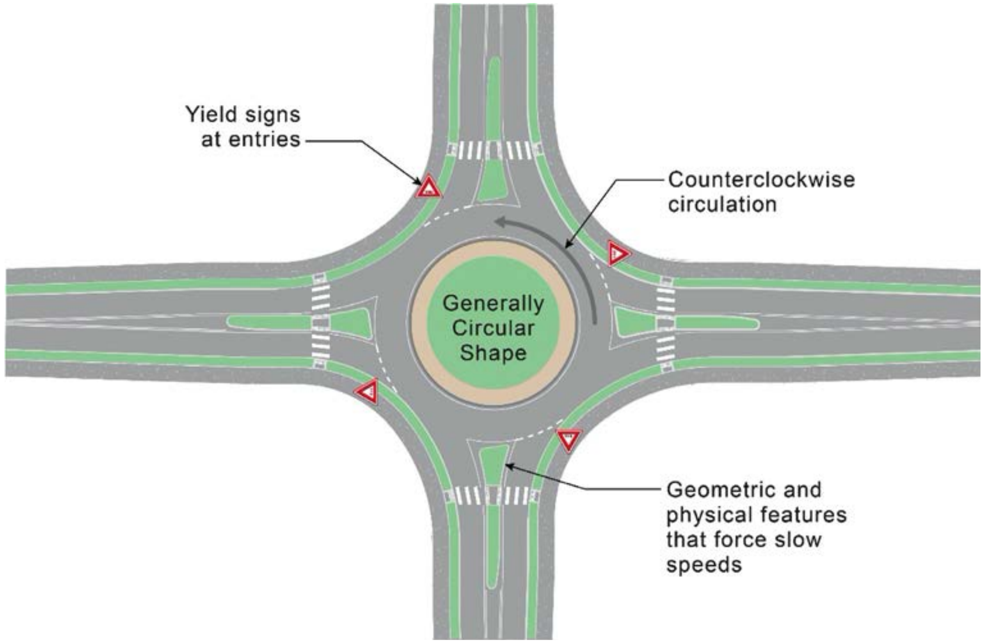
Contents

A roundabout is a circular intersection in which traffic travels counterclockwise (in the United States and other countries that drive on the right side of the roadway) around a central island and entering traffic must yield to circulating traffic. Exhibit 1.1 is a drawing of a typical roundabout, annotated to identify key characteristics and user movements. Roundabouts are designed to control motor vehicle speeds throughout the roundabout, typically 15 mph to 25 mph (24 km/h to 40 km/h). Roundabouts also reduce conflict points and severity compared with other intersection types.

1.1 Roundabout Guide Purpose and Intended Audience

The *Guide for Roundabouts* (the Guide) provides relevant roundabout planning, design, and performance information for a wide audience, including the public, elected officials, agency staff of all levels, consultants, and educators. The Guide is divided into parts that follow a generic representation of the project development process, moving from planning through construction to operations and maintenance. This incremental approach aligns the parts with common early project planning activities and the supporting information needed to evaluate intersection alternatives and advance roundabouts through final design. Information in this Guide is structured to progressively increase in detail and complexity so that the concepts introduced early are broadly understandable, with greater detail provided in later chapters to inform detailed design decisions.

Exhibit 1.1. Example roundabout.



This Guide does not set policy or standards. Rather, it provides commonly applicable principles and documents current practices while integrating relevant research findings. Roundabout planning and design in the United States continue to evolve as roundabouts become increasingly common. Principles in this document are expected to remain valid even as terminology or current trends evolve. Agencies may publish additional customized guidance that modifies or supplements the information provided here.

1.2 Organization of the Guide

The Guide is organized into five parts that follow a typical project development sequence.

- Part I, Introduction to Roundabouts, includes the Guide's purpose and intended audience, roundabout history and practice within the United States, types of roundabout projects, and program-level policy and practice considerations.
- Part II, Planning and Stakeholder Considerations, continues exploring program-level considerations and begins the project-level discussion of roundabouts. This section presents the essential considerations for planning and designing roundabouts: the performance-based design approach, user characteristics, stakeholder (including public) considerations, and intersection control evaluation (ICE).
- Part III, Roundabout Evaluation and Conceptual Design, continues the project-level discussion of safety, operations, and design. This section covers the typical ICE planning and preliminary engineering process. Part III engages the early questions in the project delivery process, especially the decision of whether a roundabout is the appropriate intersection control form for a particular location. This section supports preliminary design, including safety and operational performance assessment, life-cycle cost, and geometric design performance checks.
- Part IV, Horizontal, Vertical, and Cross-Section Design, covers preliminary design principles and performance-based design concepts, following the project delivery process from conceptual design to the final geometric configuration. Preliminary design often supports the environmental clearance and project approval needed to advance to final design. Geometric design includes horizontal and vertical alignment features as well as cross-section elements to integrate each roundabout user.

- Part V, Final Design and Implementation, follows the roundabout project delivery process from preliminary design through implementation. Discussions include final design details as well as construction and maintenance. Part V supports practitioners moving from a preliminary design into the details necessary to construct and maintain a roundabout.

1.3 History and Practice

This section describes the historical development of roundabouts in the United States and internationally, followed by the more recent history of implementation and guideline development in the United States over the past 30 years.

1.3.1 Historical Development

Circular intersections are not new, and traffic circles and rotaries have been part of the roadway network in the United States since the 19th century. One of the oldest circular intersections still in existence is Monument Circle in Indianapolis, Indiana, constructed in 1821. Another notable early traffic circle is the Columbus Circle in New York City, which opened in 1905. Traffic circles at that time served dual transportation and land-use purposes—the central islands could include park areas or civic plazas that required pedestrian access. Parking was commonly allowed within the circulatory roadway, initially for horse-drawn vehicles and later for automobiles.

AASHO (precursor to AASHTO) produced *A Policy on Rotary Intersections* in 1942 (*1*). The prevailing designs theoretically enabled free-flow operations but resulted in vehicles merging and weaving: the designs gave priority to entering vehicles, which created queues inside the circulatory roadway that frequently blocked upstream entries. High crash frequency and congestion led to rotaries falling out of favor in the United States after the mid-1950s. International experience with traffic circles became equally negative as traffic volumes increased.

The roundabouts constructed today are derived from practices developed in the United Kingdom to rectify problems associated with historical rotaries and traffic circles. In 1966, the United Kingdom adopted a rule at circular intersections requiring entering traffic to "give way," or yield, to circulating traffic (*2*). This rule allowed circulatory roadway traffic to move by preventing vehicles from entering the intersection until sufficient gaps became available in circulating traffic. The United Kingdom later developed smaller circular intersections that provided adequate horizontal curvature of vehicle paths to achieve slower entry and circulating speeds. Yield on entry and slower speeds improved the safety performance of the circular intersections by reducing crash frequency and severity.

The roundabout represents a significant improvement in operations and safety performance compared with rotaries and other traffic circles. Therefore, many countries have adopted the roundabout as a common intersection form, and some have developed extensive design guides and methods to evaluate their operational performance.

As more regions of the United States have implemented roundabouts, the public has become increasingly familiar with them. Consequently, agencies have begun designing roundabouts with the flexibility to adapt to site conditions and local context. This includes implementing smaller roundabouts or roundabouts with fully traversable features in some locations.

This Guide reflects the evolution of design and implementation, including adaptations to build roundabouts as retrofit projects at non-roundabout and existing roundabout locations, often where a roundabout would not have previously been considered feasible or practical. More recently, however, agencies have adapted their designs to capture the benefits of roundabouts in physically constrained circumstances and with increased cost consciousness. In some cases, a roundabout with design adaptations for a given location or project circumstance may be preferable to a non-roundabout intersection.

Another evolution in practice has been an increasing focus on diverse users from the early stages of planning through final design. This Guide incorporates research and emerging practices on roundabout design for pedestrians, bicyclists, and large trucks. It provides performance checks so that roundabouts are accessible for all users. Similarly, design for bicyclists has evolved considerably in the past decade, and this Guide explains principles and examples of designs that provide accessibility, comfort, and safety for bicyclists. Local design criteria and standards may differ, but this Guide provides principles that can apply even with project-type constraints and within varying local contexts.

1.3.2 Practice in the United States

Roundabout implementation has accelerated in the last 30 years within the United States. In 1998, NCHRP published *NCHRP Synthesis of Highway Practice 264: Modern Roundabout Practice in the United States*, which identified 50 known roundabouts in the United States (*3*). FHWA provided the first national guidance in 2000 with *Roundabouts: An Informational Guide* (*4*), and NCHRP updated this guidance in 2010 with *NCHRP Report 672: Roundabouts: An Informational Guide*, 2nd edition (*5*). By 2016, when *NCHRP Synthesis of Highway Practice 488: Roundabout Practices,* was published, an estimated 3,200 roundabouts had been built in the United States (*6*). A crowd-sourced online roundabout database supports an estimate of at least 8,800 roundabouts in the United States through 2021 (*7*).

Safety performance is a primary consideration in supporting roundabout implementation. The Insurance Institute for Highway Safety (IIHS) commissioned the first national study of the safety effect of roundabout conversions in 2001 (*8*). Two subsequent NCHRP studies—*NCHRP Report 572: Roundabouts in the United States* in 2007 and *NCHRP Research Report 888: Development of Roundabout Crash Prediction Models and Methods* in 2018—expanded on this initial work by updating and providing additional crash modification factors and safety performance functions for a variety of configurations and purposes (*9*, *10*). *NCHRP Synthesis 488* surveyed state departments of transportation (DOTs) on the states of their practices and documented trends in roundabout planning, design, and implementation. One key finding was that “the primary reason cited for the selection of roundabouts is improved safety performance compared with other intersection options, followed by shorter vehicular delays and higher capacity” (*6*).

Exhibit 1.2 shows the estimated number of roundabouts constructed nationally. The exhibit illustrates that roundabout implementation has grown in tandem with the development of key research and publications (*3–17*).

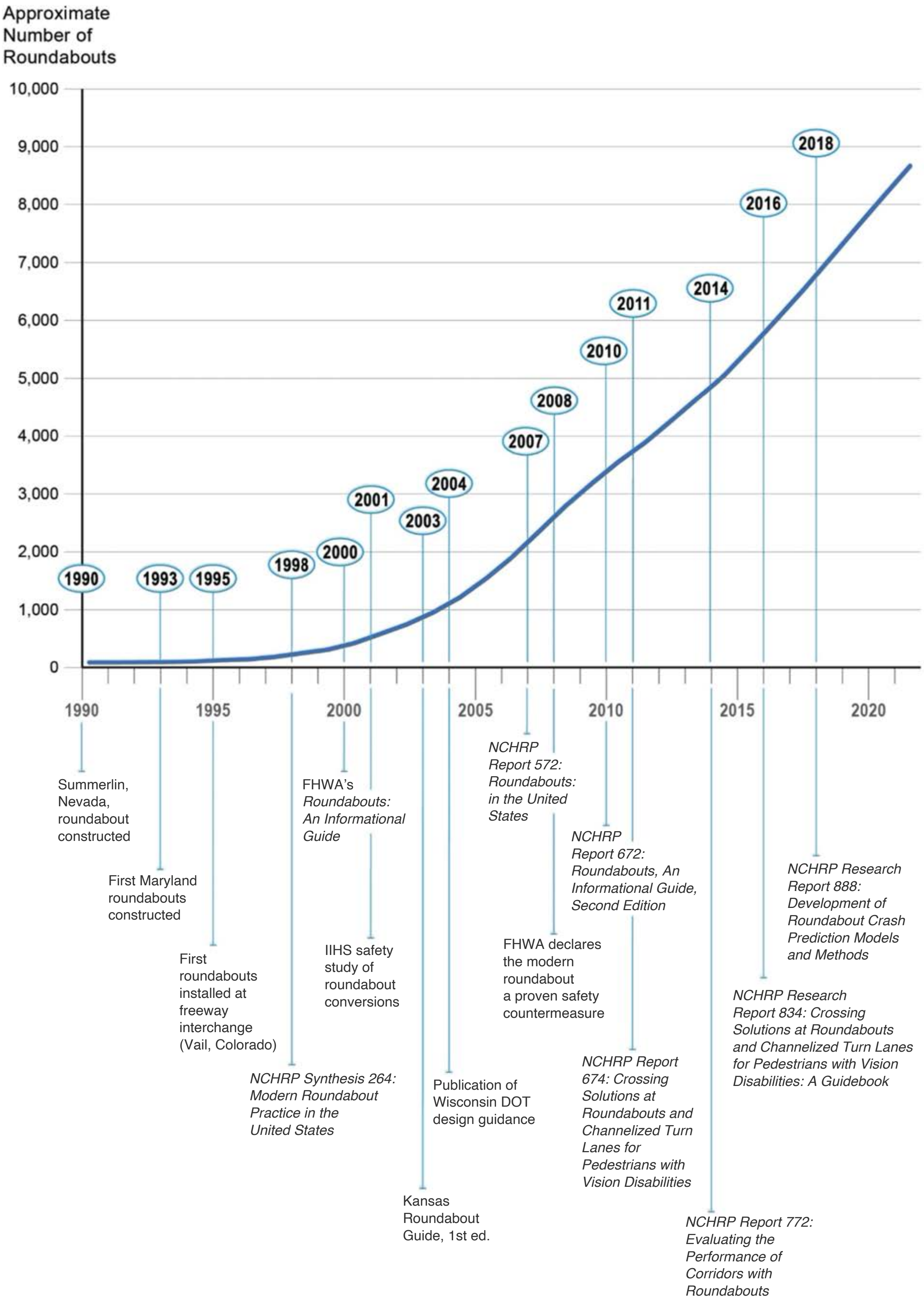
1.4 Policy and Practice Considerations

As the safety performance benefits of roundabouts continue to be documented, agencies are considering roundabouts more broadly. Roundabouts are sometimes favored because their proven safety benefits help agencies support policies, programs, and initiatives.

1.4.1 Vision Zero

A Vision Zero policy or approach aims to eliminate all traffic deaths and serious injuries. First implemented in European cities in the 1990s, Vision Zero policies have since been adopted by agencies in more than 40 communities in the United States (*18*).

Exhibit 1.2. Growth in roundabouts and development of guidance in the United States.



SOURCE: Adapted from Isebrands (*11*), using various sources (*3–10*, *12–17*).

Because roundabouts have been shown to significantly reduce fatal and serious injuries, they are an engineering solution that can be incorporated into a Vision Zero approach. Roundabouts are included among the FHWA *Proven Safety Countermeasures* (*19*). Single-lane roundabouts have been shown to reduce severe crashes by as much as 82 percent compared with two-way stop-controlled intersections and by as much as 78 percent compared with signalized intersections (*9*, *20*).

1.4.2 Safe System Approach

The safe system approach to transportation has been acknowledged practice worldwide for decades. A safe system approach removes the focus from individual behavior and places it on a holistic evaluation of five key elements of the roadway network to reduce the likelihood that people will be seriously injured in the event of a crash. This approach acknowledges human fallibility and, therefore, acknowledges the need for a system that reduces road user risk by building redundancy of safety. Various agencies describe the elements of a safe system approach in different ways but with a common intent. A safe system approach example with five elements is shown in Exhibit 1.3 and summarized below.

This example of a safe system approach has five elements (*21*):

- **Safe road users.** The safe system approach addresses the safety of all road users, including those who walk, bike, drive, ride transit, and travel by other modes.

Exhibit 1.3. Example of a safe system approach.

SOURCE: FHWA (*21*).

- **Safe vehicles.** Vehicles are designed and regulated to minimize the occurrence and severity of collisions using safety measures that incorporate the latest technology.
- **Safe speeds.** Reduced speeds can accommodate human injury tolerances in three ways: reducing impact forces, providing additional time for drivers to stop, and improving visibility.
- **Safe roads.** Designs that accommodate human mistakes and injury tolerances can greatly reduce the severity of crashes that do occur.
- **Post-crash care.** When people are injured in a collision, they rely on emergency first responders to quickly locate them, stabilize their injuries, and transport them to medical facilities. Post-crash care also includes forensic analysis at the crash site, traffic incident management, and other activities.

1.4.3 Roundabouts First Policies

Some states have internal guidance about the way roundabouts are prioritized compared with other intersection types. Some have adopted a "roundabouts first" policy that requires practitioners to consider roundabouts a priority during any intersection improvement or construction. Some state DOTs have developed their own roundabout guidelines and standards by supplementing national guidelines such as *NCHRP Report 672* (*5*), including Georgia, Kansas, Massachusetts, New York, Washington, and Wisconsin (*22–27*). These allow states to codify design, operation, and planning information specific to their state practices and policies. Where no specific state guidelines are established, current national guidance is used.

1.4.4 Performance-Based Design

The transportation industry is moving toward a performance-based design decision-making approach. In practice, this means agencies encourage a clear definition of intended project outcomes and establish performance measures for evaluating designs in relation to those outcomes. This approach has been and continues to be the basis of roundabout design.

Roundabout design is an iterative process to optimize intersection configuration in accordance with performance targets. Historically, performance was based on speed, sight distance, path alignment, and serving design vehicles. Multimodal design continues to expand with the ability to design flexibly for each project type and context. This Guide demonstrates how agencies can use roundabouts to provide design flexibility by applying consistent principles and using performance checks to evaluate the design. Chapter 3: A Performance-Based Planning and Design Approach describes this in more detail.

1.4.5 Intersection Control Evaluation

Many state DOTs have developed ICE processes for selecting the most appropriate intersection form and control and planning intersection projects. ICE provides an objective means to consider the appropriateness of intersection control or intersection types using a performance-based approach to compare alternatives.

Implementation of ICE varies among agencies, but agencies apply the same principle of developing a transparent and documented decision-making process for intersection control selection. ICE is a performance-based framework and approach with at least two stages of increasing evaluation detail. The first stage is a high-level screening of alternatives to advance viable concepts; the second and subsequent stages (if any) are more detailed analyses. The two-stage approach is consistent with typical project development: identifying and evaluating alternatives is an early planning or design step that helps agencies scope and program subsequent preliminary design evaluations as part of environmental clearance and permitting.

Agencies may also structure an ICE framework to emphasize certain performance measures that align with a site context consideration, intended project outcome, or agency preferences. ICE is described in more detail in Chapter 6: Intersection Control Evaluation.

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25. Chapter 26: Roundabouts. In *Highway Design Manual,* New York State Department of Transportation, Albany, October 6, 2021.
26. Chapter 1320: Roundabouts. In *WSDOT Design Manual*. M 22-01.20. Washington State Department of Transportation, Olympia, 2021.
27. Chapter 11: Design, Section 26: Roundabouts. In *Facilities Development Manual*, Wisconsin Department of Transportation, Madison, 2021.

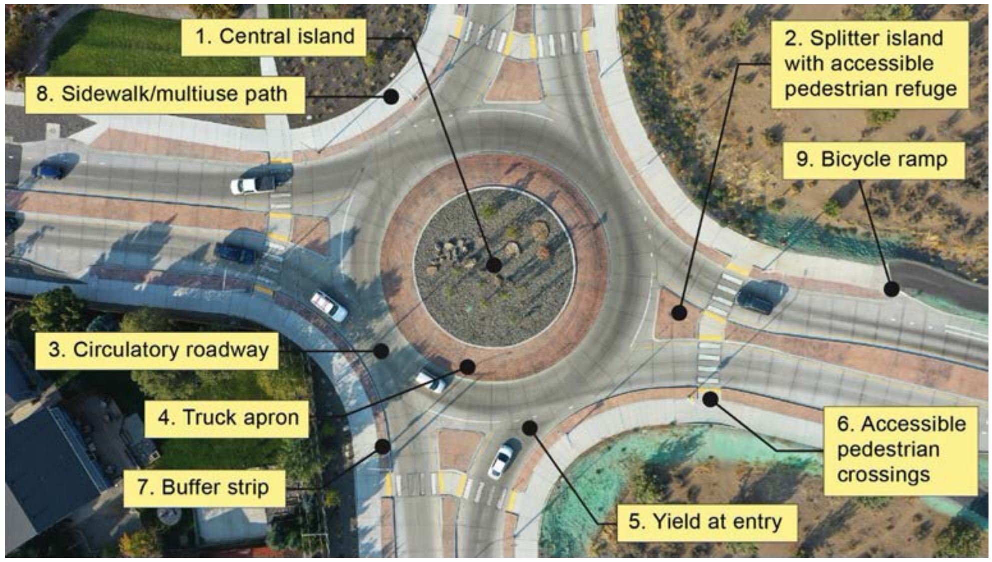
CHAPTER 2

Roundabout Characteristics and Applications

Contents

This chapter provides a general overview of roundabout characteristics as an intersection form and traffic control strategy. This chapter also compares roundabouts with other non-roundabout forms during an alternatives analysis or ICE and classifies roundabout types. The chapter also presents a discussion about where and how roundabouts may be preferable over other intersection forms because of roundabout safety and operational performance and other benefits.

Exhibit 2.1. Common roundabout features.



SOURCE: Kittelson & Associates, Inc.

2.1 Roundabout Definition and Characteristics

A roundabout is a circular intersection form in which traffic travels counterclockwise (in the United States and other countries that drive on the right-hand side of the road) around a central island and entering traffic must yield to circulating traffic. Exhibit 2.1 shows a roundabout annotated with common attributes and characteristics.

Roundabouts have specific design and traffic control features, listed in Exhibit 2.2. In constrained environments, it may be necessary to modify one or more of these components to conform to project conditions. The principles presented later in this Guide are intended to inform design decisions.

2.2 Other Types of Circular Intersections

Other circular intersection types that are not roundabouts include rotaries, signalized traffic circles, traffic calming circles, and other types of circular intersections. While the purpose of this Guide is to assist in roundabout planning, design, and performance evaluations, there is also value in distinguishing among circular intersection forms. The distinctions between circular intersection types may not always be obvious, and other circular forms may be mistaken for roundabouts. The distinction between roundabouts and other circular intersections helps support discussions about the differences between them.

2.2.1 Rotaries

A *rotary* is a circular intersection style implemented in parts of the United States in the early- to middle-20th century. While the term *rotary* has been used historically as a generic term for a traffic circle in some parts of the United States, this Guide uses the term *rotary* specifically to describe circular intersections with large diameters (often greater than 300 ft [100 m]). Exhibit 2.3 shows an example rotary.

Exhibit 2.2. Common roundabout features defined.

Feature	Description
1. Central island	The central island is the center of a roundabout around which traffic circulates. The central island may include a traversable truck apron and a non-traversable portion that is often landscaped. Sometimes, the central island may be completely traversable. The central island does not necessarily need to be circular.
2. Splitter island	A splitter island is a raised or traversable area on an approach that separates entering traffic from exiting traffic and forms part of the geometry to slow entering traffic. If raised and of sufficient width, it provides a refuge for pedestrians to cross the road in two stages.
3. Circulatory roadway	The circulatory roadway is the path vehicles use to travel counterclockwise around the central island. The circulatory roadway does not necessarily need to be circular in shape.
4. Truck apron	A truck apron is a portion of an island or exterior portion along the traveled way that is raised above the travel lanes but traversable by large vehicles. Truck aprons are most common around the central island and are sometimes needed on splitter islands or on the outside of the circulatory roadway for the same purpose.
5. Yield at entry	Entering vehicles must yield to any circulating traffic coming from the left before entering the circulatory roadway.
6. Accessible pedestrian crossing	For roundabouts designed with pedestrian pathways, the crossing location is typically set back from the entrance line, and the splitter island typically provides refuge to allow pedestrians, wheelchairs, strollers, and bicycles to pass through and make the crossing in two stages. The pedestrian crossings must be accessible per the Americans with Disabilities Act. Multilane crossings may require additional traffic control features to make the crossing accessible to all pedestrians.
7. Buffer strip	Buffer strips between the circulatory roadway and the sidewalk separate vehicular and pedestrian traffic and help guide pedestrians to designated crossing locations. Buffer strips may have landscaping or other surface types that are detectably different from a normal walking surface. This feature is an important wayfinding cue for people who are blind or have low vision.
8. Sidewalk	Sidewalks connect existing pedestrian facilities or planned networks.
9. Bicycle ramp	Bicycle ramps can allow people biking to exit the roadway in advance of the circulatory roadway and return to the roadway on the roundabout exit. Bicycle ramps need to be compatible with the surrounding system or future planned facilities. Roundabouts may also accommodate separated bicycle facilities.

Compared with roundabouts, rotaries are characterized by the following design challenges:

- Large diameters that promote increased circulating speeds and create sections of circulatory roadway that induce merging, diverging, and weaving behavior.
- Large entry radii that promote increased entry speeds, which can result in reverse priority (whereby circulating drivers yield to entering vehicles).
- Acute angle entry geometry that results in a poor viewing angle to circulating traffic and may lead to abrupt braking at the yield line or disregard of the yield sign.
- Mixed entry controls (stop signs on entry or yield signs within the circulatory roadway) that can violate a driver's expectation to yield on entry.

Some rotaries have been successfully retrofitted to include roundabout features. While it may be difficult to incorporate all the design features and characteristics of a roundabout, if the primary design principles are achieved, the retrofitted intersection may still operate more efficiently and safely than a rotary. Exhibit 2.4 shows an example rotary in the process of being converted to a roundabout—a new roundabout has been built inside the old rotary.

Exhibit 2.3. Example of rotary.

LOCATION: US 377/TX 183/Camp Bowie, Fort Worth, Texas. SOURCE: City of Fort Worth, Texas, as shown in *NCHRP Report 672* (*1*).

Exhibit 2.4. Example of rotary being converted into a roundabout.

LOCATION: Albany Avenue/Broadway/I-587, Kingston, New York. SOURCE: New York State Department of Transportation, as shown in *NCHRP Report 672* (*1*).

2.2.2 Signalized Traffic Circles

Signalized traffic circles are circular intersections used in some locations where traffic signals control one or more entry-circulating access points within the circular intersection. As a result, signalized traffic circles have different operational characteristics from roundabouts, with queue storage within the circulatory roadway and the progression of signals required.

Exhibit 2.5 provides an example of a signalized traffic circle with signalized entry-circulating access points and pedestrian access to the central island.

Although traffic signals may be used for metering in roundabouts, the entry-circulating point is governed by a yield sign.

2.2.3 Traffic Calming Circles

Traffic calming circles are typically located at local street intersections for vehicular speed management, aesthetics, or both. They are sometimes called *neighborhood traffic circles* because they are commonly used on local streets. They are often retrofits of existing intersections, using a raised central island with few other exterior intersection modifications. The intersection approaches may be uncontrolled or controlled by stop or yield signs. Traffic calming circles do not typically include raised channelization to guide the approaching driver onto the circulatory roadway but may include pavement markings. At some traffic calming circles, left-turning movements for larger vehicles are allowed to occur in front of the central island, potentially conflicting with other circulating traffic. The example in Exhibit 2.6 is an all-way, stop-controlled intersection; the example in Exhibit 2.7 is uncontrolled.

2.2.4 Other Circular Intersections

Some circular intersections that are not roundabouts fall outside the characterization in this section. These include circular intersections whose diameters are larger than the traffic calming circles typically incorporated into residential subdivisions. Some of these circular intersections have on-street parking (as shown in Exhibit 2.8), pedestrian access to the central island, or other features that distinguish them from roundabouts.

Exhibit 2.5. Example of signalized traffic circle.

LOCATION: US 1 / Hollywood Blvd., Hollywood, FL; SOURCE: Lee Rodegerdts.

Exhibit 2.6. Example of traffic calming circle with stop control.

LOCATION: SE Woodward Street/SE 58th Avenue, Portland, Oregon.
SOURCE: Lee Rodegerdts.

Exhibit 2.7. Example of traffic calming circle with no control.

LOCATION: NE 47th Street, Seattle, Washington. SOURCE: Lee Rodegerdts.

Exhibit 2.8. Circular intersection with parking along circulatory roadway.

LOCATION: Chapman Avenue/Glassell Street, Orange, California.
SOURCE: Lee Rodegerdts.

2.3 Roundabout Categories

As roundabout implementation has accelerated in the United States, so has the diversity of roundabout designs. Roundabout designs have increasingly been adapted to match site conditions and project needs, resulting in a variety of example roundabout design approaches. This section offers general terminology for various roundabout types, forms, and categories to support a common understanding and vernacular. It also encourages practitioners to consider and evaluate roundabouts in different locations, environments, and conditions. The terminology need not be interpreted as rigid or as limiting to roundabout planning, design, and implementation.

2.3.1 Roundabout Types

Exhibit 2.9 presents a general description of roundabout types. Roundabouts do not fit neatly into discrete categories. However, the exhibit summarizes roundabouts according to their fundamental design and operational elements: the number of circulating lanes, the presence of traversable elements, and common inscribed circle diameter (ICD) ranges. Although ICD values are provided, they are descriptive and often overlap across roundabout categories. The diameter alone does not establish a roundabout type or category, and roundabouts have been built with ICD values outside the range in the exhibit. In practice, roundabout configurations have been adapted to various site conditions, resulting in physical and performance characteristics that contradict the values presented. As such, **the ICD values in Exhibit 2.9 are not to be used as design constraints or targets.**

The degree of a central island's traversability is a function of two factors: ICD and the design vehicle. A roundabout with an ICD above 90 ft (27 m) typically includes sufficient space for a non-traversable central island portion and a traversable portion (truck apron). The non-traversable portion creates opportunities for locating traffic control signs and landscaping.

Exhibit 2.9. Comparison of common roundabout features across types of roundabouts.

Roundabout Feature	Mini-Roundabout	Compact Roundabout	Single-lane Roundabout	Multilane Roundabout
Central island	Traversable	May be traversable	Non-traversable, but typically includes truck apron	Non-traversable, but typically includes truck apron
Splitter islands	May be traversable with one-stage pedestrian crossing	May be traversable with one-stage pedestrian crossing	Non-traversable with one-stage or two-stage pedestrian crossing, depending on dimensions of pedestrian refuge	Non-traversable with two-stage pedestrian crossing
Common ICD range	45 ft to 90 ft (14 m to 27 m)	65 ft to 120 ft (20 m to 37 m)	90 ft to 180 ft (27 m to 55 m)	150 ft to 200 ft (46 m to 61 m)
Maximum number of circulating lanes conflicting with each entry	1	1	1	2+

NOTE: ICD values are not to be used as design constraints or targets. See Chapter 10 for further discussion.

Roundabout types have become more of a continuum than a set of specific categories. Some agencies in the United States have established their own best practices, along with unique terminology that may be different than the established use of the same terms in other countries. For example, in the United Kingdom, a *mini-roundabout* could be as simple as a painted central island (a painted dot) and accompanying roadway approach pavement markings. In Germany, a mini-roundabout may have a raised but fully traversable central island. In the United States, some agencies call a roundabout with a traversable central island and an ICD ranging from 65 ft to 120 ft (20 m to 37 m) a compact roundabout; other agencies in the United States may call it a mini-roundabout. The name is less important than the opportunity to adapt roundabouts to site conditions while achieving target operational and safety performance.

2.3.2 Roundabouts with Traversable Elements

In recent years, roundabouts with traversable elements have emerged as useful solutions where space is constrained, often in a retrofit scenario of an existing non-roundabout intersection. A principal benefit of these reduced-footprint roundabouts with traversable elements is the potential for lower-cost design and construction with limited impacts on right-of-way, utilities, and environmental resources. Such designs can be constructed within an existing intersection footprint, using permeable pavers in the central island to meet stormwater management requirements for quality and quantity.

Although a traversable central island accommodates large vehicles that seldom cross the intersection, it is designed to serve passenger cars in the circulatory roadway. Depending on the site context, the vehicles intended to drive over a traversable central island may be large trucks (e.g., an AASHTO WB-62 design vehicle) or delivery vehicles (e.g., an AASHTO SU-30 design vehicle). In some cases, the splitter islands are also traversable, and pedestrian crossings are completed in single stages.

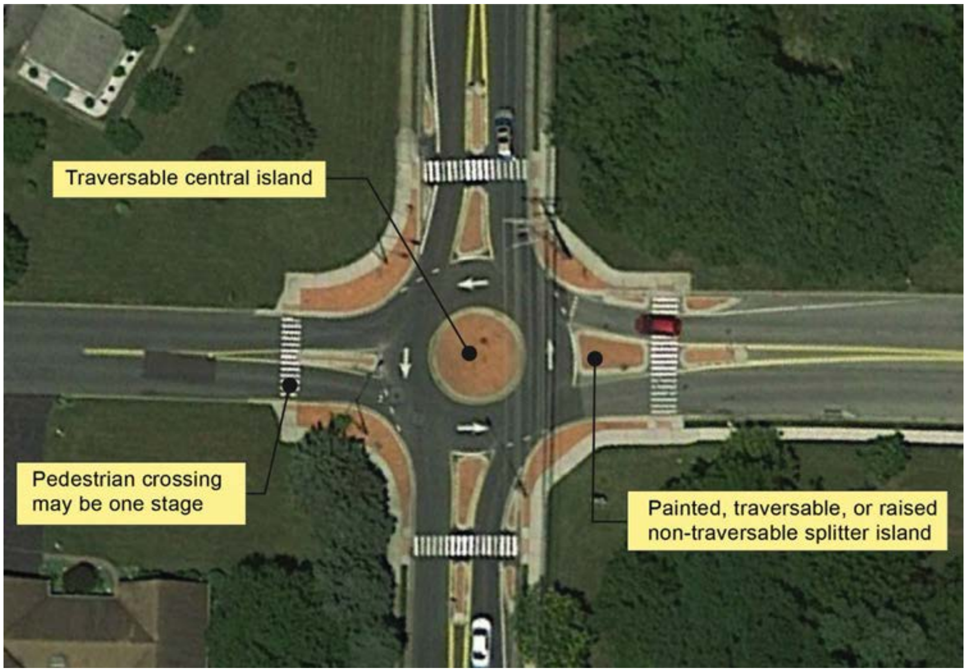
The design of a roundabout with traversable elements needs to align vehicles at entry to guide drivers to the intended path and minimize overrun of the central island to the extent possible. Exhibit 2.10 provides an example of such a roundabout. Note that the pedestrian crossings in this example are designed as one-stage crossings: there is no dedicated pedestrian refuge or waiting space between crossings in each direction of travel. Chapter 10: Horizontal Alignment and Design discusses details of pedestrian crossings.

Roundabouts with traversable elements are commonly used where right-of-way would otherwise be insufficient to accommodate the design vehicle. They are often used in low-speed urban environments with average operating speeds of 30 mph (50 km/h) or less. However, they have been built in suburban or rural locations with approach speeds higher than 30 mph (50 km/h). In such situations, roadway approach treatments to manage speeds approaching and entering the intersection are recommended. In retrofit applications, roundabouts with traversable features are relatively inexpensive because they may only require minimal additional pavement at the intersecting roads and minor widening at the corner curbs. Exhibit 2.11 and Exhibit 2.12 demonstrate roundabouts with traversable elements implemented in different contexts.

Several design strategies allow for traversable elements, as illustrated by various central island designs in Exhibit 2.13. In general, strategies that reduce the required size of the roundabout may reduce the conspicuity of the intersection and could bring conflict points closer. With central islands that are flush or domed, using other distinguishing features to draw attention to the island is encouraged. These may include paint or other features promoting conspicuity.

Similarly, the design of splitter islands may vary depending on site context. Splitter islands can be flush (painted), raised and traversable, raised and non-traversable, or feature a mixture

Exhibit 2.10. Characteristics of a roundabout with traversable features.



LOCATION: Tollgate Road/Macphail Road, Bel Air, Maryland. SOURCE: Map data ©2022 Google.

of traversable and non-traversable features on each approach—the design is dictated by the site's needs and constraints. In addition to affecting sign placement, the use of traversable features on splitter islands may affect whether pedestrians are able to use the splitter island as a refuge in a two-stage crossing.

Mini- and compact roundabouts are two types of roundabouts with traversable features. In practice, these types of roundabouts have similar features. For purposes of this discussion, mini-roundabouts have fully traversable central islands and may have traversable splitter islands, whereas compact roundabouts may have some combination of these traversable elements. The lexicon will continue to evolve, but at present, mini-roundabouts and compact roundabouts represent reduced-footprint-type designs that share a few notable distinctions. Exhibit 2.14 shows an example of a constructed roundabout with traversable elements.

Exhibit 2.11. Example of roundabouts with traversable central island and higher-speed approaches with extended splitter islands.

LOCATION: Ann Arbor-Saline Road/Textile Road, Saline, Michigan.
SOURCE: Map data ©2022 Google.

Exhibit 2.12. Example roundabout with traversable central island and painted splitter islands.

LOCATION: San Francisco Boulevard/Santa Cruz Avenue, San Anselmo, California. SOURCE: Mark Lenters.

Whether to make some or all roundabout elements traversable is a performance-based design decision based on individual project context. When designing roundabouts with traversable elements, practitioners need to consider the following:

- Although roundabouts with traversable elements are typically designed for roads with speeds of 30 mph (50 km/h) or less, they can be used on higher-speed roads if proper speed reduction designs and treatments are incorporated.

Exhibit 2.13. Central island vertical design options.

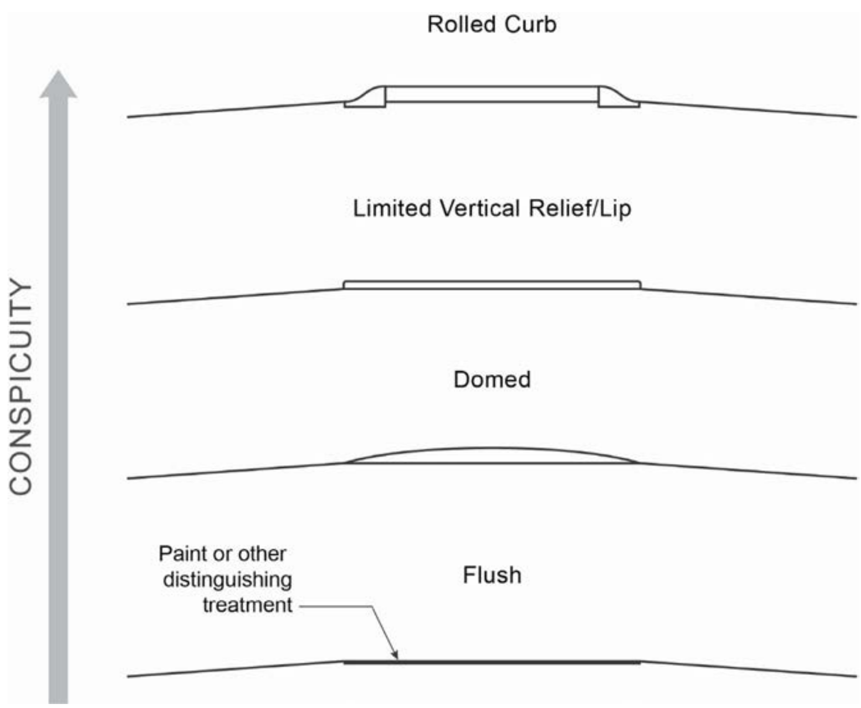


Exhibit 2.14. Example of painted splitter island at a roundabout with traversable features.

LOCATION: Thompson Creek Road/US 50 Eastbound Ramps, Thompson Creek, Maryland. SOURCE: Pete Jenior.

- Because traversable islands are lower in profile and cannot have signs or object markers, roundabouts with traversable features do not provide the same degree of visibility and channelization that larger roundabouts with raised islands provide.
- Trucks reduce the capacity of roundabouts with traversable central islands (as they will at other intersection types with compact forms) because trucks will occupy most of the intersection when turning.

2.3.3 Single-Lane Roundabouts

Single-lane roundabouts have a single-lane entry at all legs, along with one circulatory lane. These roundabouts include central islands and splitter islands that are not traversable by motor vehicles. Truck aprons are typically applied within the central island and are sometimes used within portions of the splitter island or along external curbs. Single-lane roundabouts generally feature a larger ICD than roundabouts with traversable elements (refer to Exhibit 2.9). The size of the roundabout is largely influenced by the choice of design vehicle and available right-of-way. A single-lane roundabout could have a dedicated right-turn-only lane on one or more approaches, in which case the design elements of the corresponding approaches would be multilane and have the characteristics described in Section 2.3.4.

Exhibit 2.15 illustrates the characteristics typical of single-lane roundabouts with non-traversable elements, and Exhibit 2.16 and Exhibit 2.17 provide constructed examples.

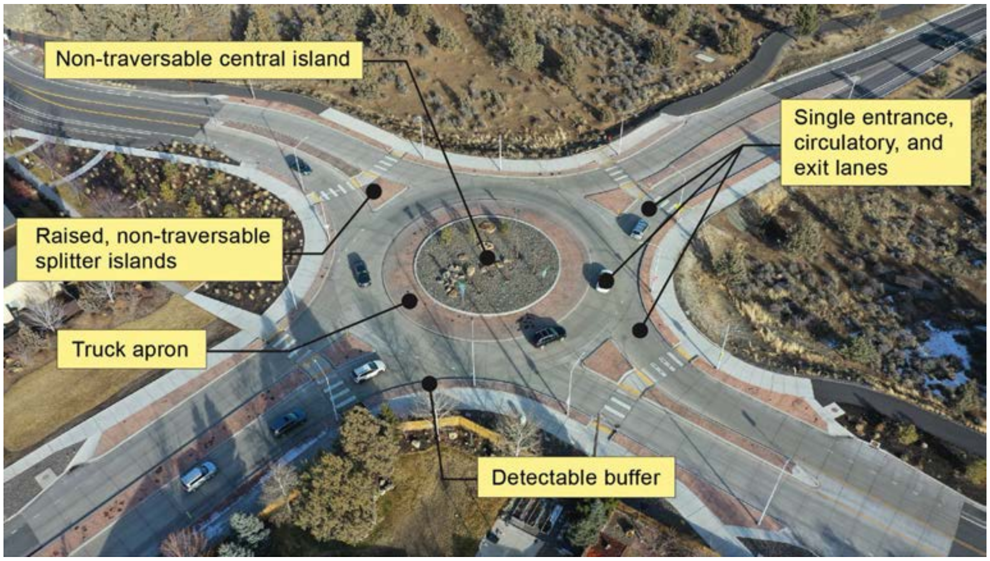
2.3.4 Multilane Roundabouts

Multilane roundabouts include at least two circulating lanes in at least a portion of the circulatory roadway. They include roundabouts with entries on one or more approaches that flare from one to two or more lanes that circulate through the roundabout. In some cases, the roundabout may have a different number of lanes on one or more approaches (e.g., two-lane entries on the major street and one-lane entries on the minor street).

Exhibit 2.18 provides an example of a multilane roundabout. The geometric design includes raised splitter islands, a truck apron, a non-traversable central island, and appropriate entry path deflection.

Multilane roundabouts have some key differences from single-lane roundabouts. They typically have higher circulating and exiting speeds than single-lane roundabouts. This is a result of

Exhibit 2.15. Typical non-traversable, single-lane roundabout elements.



SOURCE: Kittelson & Associates, Inc.

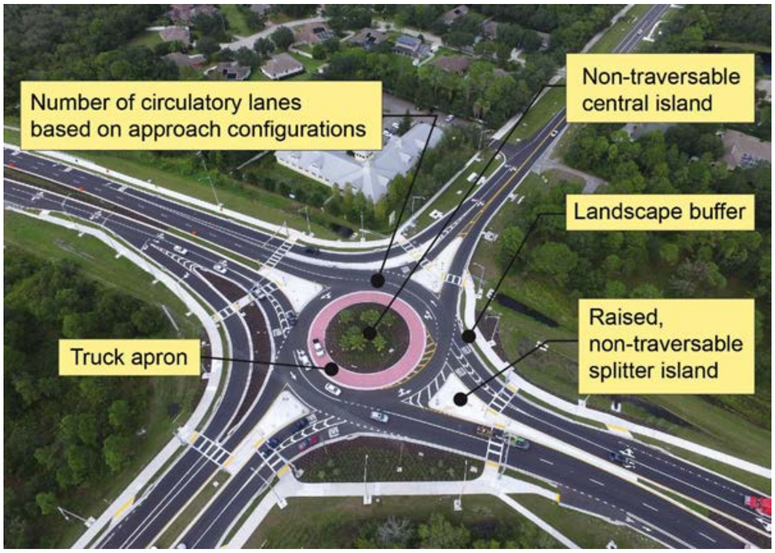
Exhibit 2.16. Example of single-lane roundabout with non-traversable central island and splitter islands.

LOCATION: Dublin, Ohio. SOURCE: Joe Sullivan.

Exhibit 2.17. Example of single-lane roundabout in rural context with extended splitter islands.

LOCATION: Bullfrog Road/Suncadia Trail, Kittitas County, Washington.
SOURCE: Map data ©2022 Google.

Exhibit 2.18. Multilane roundabout elements.



LOCATION: SR 64/Rye Road, Manatee County, Florida. SOURCE: Patel, Greene, & Associates, LLC.

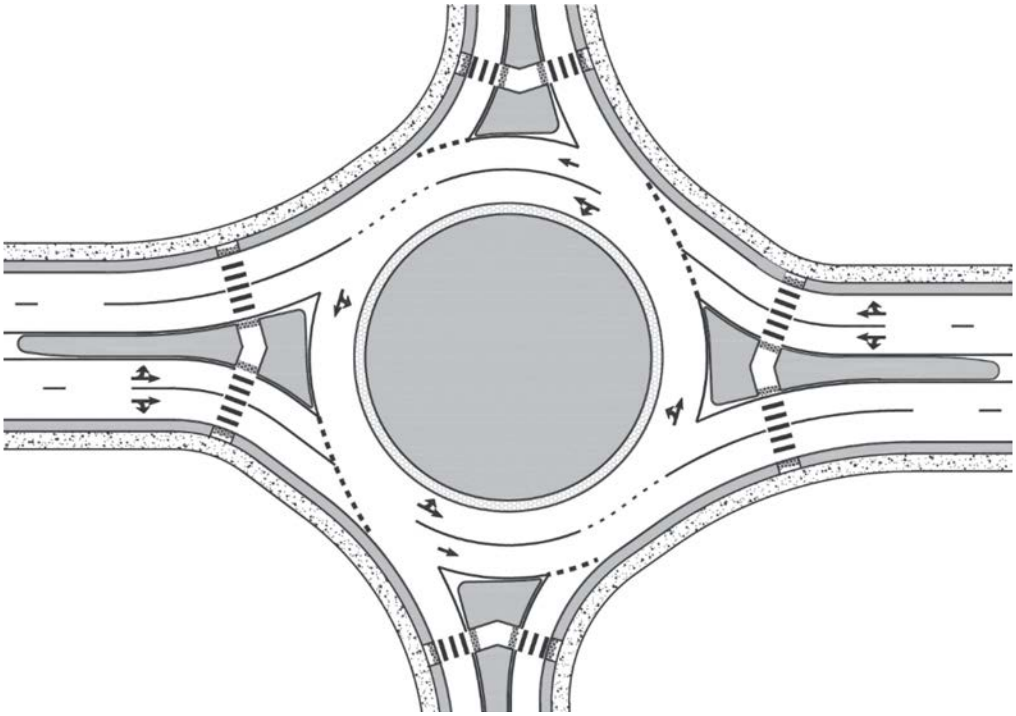
their larger ICD and wider entry and exit configurations that allow vehicles to navigate larger curve radii on their travel paths through the roundabout. Circulatory roadway widths may also vary, depending on the number of lanes and the design vehicle turning requirements. A constant width is not required throughout the entire circulatory roadway, and it is desirable to provide the minimum width necessary to serve the required lane configurations within that specific portion of the roundabout.

A multilane entry or exit also increases pedestrian crossing exposure compared with a single-lane entry or exit. Research into accessible pedestrian design has concluded that in many circumstances, additional geometric treatments, traffic control treatments, or both are needed to make the crossing accessible to all pedestrians (*2*). These design details are discussed in detail in Chapter 10: Horizontal Alignment and Design, Chapter 11: Vertical Alignment and Cross-Section Design, and Chapter 12: Traffic Control Devices and Applications.

For some typical lane configuration combinations, roundabouts may be referred to by the combination of each roadway's lane configuration. For example, a multilane roundabout that includes two entering and exiting lanes along its major roadway and a single entering and exiting lane on its minor street is commonly referred to as a "2-by-1" or "2 x 1." Exhibit 2.19 and Exhibit 2.20 illustrate common multilane configurations. In Exhibit 2.19, the number of lanes within the circulatory roadway varies to match the entry lane configuration.

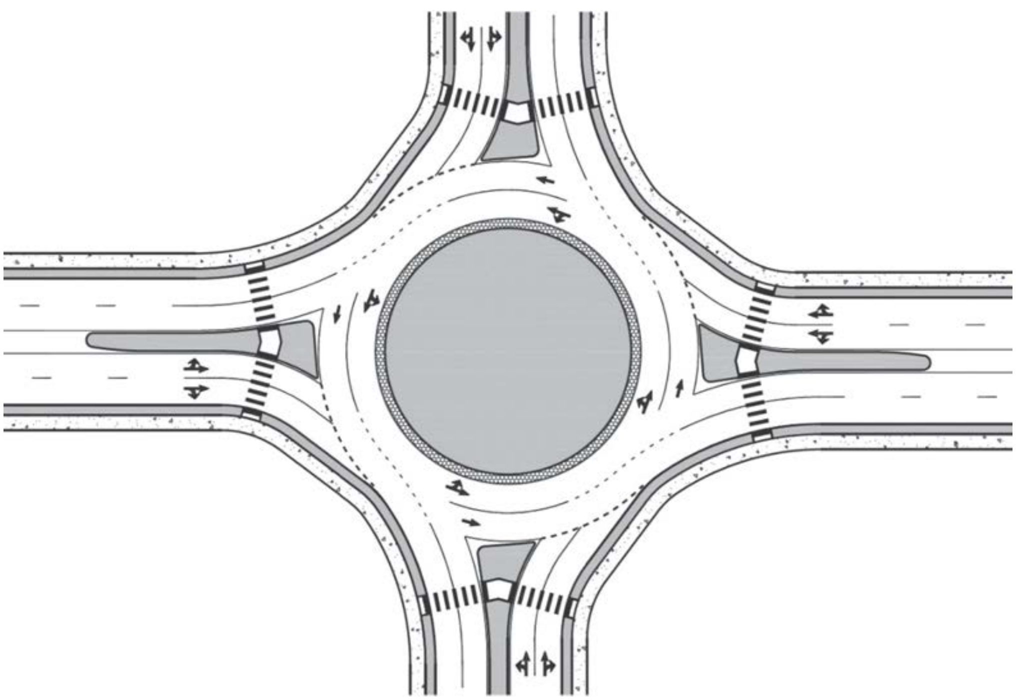
In some instances, the circulatory roadway width may have more lanes than the corresponding entrance that feeds that portion of the roundabout. For example, where dual turn lanes are provided with a two-lane upstream approach, a portion of the circulatory roadway will need two lanes. In these cases, the pavement markings are spiraled outward to enable all vehicles to reach their intended exits without being trapped or needing to change lanes in the circulatory roadway. Exhibit 2.21 illustrates this situation: as the spiral is developed, a portion of the roadway includes three lanes rather than two but retains lane continuity for the left-turning driver on the highlighted path. Although the driver has effectively been shifted from the inside lane to the outside lane, no lane change movement is required. Without the spiraling technique, drivers would be forced to change lanes.

Exhibit 2.19. Example of 2 × 1 multilane roundabout configuration.



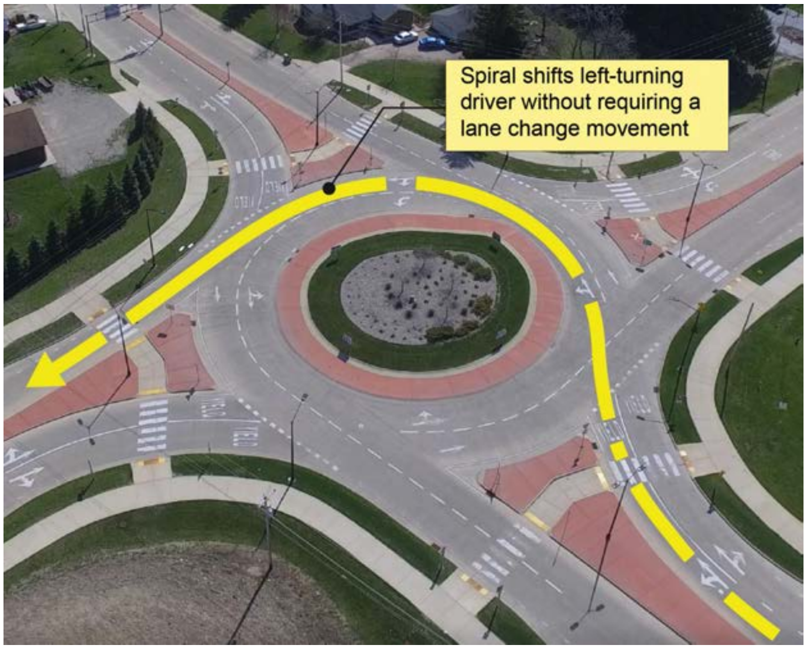
SOURCE: *NCHRP Report 672* (*1*).

Exhibit 2.20. Example of 2 × 2 multilane roundabout configuration.



SOURCE: *NCHRP Report 672* (*1*).

Exhibit 2.21. Example of multilane roundabout with spiraling.



SOURCE: Wisconsin Department of Transportation.

A *turbo roundabout* is a multilane roundabout that uses spiral road geometry and physical channelization to maintain driver lane discipline in the circulatory roadway. Spiraling and lane dividers intend to discourage lane changes that may result in weaving conflicts within the circulatory roadway. Conceptually, the intent is to guide users to appropriate lanes and eliminate lane changes while inside the roundabout. In a turbo roundabout, this objective is accomplished by emphasizing traffic separation treatments between lanes within the circulatory roadway. This separation could include raised, mountable lane dividers; flush lane dividers; or solid pavement markings—all of which discourage lane changing and promote lane discipline (*3*).

European turbo roundabouts often include perpendicular (radial) entry alignment with lane dividers to direct motorists to the correct circulating or exiting lane (see Exhibit 2.22). This concept integrates raised traffic dividers on entry, within the circulatory roadway, and within

Exhibit 2.22. European style turbo roundabout with perpendicular entries.

LOCATION: N471/Lindscheiding, Rotterdam, South Holland, Netherlands.
SOURCE: Map data ©2022 Google.

the two-lane exits. As United States practice has evolved, roundabouts have been constructed with a mix of elements that borrow from turbo roundabout designs. This creates examples in the United States that may be hard to categorize strictly as turbo roundabouts as defined in European practice. Further discussion is provided in Chapter 10: Horizontal Alignment and Design.

2.4 Considerations in Building Roundabouts

Agencies build roundabouts to achieve various goals, including

- **Safety performance.** Reduced vehicular speeds, reduced crash frequency, and reduced crash severity are chief benefits for agencies that select and install roundabouts. Roundabouts can be an integral part of a Vision Zero and safe system approach, as described in Chapter 1: Introduction.
- **Operational performance.** Reduced delay, stopping, and queuing compared with signalized and stop-control alternatives are key factors in selecting roundabouts. In many cases, roundabouts exhibit reduced emissions compared with signalized alternatives (*4*).
- **Gateway effect.** Agencies have installed roundabouts to reinforce a change of context (e.g., the interface between rural and urban areas) and promote a speed reduction on a given roadway section.
- **Placemaking.** *Placemaking* refers to creating a connection between people and their communities with more pedestrian-friendly environments than alternatives. Roundabouts can support placemaking at a single location or along corridors.

The following sections discuss some of the benefits and drawbacks of roundabouts.

2.4.1 Safety Performance

A roundabout's safety performance benefits are a product of its geometric design. At roundabouts, vehicles travel in the same direction, eliminating left-turn and head-on conflicts associated with non-roundabout intersections. Roundabout design places a high priority on speed control, typically requiring speeds of 15 mph to 25 mph (24 km/h to 40 km/h). Speed control is provided by geometric features, complemented by signing and pavement marking. Because of this, roundabouts can achieve speed control at all times of the day. Other intersection forms typically rely on traffic control devices or the impedance of other traffic to reduce speeds. Lower vehicle speeds contribute to the following safety benefits:

- More time for entering drivers to judge, adjust speed, and enter a gap in circulating traffic.
- Smaller sight triangles needed for users to see one another.
- Increased likelihood of drivers yielding to pedestrians.
- More time for all users to detect and correct their mistakes or adjust to the mistakes of others.
- Less frequent and less severe crashes, including crashes involving pedestrians and bicyclists.
- Easier intersection navigation for novice users.

Single-lane roundabouts exhibit some of the fewest total and severe crashes compared with other intersection forms (*5*). Here, drivers have no lane-use decisions to make, pedestrians cross one lane of traffic at a time, and lower speeds allow for comfortably mixed bicycle and motor vehicle flow.

Multilane roundabouts often do not achieve the same levels of crash reduction as their single-lane counterparts. Multilane roundabouts serve higher traffic volumes over more lanes compared with single-lane configurations. However, the severity of crashes is generally comparable at multilane and single-lane roundabouts (*5*, *6*). The low speeds present in roundabouts compared with those of non-roundabout intersections reduce the frequency of severe crashes.

Because of the increased number of conflicting and interacting movements, user decisions are more complex at multilane roundabouts than at single-lane designs. Pedestrians face potential multiple-threat conflicts as they cross more than one lane of traffic at a time. Pedestrians who are blind or have low vision face a complex auditory environment unless the intersection incorporates additional treatments to improve accessibility. People on bicycles traveling in the same travel lanes as motor vehicles must select the correct lane for circulating; if traveling as pedestrians, they face the same conflicts as other pedestrians. Despite the increase in conflict points relative to single-lane roundabouts, the overall crash severity of multilane roundabouts is often reduced relative to comparable signalized intersections (*5*).

Chapter 7: Safety Performance Analysis discusses roundabout safety performance in more detail.

2.4.2 Operational Performance

Roundabout vehicular traffic operations are determined by gap acceptance: entering drivers look for and accept gaps in circulating traffic. Low speeds facilitate this gap acceptance process. Further, the operational efficiency (capacity) of roundabouts is greater at lower circulating speeds because of the following two phenomena related to speed:

- The faster the circulating traffic, the larger the gaps that entering drivers require to comfortably enter the intersection. With fewer acceptable gaps, entering vehicles stop at the yield line more often.
- Entering traffic, which is first stopped at the yield line, requires even larger gaps in the circulating traffic to accelerate and travel with circulating traffic. The faster the circulating traffic, the larger this gap must be. This translates into fewer acceptable gaps and longer delays in entering traffic.

Roundabouts operating within their capacity typically operate with lower vehicle delays than other intersection forms and control types (*1*). Roundabout traffic may not need to come to a complete stop when no conflicts are present. When there are queues on one or more approaches, traffic within the queues usually continues to move. Roundabouts provide an alternative to signalized control for locations where two-way stop control fails but minor street volumes remain relatively low. Roundabouts can also serve intersections where the major movement may shift throughout the day from a *major street* movement to a *minor street* movement, especially in comparison with a two-way stop-control strategy. Roundabouts also serve intersections with relatively balanced approach volumes well (i.e., no clear “major” or “minor” street based on volumes).

Roundabouts treat all entering movements with equal priority, with no priority for major movements over minor movements. Each approach must yield to circulating traffic, regardless of whether the approach is a local street or major arterial. This may result in more delay to the major movements than a stop or signal-controlled intersection. The delays depend on the volume of turning movements and need to be analyzed individually for each approach.

Chapter 8: Operational Performance Analysis discusses roundabout operational performance in more detail.

2.4.3 Spatial Requirements

Roundabouts may require more space at the intersection than comparable stop-controlled or signalized intersections. This space requirement is dictated in part by the size and shape of the roundabout (e.g., circular versus non-circular). However, the additional space needed in the vicinity of a roundabout may be offset by reduced space needed between intersections. It may also be possible to space roundabouts closer together than traffic signals because of shorter queue lengths. Roundabouts can be as large as necessary for node capacity, keeping the roadways between nodes narrow. This is sometimes referred to by the shorthand *wide nodes, narrow roads*. For this reason, roundabouts are especially suited at interchange ramp terminal intersections because they reduce the bridge width over or under the highway.

Exhibit 2.23 depicts the lane and spatial requirements between a roundabout and a signalized intersection. The lighter shaded area indicates area that may be necessary for a roundabout but not for a signalized intersection. The darker shaded area indicates area that may be needed for a signalized intersection but not for a roundabout.

The right-of-way savings between intersections may make it feasible to accommodate parking, wider sidewalks, planter strips, bicycle lanes, or a combination of these. Another space-saving strategy is to use flared approach lanes to provide additional capacity at the intersection while maintaining the benefit of reduced spatial requirements upstream and downstream of an intersection.

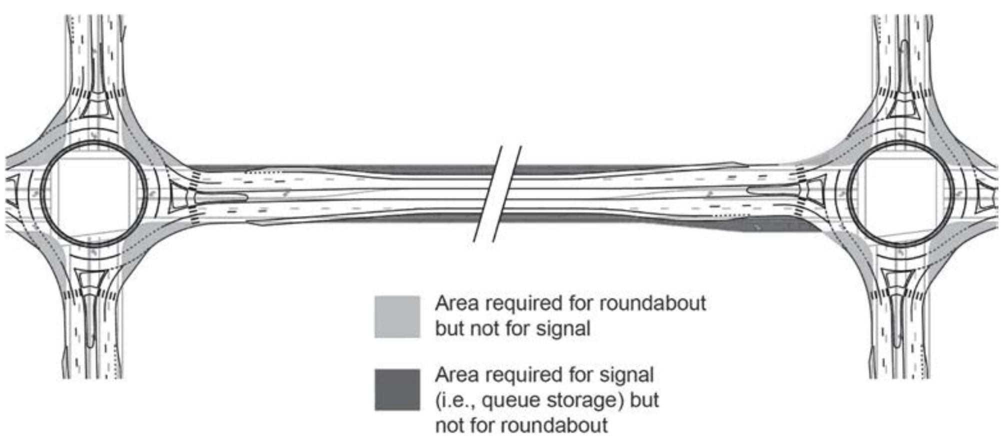
2.4.4 Access Management

Roundabouts accommodate U-turns at isolated locations or on roundabout corridors. They replace tight turning radii for vehicles U-turning from a left lane. They reduce delay to left-turning vehicles at non-roundabout intersections where additional time must be added to a cycle length to serve left-turning and U-turning traffic. The ease of U-turns supports integrating raised medians in access-managed corridors.

U-turns are rarely included at freeway interchange ramp terminal intersections. Therefore, U-turns need not be provided at roundabout ramp terminal intersections without a defined project need (and included in all alternatives under consideration).

Teardrop configurations allow unimpeded flow between ramp terminal intersections, increasing the interchange capacity. The teardrop design may also provide a smaller footprint and prevent right-of-way impacts, compared with an alternative design. However, two-way frontage roads or service interchanges, where the ramp terminal intersection connects to a two-way street, require maintenance of a portion of the circulatory roadway and, by default, allow U-turns on the cross street. Exhibit 2.24 illustrates the different design approaches on each side of a freeway interchange; the teardrop configuration does not provide for U-turns, while the circular roundabout does.

Exhibit 2.23. Spatial requirements at intersections and along roadway segments for a roundabout compared with a signal.



SOURCE: *NCHRP Report 672* (*1*).

Exhibit 2.24. Example of roundabout freeway interchange with various U-turn treatments.

LOCATION: Vail Road/I-70 Ramps, Vail, Colorado. SOURCE: Map data ©2022 Google.

2.4.5 Environmental Considerations

Roundabouts can provide environmental benefits if they reduce vehicle delay and the number and duration of stops compared with an alternative. Even when traffic volumes are heavy, vehicles in roundabouts advance slowly in moving queues rather than coming to a complete stop. This may reduce noise and air quality impacts as well as fuel consumption by reducing the number of acceleration/deceleration cycles and the time spent idling (*4*). Environmental impacts may also include the amount of impervious surface and overall footprint.

2.4.6 Operation and Maintenance Costs

A single-lane roundabout intersection as part of a new construction project can have construction costs comparable with a new signalized intersection. For a larger roundabout, the construction cost can be higher than that of a traffic signal because of its larger footprint. However, the ongoing operations and maintenance cost of a roundabout can be less than that of a signal. The service life of a roundabout is significantly longer—approximately 25 years, compared with 10 years for a typical signal (*7*). A life-cycle cost analysis would account for the ongoing costs and difference in service life. Roundabouts also provide substantial societal cost savings compared with a signal by reducing fatal and injury crashes over their service life. These factors are discussed in Chapter 6: Intersection Control Evaluation.

Although a roundabout without active traffic control devices at its pedestrian crossings does not typically include signal equipment (requiring constant power, periodic light bulb and detection maintenance, and regular signal timing updates), it can have decorative landscaping that leads to higher landscaping maintenance costs. A fair cost comparison with alternatives would include only the landscaping required for each alternative. The degree and type of landscaping appropriate at roundabouts are discussed in Chapter 14: Illumination, Landscaping, and Artwork. Illumination costs for roundabouts could be greater than that of signalized intersections if a larger area is required for coverage.

From a maintenance perspective, roundabouts are more resilient than traffic signals. For example, in the event of a power outage, roundabouts continue to operate as normal, whereas traffic signals go dark and either default to all-way stop-control operation or require manual flagging.

2.4.7 Traffic Calming

Roundabouts reduce vehicle speeds using geometric design. Consequently, speed reduction can be realized at all times of day and on streets of any traffic volume. It is difficult for drivers

Exhibit 2.25. Example of roundabout as a gateway treatment.

LOCATION: Mandalay Avenue/Acacia Street, Clearwater Beach, Florida.
SOURCE: City of Clearwater, Florida, as shown in *NCHRP Report 672* (*1*).

to speed through an appropriately designed roundabout with raised channelization requiring navigation of a curved path. Example applications include using roundabouts at the transition from a rural, high-speed environment to a low-speed, urban environment and to demarcate commercial uses from residential areas. Therefore, roundabouts can make successful gateways at the interface between rural and urban areas where speed limits change or at freeway ramp terminals. In these applications, the reduced traffic speeds reinforce the notion of a significant change in the driving environment. Exhibit 2.25 shows a photo of a roundabout providing a gateway feature between commercial and residential land uses.

2.4.8 Aesthetics

Roundabouts may serve as attractive entries or focal points for communities, creating a sense of place. It may be possible to place monuments and art in some portions of the central island if they are appropriate for the roadway context and do not pose a significant safety risk to errant vehicles (see Exhibit 2.26). Landscaping can be installed on the central island and splitter islands if requirements for sight distance are met (see Exhibit 2.27). In addition, pavement textures and colors added to truck aprons or other elements can improve the intersection's appearance. When installing landscaping or other artistic features on the central island, practitioners need to consider clear distance and offsets to reduce the safety risk of hard objects in the central island. Additional guidance for landscaping and art at roundabouts is described in Chapter 14: Illumination, Landscaping, and Artwork.

Roundabouts are also used in tourist or shopping areas to aesthetically enhance the visual environment. They have been justified as a spur to economic development, conveying to developers that the area is favorable for investment. Some are exhibited as a signature feature on community postcards, advertisements, and travelogues.

2.4.9 Unusual Geometry

Roundabouts provide the flexibility to consolidate and manage complex intersections. Exhibit 2.28 and Exhibit 2.29 illustrate two examples of innovative treatments that incorporate roundabout

Exhibit 2.26. Example of roundabout with art in the central island.

LOCATION: NE Franklin Avenue/NE 8th Street/NE 9th Street, Bend, Oregon. SOURCE: Lee Rodegerdts.

Exhibit 2.27. Example of roundabout with landscaping in the central island.

LOCATION: Sussex Drive/Rideau Gate, Ottawa, Ontario, Canada. SOURCE: Lee Rodegerdts.

Exhibit 2.28. Example of roundabout under construction with unusual geometries.

LOCATION: Vine Street (US 183), Hays, Kansas. SOURCE: City of Hays, Kansas.

Exhibit 2.29. Example of roundabout with unusual geometry.

LOCATION: US 395/E Hawthorne Avenue/Railroad Avenue/S Washington Street, Colville, Washington. SOURCE: Brian Walsh.

elements by combining what would otherwise be closely spaced intersections with overlapping turning movements and storage needs. The result is an unusual roundabout geometry that nevertheless adheres to the principles of roundabout design. Innovative applications of the core roundabout planning and design principles continue to emerge, and many examples that resolve geometric challenges exist throughout the United States.

2.5 Innovative Contexts

Roundabouts have proven to be a viable intersection control form in any context that can be served by other types of intersections. In addition to the benefits of roundabouts listed in the previous section, the following considerations are relevant to applying roundabouts in each context:

- **Hybrid implementation.** Site needs or constraints may dictate design decisions that vary from the typical roundabout characteristics described in this chapter. For example, rather than eliminate a roundabout from consideration, an agency may adapt a design to fit the site context while still capturing the chief benefits of a roundabout and adhering to performance checks.
- **Metering approaches.** There may be circumstances where signalizing one or more roundabout approaches can improve the roundabout's operations. Providing signal control at one or more roundabout approaches is referred to as *roundabout metering*, which may be appropriate when the circulating volumes eliminate adequate gaps within the circulating traffic for vehicles from an approach to enter. Metering a roundabout may improve performance by creating gaps that would otherwise not occur. Metering is discussed in more detail in Chapter 12: Traffic Control Devices and Applications.
- **Roundabouts near rail crossings.** Roundabouts are at-grade intersections, and their consideration and placement at a rail crossing deserve the same level of attention and scrutiny as other intersection control strategies (e.g., stop or signalized) or other intersection forms. Agencies have successfully implemented roundabouts near rail crossings. Exhibit 2.30 shows a roundabout and a signalized intersection at a rail crossing. Roundabouts at or near rail crossings are discussed in more detail in Chapter 12.

Exhibit 2.30. Railroad crossing through a roundabout.

LOCATION: Bass Road/N Hadley Road/Yellow River Road, Fort Wayne, Indiana. SOURCE: Map data ©2022 Google.

2.6 References

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PART II

Planning and Stakeholder Considerations

PROJECT DEVELOPMENT PROCESS

	Part I: Introduction to Roundabouts	Chapter 1: Introduction Chapter 2: Roundabout Characteristics and Applications
Planning	***Part II: Planning and Stakeholder Considerations***	**Chapter 3: A Performance-Based Planning and Design Approach** **Chapter 4: User Considerations** **Chapter 5: Stakeholder Considerations** **Chapter 6: Intersection Control Evaluation**
Identify and Evaluate Alternatives	*Part III: Roundabout Evaluation and Conceptual Design*	Chapter 7: Safety Performance Analysis Chapter 8: Operational Performance Analysis Chapter 9: Geometric Design Process and Performance Checks
Preliminary Design	*Part IV: Horizontal, Vertical, and Cross-Section Design*	Chapter 10: Horizontal Alignment and Design Chapter 11: Vertical Alignment and Cross-Section Design
Final Design Construction, Operations, and Maintenance	*Part V: Final Design and Implementation*	Chapter 12: Traffic Control Devices and Applications Chapter 13: Curb and Pavement Details Chapter 14: Illumination, Landscaping, and Artwork Chapter 15: Construction and Maintenance
Supplemental Appendix		Appendix: Design Performance Check Techniques

CHAPTER 3

A Performance-Based Planning and Design Approach

Contents

Chapter 3 outlines a performance-based planning and design approach to considering and evaluating roundabouts. To employ a performance-based planning and design approach, practitioners must first identify the desired project outcomes and understand the project-specific context, as well as the roadway and intersection users. Using this as a foundation, practitioners can determine appropriate performance measures to evaluate the trade-offs of various roundabout design decisions.

Completing these steps early in the project planning phase allows practitioners to consider the most promising concepts and tailor them to the specific project. As projects move through each development stage, some concepts may be removed by screening, while other, more promising concepts are refined and evaluated in increasing detail. Reviewing and confirming project goals throughout planning, design, and construction validates that the chosen alternative, whether a roundabout or something else, reflects the original project goals and serves the intended users. A performance-based approach is especially helpful for practitioners developing solutions and evaluating roundabouts in fiscally and physically constrained environments.

National activities and associated publications, such as FHWA's Performance-Based Practical Design initiatives and *NCHRP Report 785: Performance-Based Analysis of Geometric Design of Highways and Streets*, have resulted in a framework for executing a performance-based planning and design approach within a project (*1*, *2*). AASHTO's *Policy on Geometric Design of Highways and Streets*, 7th edition (Green Book), includes information on how practitioners can use a performance-based approach to deliver projects in a variety of contexts and project stages (*3*).

This chapter creates a foundation for other chapters to guide practitioners in evaluating trade-offs, integrating design, assessing operations, and optimizing safety performance when planning and designing roundabouts.

3.1 Ties to the Project Development Process

Historically, network planning and roadway functional classification have established parameters for roadway features, anticipated posted speeds, and set expectations for level of service. Research based on an expanded functional classification for highways and streets provided additional contexts beyond the simple categories of *urban* and *rural* to better support efforts for context-sensitive, practical design along with other performance-based planning and design approaches (*4*). The Green Book established a new framework for geometric design, incorporating expanded contexts (termed *context classification*) to emphasize a performance-based approach to geometric design. This approach emphasizes flexibility and encourages designers to take advantage of that flexibility throughout the performance-based framework (*3*).

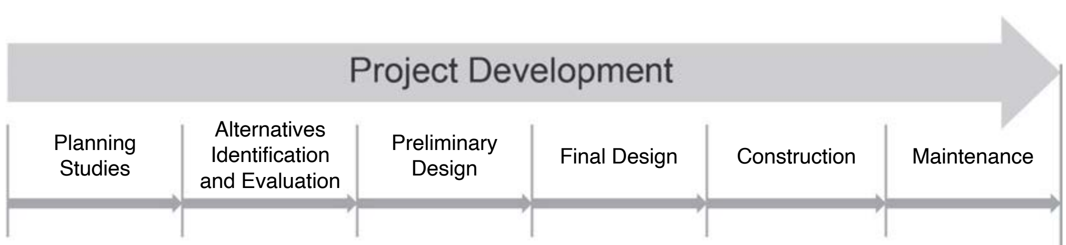
Performance goals and outcomes can influence a project even before project design begins. Early project scoping, alternatives identification, and evaluation efforts significantly influence subsequent design outcomes. As a project evolves from preliminary to final design, it becomes more difficult to modify roundabout design configurations to achieve desired outcomes. Using a performance-based planning and design approach and conducting evaluations early and continuously in the project development process increase the opportunities for design flexibility.

In this Guide, the project development process is defined according to the stages described below. Federal, state, and local agencies may use different names or other nomenclature, but they share the intent of advancing from planning to implementation. Exhibit 3.1 illustrates the overall project development process.

The steps in the project development process are as follows:

- **Planning studies.** Planning studies often include exercises, such as problem identification, that connect a project's goals to the roadway and intersection concepts under consideration. Planning studies can include isolated locations, corridor concepts, or network screening exercises such as schematics or other depictions of the intended plan. This can include limited geometric concepts on the general type or magnitude of project solutions to support programming.
- **Alternatives identification and evaluation.** The project needs identified in prior planning studies will inform concept identification, development, and evaluation. At this stage, the project context and intended outcomes guide the development of potential solutions tailored

Exhibit 3.1. Project development process.



to meet the project's opportunities and constraints. Activities at this stage can include early ICEs to assess, screen, and advance intersection forms and traffic control strategies for more detailed refinement and assessments. Chapter 6: Intersection Control Evaluation provides additional information.

- **Preliminary design.** This stage often includes engineering and environmental review activities to support project permitting, approval, and environmental clearances, typically to a 30 percent completion level. Roundabout concepts advancing from the alternative's identification and evaluation stage, including geometric evaluations, are further refined and screened during preliminary design. Often, preliminary design activities are part of the ICE process. The corresponding increased geometric design detail allows for refined technical evaluations and analyses that inform environmental clearance activities. Common components of preliminary design include
  - Horizontal and vertical alignment design,
  - Typical sections,
  - Grading plans,
  - Structure type, size, and location determinations,
  - Signing and pavement markings,
  - Illumination and traffic control devices, and
  - Drainage and utilities.
- **Final design.** During the final design stage, design elements are advanced and refined. Typical review periods include completion levels of 60 percent, 90 percent, and 100 percent before plans, specifications, and estimates for construction are final. During this stage, the level of detail increases substantially as the plan advances; however, there is little variation in design decisions.
- **Construction.** Construction activities can include geometric design decisions related to temporary streets, connections, or conditions that facilitate roundabout construction. In some cases, factors like the need to accommodate traffic during construction or the associated staging of improvements might influence the location or size of a roundabout. The intended means of construction determines many factors throughout this phase.
- **Maintenance.** Maintenance considerations can influence roundabout planning and design. For example, intersections often include intersecting underground utilities that require maintenance access. Access to a utility in the central island could influence the selected roundabout's position, size, or both (e.g., making the non-traversable central island larger to increase the space available compared with a similar location). Other maintenance considerations include landscaping and snow removal.

3.2 Project Goals

Outlining clear project goals and desired outcomes early will lay the foundation for a roundabout design that provides a beneficial and lasting impact on the roadway and the community. Identifying the project catalyst (safety, operations, speed management, access management, etc.) can help practitioners align goals and desired outcomes with the needs of the roadway users and the surrounding context. For example, a roundabout project initiated to reduce crash frequency and severity for pedestrians would not arbitrarily add lanes that increase vehicular capacity. These features can result in higher vehicle speeds and increased pedestrian crossing distances, which could counter the original goal. Project development priorities may vary across agencies, but the project catalyst can help practitioners identify appropriate project goals.

A project's goals ideally exist as a brief list of succinct points. These could be based on intersection features that best address a project catalyst or planning objective, agreeing on right-of-way investments or priorities, or assessing current and future community needs (*5*).

Project goals may derive from community values as they relate to a multimodal transportation vision and the study area's associated land-use goals. Goals can be visionary and focused on the future but need to be stated in plain, non-technical language and understood by community members. It is vital to consider safety for all users when establishing goals. At a minimum, goals will address:

- **Vision of the place.** The vision will incorporate the existing context and may relate to a desired future land-use pattern. Ideally, the vision will also include the nature of future growth and other community values, such as safety, economic development, community character, and environmental and cost impacts. Local agency plans may document the future vision of the place after being vetted with area stakeholders. Topics for discussion could relate to preserving the nature and character of the community or a specific location.

  For example, Exhibit 3.2 shows a roundabout in the lower-left corner of an aerial photograph. This roundabout is the first part of a roadway network that will serve future development within the boundary. A roundabout was selected for this location on the basis of the desired character and to support economic development associated with long-range land-use plans.
- **Desired role of the facility.** The desired role of the facility draws heavily from the characteristics of a given roadway and intersection. Practitioners need to consider these in tandem with the stakeholder-vetted regional and local vision and goals for the study area. A facility could function as a regional commuting facility with longer-distance trips, or it could serve as a local roadway with mostly short-distance trips. In some locations, "Main Street" may be a state highway. A roundabout design in a community may be uniquely different from a design outside the community on the same state highway.

  For example, Exhibit 3.3 shows an arterial corridor formerly consisting of two lanes in each direction and signalized intersections. Residents were concerned about speed and the difficulty of crossing the roadway, and businesses were concerned about a shortage of parking and lack of comfortable and aesthetically pleasing public spaces. After a comprehensive traffic management plan was completed, the roadway was reduced to one lane in each direction,

Exhibit 3.2. Example of a roundabout supporting community vision.

LOCATION: NE 18th Street/NE Cooley Road, Bend, Oregon. SOURCE: Map data ©2022 Google.

Exhibit 3.3. Example of a roundabout supporting desired role of facility.

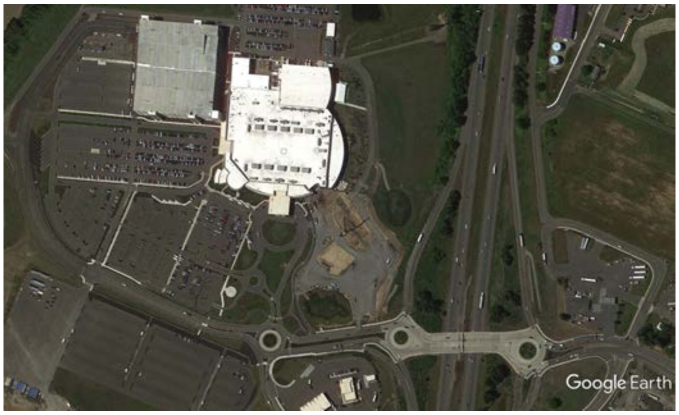
LOCATION: La Jolla Boulevard, San Diego, California. SOURCE: Map data ©2022 Google.

with landscaped street medians and diagonal parking. Roundabouts were implemented at five intersection locations, supporting a common desire for the roadway and community.

- **Major users of the facility.** The project context and the role of the facility will inform who the existing or anticipated users are. Based on observations of existing and future transportation and land-use conditions, practitioners can define who the major users of the facility are now and will be in the future. These users may include pedestrians, bicyclists, transit users, freight traffic, or motorists and demographic groups such as older adults, school children, tourists, retailers, employees, and lower-income communities for major land uses around the facility. Land uses can change over time, with a corresponding change in the types of users.

  For example, Exhibit 3.4 shows a diamond interchange with roundabout ramp terminal intersections. This interchange replaced an outdated rural diamond form that had a two-lane freeway overcrossing and stop-controlled intersections. As an interchange on an interstate freeway, the roundabouts need to address freeway traffic, including large trucks and passenger cars serving a truck stop and other travel services. The regional commercial attraction in the northwest corner of the photo brings visitors, many of whom are first-time users of these roadways. The roundabouts at the ramp terminal intersections are complemented by a roundabout serving the commercial attraction and other service commercial uses. These roundabouts were planned and designed to serve specific users of the interchange and adjacent roadways.

Exhibit 3.4. Example of a roundabout supporting facility users.



LOCATION: NW 319th Street/I-5, La Center, Washington. SOURCE: Map data ©2022 Google.

3.3 Performance Measures

How a project's effectiveness is measured depends on its catalyst. Practitioners need to understand the specific intended operational, safety, and geometric performance context for each intersection, including its intended users, to determine project-specific performance measures. Identifying and understanding each user is also important, starting with vulnerable users.

Practitioners will want to understand the difference between *accommodating* and *designing for* a given user or mode and identify performance measures that lead to appropriate evaluation of design decisions. For example, if a roundabout is primarily intended to provide motorized vehicle mobility in a rural environment, the design may be *designed for* larger design vehicles to use the roundabout routinely. However, if a roundabout is in an urban environment with few large design vehicles but many non-motorized users, the roundabout may *accommodate* the occasional larger design vehicle.

This concept can apply to specific vehicles. For example, the *design vehicle* is the largest vehicle expected to frequently make specific movements through an intersection. The roundabout will be *designed for* these vehicles. Examples include buses and single-unit trucks in urban settings, WB-62 tractor trailers in rural settings, and WB-67 tractor trailers for roundabouts on the national highway system or near freeway interchanges.

A *control vehicle* is an infrequent large vehicle for which specific movements need to be accommodated. Examples include non-articulating fire trucks in urban settings, wide farm machinery or WB-67 tractor trailers in rural settings, and oversize or overweight vehicles or other permitted loads on designated freight routes. Accommodating control vehicles may require hardened areas beyond the perimeter curbing, an oversized truck apron in the central island, and removable signs. Utility poles and underground vaults, light poles, pedestrian facilities, and other vertical elements will be placed outside the swept path of the control vehicle.

Performance measures may include qualitative objectives, such as improving walkability or creating a sense of place. Performance can also be driven by long-term considerations of maintenance (e.g., snow removal, landscaping, illumination). In some cases, a roundabout may offer the highest value if it supports safety performance and operational objectives and extends an intersection's service life until a subsequent project is complete. This means evaluations of intersection alternatives could consider a *service life* versus a defined *design year*. Performance evaluation criteria could consider the ease or cost of a future improvement beyond the anticipated service life.

Project performance may directly link to specific design choices and the specific performance of the alternatives considered. The project performance categories below have been adapted from those described in *NCHRP Report 785* to help practitioners identify project-specific performance measures (*2*).

- **Accessibility.** While the term *accessibility* is commonly associated with the 1990 Americans with Disabilities Act (ADA; 42 USC 12131-12134) and the proposed Public Right-of-Way Accessibility Guidelines (PROWAG), the intent, in this case, is to reflect the ease of navigation in and around an area. Specifically, accessibility considers each user's ability to approach the desired destination or potential opportunity for activity. This could include a pedestrian needing to navigate and cross a high-volume, multilane intersection or a large truck's ability to navigate a channelized right turn.
- **Mobility.** *Mobility* refers to the ability to move various users efficiently from one place to another.
- **User quality of service.** *User quality of service* refers to a road user's perceived quality of travel. Practitioners use this metric to assess the efficacy of movement for motorists, pedestrians, bicyclists, and transit riders.

- **Reliability.** *Reliability* refers to the consistency of performance over a series of time periods.
- **Safety.** *Safety* refers to the expected crash frequency and severity for each user. Additional information is described in Chapter 7: Safety Performance Analysis.

Chapter 9: Geometric Design Process and Performance Checks provides further detail on how performance measures are used in the geometric design process for roundabouts.

3.4 Decision-Making Framework

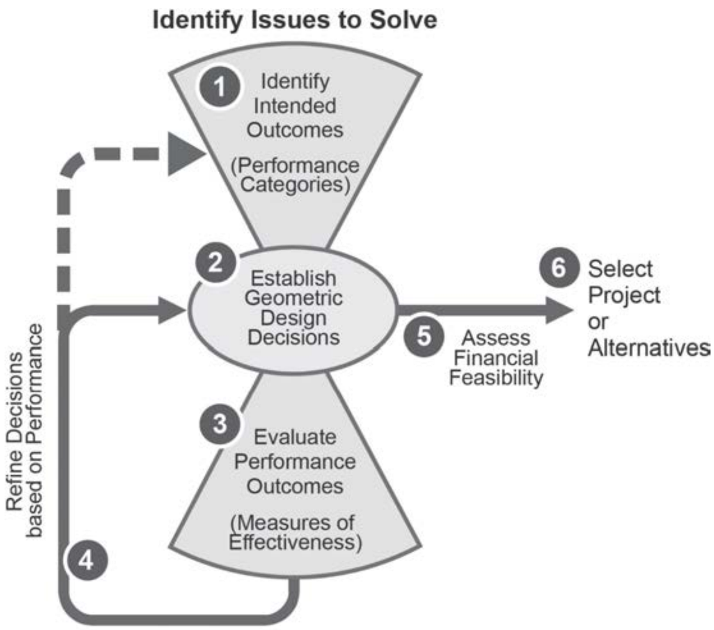
Many agencies have developed roundabout policies or ICE processes to guide designers and planners in making appropriate decisions when considering intersection traffic control. In some cases, these agencies have task forces that establish a policy for implementing roundabouts on their facilities. These policies often include background information about the geometric, safety, and operational characteristics of roundabouts; example locations where roundabouts may be considered; operational and safety evaluation discussions; and an overview of the trade-offs and general considerations for this type of intersection control.

Clear documentation of a performance-based approach can encourage effective problem solving, collaborative decision making, and greater return on infrastructure investments. *NCHRP Report 785* presents a performance-based model rooted in desired project outcomes and applied to various project levels, as shown in Exhibit 3.5 (*2*). Two other projects—NCHRP Project 20-07, Task 423, "Green Book 8 Visioning Project," and NCHRP Project 15-77, "Aligning Geometric Design with Roadway Context"—further describe a performance-based model pertaining to this framework that will support future editions of the Green Book (*6*, *7*).

This performance-based approach considers

- Identifying desired project outcomes and performance metrics,
- Establishing design decisions on the basis of desired outcomes,
- Evaluating the performance of the design,

Exhibit 3.5. Performance-based approach.



SOURCE: *NCHRP Report 785* (*2*).

- Iterating and refining the design to align solutions with desired outcomes,
- Assessing the financial feasibility of the alternatives,
- Selecting a preferred alternative that aligns with the desired outcomes, and
- Reassessing desired outcomes if no acceptable solution is identified.

This fundamental model provides a decision-making approach that can help practitioners develop and evaluate design choices within each unique contextual design environment. The focus is on performance improvements that benefit the project and system needs and allow performance analysis to guide decisions.

Roundabout design is inherently iterative, and there are no one-size-fits-all solutions. By first understanding a project's intent, a practitioner can compare performance metrics and select the design features that best achieve this objective. Although the information in this Guide provides input to help practitioners, roundabout design heavily relies on engineering judgment and design flexibility to adapt a roundabout to a given site. Perfection is rarely attained, yet a less-than-ideal roundabout may achieve safety performance benefits that exceed those of a different, optimally designed intersection form. Given the potential benefits of roundabouts, they need not necessarily be screened because ideal geometrics could not be attained.

Executing this approach involves using relevant, objective data to support design decisions along with developing an analytical approach tailored to the project's purpose and need. This requires an awareness of the resources available to quantify specific performance measures or qualitatively describe the anticipated effect of a given roadway, intersection, or interchange design.

3.5 Project Considerations

Intersection treatments and solutions often depend on the context of a roadway's location because land uses on approaching roadways can affect the intersection. Consequently, land uses and the roadway segments approaching an intersection can influence planning and design choices.

3.5.1 Land Use

Roundabouts can be designed for a range of facility types in a variety of contexts and applications. Land uses can influence road user operations, and rural or suburban areas with fewer conflicts and impediments can result in roadways with higher speeds than restricted or congested locations in urban areas. The number and types of conflicts (e.g., conflicts at driveways or closely spaced intersections or because of increasing numbers of pedestrians and bicyclists) may also influence intersection design decisions.

Context classification is the general categorization of existing or future land uses and forms. Context classification helps agencies establish generalized transportation expectations that roadway users typically anticipate within the identified land-use and transportation settings. Practitioners can establish context classifications on a broad agency level through policy and planning processes that result in agencywide designations. Alternatively, practitioners can use project-level discussions to establish a context classification for a specific project area. The Green Book establishes the following context classifications (*3*):

- Rural,
- Rural Town,
- Suburban,
- Urban, and
- Urban Core.

Project context is a broad term used to describe aspects or settings that could influence project development decisions and desired solutions. Project context includes historical, social, environmental, and economic elements. Project-specific attributes may affect specific design decisions in each context classification. Those attributes may represent unique project considerations that help practitioners refine potential project solutions and adapt to immediate project needs.

Collectively, context classification and the unique attributes of a given project are used to establish specific needs and constraints and identify a range of solutions most applicable to a given existing or desired future condition.

3.5.2 Project Type

The type of project under consideration will influence the ease of roundabout implementation. New roadways with limited conflicts that promote optimum design values provide more flexibility and allow choices to be less driven by constraints. Roundabouts on new roadways offer the greatest opportunity to implement geometric design dimensions that optimize multimodal operations and safety performance for that location.

Modifying an existing intersection is usually more challenging than installing a new roundabout, and users must optimize the configurations while balancing trade-offs. An existing circular intersection undergoing modification likely exhibited some negative performance characteristic that led to its evaluation. The modification could be for an existing roundabout that required mitigations identified by an in-service review. Compared with new alignment locations that have fewer constraints, geometric changes must be implemented in a constrained existing environment.

The Green Book establishes the following project types (*3*):

- **New construction.** New construction projects create roads on new alignment where no existing roadway is present, and they are typically subject to fewer constraints than other project types. New construction projects are not dictated by the performance or the form of an existing roadway and are designed within the identified functional class and context of the project. It may be easier to develop new roundabout configurations that serve projected high volumes while integrating pedestrians, bicyclists, and transit more effectively than on existing facilities.
- **Reconstruction projects.** Reconstruction projects use an existing roadway alignment (or make only minor changes to an existing alignment) and involve changing the basic roadway type, including widening a road to provide additional through lanes. Reconstruction projects may also include
  - Replacing another form of intersection with a roundabout,
  - Reconstructing (retrofitting) an existing roundabout (see Section 3.7),
  - Reconstructing an existing rotary into a roundabout (see Section 3.7), and
  - Reconstructing roadways adjacent to a roundabout.

  Practitioners need to consider the intended project outcomes leading to the intersection modification and focus on design choices that best address that metric within a built environment. Practitioners also need to be aware of utility impacts when modifying an existing intersection. These can include impacts in the footprint of the roundabout or its approaches that may need to be modified to meet path alignment or speed reduction targets. Practitioners need to understand how roundabout design choices may impact the existing intersection environment (such as required access to splitter islands).
- **Construction projects on existing roads.** Construction projects on existing roads keep the existing roadway alignment (except for minor changes) and do not change the basic roadway type. For design purposes, such projects are classified by the primary reason the project is being undertaken or the specific need being addressed. Typical projects on existing roads are

based on repairing infrastructure conditions or addressing a documented operational or safety performance issue. Projects on existing roads may include

- Constructing a new roundabout as a new intersection on the existing roadway,
- Converting an existing non-roundabout intersection to a roundabout,
- Modifying (retrofitting) an existing roundabout (see Section 3.7), and
- Modifying an existing rotary into a roundabout (see Section 3.7).

Practitioners who understand the catalyst for a roundabout project on existing alignment can verify that alternatives address specific safety performance, operational, or design user needs that the existing intersection did not provide. These can include safety performance (e.g., crash frequency and severity), traffic operations (e.g., congestion), operational performance (e.g., high speeds, path overlap, lane changing), or inadequate service for the intersection's range of users (i.e., pedestrians, bicyclists, transit, large trucks).

With the increase in roundabouts in the United States, retrofitting can include eliminating lanes at overdesigned roundabout intersections or modifying rotaries and traffic circles to operate as roundabouts.

3.6 Roundabouts in a System Context

Although roundabouts are commonly considered in isolated locations, they can also be part of a roadway or intersection network. To evaluate roundabouts in a system context, practitioners need to understand the features and characteristics of the adjacent roadways, intersections, and driveways as well as how those features may affect or be affected by roundabout design decisions. This section provides an overview of topics and principles; additional discussion is provided in Chapter 10: Horizontal Alignment and Design.

NCHRP Report 772: Evaluating the Performance of Corridors with Roundabouts developed performance measurement tools and techniques based on quantitative, empirical data that can assist practitioners in evaluating a roundabout corridor (*8*). In addition, *NCHRP Report 772* created a set of guidelines for corridor comparisons that incorporate quantitative and qualitative components. Evaluating key considerations of delay, travel time, access management, safety, multimodal user needs, constructability, and surrounding land-use context can guide decision making through the project development process.

3.6.1 Interchanges

Freeway ramp junctions with arterial streets are potential candidates for roundabouts at ramp terminal intersections. Roundabouts operating within their capacity are particularly beneficial in locations with limited queue storage, such as bridges or underpasses between two ramp terminal intersections. Ramp terminal intersections have interdependency that requires practitioners to understand the lane configurations and operational characteristics and needs upstream and downstream to verify that each intersection can operate effectively and serve each user. Common types of interchanges that incorporate roundabouts include

- Diamond interchanges (with or without frontage roads) and
- Partial cloverleaf interchanges.

Roundabouts at service interchange ramp terminal intersections may include non-circular shapes, such as a raindrop-shaped central island. However, U-turns are not traditionally provided along the arterial street at non-roundabout ramp terminal intersections for capacity reasons. Interchanges are significant investments that intend to serve movements between the first-order roadway (primary highway) and a second-order roadway (arterial street). Arbitrary U-turns to support access along the second-order roadway put the burden on the interchange to serve third-order traffic (public or private access), which degrades the primary interchange function.

It is best for practitioners to avoid U-turns at roundabout ramp terminal interchanges unless they are needed to serve two-way frontage roads, serve connecting roadways, or support an access management plan for the arterial. If U-turns are to be provided, the portion of the circulatory roadway that serves very low U-turn volume may accumulate road debris. Furthermore, in low U-turning volume locations, through drivers may become accustomed to the few conflicting U-turning drivers and become complacent about yielding to U-turning drivers. Exhibit 3.6 illustrates an example of roundabouts at interchange ramp terminals on Interstate 70 in Avon, Colorado.

3.6.2 Corridors with Roundabouts (and Roundabouts in Series)

Corridors of roundabouts have become more common, and roundabouts in series have shown to be effective in a wide variety of contexts throughout the United States. Corridors with roundabouts may include adjacent traffic control devices, such as stop control and signalized or roundabout intersections. This may also represent a service interchange along with the ramp terminal intersections and adjacent public intersections along longer corridors.

Case by case is the preferred approach for evaluating the performance of corridors. *NCHRP Report 772* supports practitioners throughout this process by providing a framework for comparing alternative corridor configurations that objectively informs project decisions based on each corridor's unique context (*8*). Exhibit 3.7 illustrates examples of corridors with roundabouts in Carmel, Indiana.

3.6.3 Mixed Roundabouts and Signals

Mixing roundabouts and signals along a corridor requires additional evaluation of the unique intersection control to verify the design, safety performance, and traffic operations of the entire corridor. This may include addressing the presence of a single, adjacent signal or a broader corridor that includes multiple signals that could affect the roundabout.

NCHRP Report 772 researched corridors containing signals and roundabouts, noting corridor-specific evaluations are needed for agencies to determine which form of intersection control is

Exhibit 3.6. Example of roundabout at interchange ramp terminal intersection.

LOCATION: Avon Road/I-70, Avon, Colorado. SOURCE: Map data ©2022 Google.

Exhibit 3.7. Examples of corridors with roundabouts.

LOCATION: W 106th Street and W 116th Street, Carmel, Indiana. SOURCE: Map data ©2022 Google.

operationally preferred on a given corridor and to understand the effects of mixing various types of intersection control (*8*).

Exhibit 3.8 illustrates an example of mixing roundabouts with a signalized intersection between roundabouts at the north and south ends of the corridor.

3.6.4 Closely Spaced Roundabouts

Closely spaced roundabouts may include two single roundabouts or a combined (e.g., oval, elliptical, racetrack, peanut, paper clip) configuration. When the operation of two or more roundabouts near each other is considered, the expected queue lengths at each roundabout become a focus to avoid or minimize queue spillback between roundabouts.

Closely spaced roundabouts often have a traffic calming effect on the major road. Drivers may be reluctant to accelerate to typically expected speeds between roundabouts, which can lead to safety performance benefits.

To consider two closely spaced roundabouts requires detailed evaluations to verify that design objectives for the roundabouts, considered individually and in combination, are met. This includes verifying that each approach leg has sufficient capacity to avoid queue spillback from the downstream roundabout to the upstream location. It is important that lane configurations between the roundabouts work together to allow a driver to navigate the two intersections without lane changes or weaving between them. Signing needs to be logical and consistent with geometrics. Signing is not a substitute for a geometric configuration resulting in undesirable lane configurations. Exhibit 3.9 illustrates an example of closely spaced roundabouts in Buffalo, New York.

3.7 Retrofits of Existing Circular Intersections

Rotaries, other circular intersections, and roundabouts that have been in service for some time may not be performing to expectations thus becoming a candidate for retrofit. Retrofitting could be completed as part of maintenance projects or as the result of in-service reviews, such as signing and pavement marking replacements that are part of resurfacing projects. Small-scale improvement projects are also opportunities to include signing, pavement markings, and minor curb modifications. Large-scale projects include reconstructing the entire intersection, often reducing its size and significantly realigning one or more legs.

Exhibit 3.8. Example of mixing roundabouts with a signalized intersection.

LOCATION: SR 89A, Sedona, Arizona. SOURCE: ©2022 TomTom, ©Vexcel Imaging, Microsoft Bing Maps.

Exhibit 3.9. Example of closely spaced roundabouts.

LOCATION: Harlem Road/Kensington Avenue/Wehrle Drive, Buffalo, New York. SOURCE: Howard McCulloch.

Practitioners need to understand the opportunities and trade-offs associated with various levels of retrofitting projects for existing circular intersections to create designs that better meet each user's needs as well as those of the community. When conducting in-service roundabout reviews, practitioners need to understand factors that could contribute to undesirable performance and complete performance checks as the first step toward understanding potential mitigations. These factors include

- Skew,
- Suboptimal deflection,
- Wide lanes,
- Limited tangent on entry,
- Small radii on exit,
- Excessive raised features (limits stopping sight distance),
- Limited raised features (excessive sight distance promotes higher speed),
- Path overlap, and
- High circulating speeds.

Potential modifications can be considered and evaluated within site-specific constraints. Roundabout design is often a matter of optimizing the configuration to attain adequate performance. Even if target performance cannot be fully attained, a roundabout retrofit is often the appropriate intersection form because of its beneficial safety and operational performance. Exhibit 3.10 and Exhibit 3.11 provide examples of retrofit modification at roundabouts that improved safety and operations.

Rotaries were developed before the evolution of modern roundabouts and often did not include features or qualities that result in desired roundabout performance and safety. Rotaries include several geometric features that can promote high speeds and create merge, diverge, and weaving areas in the circulatory roadway. High-speed maneuvers degrade safety performance and can result in increased congestion because of longer decision times required at faster speeds. Therefore, it may be desirable to modify a rotary to include roundabout performance attributes. This

Exhibit 3.10. Example of roundabout retrofit modification.

LOCATION: Route 188/Route 334 (Great Hill Road)/Holbrook Road, New Haven County, Connecticut.
SOURCE: Map data ©2022 Google.

Exhibit 3.11. Example of rotary retrofit modification.

LOCATION: Cony Circle (US 201/Route 9/Route 105/Cony Street), Augusta, Maine. SOURCE: Map data ©2022 Google.

could include creating roundabout-like operating characteristics, such as yield at entry, smaller entry radii, slow speed on entry, low speed differentials between successive geometric elements, and low speed differentials between conflicting movements.

In some cases, there may also be a desire to modify a traffic circle to include roundabout performance characteristics. This could include implementing roundabout operating characteristics (as noted with rotaries) as well as removing parking from the circulatory roadway and eliminating or highly managing pedestrian access to the central island. Exhibit 3.12 illustrates an example of modifying a rotary to include roundabout design elements.

Chapter 6: Intersection Control Evaluation provides further detail about ICE, which may include considering a roundabout at an existing non-roundabout intersection. Chapter 9: Geometric Design Process and Performance Checks presents a framework for assessing existing circular intersections and identifies methods for considering potential remediation approaches based on in-service performance.

Exhibit 3.12. Example of rotary retrofit modification to include roundabout design elements.

LOCATION: Route 12/Main Street/Reaville Avenue, Flemington, New Jersey. SOURCE: Map data ©2022 Google.

3.8 References

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CHAPTER 4

User Considerations

Contents

A successful roundabout meets the needs of people who travel through it. Early project planning must account for each of these users—from people traveling on foot or using personal assistive devices to drivers of the largest motor vehicles. User needs will continue to inform design decisions as projects advance to preliminary engineering and final design. Roundabout planning and design processes inherently involve assessing and balancing trade-offs among various user needs, and the project planner, designer, and implementing agency are responsible for understanding these trade-offs.

For example, the design choice to serve high vehicular demands by adding approach lanes may reduce vehicle queues and associated rear-end crashes. However, additional lanes may negatively affect safety performance for people walking and biking by lengthening crossing distances, promoting higher vehicular speeds, and increasing the number of conflicts at crosswalks. Adding circulating lanes or integrating double left- or right-turn lanes may increase traffic capacity. However,

Exhibit 4.1. Roundabout users.

Roundabout Users
• Pedestrians
• Bicycle and Micromobility Users
• Passenger Cars and Motorcycles
• Large Vehicles (Standard Trucks, Oversize or Overweight Trucks, Buses, and Other Design Vehicles)
• Emergency Vehicles
• Railroads and Light Rail Transit
• Connected and Automated Vehicles

these configurations may also result in more complex roundabouts that increase the crash frequency for motorized users.

This chapter presents an overview of roundabout user groups along with their associated characteristics. The chapter is organized by the types of roundabout users shown in Exhibit 4.1.

4.1 Pedestrians

Pedestrians are characterized as people traveling on foot or using a personal assistive device, such as a wheelchair. Of all travel modes, people walking can present the widest spectrum of abilities, including

- A wide range of ages;
- Agile to limited mobility;
- Good vision to limited or no vision;
- On foot, using assistive devices (e.g., wheelchairs), or pushing or pulling wheeled devices; and
- Traveling alone or with others.

The two populations at the ends of the age continuum and people with disabilities are at more risk at intersections than people in the middle of the age continuum and without disabilities. These pedestrians often move at slower speeds than other pedestrians and find it more difficult to cross unprotected road crossings. They generally prefer larger gaps in the traffic stream. Children lack traffic experience, can be impulsive or impatient, and have less-developed cognitive abilities. Their small size also limits their visibility to drivers. As people age, they often have more experience and judgment but may have physical limitations that affect their abilities to travel, including reduced visual acuity, visual field, hearing, and mobility.

Roundabouts have design features specifically intended to serve people walking, including the following considerations:

- Motor vehicle speeds are designed to be low, improving a driver's ability to react and yield to pedestrians. If a driver collides with a pedestrian, the kinetic energy is lower to reduce the likelihood of severe injury or death.
- Crossing locations are set back from the roundabout circulatory roadway to separate the driver decisions at the crosswalk from the driver decisions at the circulatory roadway.
- In most cases, crossings are designed to be made in two stages, crossing one direction of conflicting traffic at a time, with a raised island refuge between opposing directions of conflicting traffic.
- Pedestrians circulate the perimeter of the intersection and should be guided to the correct crossing locations by a detectable buffer between the sidewalk and circulatory roadway.

Exhibit 4.2. Example of pedestrian at a roundabout.

LOCATION: Hillsborough Street/Pullen Road, Raleigh, North Carolina.
SOURCE: Lee Rodegerdts.

Exhibit 4.2 illustrates a pedestrian navigating a roundabout. Exhibit 4.3 illustrates pedestrians and bicyclists using a shared-use path at a roundabout.

4.1.1 Pedestrian Safety and Quality of Service

For pedestrians, factors affecting safety performance and quality of service are interrelated. The quality of service for pedestrians reflects how they perceive their ability to travel safely and efficiently along a facility or through an intersection. These perceptions cover a broad range of safety, operations, and security aspects. A variety of quantitative and qualitative methods have been developed to identify a performance metric for this quality of service, including pedestrian level of service (LOS) and pedestrian level of traffic stress (LTS) (*1*, *2*).

Multiple factors influence the LTS that pedestrians experience. Some general factors relate to physical infrastructure and are constant throughout the day:

- The condition of the pedestrian facility.
- The width of the pedestrian facility.
- The width and type of any buffering between the pedestrian facility and the closest motor vehicle lane.

Exhibit 4.3. Example of pedestrians and bicyclists using a shared-use path at a roundabout.

LOCATION: NW 319th St./I-5 Southbound Ramps, La Center, Washington.
SOURCE: Kittelson & Associates, Inc.

- The number of motor vehicle travel lanes and the proximity to a pedestrian facility.
- The number of motor vehicle lanes that a pedestrian must cross.
- The distance a person must travel to cross the street, which is related to—but distinct from—the number of lanes being crossed. Skewed alignments may result in longer crossing distances over the same number of motor vehicle lanes when compared with perpendicular alignments.
- The presence (or lack) of detectable separation between pedestrians and bicyclists.

The preferred roundabout geometric design locates the pedestrian crossing back from the circulatory entrance, to improve the likelihood drivers and bicyclists will pay attention to the pedestrian crossing. The pedestrian crossing is typically separated into two stages: one crossing the roundabout entry lane or lanes and one crossing the roundabout exit lane or lanes. There may be additional crossings if separated bypass lanes are present. This generally simplified crossing environment allows the person crossing to focus their attention on one direction of oncoming traffic at a time.

Other factors that influence the pedestrian LTS are temporal, meaning they can change by time of day depending on conditions. These factors include

- **The speed of adjacent or conflicting motor vehicles.** This is often represented by the posted speed, operating speed, or a measured value, such as the 85th-percentile speed.
- **The volume of motor vehicle traffic.** This is often represented using annual average daily traffic (AADT) volumes, but the nature of the effect is felt differently by pedestrians during peak periods versus off-peak periods.
- **The speed and volume of bicycle traffic.** Spot bicycle speeds can be measured in the field or estimated. *NCHRP Report 797: Guidebook on Pedestrian and Bicycle Volume Data Collection*, provides techniques for measuring bicycle traffic volumes (*3*).

At roundabouts, lower motor vehicle speeds that are governed by proper geometric design directly improve the pedestrian's safety and quality of service. Lower speeds increase the likelihood that a driver can yield to or stop for a pedestrian and avoid a collision. If the driver cannot avoid the collision, the lower speeds reduce the severity of that collision because the motor vehicle decreases in kinetic energy. Chapter 7: Safety Performance Analysis discusses these aspects in more detail. Lower speeds also reduce stress for pedestrians with disabilities, especially where right-of-way constraints may make it impossible to provide a landscape buffer between pedestrians and the roadway.

Motor vehicle traffic volume directly influences the quality of service for a person walking. At a typical unsignalized crossing, people crossing either look for and accept gaps in traffic or look for and accept drivers yielding to or stopping for them. Each of these factors is influenced by motor vehicle traffic volume. Because these gaps or yields are needed on only one side of the street at a time, crossing at a roundabout is generally easier for people than crossing a major street at a two-way stop-controlled intersection. However, it is often difficult for people who are blind or have low vision to accurately determine gaps in traffic and yielding vehicles, especially under high traffic conditions. This will become a greater challenge at all types of intersections as the United States transitions to a higher percentage of electric vehicles that may be inaudible at slow speeds or when stopped.

Compared with single-lane roundabouts, crossing at multilane roundabouts is more difficult for all pedestrians. Multilane crossings are typically longer than single-lane crossings, so overall exposure is increased. Pedestrians at all types of intersections need assurance that all lanes are free of moving traffic before they can cross the street. Research indicates that two to three times more motorists fail to yield to pedestrians at multilane roundabout crossings than at single-lane roundabout crossings (*4*). Pedestrians also face the potential for "multiple-threat" crashes at multilane crossings at all types of intersections. This occurs when the driver in the first lane stops to yield to a pedestrian, blocking the sightlines between the pedestrian and vehicles in the next lane. If neither the driver in the next lane nor the pedestrian sees the other user in time to take evasive action, a crash can occur in the second lane. The effect of this multiple-threat challenge for people who are blind or have low vision is discussed further in the next section.

4.1.2 Accessibility

Pedestrian facilities should serve the entire pedestrian population. In the United States, accessibility is governed by civil rights legislation: the ADA of 1990 (*5*), as amended by the ADA Amendments Act of 2008 (*6*). The ADA specifies that any new or modified intersection in the United States that has pedestrian facilities must be accessible to and usable by all pedestrians. Under the ADA, as specified in the US Code of Federal Regulations (CFR), the public right-of-way is a "program" provided by state and local governments that must not discriminate against pedestrians with disabilities (28 CFR 35.150).

Any facility or part of a facility that is newly constructed by a state or local government that provides pedestrian facilities must be designed and constructed so it is readily accessible to and usable by people with disabilities (28 CFR 35.151(a)). Alterations to existing facilities must include modifications to make altered areas accessible to individuals with disabilities (28 CFR 35.151(b)).

The US Access Board has published Public Rights-of-Way Accessibility Guidelines with an amendment for shared-use paths (*7*, *8*). These guidelines address many accessibility issues found in the public right-of-way that are not addressed by 2010 ADA Standards for Accessible Design and earlier documents, such as the ADA Accessibility Guidelines (ADAAG) (*9*, *10*).

Accessibility features at roundabouts include sidewalks and crosswalks that meet surface, slope, and clearance requirements; ramps connecting sidewalks and crosswalks; detectable warning surfaces at curb ramps and splitter islands; detectable edge treatments between sidewalks and roundabout vehicular lanes to guide pedestrians to crosswalks (such as landscaping adjacent to the curb line); and signalized pedestrian crossings. FHWA has issued a memorandum stating that "the Draft Guidelines [i.e., proposed PROWAG] are the currently recommended best practices and can be considered the state of the practice that could be followed for areas not fully addressed by the present ADAAG standards" (*11*). Regardless of the proposed PROWAG's status, the absence of implementing regulations that provide minimum technical standards does not absolve a state or local government from meeting ADA requirements.

This Guide presents recommended practices for providing accessible facilities for pedestrians based on the proposed PROWAG and the latest research and implemented practices consistent with the letter and intent of the ADA. The practices are anticipated to meet these implementing regulations. Further details can be found in *NCHRP Research Report 834: Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities: A Guidebook* (*12*).

Achieving an accessible facility for pedestrians requires understanding how people with disabilities travel independently. People using wheeled assistive devices have some characteristics in common (additional details can be found in the proposed PROWAG) (*7*):

- They need a pedestrian access route with a minimum horizontal width of 4 ft (1.2 m). Within medians and refuge islands, the minimum clear width is 5 ft (1.5 m). Where the clear width is less than 5 ft (1.5 m), passing areas are needed at maximum intervals of 200 ft (61 m).

- They need curb ramps that intersect the roadway at approximately 90 degrees so that wheels reach the bottom of the ramp at the same time; if only three wheels are in contact with the surface, they lose some control and stability and may tip over. They cannot readily negotiate a vertical discontinuity more than 0.5 inches (13 mm).
- Each upslope along the travel path requires effort for people on foot or with a manual wheelchair to navigate. Cut-through designs through islands or raised crossings are easier to traverse than ramps up and down.
- People in wheelchairs, children, and people of short stature have a lower overall height and a lower eye height than the average person on foot. This affects sight lines in both directions.

Similarly, people who are blind or have low vision have other key characteristics:

- Most people cannot hear bicycles or electric vehicles over typical background noises. People who are blind or have low vision are thus at greater risk of collisions with bicyclists and may experience more stress when using paths that are shared with bicyclists than when using paths that are separated from bicyclists.
- They rely on hearing for detecting gaps between motor vehicles and for detecting whether a driver or bicyclist has yielded to them. It takes more time to detect and confirm a gap or yield using hearing than it takes using vision. It takes even more time for less experienced travelers or for people with cognitive disabilities.
- They cannot readily find crossings at non-corner locations unless there is a clearly defined path to the crossing location.
- They cannot accurately align to cross where there is no motor vehicle traffic running parallel to the crosswalk from which to take sound cues; tactile direction indicators can be added to enable accurate alignment (*13*, *14*).
- They are somewhat likely to veer out of long crosswalks unless tactile cues or audible beacons are provided to assist with maintaining their heading (*15*).
- They cannot reliably detect changes in pavement materials (such as between a combination of portland cement concrete, asphalt concrete, brick, or stamped textures), grooves in concrete, colors, or pavement markings that might be used to visually separate pedestrian facilities from motor vehicle or bicycle facilities at the same grade.
- They can readily detect vertical curbs at least 2.5 in. (50 mm) in height but cannot readily detect vertical curbs of 2 in. (40 mm) or less (*16*, *17*).
- They can detect and readily identify the presence and purpose of detectable warning surfaces consisting of truncated domes indicating the limit of the pedestrian way at street, bicycle lane, and rail crossings as well as transit boarding platforms (*18*). A minimum depth of 2 ft (0.6 m) in the direction of travel is required to enable pedestrians who travel using a long cane or dog guide to detect truncated domes and stop without stepping beyond them. In the absence of a detectable warning at the bottom of a curb ramp, they have a high probability of inadvertently stepping into a crosswalk before they have prepared to cross (*19*).
- Initial findings from recent research suggest they can detect, readily identify, and use the following tactile walking surface indicators:
  - Raised, flat-topped bars called *tactile direction indicators* that run perpendicular to the direction of travel on an associated crosswalk for the purpose of locating crossings and aligning to cross (*20*).
  - Trapezoidal delineators called *tactile warning delineators* that run longitudinally between bicycle and pedestrian facilities at the same grade (*21*).

Further details can be found in other references, including the proposed PROWAG (*7*), ADAAG (*10*), and FHWA's *Designing Sidewalks and Trails for Access*, part II of the *Best Practices Design Guide* (*22*).

Exhibit 4.4. How pedestrians should use a roundabout.

Using a Roundabout as a Pedestrian
• Pedestrians should walk around the perimeter of the roundabout and cross at designated crossing locations. They should not cross to the central island.
• Pedestrians should look and listen for approaching vehicles (both motor vehicles and bicycles) and choose a time to cross either between approaching vehicles or when an approaching vehicle is yielding.
• If the roundabout crossing has an active traffic control device, such as a flashing beacon or pedestrian signal, pedestrians should activate the beacon or signal and obey its indications. Most roundabouts have splitter islands large enough for pedestrians to cross the approach in two stages. Pedestrians cross approaching traffic from one direction, reach an island, and then cross approaching traffic from the other direction. If the splitter island is not wide enough to accommodate safe and comfortable waiting, pedestrians should carefully assess whether they can safely cross both directions of approaching traffic without stopping on the island.

4.1.3 Pedestrians' Use of Roundabouts

Exhibit 4.4 provides suggested guidance on how pedestrians should use a roundabout.

4.2 Bicyclists and Micromobility Users

Biking has long been a component of the transportation system. Bicyclists are generally defined as people traveling on human-powered, two-wheeled vehicles.

As with people walking, people biking have a wide spectrum of abilities and have been characterized into four general categories—non-bicyclists, interested but concerned bicyclists, somewhat confident bicyclists, and highly confident bicyclists—as shown in Exhibit 4.5 (*23, 24*).

Roundabouts can serve bicycle users who have a range of abilities and comfort levels. With reduced conflict points, higher visibility to bicyclists, and reduced speed differentials between people biking and people driving, roundabouts can become an integral part of the bicycle network.

Exhibit 4.5. Types of bicyclists.

SOURCE: Kittelson & Associates, Inc., adapted from Dill and McNeil (*23*).

Bicycle facilities at roundabouts need to be compatible with the surrounding bicycle network and adjacent land-use context. Depending on context and roundabout configuration, the surrounding roadway network may serve bicyclists in a variety of ways:

- In the roadway, sharing a lane with motor vehicles;
- On the shoulder adjacent to motor vehicle lanes;
- In bicycle lanes adjacent to motor vehicle lanes;
- In bicycle lanes at the same grade but laterally buffered from motor vehicle lanes;
- In physically separated bicycle one-way or two-way facilities, sometimes known as cycle tracks or protected bicycle lanes; and
- In shared-use paths with pedestrians, separated from the roadway.

Integrating bicycle and micromobility users requires careful attention to how those users interact with motor vehicles and with pedestrians. As bicycle use increases, practitioners are required to devote attention to both types of potential interactions. People biking at a roundabout need to be as comfortable as (or more comfortable than) drivers using the roadway approaches at the roundabout. However, the comfort and safety of bicyclists cannot be achieved at the expense of vulnerable pedestrians. Chapter 10: Horizontal Alignment and Design further discusses design treatments.

Exhibit 4.6 and Exhibit 4.7 illustrate examples of bicycles navigating roundabouts.

A variety of definitions for micromobility are emerging, but *micromobility* has been defined as electric-powered (usually single-person) vehicles or devices that travel at low speeds (comparable with a human-powered bicycle) and that are small, lightweight, and typically used for short-distance trips (*25*). Typical devices in this category include electric bicycles (e-bikes) and standing electric scooters (e-scooters). To date, there is little research on the interaction between micromobility users and roundabouts, including safety and operational performance characteristics. However, many of the fundamental principles associated with quality of service and safety performance for bicyclists can likely apply to micromobility users. Motorized bicycles, scooters, and other rolling devices could lead to these users reaching higher speeds compared with pedestrians and pedal cyclists. Higher speeds and speed differentials between users could increase the potential safety risk for pedestrians and bicyclists. References to bicyclists in this Guide could potentially be extended to e-bikes and standing e-scooters.

Exhibit 4.6. Example of bicyclist at a roundabout.

LOCATION: Bend, Oregon. SOURCE: Pete Jenior.

Exhibit 4.7. Aerial view of bicyclist at a roundabout.

LOCATION: Butler County, Ohio. SOURCE: Kittelson & Associates, Inc.

4.2.1 Bicyclist Safety and Quality of Service

As with pedestrians, safety performance and quality of service are interrelated for bicyclists. The quality of service for bicyclists reflects how people riding bicycles perceive their ability to safely travel along a facility or through an intersection. These perceptions cover a broad range of safety, operations, and security aspects. A variety of quantitative and qualitative methods have been developed to identify a performance metric for this quality of service, including bicycle LOS and bicycle LTS (*1*, *26*).

Roundabouts slow drivers to speeds more compatible with bicycle speeds while reducing high-speed conflicts and simplifying turn movements for people biking. Typical on-road bicyclist speeds are 12 to 20 mph (19 to 32 km/h), so designing roundabouts for circulating traffic to flow at similar speeds minimizes the relative speed difference between bicyclists and motorists. Bicyclists require special attention in multilane roundabout design, especially in areas with moderate to heavy bicycle traffic.

People biking have a range of abilities and comfort levels in mixed traffic. In all cases, bicyclists should yield to pedestrians where pedestrians and bicyclists cross. Roundabout configurations can be adapted to serve the full range of people riding bicycles. The least-skilled bicyclists may choose to travel out of traffic on adjacent sidewalks, multiuse paths, or trails. More confident bicyclists may be comfortable navigating low-speed, single-lane roundabouts. The most experienced and skilled on-road bicyclists may choose to travel through roundabouts with other vehicles.

Single-lane roundabouts are simpler for people biking than multilane roundabouts, which require bicyclists to select the appropriate lane for their direction of travel. This includes changing lanes to make left-turn movements. Single-lane roundabouts reduce the risk of motorists cutting bicyclists off when exiting the roundabout. An example of how to reduce the intersection complexity for bicyclists crossing a multilane street from a minor street is to design a roundabout with two-lane entries and exits for the major roadway and one-lane entries and exits for the minor roadway. For these reasons, multilane roundabouts require additional design considerations for people biking.

4.2.2 Bicyclists' Use of Roundabouts

Exhibit 4.8 provides suggested guidance on how bicyclists should use a roundabout and how other roundabout users should interact with bicyclists.

Exhibit 4.8. How bicyclists should use a roundabout.

Using a Roundabout as a Bicyclist
• Users should use the facility they are most comfortable with. In all cases, bicyclists should yield to pedestrians at path crossings.
• If shared bicycle–pedestrian paths are provided, bicyclists should slow down, merge into the shared path, and yield to pedestrians while in the shared path. They should be aware that some pedestrians may be unable to see or hear them and may not be able to quickly move out of their paths. Bicyclists should circulate and cross using the shared path, including using any traffic control devices that may be present at the crossings.
• If facilities are provided only for pedestrians and are not wide enough for shared bicyclist–pedestrian use, bicyclists should dismount and walk their bicycles, following all requirements for pedestrians. Bicyclists may refer to local regulations regarding biking on sidewalks.
• If no bicycle or pedestrian facilities are provided, or bicyclists are comfortable with and prefer to ride with motor vehicle traffic, they should circulate as a motor vehicle. Bicyclists should position themselves in the center of the travel lane when traversing the roundabout. They should follow all requirements for motor vehicles.

4.3 Passenger Cars and Motorcycles

Passenger cars are the most common users at most roundabouts in the United States. Passenger cars include light-duty trucks with two axles, such as vans, minivans, pickup trucks, and sport utility vehicles (*27*). Many roundabout design features intend to serve passenger car drivers of all ages, including older and young drivers (*28*). These features include the following:

- The low-speed design allows drivers more time to make decisions, act, and react, reducing the likelihood and potential severity of crashes.
- Separating decision points provides less-complicated situations to interpret, which means simpler decision making.
- Proper view angles reduce the need to look over one's shoulder.
- Low circulating speeds make it easier to judge closing speeds and gaps in traffic.

Motorcyclists share many of the same characteristics and responsibilities as automobile drivers at roundabouts. The geometric design and traffic control devices for automobile drivers are generally considered adequate for motorcyclists. However, motorcyclists are overrepresented in fatal collisions at roundabouts compared with other types of intersections. Research of fatal crashes at roundabouts in Washington State and Wisconsin found motorcycles were involved in 46 percent of all fatal crashes. This is largely because of the increased severity occurring when drivers are separated from their motorcycles and strike fixed objects, such as curbs (*29*). Chapter 13: Curb and Pavement Details discusses these design details, such as curb types.

4.3.1 Driver Characteristics

Drivers must understand how to use the key operating characteristics of roundabouts, such as determining a safe approach speed, identifying the number of lanes and which lane to be in, understanding the direction of travel on the circulatory roadway, yielding to other users, and understanding the street signs and route signs at each exit. Younger or new drivers are generally less experienced with navigating intersections, including roundabouts. Additional education and outreach during driving lessons can support younger drivers' understanding of roundabouts and the characteristics that make these intersections unique.

For older drivers, FHWA's *Highway Design Handbook for Older Drivers and Pedestrians* presents the following considerations for understanding the differences in older drivers and how those differences may increase their need for education and traffic control signing, as well as design considerations (*28*).

- Driving situations involving complex speed–distance judgments under time constraints are more problematic for older drivers than for younger drivers.
- Older drivers are more likely to be involved in crashes in which the drivers were driving too fast for the curve or, more significantly, were surprised by the curved alignment.
- Left-turn maneuvers are difficult for older drivers who have difficulty selecting acceptable gaps because of their reduced ability to judge oncoming speeds and slower response times (*30–33*). Older drivers also have more difficulty understanding left-turn displays (*34–36*).
- Left-turn crashes are particularly problematic for older drivers. Research has shown that the potential of being involved in left-turn crashes increases with age (*37*, *38*).
- Many studies have shown that loss-of-control crashes result from an inability to maintain a lateral position through the curve because of excessive speed with inadequate deceleration in the approach zone. These problems stem from a combination of factors, including poor anticipation of vehicle control requirements, the driver's prior speed, and inadequate perception of the curve demands.
- Older drivers have difficulty allocating attention to the most relevant aspects of novel driving situations.
- Older drivers generally need more time than average drivers to react to events.

Roundabouts can offer benefits to older drivers, and slower speeds can benefit both novice and older drivers as each navigates the roadway. Some potential benefits of slower intersection speeds include reduced crash severity (for a given crash type), safer merges, and more opportunities to correctly judge and enter gaps (*39*).

The slower and consistent speeds at roundabouts can cater to the preferences of older drivers by

- Allowing more time to make decisions, act, and react;
- Providing less-complicated situations to interpret;
- Reducing the need to look over one's shoulder;
- Reducing the need to judge closing speeds of fast traffic accurately; and
- Reducing the need to judge gaps in fast traffic accurately.

4.3.2 Drivers' Use of Roundabouts

Vehicle codes and associated driver's manuals vary throughout the United States. While many states are silent about requirements at roundabouts and rely on the established uses of traffic control devices and other right-of-way rules, some have amended their vehicle codes to address specific roundabout uses. Exhibit 4.9 provides examples.

Exhibit 4.10 contains suggested guidance for drivers on how to use a roundabout, based on typical rules of the road in the United States.

Exhibit 4.11 presents a graphic from the Massachusetts Department of Transportation's *Guidelines for the Planning and Design of Roundabouts*, illustrating how passenger car drivers and motorcyclists should react when emergency vehicles approach a roundabout (*44*).

4.4 Large Vehicles

Large vehicles directly affect roundabout planning and design. Large vehicles include trucks, which can be either fixed chassis or with one or more trailers; buses, which most commonly have a fixed chassis but can be articulated; and recreational vehicles. Large vehicles can include vehicles

Exhibit 4.9. Examples of roundabout-specific rules of the road.

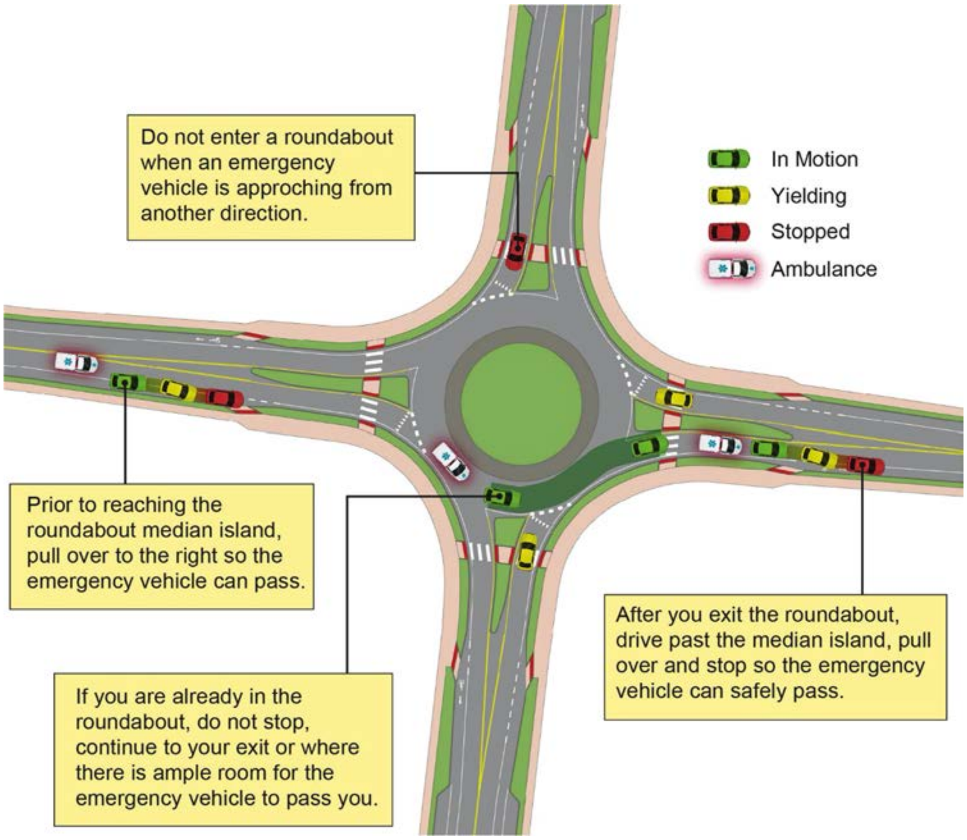
Rule of the Road	Example Legislation
Using turn signals on exiting	1) A person commits the offense of failure to use an appropriate signal for a turn, lane change or stop or for an exit from a roundabout if the person does not make the appropriate signal under ORS 811.395 (Appropriate signals for stopping, turning, changing lanes and decelerating) by use of signal lamps or hand signals and the person is operating a vehicle that is: (a) Turning, changing lanes, stopping or suddenly decelerating; or (b) Exiting from any position within a roundabout (*40*).
Allowing truck drivers to straddle lanes	Whenever any roadway has been divided into two or more clearly marked lanes for traffic the following rules in addition to all others consistent herewith shall apply: (1) A vehicle shall be driven as nearly as practicable entirely within a single lane and shall not be moved from such lane until the driver has first ascertained that such movement can be made with safety. … (5) Pursuant to subsection (1) of this section, the operator of a commercial motor vehicle as defined in RCW 46.25.010 may, with due regard for all other traffic, deviate from the lane in which the operator is driving to the extent necessary to approach and drive through a circular intersection (*41*).
Failing to yield right-of-way within a roundabout	1) A person commits the offense of failure to yield right-of-way within a roundabout if the person operates a motor vehicle upon a multilane circulatory roadway and: (a) Overtakes or passes a commercial motor vehicle; (b) Drives alongside a commercial motor vehicle; or (c) Does not yield the right-of-way to a second vehicle lawfully exiting the roundabout from a position ahead and to the left of the person's vehicle (*42*).
Requiring other drivers to yield to trucks	The operator of a vehicle shall yield the right-of-way to any vehicle or combination of vehicles with a total length of not less than 40 feet or a total width of not less than 10 feet when approaching or driving through a roundabout at approximately the same time or so closely as to constitute a hazard of collision and, if necessary, shall reduce speed or stop in order to so yield (*43*).

Exhibit 4.10. How passenger car drivers and motorcyclists should use a roundabout.

Using a Roundabout as a Passenger Car Driver or Motorcyclist

- A passenger car driver or motorcyclist should treat the roundabout as any other intersection, selecting the appropriate lane for their intended destination **before they enter the roundabout.** A passenger car driver or motorcyclist should turn left only from the leftmost lane and turn right only from the rightmost lane unless signs and pavement markings provide a different lane configuration. As with any user, a passenger car driver or motorcyclist should not change lanes once in the roundabout. In some states, using the right-turn signal is required when exiting the roundabout.
- A passenger car driver or motorcyclist should reduce their speed approaching the roundabout. They should watch for and adjust their speed to provide space for any bicyclists or micromobility users who may choose to travel in the same lane.
- A passenger car driver or motorcyclist should yield to or stop for pedestrians or bicyclists crossing the roadway or intending to cross. If there is more than one lane at the crossing, a passenger car driver or motorcyclist should not pass another vehicle that might be stopping for a pedestrian. A passenger car driver or motorcyclist should be sure they have yielded to or stopped for pedestrians before looking ahead to potential conflicting vehicular traffic in the roundabout.
- If there is a traffic control device controlling the approach or crosswalk, such as a traffic signal or beacon, a passenger car driver or motorcyclist should obey the traffic control device.
- A passenger car driver or motorcyclist must **yield to all conflicting lanes** when entering the roundabout.
- A passenger car driver or motorcyclist should not pass large trucks that are preparing to enter the roundabout or are entering, circulating, or exiting the roundabout. The trucks will likely need to occupy more than one lane to complete their movements.
- If an emergency vehicle approaches from behind and a passenger car driver or motorcyclist can do so safely, they should pull to the side where there is room for the emergency vehicle to pass. Otherwise, a passenger car driver or motorcyclist should proceed through the roundabout and pull over at the earliest opportunity. If a passenger car driver or motorcyclist is in the roundabout and an emergency vehicle is approaching from an upcoming entry, they should yield to the emergency vehicle.

Exhibit 4.11. Instructions for motorists when emergency vehicles are in roundabouts.



SOURCE: Adapted from Massachusetts Department of Transportation (*44*).

that can drive legally on the roadway without special permits and vehicles that either require permits, such as oversize or overweight (OSOW) vehicles, or vehicles that otherwise have large dimensions, such as some farm equipment.

Roundabouts have design features or operational characteristics that specifically intend to serve large vehicles:

- Raised but traversable portions of islands called *aprons* (commonly truck aprons) for trucks to use when traversing the roundabout. Aprons are common around the non-traversable portion of a central island and may be integrated as traversable portions of splitter islands. They may also be used on the outside of roundabout entries and exits next to external curbs.
- For single-lane roundabouts, designs generally allow buses to stay within the circulatory roadway.
- For multilane roundabouts, designs either allow trucks to straddle lanes throughout the roundabout or provide lane widths and design features that allow trucks to remain in their lane throughout the roundabout.

Roundabouts can be designed to serve one size of design vehicle for some movements and another size of design vehicle for others. For example, for a roundabout with a designated truck route only on the major street, it may be appropriate to design for a WB-62 or WB-67 design vehicle for major street through movements and an SU-30 or BUS-40 design vehicle for all other movements.

Exhibit 4.12 and Exhibit 4.13 illustrate examples of trucks navigating roundabouts. Exhibit 4.14 shows the perspective from the view of the truck driver using mirrors to see the rear of the truck while passing through a roundabout.

Exhibit 4.12. Example of a truck at a roundabout at an interchange ramp terminal intersection.

LOCATION: NW 319th Street/I-5 Southbound Ramps, La Center, Washington.
SOURCE: Kittelson & Associates, Inc.

Exhibit 4.13. Truck at a rural single-lane roundabout.

SOURCE: Pennsylvania Department of Transportation.

Exhibit 4.14. A truck driver's view of rear of the truck in a roundabout.

SOURCE: Ourston.

4.4.1 Designing for Versus Accommodating Large Vehicles

Large vehicles often affect key roundabout dimensions that are dictated by the clear width of the large vehicle's swept path and its ability to turn at a minimum radius. This is especially true for single-lane roundabouts, where the swept path of the truck may be the critical design dimension in many parts of the design and may dictate which parts of the roundabout need to be traversable by trucks. For example, the ability and design objective for trucks to traverse all or portions of a central island or splitter island have a direct effect on the size and footprint of a roundabout. Truck operations need to be established and documented early during roundabout planning activities and be revisited and confirmed through conceptual and final design layouts.

Early during project development, it is useful to distinguish between *designing for trucks* versus *accommodating trucks*. The distinction between designing for trucks and accommodating trucks can be described as follows:

- **Designing for trucks.** An agency may purposefully choose to serve specific types of trucks with limited or no lane encroachment commonly expected at the roundabout. Some agencies describe this as the *design vehicle*, which is the vehicle that establishes many of the design dimensions.
- **Accommodating trucks.** Accommodation is based on serving a less-frequent but larger control vehicle (or check vehicle). Accommodating this larger vehicle could affect some design features or elements by allowing lane encroachment or some predicted encroachment over curbs. This may also include hardened surfaces within the landscaped areas to accommodate these less-frequent vehicle movements.

Designing all movements for the largest possible truck can lead to negative safety and operational performance issues for other roundabout users, particularly people walking and biking. Practitioners need to configure roundabouts to best serve large vehicles without sacrificing the safety performance and comfort levels of other users. Roundabout configurations can be established to *accommodate* a larger vehicle that may only occasionally traverse the roundabout by locating landscaping, signing, and other features out of a large truck's predicted travel path. Furthermore, roundabout configurations can be tailored to match specific patterns of truck movements, such as larger trucks for through movements along a major street and smaller trucks for turning movements.

Another key decision at multilane roundabouts is whether to have trucks straddle lane lines, stay entirely within their lane, or establish some combination thereof when entering, circulating, and exiting. This decision significantly affects the roundabout's key dimensions, including its diameter and associated footprint. Chapter 10: Horizontal Alignment and Design discusses this topic in detail.

Finally, some roundabouts will serve OSOWs that require permits to travel on the roadway system. These OSOW vehicles may have specific and unique needs and are addressed in Section 4.4.3.

4.4.2 Standard Trucks

Standard trucks are vehicles normally allowed on a roadway without a special permit. For design purposes, AASHTO has established design vehicle designations based on whether the truck is a single unit (SU) or a tractor trailer combination with a given wheelbase (WB), along with the length of the truck's wheelbase from the front axle to the rear axle. This results in common design vehicles such as the SU-30, WB-40, and WB-62 (*27*).

The truck fleet in the United States has evolved in recent years. A national study of the truck fleet and its characteristics found that the combination of a tractor and a single large trailer (WB-62 through WB-67, depending on the length of the cab and placement of rear axles on the trailer) is the most common type of truck. The WB-50 has largely faded from prominence in the truck fleet (*45*). Excluded from Green Book publications beginning with the 2011 6th edition (*46*), WB-50 vehicles are not to be used for design decisions. As a result, common types of standard trucks used at roundabouts include WB-62, WB-67, and Surface Transportation Assistance Act design vehicles, with the WB-40 and SU-30 as common sizes for smaller delivery trucks.

4.4.3 Oversize or Overweight Trucks

Trucks that are larger or heavier than standard trucks require permits to travel on the roadway system and are characterized as OSOW trucks. OSOW vehicles often have one or more characteristics that influence roundabout planning and design:

- Long wheelbases that result in a larger swept path than those of a standard truck;
- Larger overswing that extends beyond the curbs, impacting signs, poles, and other street furniture;
- Low vehicle clearance that affects the vertical alignment and cross-section features, including truck apron design; and
- Height or weight combinations that require the OSOW truck to divert from a route to bypass a height-restricted or weight-restricted bridge or other constraint. This commonly occurs at freeway interchanges.

A freight network plan has to include segments that allow for the necessary turning movements where OSOW truck accommodations are needed (*47*). Agencies are advised to engage stakeholders when determining proper accommodations for OSOW trucks. These accommodations might include vertical ground clearance, sufficient clear areas, permits granted for atypical vehicle movements (such as contraflow movements), and temporary methods that protect the roundabout from encroachment (*47*). Further details are provided in Chapter 10: Horizontal Alignment and Design.

4.4.4 Buses

A variety of bus types can influence roundabout planning and design, and each can influence design vehicle dimensions and whether provisions are needed in the vicinity of the roundabout for associated bus stops. AASHTO has established design vehicles for buses, including the BUS-40 and BUS-45. Common bus types are described in Exhibit 4.15.

4.4.5 Other Large Vehicles

Depending on a project's location and context, a roundabout may require designing for or accommodating other vehicle types. These vehicles include recreational vehicles, vehicles pulling horse or boat trailers, farm vehicles, construction vehicles, and others. To properly plan and design for these vehicles, practitioners need to understand the expected number of vehicles and the frequency of their presence at the roundabout location. Similarly, use of recreational vehicles often peaks during certain seasons of the year. Evaluations of the vehicle types, numbers, and frequency of their travel through the location support decision making.

To evaluate these types of vehicles and their influences on roundabout design, practitioners need to gather user input from the industries related to these vehicles (e.g., farming, tourism, truck shipping, construction) to identify the specific vehicle specifications and accurately model the turning paths.

Exhibit 4.15. Types of buses.

Types of Buses	Description
School buses	School buses are characterized by their unique passenger types (school-aged children) and their unique scheduling and stopping patterns. As a design vehicle, school buses often have a larger distance between the rear axle and the back of the vehicle, which affects a roundabout's horizontal design and the placement of signs, poles, or other furniture around the roundabout.
Transit buses	Transit buses may include fixed chassis and articulated vehicles, and they can have a variety of wheelbase lengths as well as different distances between the bumpers and the outermost axles. These factors affect the swept path of the bus and potential impact to areas beyond the curb, such as signs, poles, and other fixed objects. Bus stops for transit buses are common in the vicinity of roundabouts, and their placement (near side versus far side) and design (stopping in-lane versus using a pullout) are to be considered early in the design process. Bus stops are a transfer point for people walking and biking, so the pedestrian and bicycle facilities at the bus stop, as well as how these people approach the bus stop and cross the street in the vicinity of the bus stop, are an integral part of the design and evaluation.
Intercity buses	Intercity buses tend to be larger, single-chassis vehicles that typically do not stop on the street, although some intercity buses used as private shuttles for employers may stop in the vicinity. At a roundabout, therefore, they may influence design vehicle passage through the roundabout but are less likely to influence bus stop location.

4.5 Emergency Vehicles

Roundabouts provide emergency vehicles the benefit of lower vehicle speeds, which may result in reduced crash risk compared with non-roundabout, signalized crossings. In roundabouts, unlike at signalized intersections, emergency vehicle drivers do not face unexpected through vehicles entering the intersection, resulting in angle crashes at high speeds.

It is imperative that roundabouts be designed for emergency vehicles. Vehicle types can vary but include large vehicles or trucks. The variability of emergency vehicles requires assessing specific vehicle type specifications to support the modeling of swept paths.

On emergency response routes, the delay for the relevant movements at a planned roundabout needs to be compared with those at alternative intersection types and a control facility. Depending on the route, an agency may consider approach and departure roadway curb-to-curb widths that facilitate passing a stopped vehicle.

4.6 Railroads and Light Rail Transit

Rail crossings through or near a roundabout may create many of the same design challenges present at other intersections. However, practitioners need to consider additional concerns present within the rail community when planning and designing roundabouts. The presence of railroads or light rail transit adjacent to or near roundabouts requires understanding and assessing how the railroad or light rail transit interacts with other users and how that will affect the roundabout's operations.

A primary concern with rail crossings and roundabouts is the queuing that can occur at the roundabout entry and extend back through the rail crossing. The railroad community also expresses concern regarding the potential for pedestrians, parking on the exit, or other factors that can create a queue in the roundabout that may block a rail crossing.

Unlike signalized intersections, most roundabouts do not have an option for clearing the queue on a roundabout approach before a train's arrival. Without the ability to clear the queue on an approach to a roundabout, motor vehicles may occupy a rail crossing when the train arrives.

Chapter 12: Traffic Control Devices and Applications discusses this topic in more detail. In addition, the FHWA *Manual on Uniform Traffic Control Devices for Streets and Highways* (MUTCD) and the FHWA and FRA *Highway-Rail Crossing Handbook* provide important information on this topic, including the use of a diagnostic team for assessing the rail crossing (*48*, *49*).

4.7 Connected and Automated Vehicles

Connected and automated vehicles (CAVs) communicate with each other and with roadside infrastructure. The connectivity element provides automated driving systems with more complete information about a vehicle's surroundings and enables cooperative vehicle maneuvers. Their cooperative control allows CAVs to operate in platoons at shorter headways than possible by either human-driven vehicles or automated vehicles without connectivity, which may increase roadway capacity. The specific opportunities for CAVs at roundabouts and vehicle-to-vehicle (V2V) communication at roundabouts are as follows:

- **Opportunities for CAVs at roundabouts.** For a human-driven vehicle waiting to enter a roundabout, the routing decision of a conflicting vehicle within the roundabout is uncertain until the vehicle commits to a circulating or exiting maneuver. Such uncertainty could create unnecessary waiting time for the entering vehicle, thus reducing entry capacity. Unlike human-driven vehicles, if the yielding vehicle and incoming vehicle are both CAVs, the two CAVs could share routing information through V2V communication. If the paths of the two CAVs do not conflict, the CAV at the entry could enter before the incoming CAV shows a visible intention to circulate or exit (*50*).
- **V2V communication at roundabouts.** When a CAV approaches a roundabout, it will automatically search for the incoming vehicles on the circulating lane or lanes via line-of-sight sensors or V2V communication. Once the V2V communication is established, the CAVs on the entering lanes and the circulating lanes share critical information, such as location, speed, acceleration, and routing decisions. By sorting the incoming CAVs by distance, the entering CAV targets the closest incoming CAV on each circulating lane and determines whether the route of the target CAV conflicts with its own intended path. If the routes (paths) do not conflict, the entering CAV enters without yielding. Note that if the first vehicle in the upcoming traffic stream is not a CAV or if its route conflicts with the subject vehicle, then the entering CAV's behavior will be controlled by gap acceptance criteria (*50*).

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CHAPTER 5

Stakeholder Considerations

Contents

This chapter provides an overview of stakeholder considerations for roundabouts. This includes identifying the stakeholders at the earliest stage of the project and involving the public in educational outreach during design stages. Outreach includes considering and discussing roundabouts in regional or local long-range transportation plans through subsequent stages of project development. Identifying users and needs early helps agencies set the foundation to execute a performance-based approach and make design decisions that further a project's intended outcomes.

There are many approaches to stakeholder outreach, with needs and interests varying by the project catalyst, project type, stage of the project development process, type of stakeholders, and specific project needs. For some projects, outreach may be limited to specific stakeholders. For example, practitioners may wish to understand what type of emergency response vehicles an area may use, or they might speak with a local farming cooperative or truck intermodal transfer facility to see what type of equipment is most common. Outreach can also include local landowners or community advocacy groups who can share key interests and needs to consider during project planning. Regarding the catalyst, it is important that stakeholder outreach be tailored to provide information most helpful in decision making associated with roundabout design.

Early investments in obtaining stakeholders' input on roadway and roundabout needs help guide decisions and promote a better understanding of project-specific preliminary design objectives. The net result is also more efficient and promotes effective project delivery. There are many documented approaches to conducting successful stakeholder outreach. However, intersection planning and design can benefit from roundabout-specific considerations if project stakeholders

Exhibit 5.1. Considerations for selecting an outreach approach.

Factor	Considerations
History of roundabouts in the area	• Is this the first roundabout in the area? • Have previous roundabouts in the area been widely accepted? • Are there rotaries or other traffic circles that may affect the consideration of a roundabout? • Is there a poorly performing roundabout that may affect perceptions about a roundabout at the study location?
Local drivers' familiarity with roundabouts	• It may be helpful to start with less complex roundabouts (e.g., single-lane roundabouts) when introducing roundabouts in a new geographic area. • A single-lane roundabout will be more easily understood than a multilane roundabout. Integrating single-lane roundabouts may help users become more comfortable with navigating a roundabout. • If a multilane roundabout is likely, there could be value in staging construction to first open the roundabout with a single lane and later conduct the expansion to the ultimate configuration.
Adequate time for public awareness	• Introducing roundabouts into new areas may require additional effort to inform the public about roundabouts and the proper way to use them. There may be value in accounting for more time in project development for a roundabout than for non-roundabout forms to address roundabout-specific outreach needs. • Public education (e.g., printed and virtual materials and in-person training) requires time for coordination, development, and distribution. Practitioners need to customize their outreach approach and tools to project-specific needs that supplement general information about roundabouts. • More experienced agencies could consider sharing education and outreach materials with other agencies starting the process to help reduce the initial efforts of developing content. • Outreach and engagement can occur with users from elementary school children to older adults. The outreach approach can account for the education and awareness needs of each user.
Type of forum for engagement	• Virtual meetings are limited in the range of media that can be used to engage and the learning styles of the audience but can efficiently reach a larger number of people. • In-person meetings can provide a multitude of media formats to fit all the learning styles of attendees but may be more difficult to schedule for best attendance.

are unfamiliar with roundabouts. When establishing an outreach approach and selecting outreach methods for projects that include roundabouts, practitioners may consider the factors summarized in Exhibit 5.1.

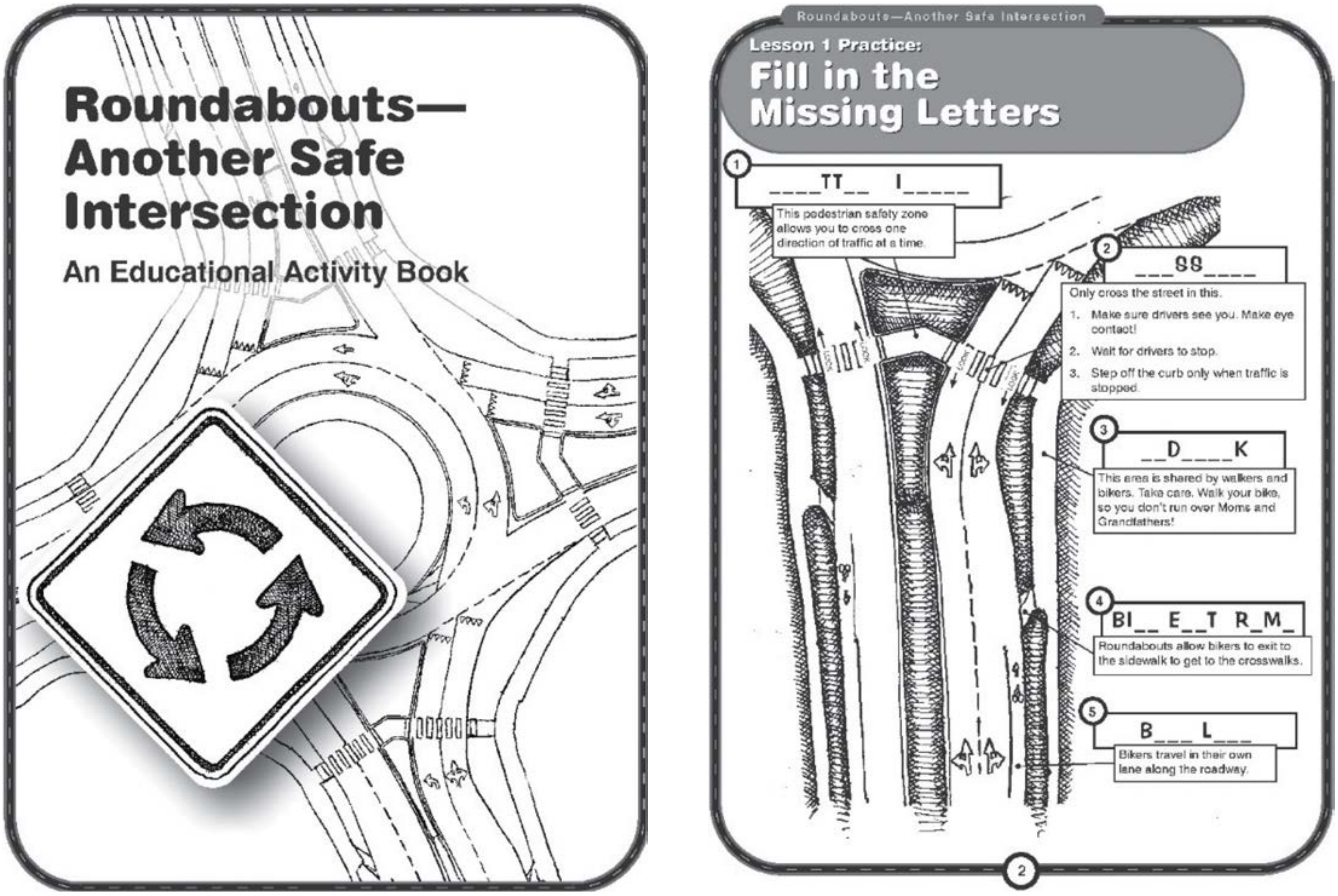
Exhibit 5.2 illustrates a children's activity book developed by the City of Bend, Oregon, to help educate school-aged children about navigating a roundabout (*1*).

Exhibit 5.3 illustrates a high school educational activity to teach students the differences between roundabouts and all-way, stop-controlled intersections (*2*).

5.1 Identifying Stakeholders

Identifying a project's stakeholders is one of the first steps to developing an outreach approach. Stakeholders can include a wide range of public and private organizations, along with potential users of various ages who may have a vested interest in the project's outcome. Early engagement

Exhibit 5.2. Example of children's educational workbook.



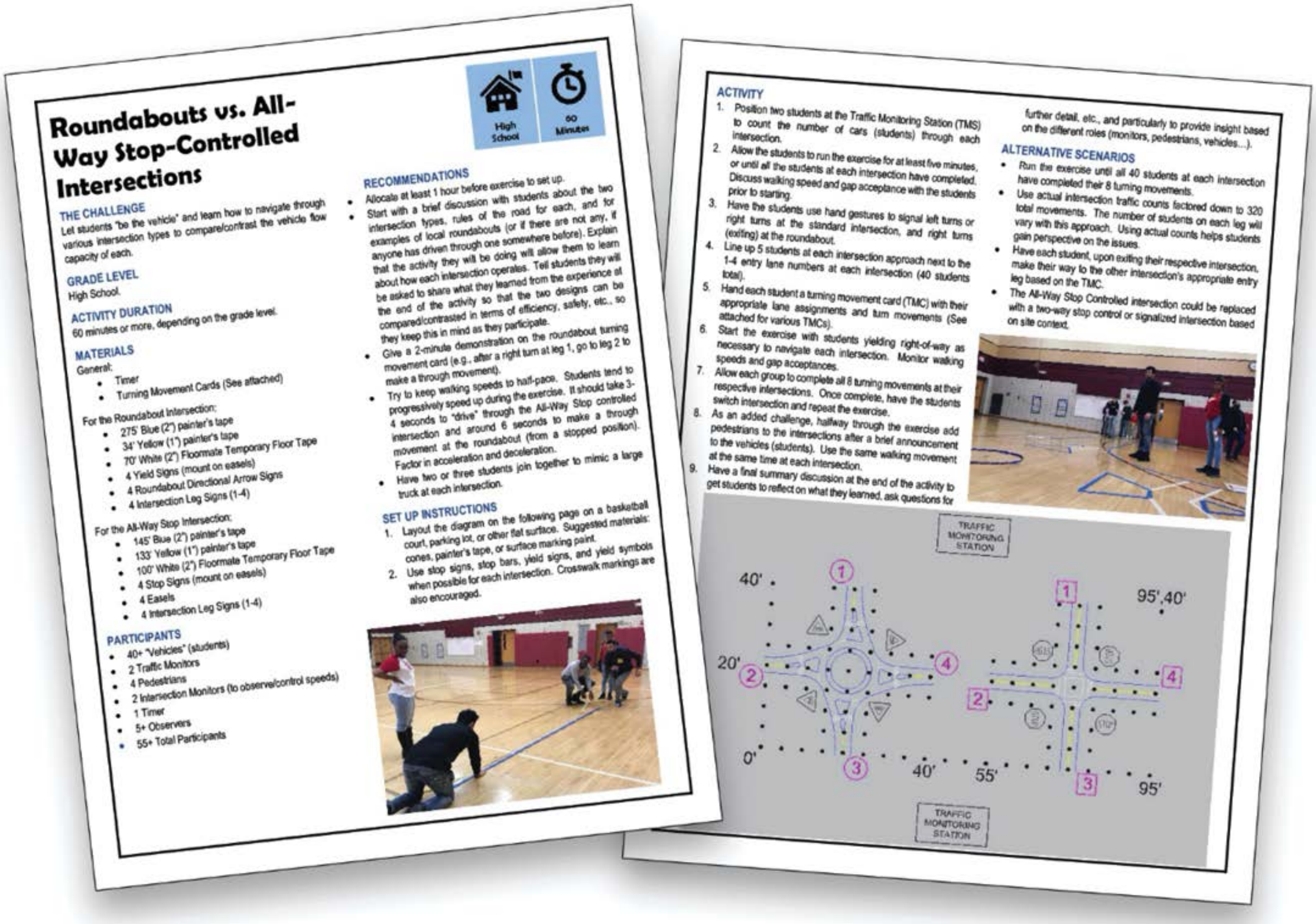
Source: City of Bend, Oregon (*1*).

and consensus-building with influential stakeholders—people to whom the community looks for leadership and trust—can be especially beneficial for a successful public engagement process.

- Public organizations may include agencies that own and maintain the roadway facilities that become part of the project. Understanding how to effectively engage and partner with agencies can improve the decision-making process. However, communications can vary depending on the experience each agency has with roundabouts. Once an agency understands the roundabout project, practitioners can collaborate with them to lead some of the outreach, increasing the community's acceptance and understanding.
- Private organizations may include trucking industry stakeholders, emergency responders, pedestrian and bicycle groups, business owners, and school representatives. These groups are commonly involved with infrastructure projects but may have limited roundabout knowledge.
- Individuals within the public can also have a significant influence on advancing a project. In some areas, individuals familiar with roundabouts can be the strongest project advocates. In other cases, the public can oppose a project simply because they do not understand the intricacies of roundabouts.

The type of project stakeholder is principally influenced by the project location and project type. Exhibit 5.4 summarizes the range of potential stakeholders to consider integrating into the outreach process.

Exhibit 5.3. Example of high school education activity.



High School | 60 Minutes

Roundabouts vs. All-Way Stop-Controlled Intersections

THE CHALLENGE
Let students "be the vehicle" and learn how to navigate through various intersection types to compare/contrast the vehicle flow capacity of each.

GRADE LEVEL
High School.

ACTIVITY DURATION
60 minutes or more, depending on the grade level.

MATERIALS
General:
- Timer
- Turning Movement Cards (See attached)

For the Roundabout Intersection:
- 275' Blue (2") painter's tape
- 34' Yellow (1") painter's tape
- 70' White (2") Floormate Temporary Floor Tape
- 4 Yield Signs (mount on easels)
- 4 Roundabout Directional Arrow Signs
- 4 Intersection Leg Signs (1-4)

For the All-Way Stop Intersection:
- 145' Blue (2") painter's tape
- 133' Yellow (1") painter's tape
- 100' White (2") Floormate Temporary Floor Tape
- 4 Stop Signs (mount on easels)
- 4 Easels
- 4 Intersection Leg Signs (1-4)

PARTICIPANTS
- 40+ "Vehicles" (students)
- 2 Traffic Monitors
- 4 Pedestrians
- 2 Intersection Monitors (to observe/control speeds)
- 1 Timer
- 5+ Observers
- 55+ Total Participants

RECOMMENDATIONS
- Allocate at least 1 hour before exercise to set up.
- Start with a brief discussion with students about the two intersection types, rules of the road for each, and for examples of local roundabouts (or if there are not any, if anyone has driven through one somewhere before). Explain that the activity they will be doing will allow them to learn about how each intersection operates. Tell students they will be asked to share what they learned from the experience at the end of the activity so that the two designs can be compared/contrasted in terms of efficiency, safety, etc., so they keep this in mind as they participate.
- Give a 2-minute demonstration on the roundabout turning movement card (e.g., after a right turn at leg 1, go to leg 2 to make a through movement).
- Try to keep walking speeds to half-pace. Students tend to progressively speed up during the exercise. It should take 3-4 seconds to "drive" through the All-Way Stop controlled intersection and around 6 seconds to make a through movement at the roundabout (from a stopped position). Factor in acceleration and deceleration.
- Have two or three students join together to mimic a large truck at each intersection.

SET UP INSTRUCTIONS
1. Layout the diagram on the following page on a basketball court, parking lot, or other flat surface. Suggested materials: cones, painter's tape, or surface marking paint.
2. Use stop signs, stop bars, yield signs, and yield symbols when possible for each intersection. Crosswalk markings are also encouraged.

ACTIVITY
1. Position two students at the Traffic Monitoring Station (TMS) to count the number of cars (students) through each intersection.
2. Allow the students to run the exercise for at least five minutes, or until all the students at each intersection have completed. Discuss walking speed and gap acceptance with the students prior to starting.
3. Have the students use hand gestures to signal left turns or right turns at the standard intersection, and right turns (exiting) at the roundabout.
4. Line up 5 students at each intersection approach next to the 1-4 entry lane numbers at each intersection (40 students total).
5. Hand each student a turning movement card (TMC) with their appropriate lane assignments and turn movements (See attached for various TMCs).
6. Start the exercise with students yielding right-of-way as necessary to navigate each intersection. Monitor walking speeds and gap acceptances.
7. Allow each group to complete all 8 turning movements at their respective intersections. Once complete, have the students switch intersection and repeat the exercise.
8. As an added challenge, halfway through the exercise add pedestrians to the intersections after a brief announcement to the vehicles (students). Use the same walking movement at the same time at each intersection.
9. Have a final summary discussion at the end of the activity to get students to reflect on what they learned, ask questions for further detail, etc., and particularly to provide insight based on the different roles (monitors, pedestrians, vehicles...).

ALTERNATIVE SCENARIOS
- Run the exercise until all 40 students at each intersection have completed their 8 turning movements.
- Use actual intersection traffic counts factored down to 320 total movements. The number of students on each leg will vary with this approach. Using actual counts helps students gain perspective on the issues.
- Have each student, upon exiting their respective intersection, make their way to the other intersection's appropriate entry leg based on the TMC.
- The All-Way Stop Controlled intersection could be replaced with a two-way stop control or signalized intersection based on site context.

SOURCE: Institute of Transportation Engineers (*2*).

5.2 Outreach at Each Project Development Stage

Understanding the people a project aims to serve is key to understanding intended outcomes. Outreach sharing, learning, and educating may take just as long as the sequential technical work. In some cases, it may be necessary to hold separate public involvement meetings for different types of stakeholders. Outreach often considers the effects of construction and the temporary roadway configurations in place during roundabout construction. Public outreach needs to commence early, as the ability to provide multimodal roundabout configurations for a given project context diminishes throughout project development, as further illustrated in Exhibit 5.5.

Sharing information and obtaining input about roundabout projects is similar to outreach for other types of projects. However, it may require special efforts to illustrate roundabout-specific concepts and principles as they compare with non-roundabout solutions that might be more familiar to an audience. The project construction method (e.g., design–build) may impact design and construction phase flexibility as well as communication with stakeholders.

Exhibit 5.6 describes potential ways to share information with stakeholders at each project development stage according to the Massachusetts Department of Transportation's *Guidelines for the Planning and Design of Roundabouts* (3).

Exhibit 5.4. Summary of stakeholder examples.

Stakeholder Groups	Examples
Federal agencies	• FHWA • National Park Service • US Forest Service • Bureau of Land Management
State agencies	• State departments of transportation • State parks and recreational departments
Local or regional agencies	• Cities, counties, and regional planning agencies • Local parks and recreational departments
Freight	• Freight and logistics divisions at the state department of transportation • Trucking industry leaders • Local trucking terminals (local to the project)
Public transit	• Local transit agencies • Paratransit agencies
Local business owners	• Adjacent or nearby commercial, retail, office, industrial, or other business
School representatives	• School districts (e.g., superintendents and school principals) • Bus route coordinators
Pedestrian and bicycle groups	• Organizations identified through coordination with local agencies
Emergency responders	• First responders, fire stations, hospitals • Fire and police chiefs
Major traffic generators	• Commercial development • Industrial area • Ports and airports • Large employment centers • Hotel industry • Sports arenas • Music venues
Neighborhood associations	• Organizations identified through coordination with local agencies
Agricultural industry	• Local agricultural cooperatives • Organizations identified through coordination with local agencies

Exhibit 5.5. Stakeholder outreach opportunities.

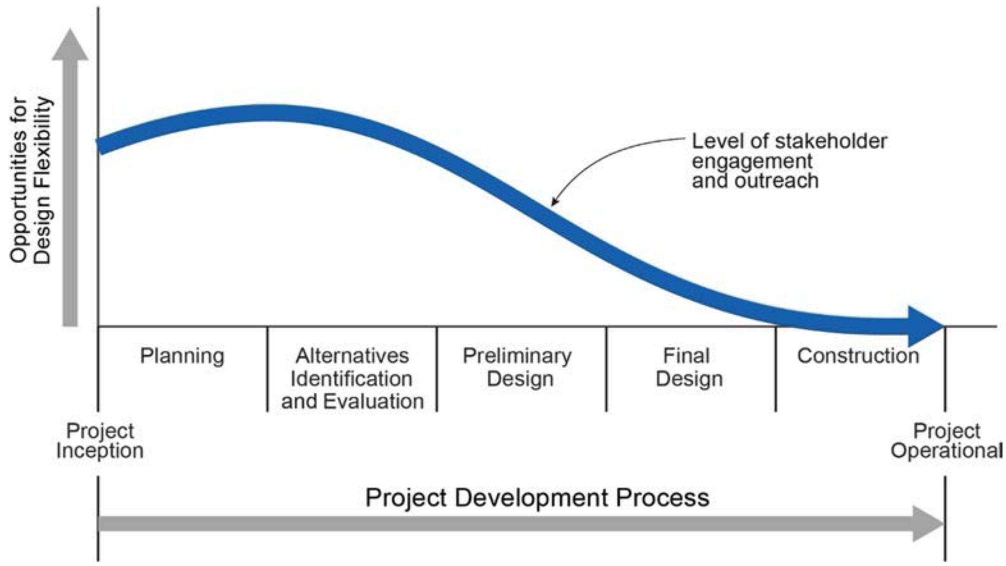
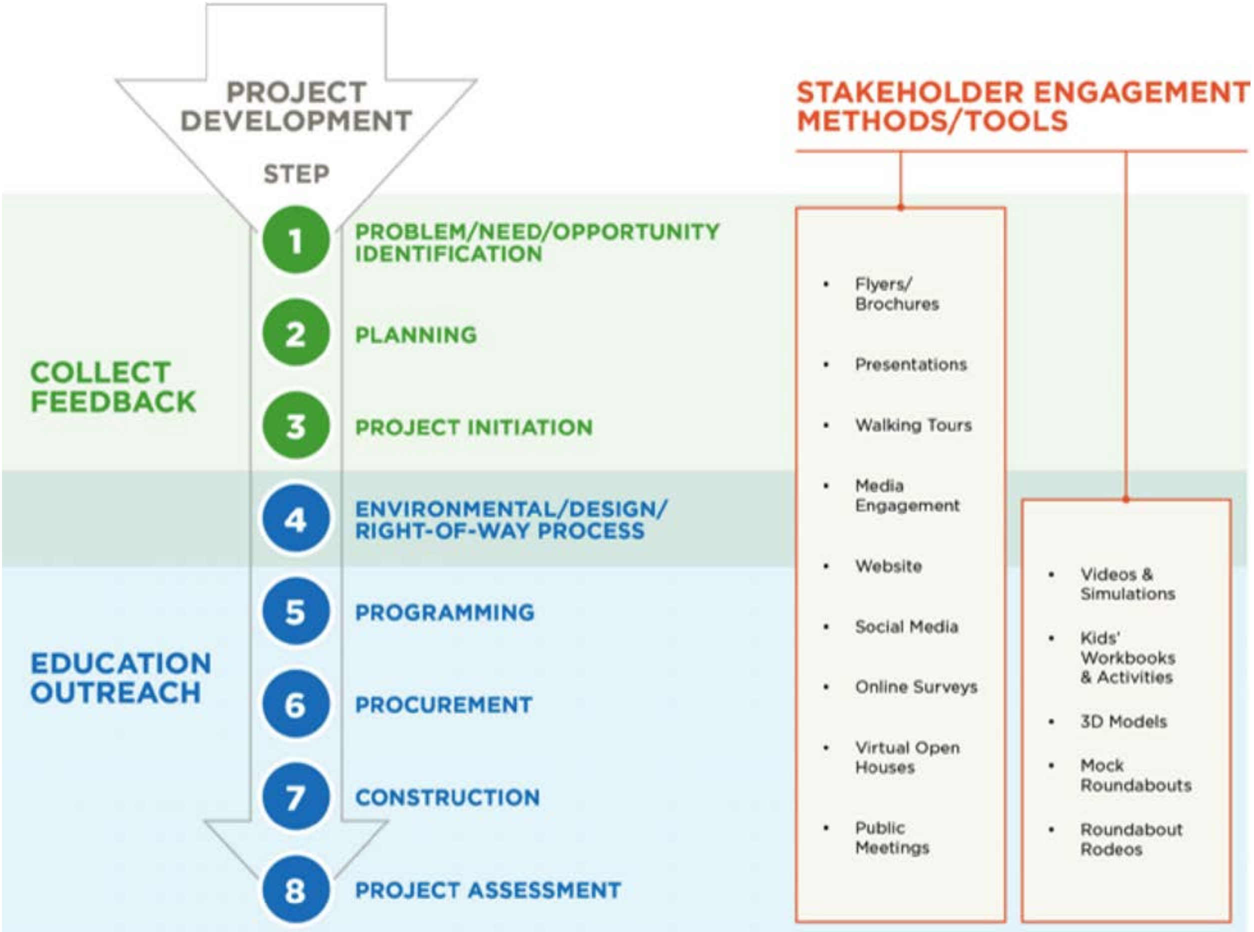


Exhibit 5.6. Example of information sharing with stakeholders.



SOURCE: Massachusetts Department of Transportation (*3*).

5.2.1 Planning

Stakeholder outreach at the planning stage can help inform user needs and design vehicles, which can set the order of magnitude for roundabout size and other early project considerations. Work at this level could be part of a long-range transportation plan, corridor plan, or another early programming exercise. A roundabout configuration will be greatly affected by the project type (e.g., undertaking new construction, reconstructing intersections, retrofitting existing circular intersections). Working with stakeholders to understand the context early in the planning stage helps inform future project decisions. Efforts at this stage could be part of intersection planning for an area, corridor, or isolated location. The level of detail at this stage could focus on conceptual traffic operations, general assessments of lane numbers, and footprint/physical impacts. Outreach could include helping stakeholders understand the impacts of various design decisions, such as the undesirable performance that might result from overdesigning a roundabout.

Outreach at this stage may include answering key questions, such as

- What is the catalyst of a project?
  - Is it driven by operational or safety concerns?
- What should be known about the project context to help adapt a solution to an existing condition?
  - How can project planning and design considerations support an intended change in a context?

- Who should be engaged in the initial planning activities, and what role shall they play as the project continues through development?
- How can early stages of ICE assess and advance control strategies?

5.2.2 Alternatives Identification and Evaluation

Work at the alternatives identification and evaluation stage can advance a concept from prior planning outcomes. Evaluations of corridors or isolated intersections regarding safety, operations, or state of good repair may also advance at this stage. Early ICE will likely have more data than in early planning activities, and the roundabouts may advance on the basis of ICE results. Connecting with project stakeholders at this stage can help advance project activities. Likewise, sharing project catalysts along with learning project context issues can guide future project evaluations. Outreach at this stage may include

- Comparing intersection footprints (at the roundabout and the approaches) for comparable overall performance metrics between intersection control strategies,
- Understanding how maintenance needs or traffic control during construction may influence ICD placement and sizing,
- Sharing information about roundabout operations and safety performance checks to establish an appropriate project footprint,
- Comparing or considering the competing needs of various users,
- Incorporating pedestrian and bicyclist needs as part of larger land-use planning activities, and
- Assessing environmental approval process needs and understanding the level of environmental evaluations and general magnitude of the project to anticipate costs and plan future stakeholder outreach.

5.2.3 Preliminary Design

As projects advance from prior efforts, preliminary design will include technical evaluations to support project environmental documentation and alternatives selection. Once control strategies from the prior development stage have advanced, preliminary design activities will help inform engineering details that allow project comparisons.

Project development and environmental clearance generally include outreach and public engagement activities that become more extensive as projects become more complex or environmental clearance needs become vigorous (e.g., categorical exclusion versus environmental assessment). Projects involving environmental clearance often have legal requirements for outreach during the project development process and may require special outreach associated with roundabouts compared with non-roundabout alternatives.

The same technical topic reviews occur at the preliminary design level but in more detail (e.g., truck path assessments, intersection sight distance evaluations, assessments of critical three-dimensional design elements).

Stakeholder outreach helps define project needs and garner project support. There can often be two levels of outreach:

- Overall project details and schedule and
- Roundabout-specific education.

At this stage, practitioners will begin defining or redefining right-of-way needs. Specific outreach can help practitioners understand and minimize direct or indirect right-of-way impacts on adjacent properties. Getting stakeholder input regarding landscaping choices and visual art or gateway treatments at the roundabout can also help practitioners integrate the design into the community.

5.2.4 Final Design

Activities and needs during final design of roundabouts are consistent with other intersection forms. As three-dimensional design details are completed, practitioners adapt and adjust the roundabout concepts that advanced from prior stages and adjust them to mitigate site-specific impacts. Final design can include utilities or construction sequencing associated with maintaining traffic flow or land-use access during construction.

The opportunity to affect the roundabout configuration is limited at this point in the process. Because the design is final, stakeholder outreach and engagement may shift from gathering feedback and general education to include more one-on-one time with specific property owners. Site adaptation is sometimes necessary (such as when an expensive utility has been missed), and changes to the roundabout may require reaching out to parties who may be newly or differently affected.

5.2.5 Construction, Operations, and Maintenance

Outreach activities during construction, operations, and maintenance are similar to those during implementation of other intersection projects. New construction may provide the greatest degree of flexibility, as project constraints may be fewer than those of other conditions. If development on adjacent land is limited, outreach needs may be as well.

Reconstructing intersections and retrofitting existing circular intersections can require extra effort in construction sequencing or longer construction times, as roundabouts often have a larger footprint than conventional intersection forms. The constrained environments may require more, even continuous, engagement with adjacent property owners.

Roundabout footprints at the intersection or the approaches may require special considerations for construction staging or traffic handling during construction. Outreach could focus on reducing the construction effects on adjacent properties (i.e., limited closures or shorter duration temporary roadway configurations). Practitioners might also need to address wayfinding to businesses and temporary sidewalks, trails, or other pedestrian or bicycle facilities. Pre-marking signing and striping designs before permanent installation can help practitioners verify that traffic control devices are installed correctly. Pre-marking could include sign locations, heights, and sign face angles, along with pavement markings and delineators.

5.3 Outreach Approaches

A roundabout may affect various stakeholders in different ways, leading to unique concerns that may not emerge during discussions about non-roundabout intersections. For example, representatives from the police and fire department might focus on emergency vehicle navigation through the roundabout and how it could affect response time. Parents may be concerned about how their teen drivers may understand the roundabout or how comfortable they will be walking through with their children. All outreach content needs to target specific stakeholders.

It is essential to tailor communication about the meeting's purpose to each audience. For example, if a community meeting aims to share the unique aspects of roundabouts in addition to overall project details, then it could present introductory information about roundabouts. This may include highlighting the differences between roundabouts and other intersection types, providing guidance on how to drive through a roundabout, and describing the advantages and disadvantages of roundabouts. In some cases, basic roundabout introductory material may be the primary information presented. In other cases, more specific project information, stakeholder impacts, and specific community concerns and needs may be addressed. Outreach approaches should emphasize safety for each unique user.

Technical explanations of the design and operations may be appropriate for certain stakeholders, while more general educational discussions may be all that is necessary for others. The level of effort can vary considerably depending on whether this is the first roundabout in an area or the local community has had a poor recent roundabout experience.

It is crucial that outreach approaches consider a community's cultural diversity. Communication may include presenting information in multiple languages and organizing meetings at locations and times convenient and comfortable for stakeholders. Interpreters at public meetings can also verify that information is communicated to each community member in attendance.

5.3.1 Levels of Outreach

Outreach information may be presented at a program level or project level with a variety of tools.

- **Program-level outreach.** Program-level techniques provide state and local agencies with consistent messages and themes regarding a roundabout program. This allows senior, mid-level, and junior staff to support common perspectives. A program-level approach can help agencies share, internally and externally, policies such as "roundabouts first" or ICE. Examples may include agency websites, brochures, in-person training, or formal peer review of agency roundabout designs. Roundabouts may be strategies in long-range safety programs or Vision Zero programs; in other words, program-level roundabout information would be integrated as a supporting element of other programs.
- **Project-level outreach.** Project-level outreach varies by type of project. For new construction, the emphasis may be on project messaging and why roundabouts are being considered or proposed. Reconstructing intersections may require more information sharing about project catalysts, learning from stakeholders about intended project outcomes, and adapting within constrained site conditions. Outreach efforts for retrofitting an existing circular intersection might tell stakeholders about the purpose of proposed changes and how the proposed roundabout would differ from the existing circular intersection.

  Project-level outreach includes sharing project-specific information (e.g., need and purpose), supplemented by information that educates the stakeholders about roundabouts. This additional educational outreach can sometimes add to the outreach timeline, which is a smaller part of the overall project timeline.

5.3.2 Methods and Tools

The methods and tools used for program-level and project-level outreach depend on the type of stakeholders and the stage of the project development and can be tailored to the different learning styles of the audience. Public meetings are often an effective way to communicate information and gather input from a specific group of individuals. In other cases, a general announcement, such as a newspaper article, website, or other media outreach, can inform a larger group of individuals, although gathering information is more difficult (except possibly for online methods).

Printed materials include the following:

- **Flyers and brochures** can create general awareness of roundabouts, educate the public about roundabouts in their communities, or advertise specific projects to educate affected stakeholders. Information may include
  - Basics about what roundabouts are and where they can be found;
  - Differences between roundabouts and other types of intersections;
  - Instructions on how to use the roundabout as a motorist, bicyclist, and pedestrian; and
  - Illustrations of the signing and striping drivers may see at a roundabout.

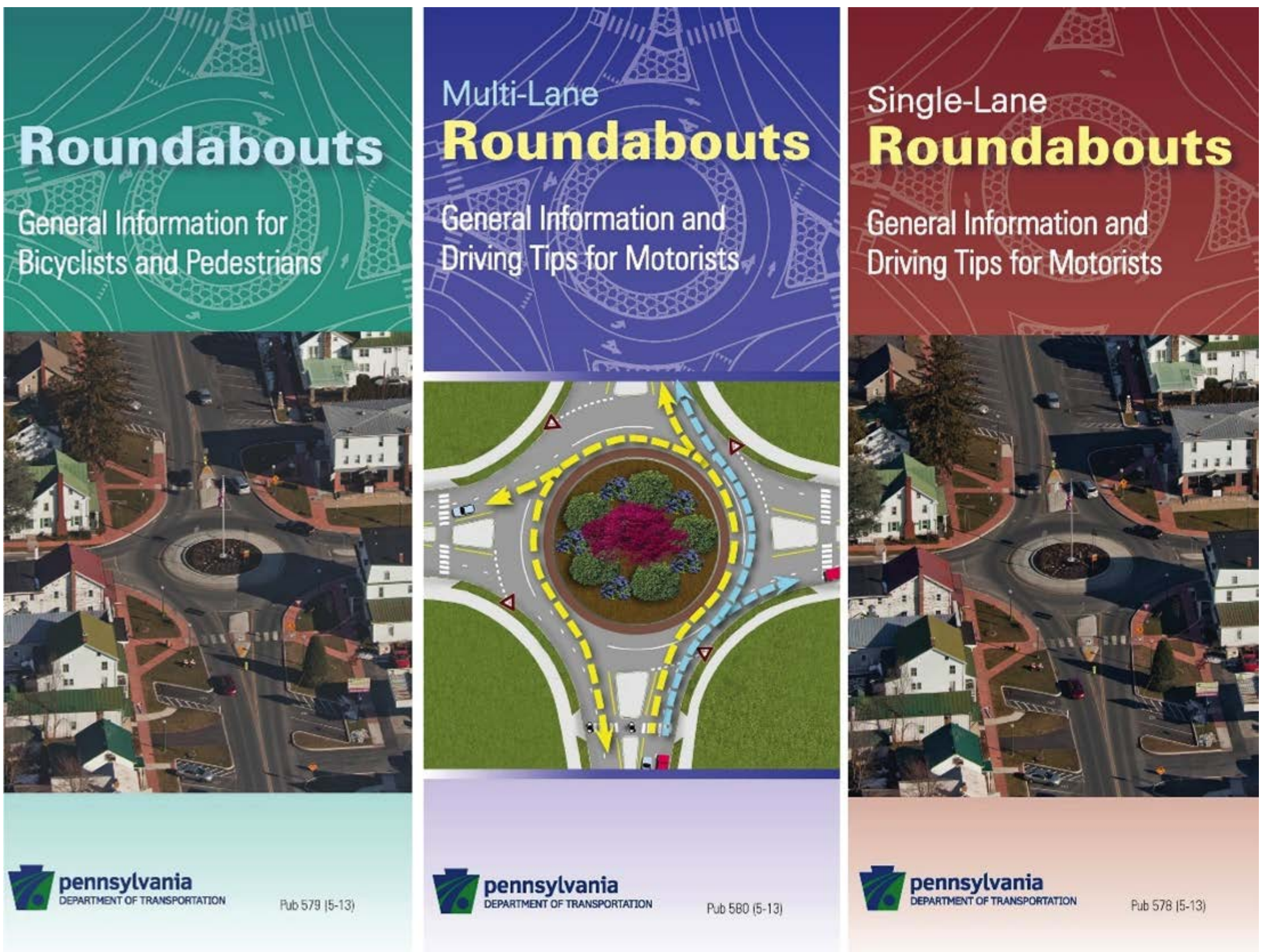
- **Media engagement** may include newspaper articles to provide information on upcoming projects or announcements about in-person training or public meetings.
- **Children's workbooks** can explain how to navigate a roundabout and bring awareness to roundabouts in the community or near schools.
- **3-D models** of roundabouts and roundabout features can communicate with people with visual disabilities.

Exhibit 5.7 illustrates an example set of user guidance brochures.

Virtual materials include the following:

- **Presentations** can convey details about roundabouts or a specific project.
- **Social media** helps engage the community and allows feedback.
- **Videos and simulations** can explain how roundabouts are used. This may include
  - Video footage of existing roundabouts and narration about their operational and safety characteristics,

Exhibit 5.7. Examples of user guidance brochures.



SOURCE: Pennsylvania Department of Transportation (*4–6*).

  - Video footage of stylized animated roundabouts and users,
  - Videos shown at regular intervals on agency access television channels, and
  - Static or dynamic photo imaging of before-and-after conditions.
- **Online surveys** can gather specific input at the project level.
- **Websites** can provide general roundabout information and project-specific information or updates. This may include
  - Simulation tools showing vehicles navigating through the intersection and
  - Additional web links and resources for the public to learn more detailed information or read about roundabouts in other areas.

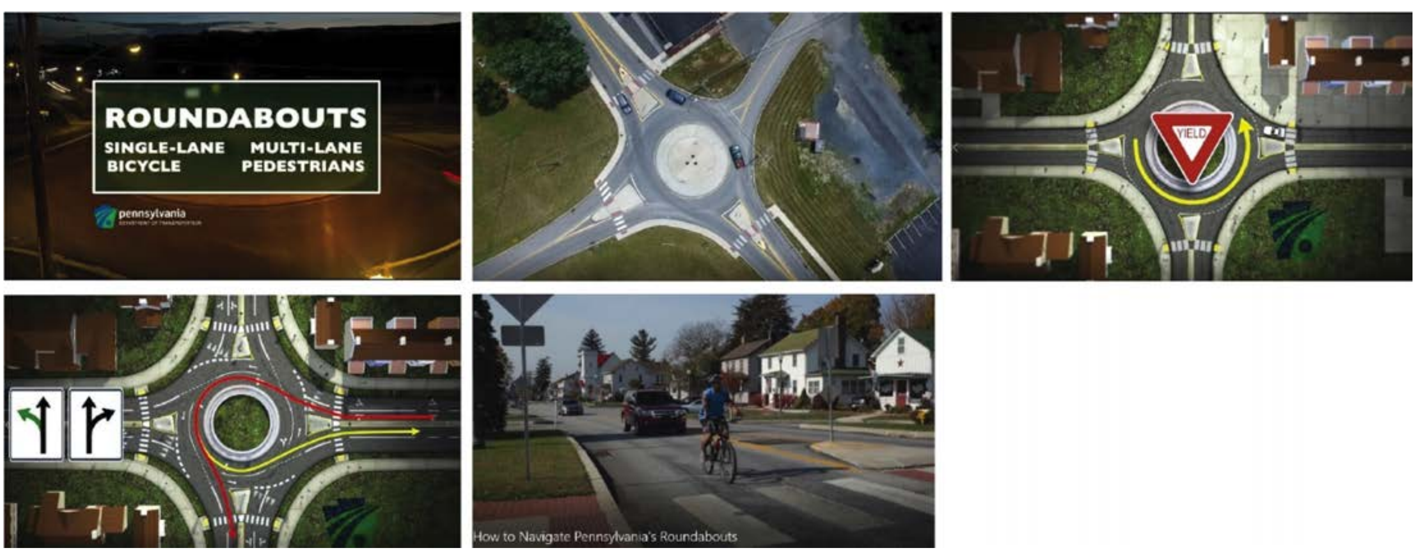
Exhibit 5.8 shows frame captures from an informational video that gave general information about how to navigate a roundabout. The video includes information about single-lane and multilane roundabouts and shows simulation videos with instructions for users (*7*).

Exhibit 5.9 and Exhibit 5.10 illustrate websites from state agencies designed to provide general information for roundabouts and state-specific resources.

In-person engagement methods include the following:

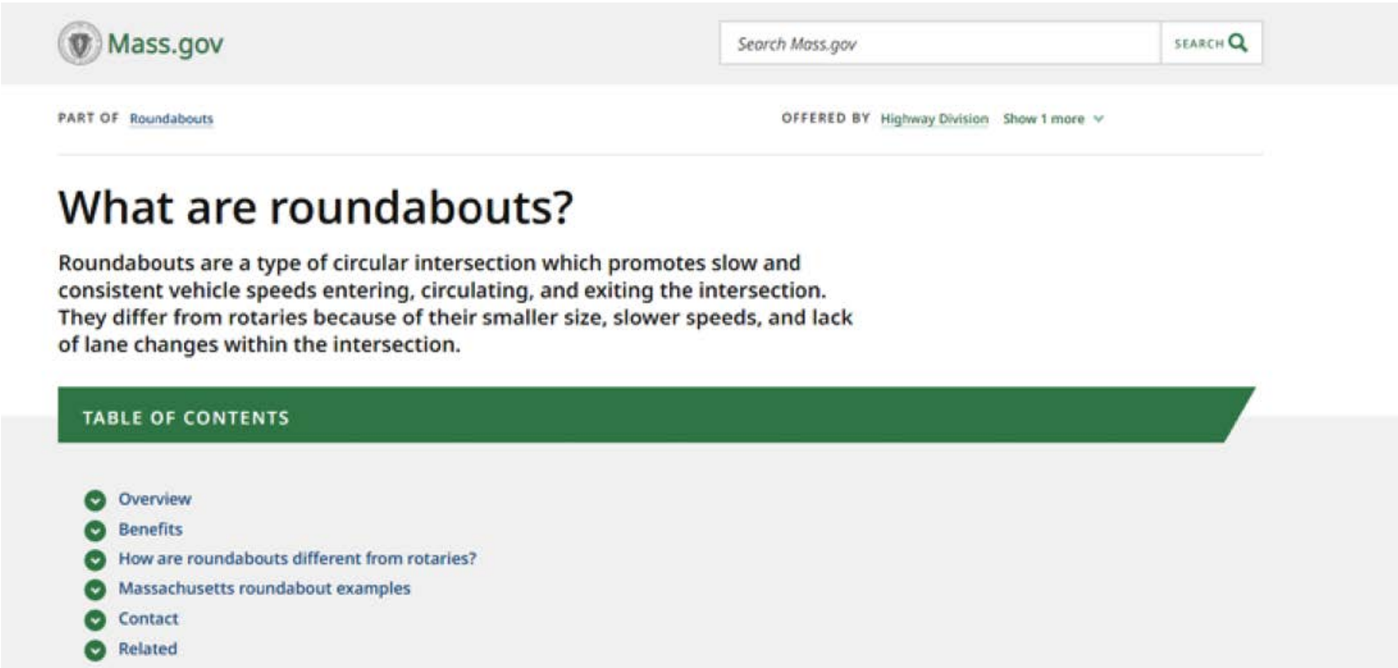
- **Mock roundabouts** with scaled plots can be used with scaled toy vehicles to demonstrate roundabout operations and navigation.
- **Roundabout rodeos** create closed-course driving exercises on full-size roundabout setups, allowing stakeholders to walk, bike, and drive through roundabouts.
- **Walking and biking tours** allow stakeholders to visit and discuss existing roundabouts.
- **Children's activities,** including group tours of roundabouts or play activities on scaled models, can help stakeholders visualize their children navigating roundabouts.
- **Public meetings** allow stakeholders to discuss specific roundabout projects and provide general awareness of roundabouts. Public meetings can be useful to
  - Engage the public in the design process,
  - Identify potential problems early in project planning, and
  - Gain overall acceptance throughout the process.

Exhibit 5.8. Frame captures of informational video on navigating a roundabout.



SOURCE: Pennsylvania Department of Transportation (*7*).

Exhibit 5.9. Instructional website from the Massachusetts Department of Transportation.



SOURCE: Massachusetts Department of Transportation (*8*).

Exhibit 5.11 and Exhibit 5.12 illustrate mock roundabouts that included a scaled version of the proposed roundabout design to aid in discussions with stakeholders.

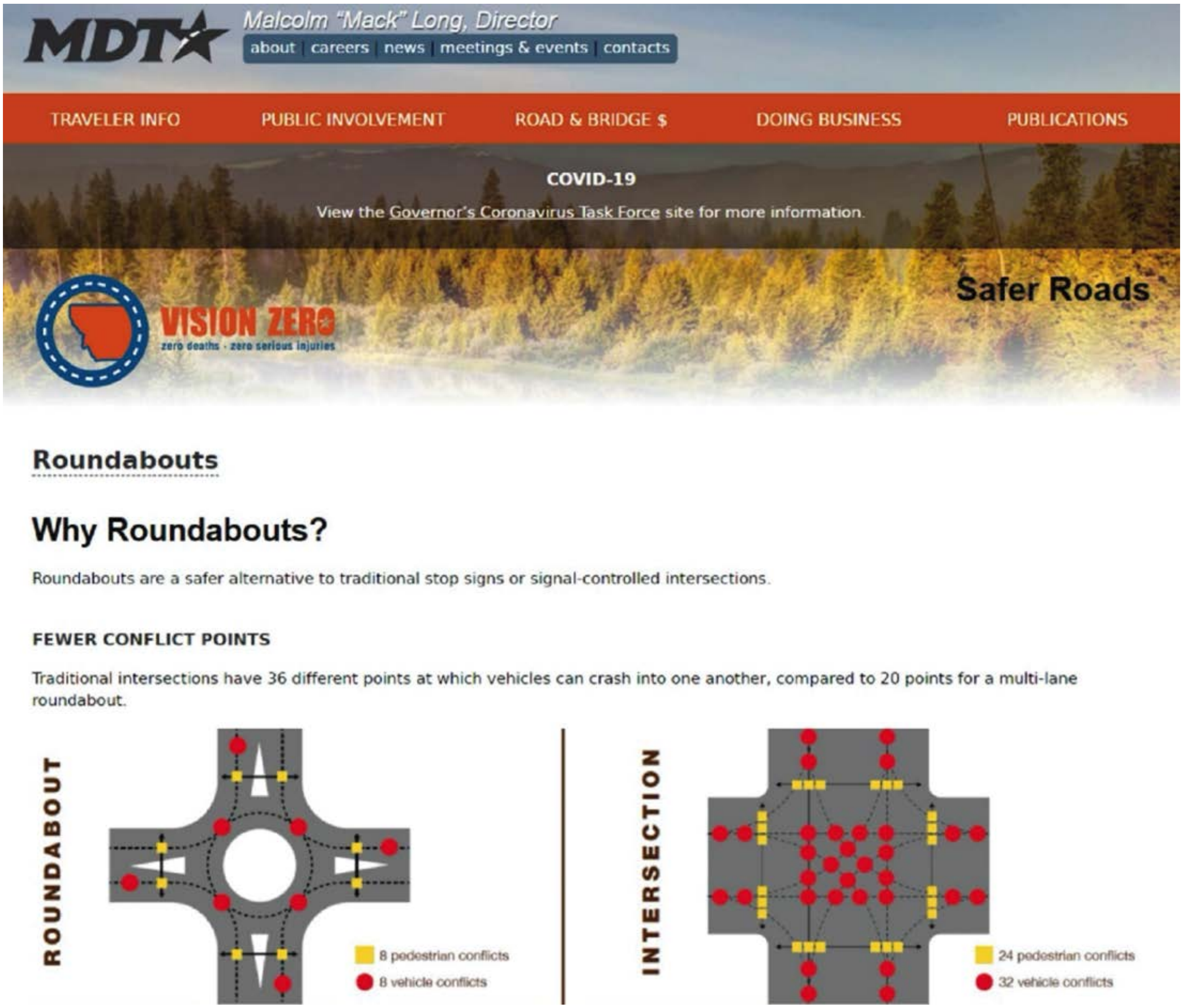
For some projects, it may be useful to conduct specific roundabout training for police and fire departments. This allows them to ask questions they may not want to ask in a public setting and to review with their staff how to stage at a roundabout when responding to a collision, how to direct traffic at a roundabout (if ever needed), and what citations can be issued at a roundabout. Exhibit 5.13 illustrates an example of a private meeting with a police department about a new roundabout project.

In-person outreach meetings should consider various learning styles (e.g., tactile, auditory, visual) and may take an approach that addresses more than one style. Exhibit 5.14 illustrates a public meeting that included printed aerials, mock roundabout models, and informational videos to communicate with a variety of stakeholders.

Exhibit 5.15 and Exhibit 5.16 show photos from truck field trials (sometimes called "roundabout rodeos") that were facilitated by the Alaska Department of Transportation and Public Facilities and the Oregon Department of Transportation, respectively. These truck field trials allow the project team to test truck navigation through a proposed roundabout. The project team set up a driving course in an open area, marking the actual roundabout design with flagging tape, paint, and temporary traffic control devices. Project designers, agency staff, and truck drivers observed various standard trucks and oversize or overweight vehicles navigate through the roundabout design. In both cases, the observations and discussions led to a design that better accommodated the various types of trucks expected to use the roundabout.

Exhibit 5.17 shows a photo from a walking tour in Barnstable, Massachusetts, that allowed agency staff to conduct field observations of an existing roundabout.

Exhibit 5.10. Instructional website from the Montana Department of Transportation.



SOURCE: Montana Department of Transportation (*9*).

Exhibit 5.11. Mock roundabout in Wheatland, Virginia.

SOURCE: Andy Duerr.

Exhibit 5.12. Mock roundabout in Overland Park, Kansas.

SOURCE: Erin Ferguson.

Exhibit 5.13. Example of meeting with a police department.

SOURCE: Jay VonAhsen.

Exhibit 5.14. Example of using multimedia in an in-person meeting.

SOURCE: Ourston.

Exhibit 5.15. Example of truck field trial from the Alaska Department of Transportation and Public Facilities.

SOURCE: Lee Rodegerdts.

Exhibit 5.16. Example of truck field trial from the Oregon Department of Transportation.

SOURCE: Kittelson & Associates, Inc.

Exhibit 5.17. Example of walking tour.

LOCATION: US 6/Route 149, Barnstable, Massachusetts. SOURCE: Alek Pochowski.

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CHAPTER 6

Intersection Control Evaluation

Contents

This chapter provides a general overview of ICE activities and the relationship to roundabout planning and design. ICE describes an evaluation framework that helps practitioners select a preferred intersection control type (e.g., stop, yield, signal) and form (i.e., configuration). ICE processes have been implemented primarily at the state level. However, ICE occurs at regional, county, and local levels across the United States, and FHWA provides guidance on ICE practices (*1*).

ICE is a performance-based approach that allows agencies to select appropriate performance measures and evaluate alternatives on the basis of a project's context, advancing potential solutions that provide the highest benefit in line with project-specific, community, and agency goals. ICE provides objective and replicable screening and evaluation tools or methods to evaluate alternatives at project planning and design stages and has historically been implemented to provide fair consideration for intersection forms and control types other than traditionally arranged stop- and signal-controlled alternatives.

Typically, an initial pool of candidate intersection alternatives is filtered to support decision making that leads to a preferred intersection form and control type. ICE provides a way to evaluate roundabout and non-roundabout intersection types, including emerging intersection forms.

6.1 Policy and Legal Considerations

ICE describes an evaluation framework or process that may or may not be associated with an explicit agency policy. Some agencies have implemented policies that establish applicability and legal underpinnings for the process. ICE may complement other agency policies or goals, including

- **A preferential policy.** This refers to a policy in a system planning document that records a preference for certain intersection forms (e.g., a "roundabouts first" policy). ICE can incorporate such a policy in its decision criteria.
- **Adherence to other agency goals.** A policy may require ICE to align with other agency prerogatives, such as a complete streets policy, a Vision Zero program, or multimodal design standards associated with roadway functional or context classifications.
- **Policies related to an ICE trigger.** An agency can establish a policy regarding the circumstances that require ICE—for example, a proposed addition, expansion, or modification of access to or from the agency's roadway network.

6.2 Typical ICE Steps

ICE processes vary according to the jurisdictions implementing them. Notable differences include the trigger that initiates the ICE process, the number and definition of activities in each step, decision criteria, and the outcome and documentation of the process. ICE is typically conducted in two or three steps, with the intent to conduct the evaluations commensurate with the level of available information associated with project development planning and design activities. These typical steps are as follows:

- **Step 1 and/or 2: Scoping and screening.** Often conducted in a single step, scoping and screening define and consider, at a high level, the range of possible intersection control and form strategies. The evaluation includes defining viable initial alternatives and proceeding with high-level analysis to arrive at a shortlist of alternatives that merit further consideration. These efforts may be conducted using simple checklists or planning-level evaluation measures. The results may screen some alternatives and advance promising strategies for more detailed evaluations.
- **Step 2 or 3: Alternative selection.** This step advances the concepts from the prior step or steps to identify a preferred alternative. That alternative is determined by the results of more detailed evaluations conducted during typical preliminary engineering activities. These engineering activities are often associated with environmental evaluations and other project approval activities to advance a single alternative to the final design stage.

During each step, ICE efforts are best conducted while integrating stakeholder input and customizing performance metrics for unique project needs and documented intended outcomes. With intended outcomes clearly defined, performance measure evaluation may be tailored to avoid unnecessary analysis that may not differentiate candidate solutions.

Some agencies leverage existing computation and analysis, such as the FHWA's Capacity Analysis for Planning of Junctions (Cap-X) or Safety Performance for Intersection Control Evaluation (SPICE) tools (*2*, *3*). Evaluations may include or support the use of spreadsheets incorporating the life-cycle analysis detailed in *NCHRP Web-Only Document 220: Estimating the Life-Cycle Cost of Intersection Designs* (*4*). Other agencies offer more flexibility for applying relevant performance measures and specify the parameters for analysis if it is to be conducted.

Chapter 7: Safety Performance Analysis, Chapter 8: Operational Performance Analysis, and Chapter 9: Geometric Design Process and Performance Checks provide roundabout evaluation and analysis techniques suitable for any step of project development and, therefore, any step of ICE—from high-level screenings to detailed analyses that result in a life-cycle cost analysis.

6.3 Connection to Project Development Process

The common ICE steps are compatible with early project planning levels to support state, regional, subarea, or local network planning. Chapter 3: A Performance-Based Planning and Design Approach defines the general stages of the project development process: planning, alternatives identification and evaluation, preliminary design, final design, construction, and maintenance.

ICE activities can support development and evaluation of alternatives before environmental approvals, and later ICE steps will align with more detailed engineering evaluations that support environmental clearance documentation. Design flexibility peaks during the step when alternatives are first identified and evaluated and when project costs and impacts are still relatively low. Later stages of final design offer little opportunity to revisit early project decisions, so ICE typically does not continue past the preliminary design stage.

When ICE is conducted early in the project development process, a generalized answer may be acceptable. For example, ICE may simply answer the question, What are the feasible alternatives at this location? rather than progressing to a single preferred alternative. For example, Exhibit 6.1 depicts a planning-level assessment of a roundabout footprint. The footprint assessment in this example can be derived from available turning movement counts and planning-level assessments of lane numbers and arrangements. Resources to estimate the necessary intersection footprint at this level are available in Parts III and IV of this Guide.

The example in Exhibit 6.1 is presented at a sketch level (commensurate with a Step 1 ICE screening) over a scaled aerial photo with sufficient detail to identify any obvious conflicts. The same sketch-level footprint exercise would apply to all viable alternatives and could represent sufficient evaluations to determine the feasibility of a roundabout or other alternatives at the location. Depending on the project development stage and the results of a similar preliminary screening, not all ICE activities may be necessary, as the example demonstrates.

Exhibit 6.1. Example sketch-level roundabout footprint assessment.

SOURCE: Map data ©2022 Google.

6.4 Project Considerations

ICE is based on establishing and objectively screening intersection alternatives that could meet a project's needs. An agency can customize the evaluation process for a given location based on the following:

- **Project development stage.** ICE is beneficial early in the project development process because it helps practitioners maintain flexibility and the ability to iterate. Early in the project development process, detailed data may not be available. Accordingly, practitioners need to adjust the detail of the analysis to the data available and the stage of project development.
- **Land-use environment and context.** The existing and planned land-use context can help practitioners define an intersection's primary intended users and appropriate parameters, such as speeds and level of access. Context classification helps define anticipated expectations for each user and guides project assessments.
- **Project type.** The project type—new construction, reconstruction, or projects on existing roads—will influence flexibility concerning geometric constraints and alternatives. More complex evaluations may be necessary for reconstructing intersections and retrofitting existing intersections, whereas new construction may present fewer technical issues and less design flexibility.
- **User needs.** Defining the intended users and the associated design decisions helps practitioners articulate trade-offs associated with design decisions and alternatives.
- **Integration of safety and operations.** A project's safety performance and operational performance need to be clearly defined and can be analyzed using methods described in this Guide.

6.4.1 Users and Their Needs

ICE first defines who the users will be and then establishes geometric forms that best address their needs, optimized for project-specific considerations. User quality of service and safety performance set the foundation for scoping and screening viable alternatives. Examples include the following:

- How do large trucks or other design vehicles and the design approach (i.e., designing for versus accommodating) affect the size of the roundabout?
- How does quality of service for pedestrians and bicyclists influence planning and design decisions for the types of treatments integrated into the configuration?
- How should capacity for motor vehicles or other mobility measurements align with the intended project outcomes?

These considerations help practitioners compare trade-offs in design decisions. For example, selecting a right-turn treatment (e.g., right-turn bypass lane with a lane addition, right-turn bypass lane with yield control, right-turn-only lane at the roundabout entry) affects several performance measures: motor vehicle operational performance; bicycle safety and comfort; and pedestrian safety, comfort, and accessibility. User needs and desired project outcomes can help guide decision making in such an example if conducted early in the process.

6.4.2 Size and Space Requirements

A roundabout's lane configuration affects its capacity and its size. Planning-level tools can often be adequate in early ICE steps depending on the data and inputs available. These planning-level methods do not include detailed information such as signal timing, allowances for five-leg roundabouts, and other nuances. They are generalized, easy to apply, and helpful during early ICE activities. Planning-level tools include many assumptions about input values. When analyzing atypical circumstances, practitioners need to consider whether the screening tools would be valid given their assumptions. Chapter 8: Operational Performance Analysis discusses assessment techniques for determining the appropriate lane configuration.

Intersection footprint, including intersection approach configuration (e.g., raised medians, splitter island presence, driveway access points, turn restrictions), is a primary ICE consideration. These space estimates can influence screening decisions. As with lane requirement estimates, planning-level roundabout footprint estimates can be determined with limited inputs.

Roundabout size is typically based on its ICD and a selected planning buffer outside its perimeter to account for features such as curb, gutter, landscaping buffers, facilities for bicyclists and pedestrians, utilities, and grading needs. Depending on the level of detail in project planning, topography, and other location-specific factors, this buffer could range in width from 20 ft to 35 ft (6 m to 11 m). The following factors affect the ICD:

- **Traffic operations.** ICD size is directly related to the number of circulating lanes required. Lane configuration requirements are typically determined by peak hour traffic volumes, but daily traffic volumes may sometimes be sufficient for planning purposes.
- **Roadway approach and intersection angle (skew).** Non-perpendicular intersection angles between approach legs can contribute to a larger ICD than perpendicular approach legs.
- **Number of legs at the roundabout.** A larger ICD is typically required when a roundabout serves more than four legs.
- **Size of the design vehicle.** With larger design vehicles, a roundabout may require a larger ICD to accommodate movements through the roundabout.
- **Details beyond the ICD edge of traveled way.** The presence and width of the gutter pan, the buffer to the pedestrian walkway, bicycle lanes, landscaping, and clearance to attain intersection sight distance influence roundabout footprint estimates.

Roundabouts can often reduce spatial requirements on approaches compared with non-roundabout intersections. This effect of providing capacity at the intersection while reducing lane requirements between intersections is known as the *wide nodes, narrow roads* concept, as discussed in Chapter 2: Roundabout Characteristics and Applications. However, there may be special footprint considerations outside the ICD and planning buffer.

Roundabout approaches can also be a determining factor when assessing roundabout sizing needs and feasibility. A roundabout's approach footprint may also be influenced by the approach centerline angles (i.e., offset left or radial). Iterating to optimize the size, location, and entry alignment can help practitioners achieve balance for a given design and determine potential footprint needs within the intersection's influence area. Approach speeds may also influence the size and length of splitter islands. Multilane roundabout entries may have special geometric design requirements that can influence the roadway alignment upstream of the intersection to attain path alignment and target entry speeds. Chapter 10: Horizontal Alignment and Design discusses these design influences and trade-offs in more detail.

Practitioners need to identify the design vehicle and the intended approach to support its movements through the intersection. The roundabout may either *design for* or *accommodate* trucks (discussed further in Chapter 4: User Considerations and Chapter 10: Horizontal Alignment and Design). However, for parity, the other alternatives also need to be designed to accommodate the same vehicles and movements as the roundabout. Other design details may be presented to accommodate a high volume of a particular user group—for example, a school crossing near an elementary school may necessitate enhanced crossing features. The design constraints may vary across intersection alternatives, but the designs need to achieve similar outcomes.

Other parameters beyond a roundabout's physical footprint may affect the space it requires and need to be considered during ICE. For example, access management needs at the splitter islands can necessitate off-site considerations, such as access easements or roadway connections behind facilities to serve adjacent properties (i.e., driveways via alternative routes). Raised left-turn channelization at traffic signals creates a similar impact, and practitioners need to assess the two intersection types consistently.

Such constraints will be dictated by the project site and type. Reconstructing intersections and retrofitting an existing circular intersection may present more constraints than new construction. Size and space constraints can also affect other intersection alternatives.

6.5 Evaluation of Alternatives

After the initial screening stage is complete, later ICE steps may be based on more detailed evaluations of the remaining viable alternatives. This evaluation includes the selected performance measures that align and assess consistency with agency prerogatives and intended project outcomes. These performance measures may be similar to those from earlier screening but at an increased level of detail. For example, perhaps actual pedestrian counts are available in later ICE steps that were not available during early project planning.

Many agencies will employ benefit–cost analysis to identify a preferred alternative. A life-cycle cost estimation is useful to compare factors that can be readily monetized. *NCHRP Web-Only Document 220* describes a spreadsheet-based tool and provides documentation for converting metrics into monetary values and considering immediate and long-term costs to allow for a life-cycle cost evaluation. The methodology uses input parameters, including the value of time and reliability, unit costs of emissions and crashes, and a discount rate (*4*). Some agencies have used *NCHRP Web-Only Document 220* to build custom computational engines.

A detailed evaluation will ideally be **informed by** such a cost comparison, but not dictated by it. Further, not all metrics can or should be readily monetized as a cost, and some benefits may be similarly difficult to quantify. Political salience, community goodwill, aesthetic considerations, and social equity concerns are a few examples of influential metrics that are not readily convertible to a dollar amount and comparable on a cost basis. These factors may be among the most important and influential when comparing intersection alternatives.

Roundabouts may provide a comparative advantage or disadvantage to alternatives when non-monetizable factors are considered, and a detailed evaluation will incorporate the site context. Regardless of the factors used, a fundamental tenet is to maintain parity when assessing intersection alternatives. This Guide provides the considerations and methods for roundabout evaluation, but the same principles need to apply across alternatives. In many cases, the challenges present at a project site will have the same effect on non-roundabout intersections.

6.6 Interim and Ultimate Configurations

Roundabouts offer the potential for phased implementation. As part of ICE, an agency must select appropriate horizon years or design years, as discussed further in Chapter 8: Operational Performance Analysis. A single-lane roundabout may initially be a viable consideration if future growth needs are uncertain and may prevent provision of excess capacity. Operating a multilane roundabout as a single-lane configuration until traffic volumes grow could reduce crash risk compared with a multilane roundabout operating well under capacity.

When considering a phased implementation approach, an agency can establish interim and ultimate configurations to meet target safety and operations performance for the selected horizon or design years as appropriate. Initial implementation phases need to retain critical components of the ultimate configuration to keep it viable. For example, a wide median and splitter island may be designed as part of an interim single-lane roundabout such that the roadway can be widened into the median and splitter island when converting to a multilane roundabout. Both the interim and ultimate configurations need to meet all design performance objectives. Chapter 9: Geometric Design Process and Performance Checks and Chapter 10: Horizontal Alignment and Design provide more detail on design performance objectives and techniques for phased implementation, respectively.

6.7 ICE Example

This section provides an ICE example, from a Step 1 intersection screening assessment that validates roundabout feasibility through a Step 2 detailed analysis to refine and customize the recommended roundabout alternative to site conditions.

The study location (Intersection 1) is an existing all-way, stop-controlled (AWSC) intersection located on a two-lane rural highway (the major road) with a posted speed of 55 mph (88 km/h). The minor road is a two-lane collector road. The intersection includes left-turn channelization along the major road approaches (Exhibit 6.2). Approximately 100 ft (30 m) to the south of the intersection is an adjacent three-leg intersection (Intersection 2).

The intersection operates within agency LOS thresholds under existing conditions but is projected to fall below standards in the future analysis year. Therefore, the primary impetus of the project is to address future predicted operational deficiencies.

A two-step ICE is conducted. Step 1 conducts enough technical analysis to screen and advance promising intersection control strategies and intersection form alternatives. Step 2 includes a detailed analysis of remaining alternatives to refine and advance a preferred alternative based on site conditions.

6.7.1 ICE Step 1

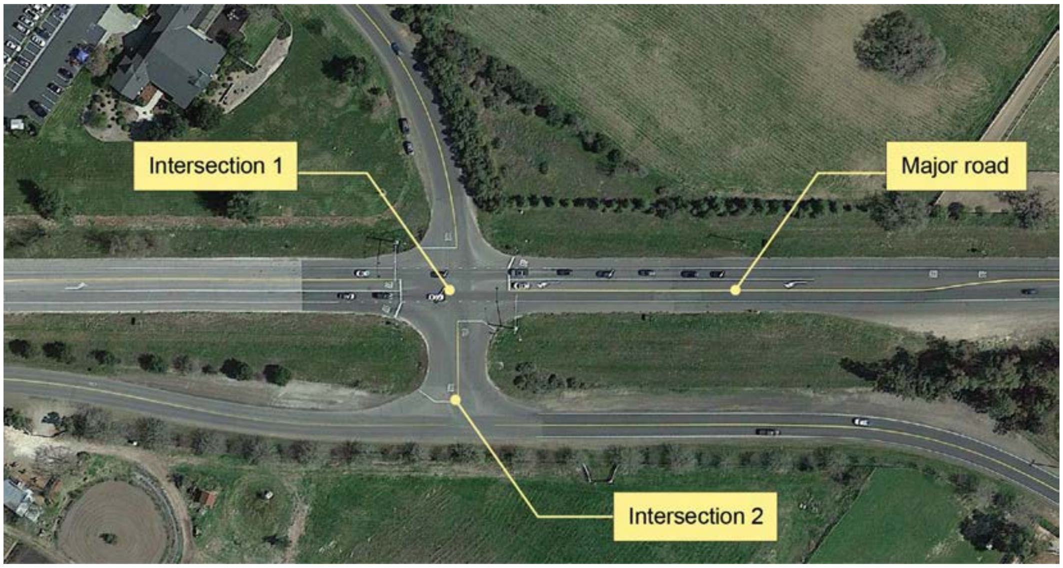
The Step 1 assessment identifies the following typical measures to test alternatives in relation to intended project outcomes:

- Operational performance and LOS;
- Storage capacity, especially between closely spaced intersections (95th-percentile queue lengths); and
- Safety and cost (benefit–cost ratio based on projected collision cost savings and conceptual cost estimates).

The Step 1 ICE identifies and screens a range of practical traffic control alternatives:

- No-build alternative: AWSC at Intersection 1, two-way stop control (TWSC) at Intersection 2.
- Alternative 1: Signal at Intersection 1, AWSC at Intersection 2.

Exhibit 6.2. ICE example—study intersection.



SOURCE: Map data ©2022 Google.

- Alternative 2a: Roundabout at Intersection 1, roundabout at Intersection 2.
- Alternative 2b: Five-leg roundabout consolidating the two intersections.
- Alternative 2c: Roundabout at Intersection 1, TWSC at Intersection 2.

The performance criteria are applied sequentially to screen alternatives for fatal flaws. Step 1 analysis concludes with a summary as follows:

- The no-build alternative is rejected. It would be over capacity in the future-year analysis scenario.
- Alternative 1 is rejected. The signal control provides sufficient capacity in the future-year analysis scenario but provides insufficient storage between intersections and could result in safety performance similar to the existing intersection. Therefore, on the basis of the performance evaluation, this alternative is eliminated before sketch concepts are developed.
- The roundabout alternatives provide sufficient capacity in the future-year analysis scenario, result in less delay and shorter queues than other alternatives, and are the most cost effective according to a benefit–cost evaluation of future crash reduction.

Conceptual footprint sketches are laid out for the remaining alternatives. Exhibit 6.3 presents an example footprint sketch concept for Alternative 2a.

The Step 1 screening recommends further study of Alternatives 2a and 2b to include

- Refined preliminary engineering and design,
- Design performance checks, and
- Optional traffic microsimulation of the project area.

Ultimately, Alternative 2b (five-leg roundabout consolidating the intersections) is rejected, and Alternative 2a is refined so that practitioners can conduct planning-level cost opinions and advance the recommendation for more detailed evaluations in Step 2.

6.7.2 ICE Step 2

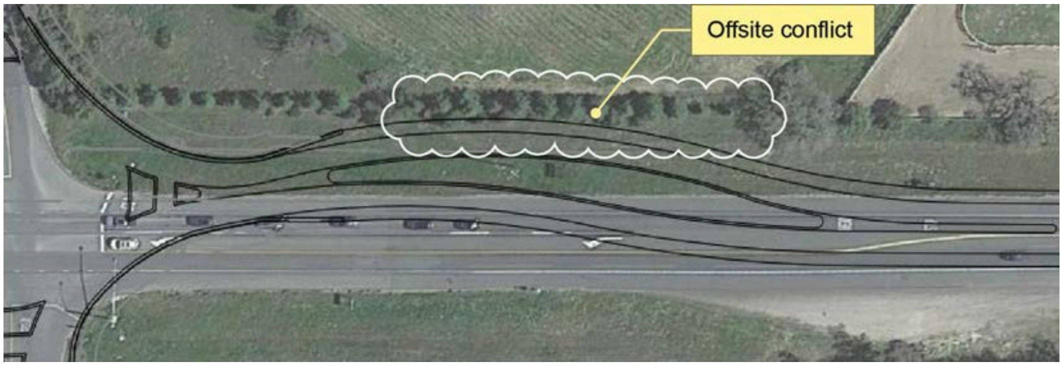
The Step 2 assessment evaluates Alternative 2a in more detail as the project is advanced to the next step of project development and more engineering and environmental data are available. During Step 2, off-site conflicts are discovered in the northeast corner of the intersection as the preliminary concept is refined (Exhibit 6.4a).

To reduce the right-of-way footprint, the team investigates two entry treatments. They explore a softer curvilinear alignment (Exhibit 6.4b), but that design does not resolve the issue. The approach is further refined to provide a tangential alignment that could prevent off-site

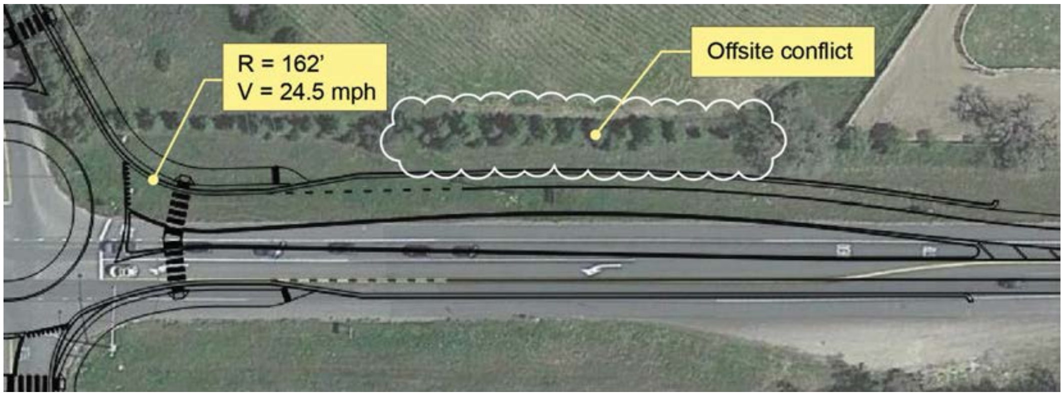
Exhibit 6.3. ICE example—conceptual sketch for Alternative 2a, roundabouts at intersections 1 and 2.

SOURCE: Kittelson & Associates, Inc.

Exhibit 6.4. ICE example—(*a*) As part of Step 2 design refinement, the project team identified off-site conflict. (*b*) A softer entry curve was explored but did not resolve the conflict. (*c*) The revised Step 2 roundabout approach included a tangent approach to resolve off-site conflicts. The relevant performance checks validated the design approach.



(a)

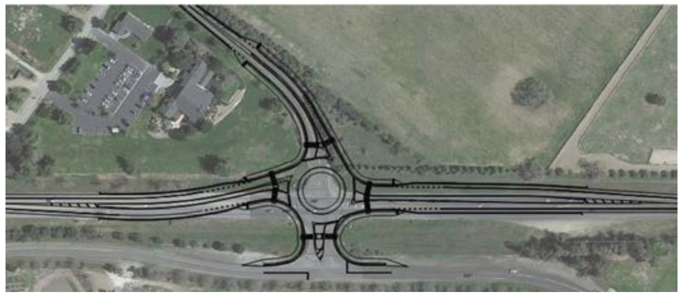


(b)

(c)

SOURCE: Kittelson & Associates, Inc.

Exhibit 6.5. ICE example—intersection alternative recommended for final design.



SOURCE: Kittelson & Associates, Inc.

conflicts (Exhibit 6.4c). As a result, the tangent approach design is refined and supported by relevant performance checks. Performance checks helped validate and advance the alternative shown in Exhibit 6.5 to the next stage of project development (final design).

6.7.3 Summary

In this example, Step 1 evaluated and compared five control and form alternatives in relation to the existing condition and forecast planning scenario. Operations and safety assessments gave a basis to screen alternatives and advance a promising solution, and a sketch-level concept was developed for each alternative as an initial test of viability. Ultimately, the subsequent Step 2 activities identified off-site conflicts with the initial concept. Optional treatments to address identified issues refined the basic control and form alternative to meet project needs.

ICE is adaptable. Had the constraints identified in Step 2 been available during Step 1 activities, the constraints could have been included during Step 1 screening. ICE intends to structure analysis to provide an objective and replicable process with documentable decisions. At the same time, the sequencing of activities is flexible to reduce unnecessary analysis. Therefore, the activities in ICE may be sequenced to answer the critical questions that support project decision making.

6.8 References

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PART III

Roundabout Evaluation and Conceptual Design

PROJECT DEVELOPMENT PROCESS

	Part I: Introduction to Roundabouts	Chapter 1: Introduction Chapter 2: Roundabout Characteristics and Applications
Planning	*Part II: Planning and Stakeholder Considerations*	Chapter 3: A Performance-Based Planning and Design Approach Chapter 4: User Considerations Chapter 5: Stakeholder Considerations Chapter 6: Intersection Control Evaluation
Identify and Evaluate Alternatives	*Part III: Roundabout Evaluation and Conceptual Design*	Chapter 7: Safety Performance Analysis Chapter 8: Operational Performance Analysis Chapter 9: Geometric Design Process and Performance Checks
Preliminary Design	*Part IV: Horizontal, Vertical, and Cross-Section Design*	Chapter 10: Horizontal Alignment and Design Chapter 11: Vertical Alignment and Cross-Section Design
Final Design Construction, Operations, and Maintenance	*Part V: Final Design and Implementation*	Chapter 12: Traffic Control Devices and Applications Chapter 13: Curb and Pavement Details Chapter 14: Illumination, Landscaping, and Artwork Chapter 15: Construction and Maintenance
Supplemental Appendix		Appendix: Design Performance Check Techniques

CHAPTER 7

Safety Performance Analysis

Contents

This chapter presents principles for roundabout safety performance and analysis, including general roundabout safety characteristics compared with other intersection types and quantitative models for estimating and predicting crashes. Quantitative analysis techniques include planning-level, intersection-level, and leg-level models to estimate the expected number of crashes at roundabouts compared with other intersection types and in relation to design characteristics. This chapter presents

- Principles of roundabout safety performance,
- Documented crash characteristics at roundabouts,
- Crash modification factors for roundabout conversions from other intersection types and modification of roundabout design elements, and
- Guidance for practitioners on using predictive models to estimate crashes at roundabouts.

Safety performance is a critical aspect of intersection planning, design, and evaluation. However, it does not exist in a vacuum. Every project has a unique context and constraints that influence design decision making. Safety performance evaluations help practitioners quantify and consider design trade-offs. Even within a discussion about safety performance, design decisions may reduce risk of one type of conflict or crash while increasing risk of another type. The principles and methods presented in this chapter, combined with the operational analysis to inform design needs and the performance checks in Chapter 9: Geometric Design Process and Performance Checks, will inform consideration of safety performance trade-offs.

7.1 Introduction

This chapter defines safety performance as the number and severity of crashes over a given period (defined in the *Highway Safety Manual* [HSM] as *objective safety*) (*1*). Distinct from safety performance are the concepts of comfort (also referred to as *security* and defined in the HSM as *subjective safety*) and accessibility. Comfort describes a user's experience and perception, and accessibility describes the ability of all people to use a facility (*1*). Comfort and safety performance are often—but not always—correlated.

Because crashes are infrequent and random, the observed number and severity of crashes over a given period may not reflect the long-term or expected average. This is particularly true for crashes involving pedestrians and bicyclists, who represent a small share of the travel volume at intersections in the United States. Therefore, an understanding of safety principles, influencing factors, and evaluation methods can augment a review of crash history.

A range of safety performance evaluation options is available, from qualitative methods that require no more than a basic lane configuration and arrangement to intersection-level and leg-level crash prediction models that require design details and local calibration with historical crash data. This chapter summarizes techniques, explains the appropriate context for their use, and describes the implications of roundabout safety performance for intersection planning and design.

Understanding the safety performance effect of geometric design elements and traffic exposure equips the practitioner to maximize safety for motor vehicle occupants, pedestrians, and bicyclists. Safety models also support roundabout planning and design by comparing roundabout safety performance with other intersection types and quantifying the safety performance effects of certain design decisions. For example, lane number, lane width, and entry alignment may initially be established by site context and agency operational targets. However, these choices can be evaluated against their implications for intersection safety performance to help make a decision that balances competing demands.

7.2 Conflict Types and Conflict Points

The number and types of conflict points at intersections explain why roundabouts are a proven safety strategy (*1*, *2*). This section discusses user conflicts and conflict points as well as their associated risk and severity. In general, roundabouts eliminate, reduce, or alter conflicts that often occur at other intersection types, thereby reducing crash frequency and severity. Their design eliminates some of the most severe conflict and crash types so that mistakes or illegal maneuvers (e.g., violating traffic control) are less likely to result in death or serious injury.

A conflict point is a location where road user paths intersect. The number and type of conflict points present directly influence intersection safety performance. At-grade intersections are planned points of conflict that unavoidably include a concentration of conflict points (*3*).

The number, type, and characteristics of conflicts vary across intersection types, and analyzing them can help practitioners evaluate intersection alternatives, informing planning and design decisions.

User risk at an intersection is influenced by the number of conflict points present and the following factors:

- **Exposure** is measured by the two conflicting stream volumes (of any relevant mode) at a given conflict point.
- **Severity** is based on the relative velocities of the conflicting streams (speeds and trajectories).
- **Movement complexity** is based on the task complexity for users making specific movements (type of traffic control, number of lanes crossed, presence of concurrent decisions, nonintuitive vehicle movements).
- **Vulnerability** is based on the ability of a member of each conflicting stream to survive a crash (determined by the relative mass and protection provided by the vehicles or parties involved, which are respectively minimal and non-existent for a person walking or biking).

Intersection design can affect conflict types and user experience in several ways:

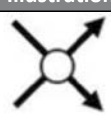
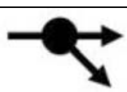
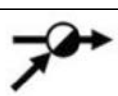
- Separating conflicts by assigning priority or by timing vehicle travel using separated signal phases. Conflicts may arise from legal and illegal maneuvers, even if a conflict is separated in time or priority by a traffic signal or regulatory sign. Traffic control devices can significantly reduce the complexity of many conflicts but not eliminate them, because drivers may ignore them (e.g., red light running).
- Separating conflicts in space by designating separate locations for users or movements.
- Reducing the severity of conflicts by reducing speeds or making the angle of interaction between conflicts less perpendicular.
- Reducing the likelihood of a crash by simplifying user tasks at conflict points.

User vulnerability is not a factor the practitioner can control. Vehicle design can mitigate vulnerability for motor vehicle occupants, but pedestrians and bicyclists are more exposed to severe conflicts because there is no vehicle surrounding them to dissipate energy from a crash (*4*).

There are three basic types of conflict points, shown in Exhibit 7.1. In addition to these conflict types, queuing conflicts—typically rear-end crashes—can occur upstream of any conflict point where a vehicle may slow down or stop to avoid conflicting traffic (motor vehicles, bicyclists, or pedestrians).

A conflict's potential severity is a function of the energy released during a resulting crash, which itself is a function of mass and the square of the velocity—a combination of speed

Exhibit 7.1. Conflict types.

Illustration	Definition
	A **crossing conflict** is a conflict point where distinct movements intersect. The associated crash type is most commonly head-on crashes and right-angle crashes.
	A **diverging conflict** is a conflict point caused by separating one travel path into two that is accompanied by a speed differential (e.g., a lead vehicle slowing to make a turn). An example is a right turn from a through movement. The associated crash type is most commonly a rear-end crash.
	A **merging conflict** is a conflict point caused by joining two travel paths into one. An example is a vehicle turning right into a vehicle making the accompanying through movement. The associated crash type is most commonly a sideswipe or right-angle crash.

and trajectory angle—of the vehicles involved. This helps practitioners consider the different conflict point types. For example, diverging conflicts with shallow angles and negligible speed differentials are rarely a significant concern and may be omitted from a conflict point study for simplicity. Minimizing the velocity differential of intersecting paths can reduce conflict severity.

7.2.1 Roundabouts Compared with Other Intersections

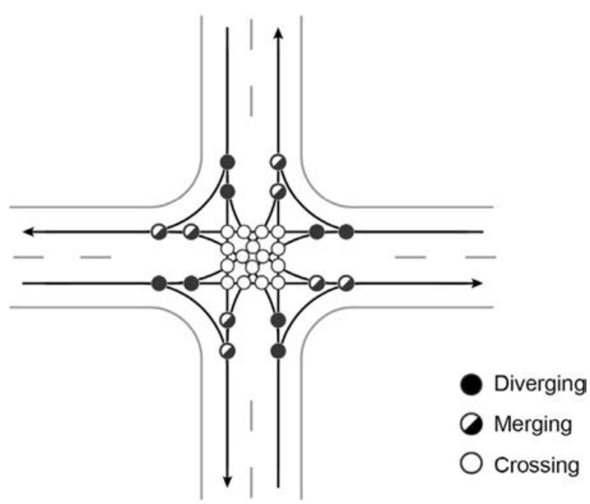
A four-leg stop-controlled or signalized intersection with four legs and a single lane on each approach has been traditionally described as having 32 conflict points for motor vehicles: 16 crossing, 8 merging, and 8 diverging. Exhibit 7.2 shows this configuration.

- The **16 crossing conflicts** present within the center of the stop-controlled or signalized intersection are caused by the intersection of conflicting or opposing through and left-turning vehicles. Of all conflicts at a stop-controlled or signalized intersection, these are commonly the most severe because the differences in velocities between conflicting vehicles are large. The **traffic control device** is typically used to manage these conflicts, although geometry is sometimes used (e.g., displaced left-turn movements).
- The **8 merging conflicts** for motor vehicles at a stop-controlled or signalized intersection are comparable with crossing conflicts because of the relative difference in velocities between through and turning vehicles. The **traffic control device** is typically used to manage these conflicts, although geometry is sometimes used (e.g., acceleration lanes).
- The **8 diverging conflicts** for motor vehicles are caused by the relative difference in speeds between through and turning vehicles. **Geometry** is typically used to manage these conflicts (e.g., providing separate turn lanes).

Exhibit 7.3 presents the conflict diagram for a single-lane roundabout with four legs. This conflict diagram has some notable features:

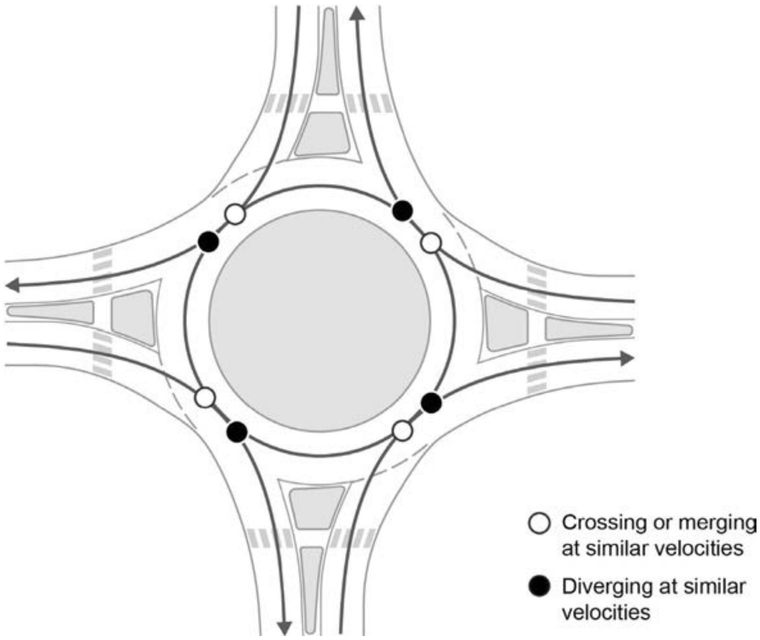
- The 16 crossing conflicts and 8 merging conflicts for motor vehicles reduce to **4 crossing or merging conflicts** with similar velocities. The **geometry of the roundabout** primarily manages these conflicts. First, the central island eliminates the more severe crossing conflicts for left-turning vehicles. Second, the crossing conflicts that remain—through movements crossing through movements—have lower relative velocities because of the geometric speed

Exhibit 7.2. Conflict point diagram for signalized or stop-controlled intersections.



SOURCE: Adapted from *NCHRP Report 672* (*5*).

Exhibit 7.3. Conflict point diagram for single-lane roundabouts.



SOURCE: Adapted from *NCHRP Report 672* (*5*).

control of the roundabout, even though they are also managed by the traffic control device (i.e., yielding to circulating vehicles).

- The 8 diverging conflicts reduce to **4 diverging conflicts** for motor vehicles at a roundabout because of coincident paths for each movement. The **geometry of the roundabout** is used to manage these conflicts. For many roundabouts, these diverging conflicts are essentially coincident with the crossing or merging conflict.

Exhibit 7.4 summarizes the conflict points for both cases. The roundabout replaces the crossing and merging conflicts with large differentials in velocity with a smaller number of crossing conflicts that have similar velocities.

Exhibit 7.4. Number of conflict points by intersection type.

Conflict Point	Single-Lane Signalized or Stop-Controlled Intersection, Four Legs	Single-Lane Roundabout, Four Legs
Crossing with relatively large differences in velocity	16	0
Merging with relatively large differences in velocity	8[a]	0
Crossing or merging with similar velocities	0[a]	4
Diverging with relatively large differences in velocities	8[a]	0
Diverging with similar velocities	0	4
Total conflict points	**32**	**8**

[a]May be managed with geometry by adding turn lanes, acceleration lanes, etc. SOURCE: Adapted from *NCHRP Report 672* (*5*).

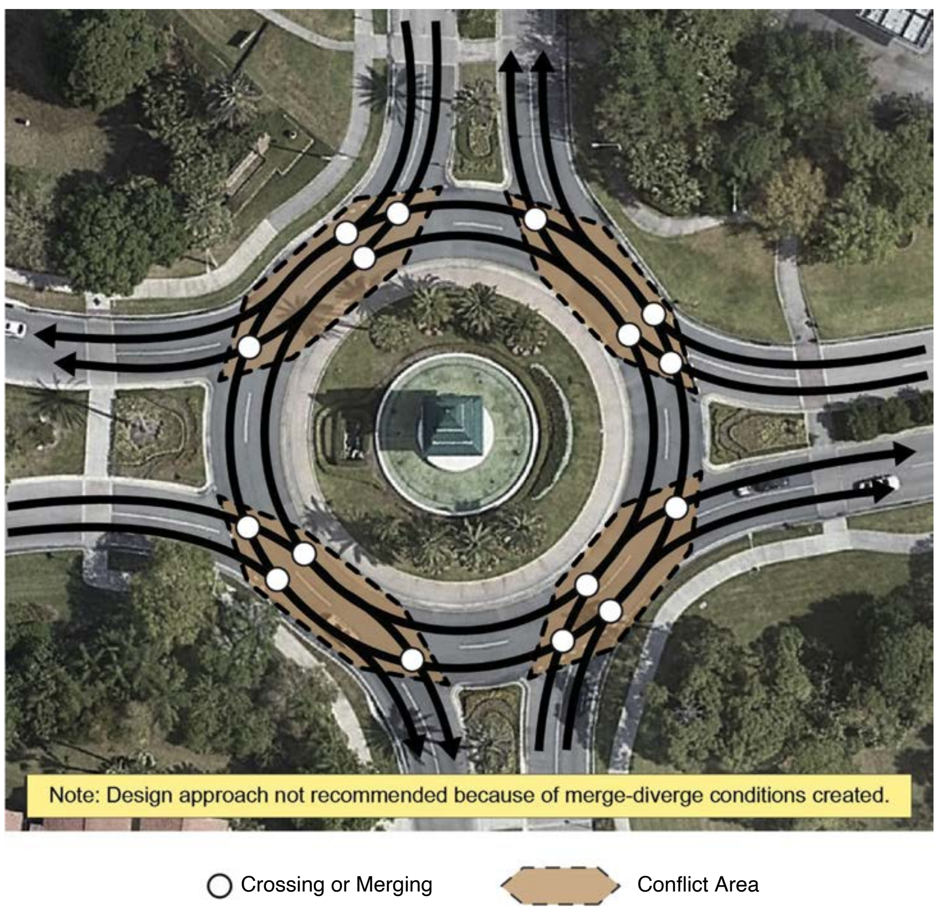
Lower relative velocities result in less severe crashes. Empirical data from multiple studies in the United States and worldwide confirm real-world experience with this reduction in severity—up to an 87 percent reduction in injury crashes compared with two-way stop-control intersections and 78 percent compared with signalized intersections (*1*, *2*, *6*, *7*).

7.2.2 Conflict Points at Multilane Roundabouts

Multilane roundabouts have more conflict points than single-lane roundabouts because of additional lanes and the associated width between curbs (as with any larger intersection). This section discusses this influencing factor and visually presents the resulting conflict points. This discussion briefly addresses design details and presents comparative examples to explain how design geometrics relate to safety, as demonstrated by conflict points.

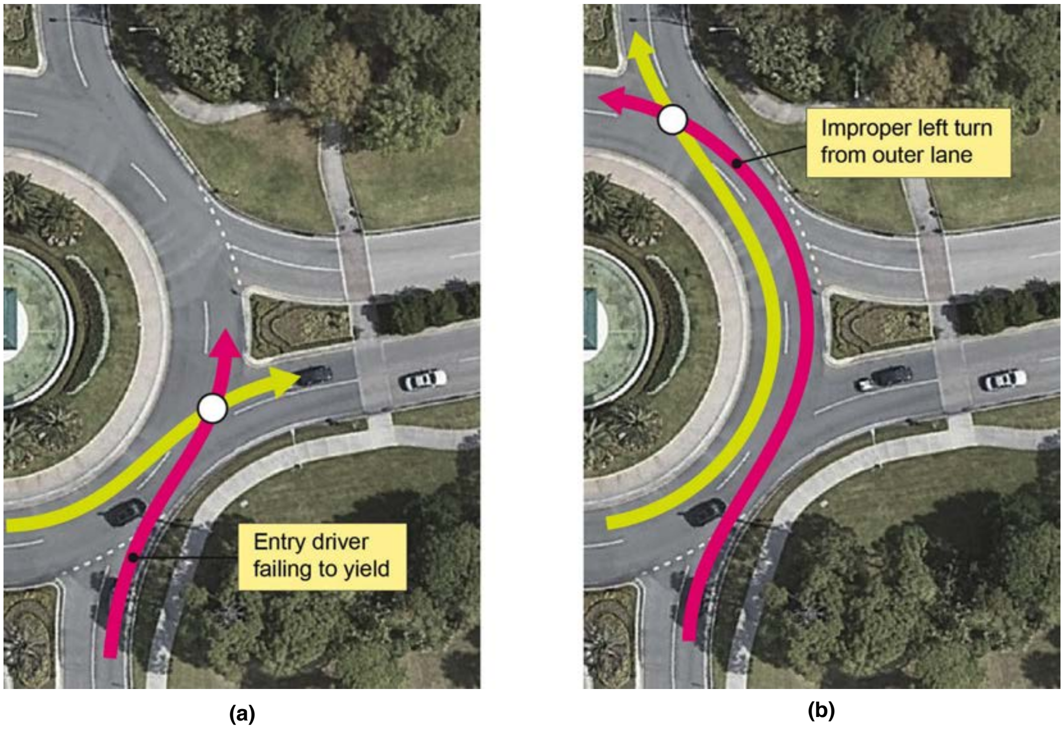
A multilane roundabout's geometric configuration is believed to directly impact conflict potential. Exhibit 7.5 through Exhibit 7.6 illustrate this relationship using a series of multilane roundabout concepts, each designed to serve two through lanes on each leg. The additional conflicts are generally low-speed, sideswipe conflicts with low severity, as the conflict point diagrams indicate. Therefore, although the number of conflicts increases at multilane roundabouts compared with single-lane roundabouts, the overall severity of conflicts is comparable with single-lane roundabouts and is typically less than other intersection alternatives (*7*).

Exhibit 7.5. Conflict diagram for multilane 2 × 2 roundabout with undesirable separation between entry and exit legs.



SOURCE: Google Earth.

Exhibit 7.6. Multilane sideswipe crashes caused by (*a*) failure to yield on entry and (*b*) improper lane use.



SOURCE: Google Earth.

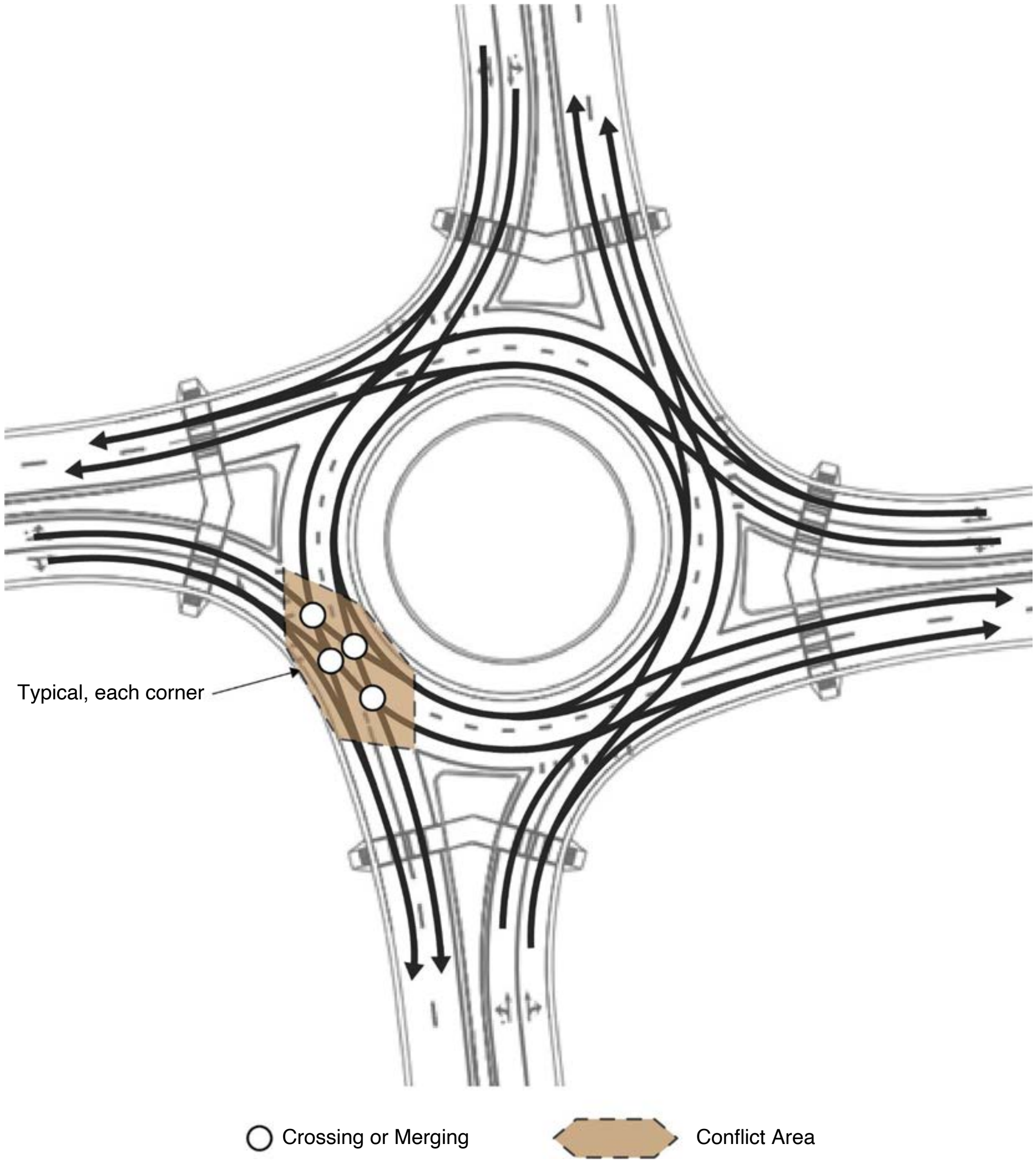
Exhibit 7.5 shows a multilane roundabout design that is not recommended because of the merge–diverge conditions it creates in the circulatory roadway. Chapter 10: Horizontal Alignment and Design discusses how practitioners can address such conditions. In the United States and internationally, this design has increased crash numbers, particularly those involving property damage at each exit-circulating junction (*7*). The roundabout has been designed by effectively taking a single-lane design and expanding it to two lanes at each entry, exit, and circulatory roadway. The separation between the entry of one leg and the exit of the next leg creates a weaving segment of two-lane circulatory roadway between legs. The conflict points illustrated in Exhibit 7.5 can be organized into conflict areas—the spaces containing related entering–circulating–exiting conflict points.

This configuration has resulted in increased crash frequency involving property damage at each exit-circulating junction. Two factors cause these exit-circulating crashes (*8*):

- **Failure to yield on entry (Exhibit 7.6*a*).** The most common failure to yield conflict occurs when a driver in the right entry lane enters next to a driver exiting from the left circulating lane. Both drivers are using the correct lanes for their intended movements, but the entering driver does not perceive the potential conflict.
- **Improper lane use (Exhibit 7.6*b*).** Drivers use the right entry lane for left-turn movements or the left entry lane for right-turn movements. These movements are partly induced by the segment of circulatory roadway that visually separates one leg from another and the misperception that the roundabout is a series of T-intersections, rather than a single intersection.

Exhibit 7.7 and Exhibit 7.8 present two possible techniques to mitigate these conflicts. Both provide clear lane assignment on approach before entry, and both emphasize speed control to manage the severity of potential conflicts.

Exhibit 7.7. Multilane 2 × 2 roundabout with entries and exits crossing one another.

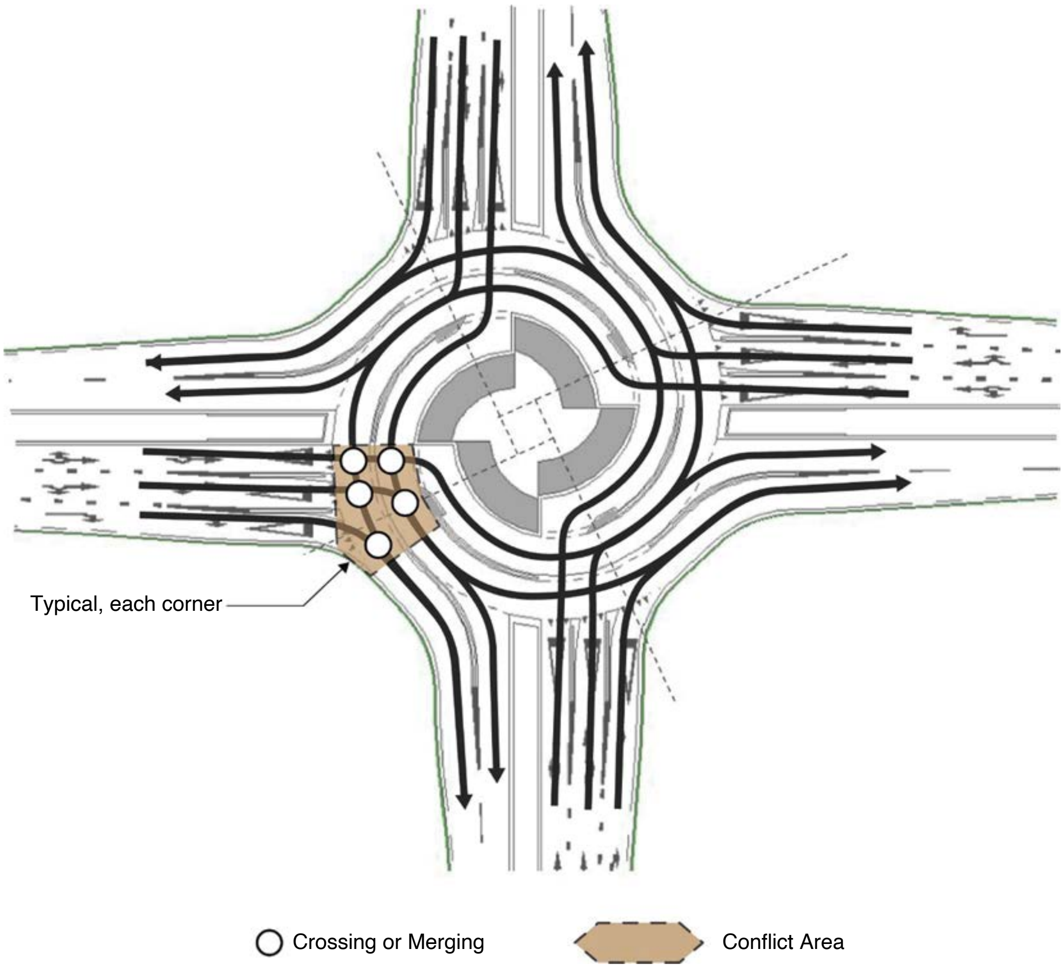


SOURCE: Adapted from Georgia Department of Transportation (*9*).

The first technique is shown in Exhibit 7.7, where the entries and exits are brought closer together and cross one another, often by using a smaller diameter and offsetting the entry to the left of the center to manage entry speeds. This design has the entry paths cross the exit paths, rather than having the entry paths join into the circulatory roadway and then separate at the next exit. Proper geometric design manages the speeds and alignment of this crossing conflict, and the conflict area is kept as small as possible to reduce complexity. Further details of this configuration are discussed in Chapter 10.

A second technique, described in Chapter 2: Roundabout Characteristics and Applications as the turbo roundabout, is shown in Exhibit 7.8. In this configuration, the segment of circulatory roadway between legs is retained but managed with strict lane discipline (frequently including physical channelization). To provide two through movements for each of the four legs, this technique requires the segment of circulatory roadway between legs to have three lanes.

Exhibit 7.8. Multilane (turbo) roundabout with strict lane discipline.



SOURCE: Adapted from Fortuijn (*10*).

The turbo roundabout increases the total number of crossing and merging conflict points to five in each quadrant, compared with four in the 2 × 2 roundabout, because the turbo roundabout requires a right-turn-only lane.

The example shown in Exhibit 7.7 manages conflicts by reducing the size of the conflict area. By contrast, the example shown in Exhibit 7.8 physically separates the conflicts and forces lane selection in advance of the intersection (reducing task complexity at the intersection entrance). All multilane designs must provide appropriate lane selection in advance of the roundabout, but the turbo roundabout forces it with physical separation. Chapter 10: Horizontal Alignment and Design discusses this configuration further.

7.2.3 Trucks

Large trucks have larger turn radii than passenger vehicles and a tendency to over-track along curves. Therefore, they can introduce additional conflicts at multilane roundabouts beyond those already discussed. Multilane roundabout designs typically provide space for trucks to stay in-lane throughout or require trucks to straddle lanes.

In general, the multilane roundabouts that provide space for trucks to stay in-lane have larger radii and wider circulatory lane widths than those that require trucks to straddle lanes.

These larger radii and widths typically result in higher speeds and longer pedestrian crossings (increased pedestrian exposure), which are aspects of conflicts that increase user risk. The design approach for trucks needs to be established early in project planning and design, as it can affect the safety performance and operational effects for other users. Truck design considerations are presented in Chapter 10: Horizontal Alignment and Design.

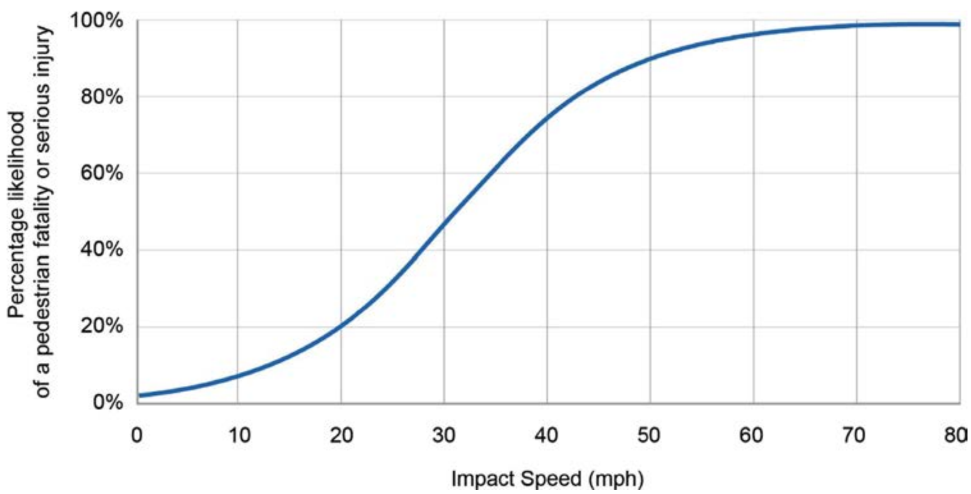
7.2.4 Pedestrians

All at-grade intersections present conflicts between motor vehicles and pedestrians at pedestrian crossing locations. Pedestrians are vulnerable road users with no protective vehicle to dissipate crash energy. Exhibit 7.9 presents the likelihood of a pedestrian dying or being seriously injured if they are hit by a motor vehicle. For example, pedestrians struck at vehicle speeds of 30 mph (48 km/h) have a 50 percent average likelihood of death or serious injury. Higher speeds significantly increase this hazard. Results are impacted by age, gender, size, and other characteristics of the person involved.

Safety for pedestrians who are blind or have low vision is a major concern for intersection design, including roundabouts. According to the Centers for Disease Control and Prevention, at least 1 million Americans are blind and another 3 million have low vision even after correction. These numbers are expected to grow as the population ages and diabetes and other chronic diseases become more common (*11*). For these pedestrians, safety and accessibility challenges exist everywhere that vehicle conflict points exist. Chapter 9: Geometric Design Process and Performance Checks discusses accessibility at roundabouts in more detail.

Existing research into pedestrian safety at roundabouts has been limited in its ability to establish pedestrian volumes and exposure alongside historical crash data at roundabouts. Because pedestrian-involved crashes represent a small portion of historical roundabout crashes—approximately 1 percent of the total number of crashes in *NCHRP Research Report 888: Development of Roundabout Crash Prediction Models and Methods*—it has not yet been possible to draw conclusions about comparative or predictive pedestrian risk at roundabouts versus other intersection types (*12*). Pedestrian crash history at roundabouts is discussed more in Section 7.3.2.

Exhibit 7.9. Likelihood of pedestrian death or serious injury in relation to vehicle impact speed.



SOURCE: Adapted from Porter et al. (*3*).

Pedestrian–vehicle conflicts at intersections can be categorized by their exposure, severity, and movement complexity for the pedestrian and the driver. The severity is a function of vehicle speed at the conflict point. Movement complexity can be characterized by traffic control, the number of lanes crossed, the speed of conflicting traffic, and any simultaneous tasks or cognitive demands (e.g., drivers seeking gaps in traffic).

Exhibit 7.10 shows the conflict points present at TWSC intersections, signalized intersections, and roundabouts of two intersecting two-lane roadways. Exhibit 7.11 characterizes the conflict points by complexity, indicated by whether the conflict is separated by traffic control and whether a driver is simultaneously seeking a gap in traffic. AWSC intersections are not presented, as all conflict points are stop controlled and do not require drivers to judge gaps (though drivers do need to assess whether it is their turn to proceed).

The exhibits show that, even though each intersection includes the eight conflict areas shown in Exhibit 7.10, a single-lane roundabout changes the number and type of conflict points

Exhibit 7.10. Pedestrian–vehicle conflict points at (*a*) TWSC intersection, (*b*) signalized intersection, and (*c*) roundabout.

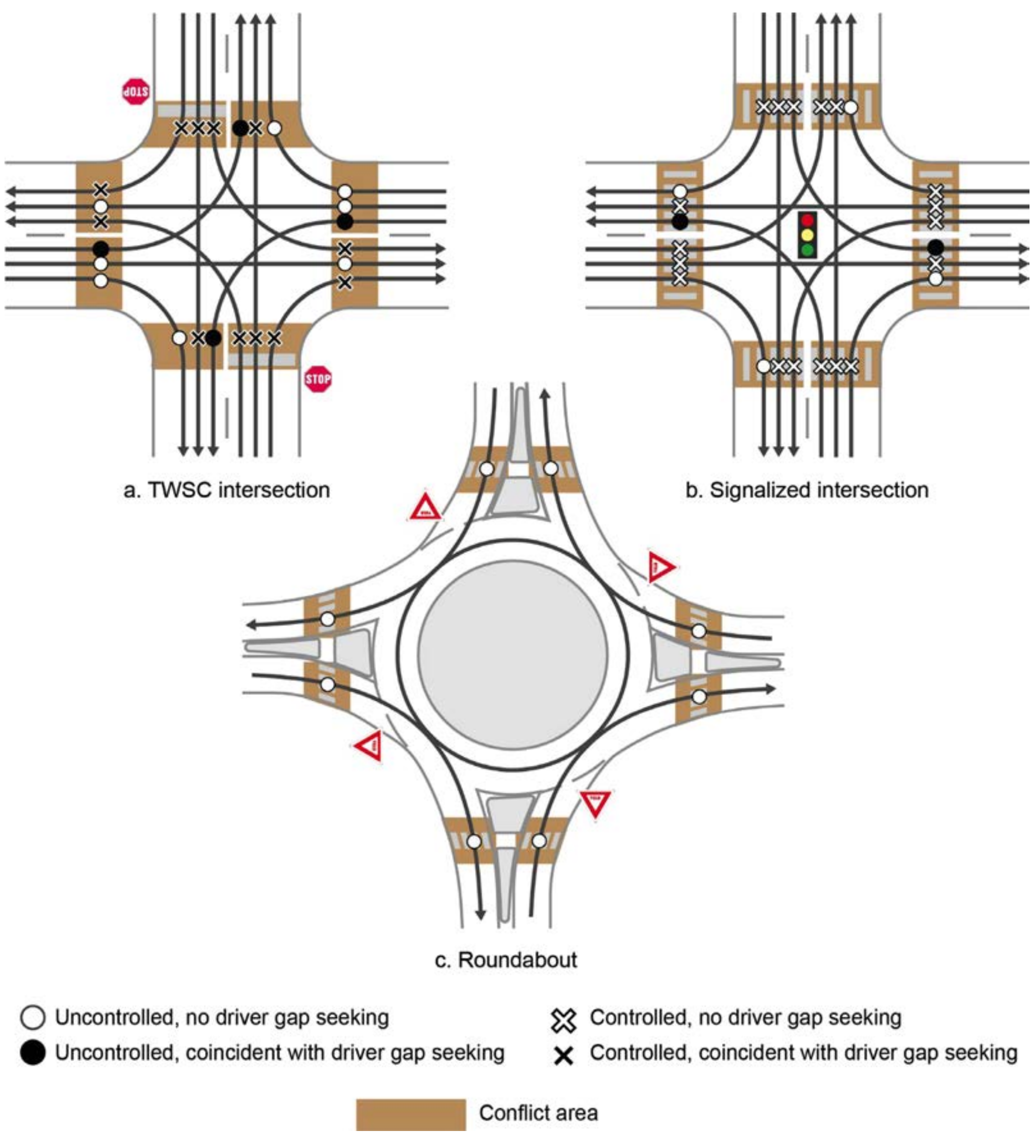


Exhibit 7.11. Vehicle–pedestrian conflict points by intersection type.

Conflict Point Type	TWSC	AWSC	Signalized	Roundabout
Controlled with no driver gap seeking (less complex)	0	24	18	0
Controlled with driver gap seeking (more complex)	12	0	0	0
Uncontrolled with no driver gap seeking (less complex)	8	0	4	8
Uncontrolled with driver gap seeking (more complex)	4	0	2	0
Total vehicle–pedestrian conflict points	**24**	**24**	**24**	**8**

NOTE: The conflict point counts for the signalized case assume that the two major street left turns have dedicated protected left-turn signal phases, and the two minor street turns have permissive left-turn signal phases.

within each area. The exposure, severity, and complexity of pedestrian–vehicle conflict points vary by intersection control, including four notable differences:

- **TWSC intersections.** As shown in Exhibit 7.11, half of pedestrian–vehicle conflicts include uncontrolled vehicle movements, including left turns from the major street to the minor street. Those conflicts require drivers to judge a gap and complete a left turn to clear the intersection, reaching the pedestrian conflict point as they accelerate out of a turn to leave the intersection. The controlled movements are nearly as complex, given that drivers are required to judge gaps in traffic and yield to pedestrians simultaneously.
- **AWSC intersections.** At AWSC intersections, drivers are not required to judge gaps but do need to assess when it is their turn to proceed. The conflicts are simple compared with other driver tasks, and the severity of conflicts depends on the vehicle path and whether the driver accelerates out of the intersection.
- **Signalized intersections.** Signals separate most pedestrian–vehicle conflicts in time. The exceptions are right turns (for which vehicle and pedestrian signal phases are typically concurrent) and left turns with a permissive signal phase. The latter case is akin to the major street to minor street left turn at a TWSC intersection: drivers judge a gap and commit to a turn while they must simultaneously determine whether to yield to pedestrians.

  At signalized intersections that allow right turns on red (legal in most of the United States and Canada), four additional conflict points increase risk for pedestrians because a driver will look to the left for a gap (in the opposite direction of a crossing pedestrian). In some cases, drivers turning right on red move into the crosswalk to improve their sightlines to the left and force pedestrians to pass either in front of or behind them.
- **Roundabouts.** The roundabout design typically offsets the pedestrian crossings from the circulatory roadway so that drivers do not have coincident decisions to yield to pedestrians while they judge gaps in circulating traffic (when entering) or turn to leave the circulatory roadway (when exiting). Chapter 10: Horizontal Alignment and Design details pedestrian crossing design and location. This approach, assumed in Exhibit 7.10 and Exhibit 7.11, collapses each conflict area from the three conflict points found in the other intersection designs to a single conflict point.

  From a pedestrian's perspective, roundabout crossings are consistently simple because the splitter island between the entry and the exit allows pedestrians to resolve conflicts with entering and exiting vehicles separately, only crossing one traffic stream at a time. Contrast this with the pedestrian crossings at TWSC and signalized intersections in Exhibit 7.10, where pedestrians are exposed to multiple traffic streams during the same crossing.

In all cases, driver violation of traffic control can lead to the most severe pedestrian–vehicle conflicts, particularly for through movements completed at a typical approach speed.

Multilane intersections, including multilane roundabouts, present a more complex environment for pedestrians. Multilane roundabouts feature more conflict points and a greater volume of vehicles collectively passing through (i.e., more exposure). Vehicle speeds at pedestrian–vehicle conflict points are higher at multilane roundabouts than at single-lane roundabouts. Furthermore, pedestrians must cross multilane entry or exit legs, exposing them to multiple-threat crossings, where a driver in one lane might yield but a driver in an adjacent lane might not. Typically, proper multilane roundabout design locates pedestrian conflict points away from other driver decision points (i.e., offset from the circulatory roadway) so that the drivers' task is still relatively uncomplicated and not coincident with other decisions at pedestrian conflict points.

7.2.5 Bicyclists

Bicyclists, like pedestrians, are vulnerable road users who lack any surrounding enclosure to dissipate crash energy. Because bicyclists typically ride to the right of motor vehicle traffic on segments between intersections, they face additional conflicts when they need to merge into the flow of motor vehicle traffic or where motor vehicles cross their path. All intersections present design challenges and safety concerns about vehicle–bicycle conflict points.

As with pedestrian safety, existing research into bicyclist safety at roundabouts has been limited in its ability to establish exposure alongside historical crash data. Bicyclist-involved crashes represent a small portion of historical roundabout crashes (less than 1 percent in *NCHRP Research Report 888*), so it has not yet been possible to draw conclusions about comparative or predictive bicyclist risk at roundabouts versus other intersection types (*12*).

This section applies the principles of conflict points to articulate roundabout characteristics in relation to bicyclist safety. Bicyclist and pedestrian crash history at roundabouts is discussed more in Section 7.3.2. Chapter 4: User Considerations presents the commonly defined categories of bicyclists. The types of riders—interested but concerned, somewhat confident, and highly confident—vary in their desired approach to riding in and through roundabouts (*13*):

- The **interested but concerned** bicyclists may choose to travel out of traffic on adjacent sidewalks, multiuse paths, or trails.
- **Somewhat confident** bicyclists may be comfortable navigating low-speed single-lane roundabouts in travel lanes with motor vehicles.
- **Highly confident** bicyclists may choose to travel through all roundabouts with other vehicles.

Designing a bicycle lane at the exterior of the circulatory roadway is an impractical solution that is to be avoided, as it creates overlap between bicycle movements and exiting motor vehicle movements (i.e., a right-hook conflict).

Speed is a fundamental factor in bicyclist safety at conflict points. Typical speeds for casual bicyclists range from 8 to 12 mph (13 to 20 km/h), with speeds for experienced bicyclists reaching up to 25 mph (40 km/h) on level grades (*14*). Designs that constrain vehicle speeds to similar values minimize relative speeds and reduce crash and severity risk. Design features that slow motor vehicles approaching and departing the roundabout are beneficial treatments that help create merging opportunities for bicyclists (*5*).

If shared bicycle–pedestrian paths with ramps to and from the bicycle lane are provided, bicyclists can use the ramp to exit the roadway in advance of the roundabout, follow a path through the intersection like a pedestrian, and then use another ramp to return to the roadway. These bicyclists experience the same conflict points with motor vehicles as described for pedestrians in Section 7.2.4. However, the convergence of bicyclists and pedestrians can introduce new conflicts to be addressed during design. Chapter 9: Geometric Design Process and Performance Checks and Chapter 10: Horizontal Alignment and Design discuss this further.

7.3 Roundabout Crash Types and Factors

Because the conflict points at roundabouts are different from those at other intersections, the resultant crash types are also different. Roundabout crash history helps illustrate the risk of certain crash types and movement patterns.

The most comprehensive review of US roundabout crash types to date is *NCHRP Research Report 888*. This report provides analysis results of crashes at roundabouts in nine states over an array of available years of crash data (*12*). Exhibit 7.12 shows the percentage of the main crash types found in that review. **The comparison between fatal and injury crashes and property damage only (PDO) crashes shows that single-vehicle crashes are associated with more severe outcomes at roundabouts than multiple-vehicle crashes**—they account for 33.4 percent of fatal and injury crashes, which is higher than the accompanying 23.1 percent share of PDO crashes.

7.3.1 Fatal Crashes

Research published in 2015 documents a review of all reported fatal crashes at roundabouts in the United States between 2005 and 2013 (46 total) (*15*). The analysis compares contributing factors in those roundabout fatal crashes with fatal crash factors of all reported fatal crashes in 2012 at other intersection types in the United States.

Exhibit 7.13 shows that many more fatal roundabout crashes from 2005 to 2013 were single vehicle as opposed to multiple-vehicle crashes, unlike at other intersections. Fixed-object crashes, including those involving vehicles hitting the curb, were the most common fatal crash types. Eighty-five (85) percent of fatal crashes at roundabouts involved a vehicle striking a fixed object (76 percent were vehicles hitting the curb).

A higher percentage of fatal crashes involved motorcycles at roundabouts than at other intersections. Many of the fatal motorcycle crashes reviewed involved a motorcyclist losing control

Exhibit 7.12. Motor vehicle crash type and severity distribution at US roundabouts.

Number of Vehicles Involved	Crash Type	Number (Percent)	
		Fatal and Injury	Property Damage Only
Multiple vehicles	Head on	9 (0.9%)	36 (0.7%)
	Right angle	105 (11.0%)	689 (14.1%)
	Rear end	283 (29.7%)	1037 (21.2%)
	Sideswipe, same direction	101 (10.6%)	771 (15.8%)
	Other	137 (14.4%)	1,228 (25.1%)
	Total	**635 (66.6%)**	**3,761 (76.9%)**
Single vehicle	Animal	0 (0.0%)	24 (0.5%)
	Fixed object	171 (17.9%)	746 (15.2%)
	Other object	0 (0.0%)	8 (0.2%)
	Parked vehicle	1 (0.1%)	11 (0.2%)
	Other	142 (14.9%)	217 (4.4%)
	Unknown	5 (0.5%)	128 (2.6%)
	Total	**319 (33.4%)**	**1,134 (23.1%)**
Total		954 (100.0%)	4,895 (100.0%)

NOTE: Fatal and injury crashes were observed at 321 roundabouts and property damage only crashes at 346 roundabouts, over selected years of data. SOURCE: Adapted from *NCHRP Research Report 888*, Tables 5-66 and 5-68 (*12*).

Exhibit 7.13. Fatal crash factors in the United States as share of reported fatal crashes, roundabouts, 2005–2013, versus all intersections, 2012.

Crash Type	Percent of Fatal Crashes	
	At Roundabout, 2005–2013	At Other Intersections, 2012
Multiple-vehicle crashes	17	67
Single-vehicle crashes	83	33
Vehicle struck fixed object(s)	85	11
Motorcycle involved	46	23
Speed cited	57	20
Impaired driving cited	52	21
Bicyclist involved	2	4
Pedestrian involved	0	16
Light conditions (non-daylight)	57	43

SOURCE: Steyn et al. (*15*).

and subsequently striking a curb. Bicyclist- and pedestrian-involved crashes as a share of total fatal crashes were lower than at other intersection types, though any understanding of the comparative volumes or exposure rates for these users has not been established.

7.3.2 Crashes Involving Pedestrians and Bicyclists

There is limited US-based research specific to bicycle and pedestrian safety performance at roundabouts, in part because these users make up a small portion of reported crash history. Although no formal studies available for this Guide have documented fatal crashes involving bicyclists or pedestrians, there are anecdotal reports of a small number (likely less than 10 as of 2022) of bicyclist-involved fatal crashes and a small number (likely less than 10 as of 2022) of pedestrian-involved fatal crashes since the first roundabout was constructed in the United States.

As noted previously, *NCHRP Research Report 888* found bicycle and pedestrian crashes make up a minor proportion of total crashes reported at single-lane and multilane roundabouts, with 0.4 percent for bicyclists and 1.1 percent for pedestrians (*12*). Exhibit 7.14 presents the share of reported crashes involving bicyclists and pedestrians. Because of the infrequency of reported crashes, the study could not develop predictive safety performance functions for bicyclist- or pedestrian-related crashes. No predictive crash tools for bicyclist or pedestrian crashes at roundabouts are available at the time of this writing.

Exhibit 7.14. Bicyclist and pedestrian crashes at US roundabouts.

Crash Type	Number (Percent)		
	Rural	Urban	Total
Bicyclist	14 (0.7%)	60 (1.2%)	74 (1.1%)
Pedestrian	7 (0.4%)	18 (0.4%)	25 (0.4%)
Total reported crashes	1,938 (100%)	4,833 (100%)	6,771 (100%)
Number of sites	105	250	355
Number of study years of data	508	1,580	2,088

SOURCE: Adapted from *NCHRP Research Report 888*, Table 6-38 (*12*).

7.4 Roundabouts Compared with Other Intersection Types

Crash modification factors (CMFs) available from the HSM, Part D, and the FHWA CMF Clearinghouse provide quantitative insights about roundabout safety performance compared with stop-controlled and signalized intersections (*1*, *2*). A CMF represents the expected change in crashes with implementation of a treatment. For example, a CMF of 0.7 would indicate an expected reduction in crashes of 30 percent, resulting in a post-treatment, long-term average of just 70 percent of the pre-treatment average. Lower CMFs indicate a greater expected crash reduction. CMFs are empirical and estimated using statistical methods; therefore, a given CMF will have some standard error that represents a margin for its expected value. Exhibit 7.15 provides CMFs related to conversions from stop-controlled or signalized intersections to roundabouts. The CMFs indicate several findings:

- **Severity.** Roundabouts reduce injury crashes more dramatically than various combinations of all crash severities.
- **Control type before.** Converting intersections with signals and TWSC to roundabouts offers highly significant safety benefits. The benefits are greater for injury crashes than for all crash types combined. For the conversions from AWSC, there is no apparent safety performance effect.
- **Number of lanes.** The safety benefit is greater for single-lane roundabouts than for two-lane configurations for urban and suburban roundabouts that were previously TWSC.
- **Setting.** The safety benefits for rural installations studied, all of which were single lane, were greater than for urban and suburban single-lane roundabouts.

Exhibit 7.15. Crash modification factors for converting a stop-control or signalized intersection to a roundabout.

Treatment	Setting	Crash Type		Source
		All	Injury	
TWSC to single-lane roundabout	Rural	0.29	0.13	HSM (*1*)
	Suburban	0.22	0.22	HSM (*1*)
	Urban	0.61	0.22	HSM (*1*)
TWSC to two-lane roundabout	Suburban	0.81	0.32	HSM (*1*)
	Urban	0.88	NA	HSM (*1*)
TWSC to single-lane or two-lane roundabout	Suburban	0.68	0.29	HSM (*1*)
	Urban	0.71	0.19	HSM (*1*)
	All	0.56	0.18	HSM (*1*)
AWSC to single-lane or two-lane roundabout	All	1.03	NA	HSM (*1*)
Signalized intersection to single-lane roundabout	All	0.74	0.45	Gross et al. (*6*)
Signalized intersection to two-lane roundabout	Suburban	0.33	NA	HSM (*1*)
	All	0.81	0.29	Gross et al. (*6*)
Signalized intersection to single-lane or two-lane roundabout	Suburban	0.58	0.26	Gross et al. (*6*)
	Urban	0.99	0.40	HSM (*1*)
	Urban	1.15	0.45	Gross et al. (*6*)
	3-approach	1.07	0.37	Gross et al. (*6*)
	4-approach	0.76	0.34	Gross et al. (*6*)
	All	0.52	0.22	HSM (*1*)
	All	0.79	0.34	Gross et al. (*6*)

Note: NA = not available.

7.5 Safety Surrogate Measures

A range of safety analysis methods can apply to roundabouts. This section presents surrogate measures and methods as well as predictive tools that analysts may consider at various stages of project development and during an ICE. The methods available provide different levels of detail, but more detail is not always necessary or helpful. **Sometimes even noting the potential for fatal and serious injury crash reduction is sufficient for a project's context compared with a more detailed safety analysis.**

So far, this chapter has presented a qualitative conflict point analysis that helps practitioners understand and communicate the principal elements that influence safety performance at intersections. However, simply counting and categorizing conflict points does not adequately measure quantitative safety. It also does not provide a surrogate measure that can meaningfully substitute for a predictive safety performance evaluation when evaluating or comparing alternatives (as typically required for an ICE).

Surrogate safety measures can indicate a roundabout's safety performance. Some measures are available during the planning stages when only concept designs are available. Others are appropriate for evaluating an operating roundabout. Exhibit 7.16 presents these surrogate measures.

7.5.1 Safe System for Intersections Method

A similar but more detailed method of surrogate intersection safety evaluation is provided in FHWA's *A Safe System–Based Framework and Analytical Methodology for Assessing Intersections* (*3*). This report details a methodology for evaluating how well an intersection aligns with safe system principles based on conflict point identification, exposure, kinetic energy transfer, conflict point severity, and intersection movement complexity.

Based on intersection configuration and volume data typically available during Stage 1 ICE as well as a set of geometric and speed assumptions, the methodology calculates an intersection-wide score from 0 to 100 that measures alignment with the Safe System for Intersections method. A score of 100 indicates an intersection design that is aligned with safe system concepts and has a

Exhibit 7.16. Surrogate safety assessment methods.

Surrogate Safety Assessment Method	Applicability
Safe System for Intersections method	This method was developed for application during early alternatives evaluation or early levels of concept design (e.g., Stage 1 ICE). It could also apply to in-service roundabouts. See Section 7.5.1 and FHWA (*3*).
Design flag assessment	This method for identifying bicycle and pedestrian needs was developed for application during early alternatives evaluation or early levels of concept design (e.g., Stage 1 ICE). It can also apply to in-service roundabouts. See Chapter 9: Geometric Design Process and Performance Checks, Appendix: Design Performance Check Techniques, and Kittelson et al. (*16*).
Vehicle speeds at conflict areas	Fastest path methodology can evaluate speeds for planned intersections (see Chapter 9). Field-measured speeds can evaluate in-service intersections.
Pedestrian crossing evaluation	Pedestrian crossing surrogate measures can be evaluated at a planning level by measuring crossing distances and evaluating sight distance (see Chapter 9 and the Appendix). For in-service intersections, the practitioner can measure crossing distances, evaluate sight distances, or measure yielding rates.
In-field conflict study	This method can only be conducted at existing roundabouts and is more common in research applications. See Section 7.5.2 for further detail.

reduced likelihood of fatal or severe injury crashes. The report is accompanied by a computational spreadsheet that calculates the method's measures of effectiveness and allows users to inspect and adjust input assumptions.

7.5.2 In-Field Conflict Study

An in-field conflict study measures the potential for crashes. Typically, a conflict study involves an in-field observation of a location or a video recording that is later analyzed. The analysis documents observed conflicts, which occur when two drivers are on a collision course and one or both drivers must take some evasive action to avoid a crash. The observed conflicts can be classified and counted on the basis of location, time to collision, and type of conflicts as well as the corresponding crash type avoided. The number of conflicts can be normalized by the volume of vehicles observed to provide a quantitative and comparable measure. Examples can be found in the FHWA study *Accelerating Roundabout Implementation in the United States,* Volume VII of VII—*Human Factor Assessment of Traffic Control Device Effectiveness* (*8*).

7.6 Safety Predictive Methods

Building on the models documented in *NCHRP Report 572: Roundabouts in the United States*, *NCHRP Research Report 888* developed three types of crash prediction models for roundabouts (*17*, *12*):

- **Intersection-level models for planning.** These models can be applied early when determining intersection control and type. They can also be part of network screening to assess the safety performance of several roundabouts.
- **Intersection-level models for design.** These models can supplement roundabout-specific design decisions, such as the number of entering and circulating lanes.
- **Leg-level models for design.** These models can supplement design decisions at the leg level. These models are not intended to predict the total crashes at a roundabout; that should be done using the intersection-level models.

Calibrating these models is essential to making accurate and trustworthy crash predictions. This is particularly true when comparing the crash predictions with those from other models (e.g., comparing the roundabout crash prediction with a crash prediction for a traffic signal). Model calibration is discussed further in Section 7.6.5.

7.6.1 Planning-Level Crash Prediction Models for Network Screening

As the HSM describes, network screening is a process for reviewing a transportation network to identify and rank sites based on a selected performance measure (for example, how much adding a safety countermeasure might reduce crash frequency). Sites identified are subsequently studied in more detail to identify crash patterns, contributing factors, and appropriate countermeasures. Network screening can also help agencies formulate and implement policy, such as prioritizing the treatments that might address common crash patterns.

NCHRP Research Report 888 includes roundabout safety prediction models intended for planning or network screening applications. Models were developed with AADT predictor variables. In some cases, models with select additional variables that may be known at the planning stage of roundabout construction were also developed. Each model predicts the average crash frequency of one roundabout, including crashes within the circulating roadway and those on the roundabout legs considered to be related to the roundabout (i.e., the leg geometry or operation was likely a contributing factor in the crash). Practitioners can use these models during planning stages to compare results from similar models that apply to other intersections.

In network screening, an Empirical Bayes–adjusted crash prediction model uses documented crash history along with predictive measures to assess how well an existing roundabout performs relative to other similar roundabouts or other intersection types. Practitioners may compare models to the average expected crash frequency at other collection sites. For other sites included in the screening (i.e., intersections other than roundabouts), the appropriate models need to be selected and recalibrated if necessary. Many jurisdictions may have calibrated their own models for various intersection types; otherwise, models from other sources may be adapted by estimating a recalibration multiplier. The HSM details this approach as well as network screening methods.

NCHRP Research Report 888 presents nine models—total, fatal and injury, and PDO crash prediction models—for three types: rural single-lane and two-lane roundabouts, urban single-lane roundabouts, and urban two-lane roundabouts. Crashes are predicted to increase with the following input conditions:

- Increases in traffic volumes on the major and minor roads (all models).
- Four intersection legs instead of three (all models).
- Two circulatory lanes instead of one (rural model).

7.6.2 Safety Performance for Intersection Control Evaluation

FHWA's SPICE tool compares intersection alternatives with predicted safety performance (*18*). As the name implies, the tool is used with limited data inputs, typically as part of ICE. The SPICE tool uses the available safety performance functions (SPFs) and high-quality CMFs to predict crash frequency and severity for a variety of intersection control strategies.

The SPICE tool specifies the predicted crash frequency and crash severity for each control evaluation strategy, and practitioners can analyze a single year or the lifespan of a project. SPICE is a spreadsheet tool that relies on research-backed SPFs and CMFs, so not all intersection types may be available for comparison. Among the unavailable intersection types are emerging concepts that do not have an extensive body of research. The SPICE tool includes values for predicted total crashes at single-lane roundabouts and some common multilane roundabout configurations.

7.6.3 Intersection-Level Crash Prediction Models for Design

NCHRP Research Report 888 developed crash prediction models to be applied at the intersection level with more detail than the planning-level models previously described. These models evaluate the type of roundabout features and design elements typically considered during preliminary design phases. Practitioners can consult these models to make decisions, such as how many entering and circulating lanes are appropriate.

The models include factors to predict all crash types (the same types presented in Exhibit 7.12) except motor vehicle–pedestrian and motor vehicle–bicycle crashes. Eight models were developed: one for each combination of three-leg versus four-leg roundabouts, one versus two circulating lanes, and fatal/injury versus PDO crash frequencies. Each model includes an indicator variable to distinguish rural and urban roundabouts.

Each of these crash prediction models applies calibrated CMFs to adjust the SPF so that it reflects conditions that may be different from the base design condition. The models are not reproduced here, but the effect the CMFs have on the crash prediction indicates the effect the roundabout design features may have on safety performance. CMFs can apply to the entire roundabout or to each leg and then aggregated back to the intersection level.

7.6.4 Leg-Level Analysis Techniques

NCHRP Research Report 888 developed leg-level crash prediction models to predict the average frequency of crashes associated with a specific roundabout leg and its design features, disaggregated by specific crash type. These models are meant for design-stage applications and include one or more CMFs that can adjust the predicted crash frequency to reflect the safety influence of existing or proposed roundabout design elements.

The models indicate the following relationships between design variables and expected crashes:

- **Entering–circulating crash models.** An increased ICD, increased angle to the next leg, and the presence of a bypass lane are associated with a reduction in crashes. For legs with two circulating lanes, crashes decrease with increased circulating width.
- **Exiting–circulating crash models.** With two circulating lanes and one exiting lane, a larger ICD is associated with fewer crashes. Increased circulating width is associated with an increase in crashes when one circulating lane is present and a decrease when two circulating lanes are present.
- **Rear-end approach crash models.** An increased number of access points on approach is associated with an increase in crashes. An increase in the number of luminaires on the approach is associated with a decrease in crashes.
- **Single-vehicle approach crash models.** An increase in posted speed limit is associated with an increase in crashes.
- **Circulating–circulating crash models.** At legs with two circulating lanes, an increased circulating width is associated with a decrease in crashes.

7.6.5 Model Calibration

Because crash prediction models like those included in *NCHRP Research Report 888* do not account for jurisdiction-specific differences, the HSM contains calibration techniques to modify tools for local use. This is necessary because of differences in factors such as driver populations, local roadway and roadside conditions, traffic composition, typical geometrics, and traffic control measures. There are also variations in how each state or jurisdiction reports crashes and manages crash data. Calibration does not make the crash data uniform across states. Similarly, applying HSM and similar models outside the United States and Canada is inadvisable, as is applying international models to intersections in the United States.

The calibration factors will have values greater than 1.0 for roadways that, on average, experience more crashes than the roadways used to develop the SPFs. Roadways that, on average, experience fewer crashes than the roadways used to develop the SPFs will have calibration factors less than 1.0.

NCHRP Research Report 888 **cautions that calibration is critical for the planning-level, intersection-level, and leg-level models to accurately inform project design decisions. Using the models without calibration could lead to incorrect conclusions. If local calibration is not possible, practitioners are advised to compare the CMFs presented in the HSM across intersection types.**

7.7 Assessment of Existing Circular Intersections

Any intersection, whether a roundabout or another form, may experience safety performance issues. Exhibit 7.17 presents issues that may exist at roundabouts along with a sample of potential remedies. These examples are not intended to be exhaustive but instead illustrate common issues that may arise and the levels of intervention that can address them.

Exhibit 7.17. Diagnostics of safety performance issues.

Safety Issue	Possible Causes	Possible Remedies
High frequency of sideswipe near-misses or crashes in multilane sections of roundabout	• Improper lane use, such as left turns or right turns from the wrong lane • Overlapping vehicle path trajectories • Entry path overlap	• Eliminate lanes where possible • Modify lane configuration to eliminate exclusive lanes on entries that drop within the roundabout (e.g., left-turn-only lanes) • Use physical spirals (truck apron extensions) rather than striped spirals next to truck apron • Realign roundabout entries, exits, or both to improve path alignment • Improve upstream lane selection cues (signs and pavement markings) • Modify circulatory roadway geometry and markings to discourage or restrict lane changes
High frequency of angle crashes	• Failure to yield on entry (typically outside entering lane failing to yield to inside circulating lane at multilane roundabouts) • Enlarged conflict area • Acute entry angles	• Reduce lanes to single-lane movements where possible • Realign roundabout approaches to remove lane assignment ambiguity • Adjust lane configurations on multilane roads to balance lane use
High frequency of single-vehicle crashes	• Drivers lose control within circulatory roadway and strike curbs or fixed objects • Drivers do not slow to appropriate speed on entry	• Relocate or remove fixed objects in “high-risk” locations • Introduce approach reverse curves for transitional approach speed reduction • Realign entry to create longer smooth arcs upstream of the entrance point • Provide treatments to enhance intersection visibility (e.g., constructed central island, signing, lighting)
High frequency of motorcycle crashes	• Motorcyclists lose control at entry or within circulatory roadway	• Install high-friction surface treatments to pavement and pavement markings • Provide speed reduction measures on approach to manage speeds
Pedestrians unable to find gaps at multilane exits	• Exiting drivers do not yield because of speeds, volumes, or sight distance	• Provide active traffic control device for pedestrian crossing (e.g., rectangular rapid flashing beacon [RRFB], pedestrian hybrid beacon [PHB], pedestrian signal) • Verify relevant performance checks and realign leg or reposition crossing to affect speeds or available sight distance • Eliminate lanes where possible • Add raised crossings

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CHAPTER 8

Operational Performance Analysis

Contents

This chapter discusses operational performance analysis for roundabouts and other circular intersections. Analysis techniques include planning-level, volume-based circulatory, and entry lane requirements, as well as overviews of the *Highway Capacity Manual*, 7th edition, (HCM) methodology, deterministic software methods, and simulation methods (*1*). All modes of travel—motorized vehicles, bicyclists, and pedestrians—are part of an operational performance analysis, although each technique's level of development analysis varies by mode of travel.

This chapter

- Presents the principles of roundabout operations for each mode of travel.
- Describes the measures of effectiveness that determine roundabout performance.
- Describes the analysis tools used to implement capacity and performance analysis procedures.

The roundabout planning and design process is iterative, and design choices and decisions can be informed by operational performance analysis. However, operational performance analysis results alone cannot solely dictate planning and design decisions. Each project's context is unique, and the range of users and needs varies. Establishing the roundabout lane configuration depends on professional judgment that considers each project individually.

For example, the decision to use a single-lane entry versus a two-lane entry goes beyond a simple, binary decision based solely on operational performance. Safety performance, accessibility, project context and constraints, intended design life, and other factors all contribute to the decision process. Adding lanes can increase overall crash risk, especially for vulnerable users. Multilane pedestrian crossings without supplemental treatments can reduce accessibility for people who are blind or have low vision. Multilane roadways introduce signing and navigational needs related to lane choices through the system. Many decisions that operational performance analyses commonly indicate—multiple through lanes, double left-turn movements, right-turn bypass lanes of various types, and so on—may have operational impacts upstream and downstream of the subject roundabout. Operational performance analysis at a given roundabout always needs to be conducted with this larger set of considerations in mind.

8.1 Introduction

Operational performance analysis is a foundational part of project development, used to size alternatives and to compare their performance. Various methodologies are available to analyze roundabout performance, each with applications to various stages of the project development process. All operational analysis methods are approximations, and it is the practitioner's responsibility to use the appropriate tool to conduct the analysis.

Decisions about the type of operational analysis method to employ are based on several factors:

- What stage of the project development process does this operational analysis support?
- What data are available?
- Can the method produce the outputs desired, such as volume-to-capacity ratios or animation?
- Is the analysis of existing or projected conditions? If projected conditions, what level of precision do the projected conditions support?
- Is the analysis for peak hours only or for other hours as well (such as for daily analysis)?

Exhibit 8.1 summarizes where to apply operational analysis tools during various stages of the project development process. Note that this is not an exhaustive list.

Whether for simple planning-level analyses or complex operational-level analyses, software tools frequently facilitate an efficient alternatives analysis. The key to effectively using software is to

Exhibit 8.1. Selecting an analysis tool.

Stage of Project Development Process	Application	Input Data Needed	Potential Operational Analysis Tool
Planning studies	Planning-level sizing to determine number of lanes	Daily traffic volumes	Planning techniques in Guide, Chapter 8
	Planning-level sizing to determine number and assignment of lanes	Peak hour traffic volumes	Planning techniques in Guide, Chapter 8; HCM; Cap-X; other deterministic software
Alternatives identification and evaluation: Step 1 ICE	Conceptual design of roundabouts with up to two lanes	Peak hour traffic volumes	HCM; Cap-X; deterministic software
	Conceptual roundabout design with configurations outside the scope of the HCM (see Section 8.7 for further discussion)	Peak hour traffic volumes, geometry	Deterministic software
	Conceptual-level bicyclist and pedestrian quality of service analysis	Geometry	Techniques in Guide, Chapter 9
Alternatives identification and evaluation: Step 2 ICE	Refining conceptual roundabout design	Peak hour traffic volumes, geometry from Step 1 ICE	HCM; Cap-X; deterministic software
	Refined analysis of bicyclist quality of service	Bicyclist volumes, intended methods of traversing roundabout	Techniques in Guide, Chapter 9
	Refined analysis of pedestrian quality of service	Vehicular traffic and pedestrian volumes, crosswalk design, traffic control	HCM; deterministic software; simulation; techniques in Guide, Chapter 9
	Analysis of metering treatments	Vehicular traffic, signal configuration	Deterministic software; simulation
	System analysis	Traffic volumes, geometry	HCM; deterministic software; simulation
	Public involvement with animation of proposed alternatives	Traffic volumes, geometry	Simulation

understand the fundamental principles of roundabout and intersection operations and to interpret software results appropriately when planning and engineering.

8.2 Operational Analysis Principles

Analyzing a roundabout's operational performance is relatively simple, although the techniques for modeling performance can be complex. This section presents core operational features and how they can be affected by user characteristics, user behavior, and geometry.

8.2.1 Core Operational Features

A few operational features are characteristic of roundabouts:

- Drivers slow down because of the intersection's geometric configuration.
- If the roundabout has more than one lane, drivers select the lane appropriate for their intended destination in advance of the entry point, **as is done at other intersections.**

- Drivers yield to or stop for bicyclists and pedestrians using the crosswalk, bicyclists and pedestrians wait for and accept gaps in motor vehicle traffic, or a combination thereof.
- Entering drivers yield to circulating drivers.

From a modeling perspective, these operational features affect modeling techniques in the following ways:

- Drivers must yield the right-of-way to circulating vehicles and accept gaps in the circulating traffic stream. Therefore, traffic patterns and gap-acceptance characteristics directly influence a roundabout's operational performance.
- Roundabout geometry directly influences its operational performance. The extent to which this influence is affected by the lane configuration or by design details (e.g., diameter) is discussed further in this section.
- Although the rules of the road throughout the United States require drivers to stop for or yield to pedestrians, actual practice tends to be more ambiguous, with a mixture of drivers yielding and pedestrians waiting for gaps. In some cases, the pedestrian crossing may be controlled by a traffic signal or pedestrian hybrid beacon or be supplemented with an active warning device. This complicates the modeling process.
- Because some roundabouts allow bicyclists to choose whether to circulate with motor vehicles or pedestrians, most modeling techniques include bicyclists as part of each mode (if they are included at all). Most modeling techniques do not analyze bicycle-specific facilities.

A variety of real-world conditions related to user characteristics and behavior can affect a given modeling technique's accuracy. Practitioners are cautioned to consider these effects and determine whether they are significant for the type of analysis being performed. For example, the level of accuracy needed for a rough, planning-level sizing of a roundabout is considerably less than that needed to determine the likelihood of queue spillback between intersections.

8.2.2 Effect of Pedestrians

Research on the operational performance of pedestrians at roundabouts has largely focused on the interaction between motor vehicles and pedestrians at crosswalks. The HCM provides techniques for estimating the effect of pedestrian crossings on motor vehicle capacity and is expressed as an adjustment factor to the estimated entry capacity (*1*).

For generalized midblock crossings, the HCM also offers techniques for estimating the effect of motor vehicles on pedestrian delay. There is limited research on delay for pedestrian crosswalks at roundabouts; NCHRP studies have largely focused on the relative delays between pedestrians with and without blindness or low vision (e.g., *2*). Similarly, the HCM provides estimates, based on NCHRP research, of driver yielding behavior at generalized midblock crossings. Research on predicting pedestrian delay specifically at roundabout crossings has been limited (*3*, *4*).

8.2.3 Effect of Bicyclists

There is little well-documented research on the operational performance of bicyclists at roundabouts or of the operational effects of other modes on bicyclists. The typical practice has been to treat bicyclists in operational models as either motor vehicles with a smaller passenger car equivalent (e.g., 0.5) or as pedestrians using the crosswalks.

8.2.4 Effect of Motor Vehicle Drivers

Research has found a variety of conditions influencing operational performance (*1*):

- **Exiting vehicles.** While the circulating flow directly conflicts with the entry flow, the exiting flow (to the same leg as the subject entry) may also affect a driver's decision about when to enter the roundabout. This phenomenon is like the effect of the right-turning stream approaching from the left side of a two-way, stop-controlled intersection. Until these drivers complete their exit maneuver or right turn, other drivers may be uncertain about the exiting or turning vehicle's intentions at the yield or stop line.

- **Changes in effective priority.** When both the entering and conflicting flow volumes are high, limited priority (when circulating traffic adjusts its headways to allow entering vehicles to enter), priority reversal (when entering traffic forces circulating traffic to yield), and other behaviors may occur. A simplified gap-acceptance model may not give reliable results.
- **Oversaturation.** When an approach operates over capacity during the analysis period, the actual circulating flow downstream of the entry over capacity will be less than the demand. The reduction in actual circulating flow may, therefore, increase the capacity of the affected downstream entries.
- **Turning movement patterns.** Turning movement patterns may influence the capacity of a given entry, especially for multilane roundabouts where lane use for both the entry and circulating flows may vary on the basis of turning movements.

In addition to these effects, drivers of trucks and other large vehicles have several notable influences on roundabout operational performance:

- Large vehicles are longer than other vehicle types and occupy a greater queue storage space per vehicle.
- Large vehicles often have different performance characteristics that influence speeds and acceleration rates. As an example, trucks often need more time to accelerate from a complete stop.
- At multilane roundabouts, trucks with trailers may occupy more than one lane simultaneously, potentially having a greater impact than staying completely within a lane. Interviews with trucking industry representatives and field observations of several multilane roundabouts confirm that truck drivers often straddle lanes, even in multilane roundabouts designed to allow trucks to stay in their lane while entering or circulating.
- At small roundabouts with traversable central islands, trucks and other large vehicles typically occupy much of the circulatory roadway and central island when making through or left-turn movements. This simultaneously blocks all other entries in addition to the one the large vehicle driver is using.

Each of these factors is captured to varying degrees within the different levels of operational analysis tools, with the more detailed models able to capture more effects. For planning-level models, the effects of large vehicles are often ignored. In the HCM and other deterministic models, for example, some of these factors are addressed through passenger car–equivalent factors based on aggregate observation of performance. In simulation models, the truck movements can be modeled individually and explicitly, thus significantly increasing data entry, calibration, and validation requirements.

8.2.5 Effect of Geometry

Geometry plays a significant role in roundabout operational performance in several ways:

- Geometry affects vehicle speed through the intersection, thus influencing travel time.
- Geometry sets the number of lanes over which entering and circulating vehicles travel as well as the number of lanes pedestrians must cross. The widths of the approach roadway and entry determine the number of vehicle streams that may form side by side at the yield line and govern the rate at which vehicles may enter the circulating roadway. The number of lanes pedestrians must cross affects pedestrian delay, safety performance, and accessibility.
- Geometry can affect the degree to which flow in each lane is facilitated or constrained. For example, the angle at which a vehicle enters affects the speed of that vehicle, with more perpendicular entries

requiring slower speeds and longer headways for acceptable gaps. Likewise, the geometry of multilane entries may influence the degree to which drivers are comfortable entering next to one another.

- Geometry may affect drivers' perception of how to navigate the roundabout and their corresponding lane choice approaching the entry. Lane alignment that aims drivers away from the intended lane can increase friction between adjacent lanes and reduce capacity. Imbalanced lane flows can increase the delay and queuing on an entry even if it is operating below its theoretical capacity.
- Geometry may affect bicyclists' decisions to use any bicycle-specific facilities provided. In the absence of bicycle-specific facilities, geometry can affect a bicyclist's decision to circulate as a motor vehicle or as a pedestrian.

For some models, the geometric elements of a roundabout, together with the volume of traffic desiring to use a roundabout at a given time, may directly determine the efficiency with which the roundabout operates for each mode. For example, geometric elements and traffic volume form the core of models commonly used for motor vehicle performance, including the Kimber model from the United Kingdom (*5*). Recent US-based research suggests that while aggregate changes in geometry are statistically significant, minor changes in geometry are masked by the large variation in behavior from driver to driver (*6*, *7*). As a result, the extent to which geometry is modeled depends on the available data and the modeling technique employed.

8.3 Operational Performance Measures

Performance measures can be determined from operational analysis methods. Some, such as volume-to-capacity ratio, can be obtained from planning-level and operational-level models. Others, such as queue length, can only be obtained from more detailed operational-level models. This section presents the most common measures used and a discussion about interpreting results.

8.3.1 Volume-to-Capacity Ratio

The volume-to-capacity ratio compares demand at a roundabout entry with its capacity and directly assesses a given design's sufficiency. For a given entry lane, the volume-to-capacity ratio, x, is calculated by dividing the lane's demand flow rate by the lane's calculated capacity (i.e., $x = v/c$).

The choice of a threshold for an acceptable volume-to-capacity ratio can significantly affect design. The HCM does not define standards for operational performance; however, international and domestic experience has suggested that volume-to-capacity ratios in the range of 0.85 to 0.90 represent an approximate threshold for satisfactory operation. When the degree of saturation exceeds this range, the roundabout's operation enters a more unstable range in which conditions could deteriorate rapidly, particularly over short periods of time. Queues may carry over from one 15-minute period to the next, and delay can increase exponentially.

The authors of this Guide have found anecdotally that building to a volume-to-capacity ratio of 0.85, particularly for a design year 20 years into the future, often results in more lanes being added to a roundabout than may be necessary or appropriate for the context. As such, **a volume-to-capacity ratio of 0.85 need not be considered an absolute threshold;** in fact, acceptable operations may be achieved at higher ratios. Practitioners are encouraged to consider the following actions:

- Using a similar volume-to-capacity ratio or other performance threshold when evaluating each intersection control strategy, for parity when assessing and comparing each intersection form's operational performance.
- Using an interim horizon year, such as a horizon year of 10 years after opening, to determine whether an interim design with fewer lanes would be appropriate and safer to build initially.

Preserve the right-of-way and configure the roundabout for a potential future expansion. This type of phased implementation is discussed further in Chapter 10: Horizontal Alignment and Design.
- Using hourly time periods for analysis of future conditions (i.e., peak hour factor of 1) instead of peak 15-minute time periods. Forecasted volumes rarely have the level of detail to support 15-minute time periods.
- Conducting a sensitivity analysis to evaluate whether changes in traffic volume assumptions, lane configuration, or other geometric features have dramatic impacts on delay or queues.
- Examining the assumptions used in the analysis, such as the accuracy of forecast volumes.
- Considering the relationship between operational performance and other factors, such as context and community needs.

8.3.2 Delay

Delay is a standard parameter that measures an intersection's performance and can be applied to all modes of travel. Several delay measures are used in practice:

- Total delay,
- Control delay,
- Stopped delay, and
- Geometric delay.

Control delay and *stopped delay* are related, with control delay being the broader term used in the HCM. Control delay is that portion of delay equal to the time that a driver spends decelerating to a queue, queuing, waiting for an acceptable gap in the circulating flow while at the front of the queue, and accelerating out of the queue. Stopped delay is that portion of control delay where the driver is stopped in a queue or the first position waiting to enter the roundabout. As such, control delay and stopped delay directly depend on traffic conditions at the intersection and can vary as conditions change.

For pedestrians, control delay is the portion of delay waiting to cross the street. It depends on the traffic control for the crossing, the volume of conflicting vehicular traffic, and the propensity for drivers to yield to pedestrians if uncontrolled. Bicyclists would experience control delay like that for drivers or pedestrians, depending on their means of navigating the roundabout.

Geometric delay is a component of delay present at all intersections, including roundabouts. Geometric delay is the additional time a single vehicle with no conflicting flows spends slowing down to the negotiation speed, proceeding through the intersection, and accelerating to a normal operating speed. Importantly, geometric delay is caused by only the curvature of the movement and not by the deceleration and acceleration from a queued condition. While geometric delay is often negligible for through movements at a signalized or stop-controlled intersection, it can be more significant for turning movements at those intersections and for all movements through a roundabout. The HCM considers geometric delay in its estimates of corridor travel time but does not calculate it for individual intersection analyses.

For comparison of roundabouts with other intersection types, it may be useful to compute the average control delay by approach or by intersection. The control delay for an approach is calculated by computing an average of the delay for each lane on the approach, weighted by the volume in each lane. Similarly, the control delay for the intersection is calculated by computing a weighted average of the delay for each approach.

8.3.3 Travel Time

Travel time is a common performance measure used to analyze corridors or system impacts. Travel time includes the total delay at each intersection—control delay and geometric delay—and the travel time between intersections. As such, travel time captures broader system effects, including potential out-of-direction travel time (called *extra distance travel time* in the HCM) for one or more modes created by a particular configuration.

Travel time can be useful for the following comparisons:

- Comparing a series of roundabouts with a series of other intersection types.
- Comparing roundabouts and other simple intersection forms with alternative intersection forms that include indirect left-turn movements, such as median U-turn intersections, restricted crossing U-turn intersections, and other at-grade forms.
- Comparing roundabouts and other simple intersection forms with grade separations or interchanges.

Travel time can be estimated with HCM techniques that incorporate methods developed from *NCHRP Report 772: Evaluating the Performance of Corridors with Roundabouts*, other deterministic software, and simulation (*8*). When comparing model results, practitioners need to verify that geometric delay is treated consistently across models.

8.3.4 Queue Length

Queue length needs to be considered when assessing the adequacy of a geometric design. The estimated length of a queue can also provide additional insight into the roundabout's operational performance compared with other intersection types. Queues at roundabouts tend to move continuously, unlike those at signalized intersections, and they tend to be shorter than stop-controlled movements.

Practitioners need to check the queue length calculated for each lane against available storage as they would for all intersection forms. Exceeding available storage is not necessarily a fatal flaw, but it may affect the selected operational modeling method's accuracy. The queue in each lane may interact with adjacent lanes in one or more ways:

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

Should one or more of these conditions occur, practitioners can conduct a sensitivity analysis using the methodology by varying the demand in each lane. Practitioners may also use an alternative tool sensitive to lane-by-lane effects.

8.3.5 Environmental Performance Measures

Several environmental performance measures that directly relate to operational performance are commonly used, including

- Fuel consumption and
- Emissions, such as carbon monoxide (CO), carbon dioxide (CO_2), and nitrous oxides (NO_x).

8.4 Quality of Service and Level of Service

The concept of quality of service provides the opportunity to evaluate how design choices impact each mode of travel: walking, biking, driving, and using transit service. The HCM defines quality of service as how well a transportation facility or service operates from a traveler's perspective (*1*). Level of service (LOS) is a letter-graded stratification of a selected performance measure to represent quality of service; it does not capture all aspects of quality of service. This section discusses these important concepts and how they apply to roundabouts in more detail.

8.4.1 Quality of Service

Quality of service allows consideration across all modes and thus can be a valuable part of ICE. Examples of factors applicable to roundabouts that influence the traveler-perceived quality of service include the following, some of which extend beyond the HCM's scope (*1*):

- Travel time, speed, and delay;
- Number of stops incurred;
- Travel time reliability;
- Comfort (e.g., bicyclist and pedestrian interaction with and separation from traffic, pavement quality);
- Convenience (e.g., directness of route);
- Safety performance (actual or perceived);
- User cost;
- Availability of facilities and services;
- Facility aesthetics; and
- Informational availability (e.g., wayfinding signage).

The HCM provides quantitative measures of quality of service for each of the four principal modes of travel on an urban street segment, resulting in a traveler perception score that can be compared across modes. At the intersection level, research is less complete. The HCM provides methods for determining pedestrian traveler perception scores for signalized and two-way, stop-controlled intersections as well as methods for determining bicyclist traveler perception scores for signalized intersections only. However, no specific traveler perception scores specific to roundabouts are available because of a lack of comparable research.

Instead of specific methodologies in the HCM or other references, this Guide uses design performance checks that capture many aspects of quality of service qualitatively. These are discussed further in Chapter 9: Geometric Design Process and Performance Checks.

8.4.2 Level of Service

The HCM defines LOS as a quantitative stratification of one or more performance measures that represent the quality of service for that mode of travel. The HCM uses a time-based measure—either control delay or travel time—as the service measure for all interrupted facilities: signalized intersections, unsignalized intersections, interchange ramp terminals, alternative intersections, and urban street segments. For roundabouts, the HCM defines LOS for motor vehicles using control delay, with LOS *F* assigned if the volume-to-capacity ratio of a lane exceeds 1.0, regardless of the control delay. For assessment of LOS at the approach and intersection levels, LOS is based solely on control delay.

The HCM uses the same LOS thresholds for roundabouts as for other unsignalized intersections, rather than the LOS thresholds for signalized intersections. All HCM methodologies for unsignalized intersections share a similar equation form for estimating control delay, so similar volume-to-capacity ratios produce similar control delays. In addition, drivers at roundabouts must make judgments about entering gaps similarly to how they would at two-way, stop-controlled intersections; these judgments become more challenging at higher volume-to-capacity ratios. As a result, drivers may not perceive the same amount of control delay at roundabouts as they do at signalized intersections. Some practitioners prefer using the signalized intersection LOS thresholds for roundabouts or an intermediate set of LOS thresholds between signalized and unsignalized intersections.

This Guide recommends that, rather than arbitrarily change LOS definitions from those recommended in the HCM, practitioners use the underlying performance measure—control delay—for direct comparison across intersection types. The performance measures themselves—control delay, volume-to-capacity ratios, queue length, and other measures—are more suitable for comparisons, as they allow more nuanced decisions than LOS, which is based solely on control delay. If the user's perception of quality of service is important in the evaluation, then LOS can be used as recommended in the HCM.

8.5 Reporting and Interpreting Results

Reporting and interpreting results centers on assessing the competing needs and performance trade-offs among modes of travel at a roundabout. Design decisions that improve the quality of service for one mode can have detrimental effects on other modes; these effects may not be realized if practitioners do not deliberately examine each mode of travel. Each performance measure described in Section 8.4 provides a unique perspective for each mode on the quality of service at which a roundabout will perform under a given set of traffic and geometric conditions. Practitioners need to estimate as many of these parameters as they can to obtain the broadest possible evaluation of a given roundabout design's performance.

For example, dedicated right-turn lanes that form their own lane downstream of the roundabout provide the highest motor vehicle capacity compared with other right-turn treatments. However, this capacity is often only needed during peak hours and for projected future years. During off-peak periods, this high-capacity right-turn treatment increases crossing distances and conflicting vehicle speeds for pedestrians. The dedicated right-turn lane also significantly increases conflicts for bicyclists, with the conflicts most acute upstream and downstream from the roundabout where bicyclists traveling through the roundabout cross paths with turning motor vehicle drivers. Careful assessment of the quality of service for all modes—even if only in a qualitative sense—is necessary to provide the best design for a given context.

For motor vehicle performance, results need to be reported at two levels of detail for each relevant analysis period:

- Performance measures for **the intersection as a whole,** such as control delay, enable comparisons with other alternatives.
- Performance measures **for each approach or each lane**—such as volume-to-capacity ratio, control delay, and queue length—assess whether the proposed alternative would perform as intended. Aggregating performance measures to the intersection level without considering the approach or lane level may mask deficient performance characteristics of individual approaches or lanes. Practitioners are encouraged to refer to the HCM for further discussion on this important topic.

8.6 Planning-Level Analysis Techniques

This section discusses planning-level operational performance techniques to determine which type of roundabout is appropriate at a given intersection. Capacity and size are interrelated based on the number of lanes required to accommodate forecasted traffic volumes.

8.6.1 Planning-Level Operational Assessment Using Daily Traffic Volumes

A basic question at the early stages of project development is, How many lanes will likely be needed to serve motor vehicle demand? The number of lanes affects roundabout capacity and size. This section provides sketch-level considerations for the initial roundabout feasibility screening. More detailed operational analyses may be required at later stages to confirm the sketch-level findings.

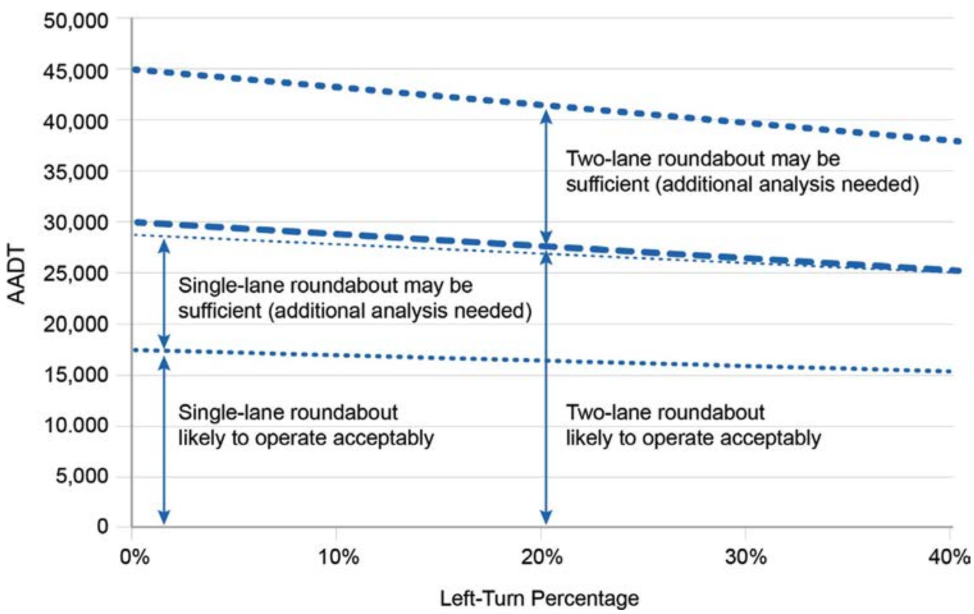
Sketch-level planning often requires an initial screening of alternatives when daily volumes (e.g., AADT) are known but more detailed information may not be available. Exhibit 8.2 presents ranges of daily traffic volumes to identify scenarios under which single-lane and two-lane roundabouts may perform adequately. Using a range of left turns from 0 percent to 40 percent of the total volume as an input improves the prediction of the potential capacity. The percentage of left turns on any given approach affects the conflicting volumes on other entries. Therefore, the potential capacity of the roundabout is reduced as the percentage of left turns increases. Capacities are derived from HCM capacity equations (*1*).

Exhibit 8.2 depicts four general ranges of volumes. These ranges represent the volume thresholds at which single-lane or two-lane roundabouts should operate acceptably. This exhibit also presents ranges of volumes over which more detailed analysis is required. This procedure offers a simple, conservative method for estimating roundabout lane requirements. For example, if the AADT volumes fall within the lowest range of volumes indicated in Exhibit 8.2, a single-lane roundabout is unlikely to have operational problems at any time of the day. This exhibit applies to the following conditions, with other conditions requiring more detailed analysis:

- Capacity estimates derived from HCM capacity equations.
- Ratio of peak hour to daily traffic (K) of 0.09 to 0.10.
- Direction distribution of traffic (D) of 0.52 to 0.58.
- Ratio of minor street to total entering traffic of 0.33 to 0.50.
- Acceptable volume-to-capacity ratio on the most critical lane of 0.70 to 0.90, representing a practical capacity limit for planning purposes.

The intermediate threshold for each type of roundabout (one lane and two lane) is based on the most conservative combination of these conditions; the upper threshold is based on the combination to produce the highest AADT (e.g., K of 0.09, D of 0.52, the minor street ratio of 0.50, and the volume-to-capacity ratio of 0.90). It is suggested that a reasonable approximation

Exhibit 8.2. Planning-level daily intersection volumes for a four-leg roundabout.



SOURCE: Derived from HCM (*1*).

of lane requirements for a three-leg roundabout may be obtained using 75 percent of the service volumes shown in Exhibit 8.2.

8.6.2 Planning-Level Operational Assessment Using Peak Hour Turning Movements

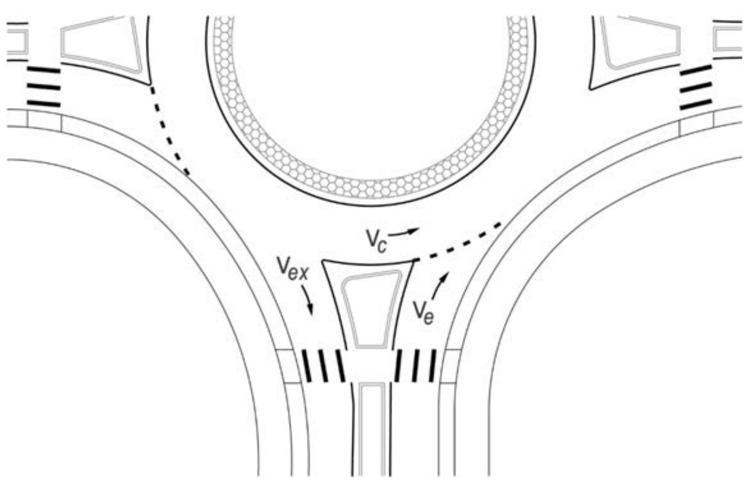
Where existing or projected turning movement data are available at the planning level, practitioners can improve their estimate of the required lane configurations. Even if future projections of turning movements are not available, estimating future turning movements using existing turning movements and a reasonable annual growth rate may be sufficiently accurate for this planning exercise. The procedure provided within this section is a simplification of the capacity estimates presented in Section 8.7.

Roundabout entry capacity is generally driven by the combination of entering and conflicting traffic present at each roundabout entry. High conflicting volumes reduce the opportunity for vehicles to enter the roundabout, thereby reducing the capacity of a particular entry. Conversely, where low conflicting traffic volumes are present, the approach leg will have a higher capacity and allow for more vehicles to enter the roundabout. Each approach leg of the roundabout is evaluated individually to determine the number of entering lanes required on the basis of the conflicting flow rates. The number of lanes within the circulatory roadway is then the number of lanes needed to provide lane continuity through the intersection. More detailed lane assignments and refinements to the lane configurations can be determined later through a more formal operations analysis. The traffic flows at a roundabout entry are shown in Exhibit 8.3.

This Guide includes a planning-level manual technique that requires calculating entering and circulating flow rates (v_e and v_c, respectively) for each roundabout leg. Although the following sections present a numerical methodology for a four-leg roundabout, this methodology can be reduced or expanded to any number of legs. The exiting flow, v_{ex}, is used for right-turn bypass lanes in the HCM and other deterministic models but is not needed for the planning-level assessments in this section.

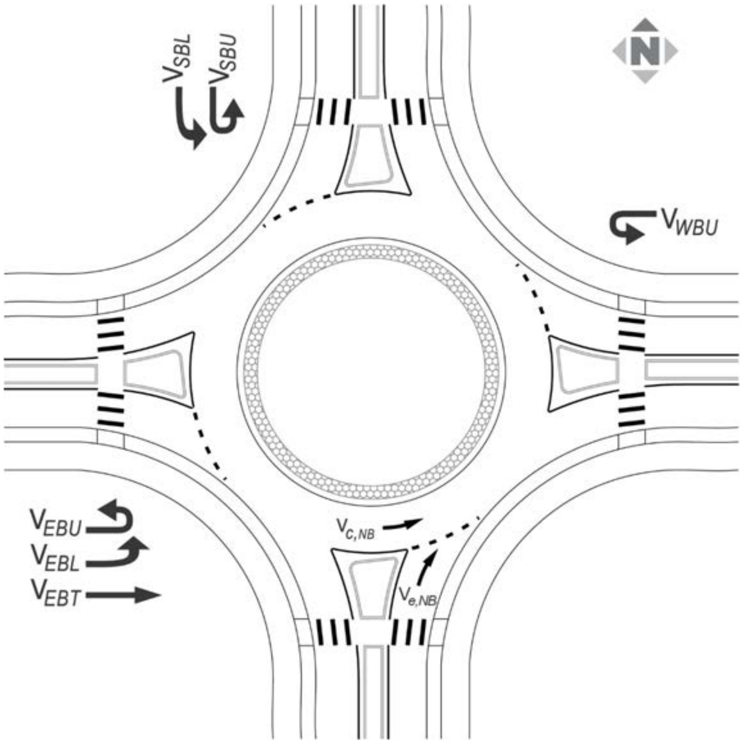
The conflicting flow rate opposing a given entry is defined as the flow circulating immediately upstream of where the entry flow joins the circulatory roadway. Exhibit 8.4 shows the turning movements that constitute the conflicting traffic volume at the northbound entry, such that $v_{c,NB} = v_{EBT} + v_{EBL} + v_{EBU} + v_{SBL} + v_{SBU} + v_{WBU}$.

Exhibit 8.3. Traffic flows at a roundabout entry.



SOURCE: HCM (*1*).

Exhibit 8.4. Calculation of conflicting flow.



SOURCE: Adapted from HCM (*1*).

Exhibit 8.5 illustrates planning-level capacity estimates using peak hour volumes of vehicles per hour (veh/hr) for a variety of single-lane roundabouts as well as for two-lane roundabouts. Estimates for single-lane and double-lane entries for roundabouts with non-traversable central islands were derived from HCM models with default values (*1*). The estimate for a single-lane roundabout with a traversable central island was derived from research that used simulation in the absence of field data for at-capacity operation (*9*). The planning-level capacity estimates in Exhibit 8.5 are practical capacity estimates that assume a volume-to-capacity ratio of 0.90; higher capacities may be achievable but require more detailed operational analysis. In addition, the curve for the two-lane entry assumes two through lanes with reasonably similar volumes in each lane using the HCM default values for lane utilization.

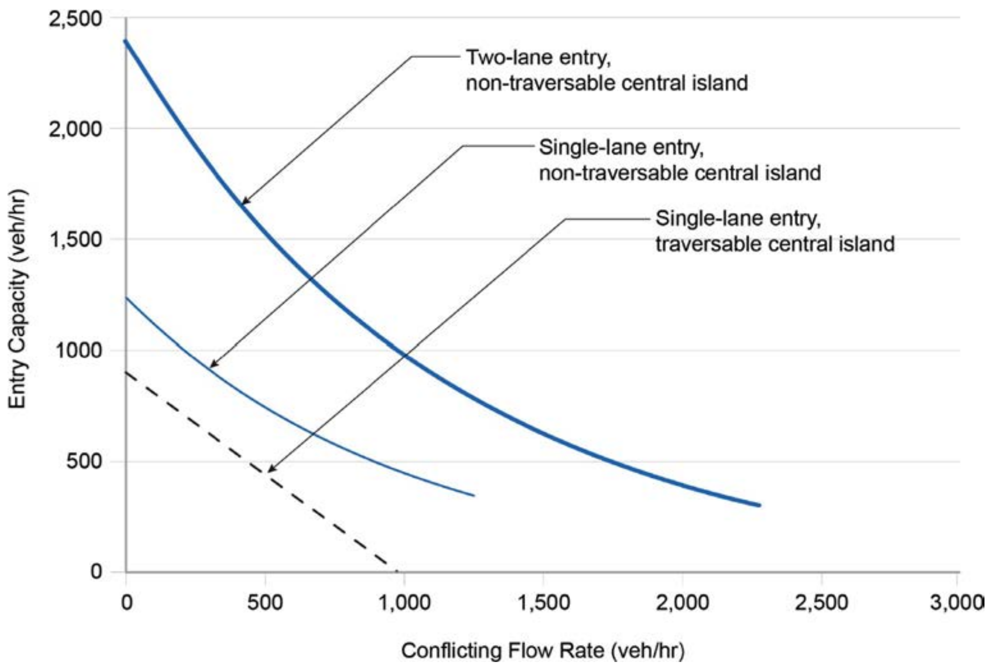
Exhibit 8.6 presents a simplified table that uses the sum of entering and conflicting flows as a planning guide on the type of roundabout and number of lanes that may be needed. The table can be augmented or superseded by Exhibit 8.5 or the detailed analysis discussed in sections 8.7 through 8.10.

8.6.3 Comparative Performance

It can be useful to examine the relative operational performance for motor vehicle users across two-way stop-controlled intersections, all-way stop-controlled intersections, signalized intersections, and roundabouts. *NCHRP Report 825: Planning and Preliminary Engineering Applications Guide to the Highway Capacity Manual* illustrates intersection control type as a function of peak hour volume for major and minor streets (*10*).

These illustrations, reproduced in Exhibit 8.7 and Exhibit 8.8, illustrate a comparison across intersection types for a range of major and minor street peak hour volumes with consideration of the MUTCD traffic signal warrants (*11*). These illustrations depict control delay for motor vehicles

Exhibit 8.5. Planning-level practical capacity estimates using peak hour volumes for a given entry.



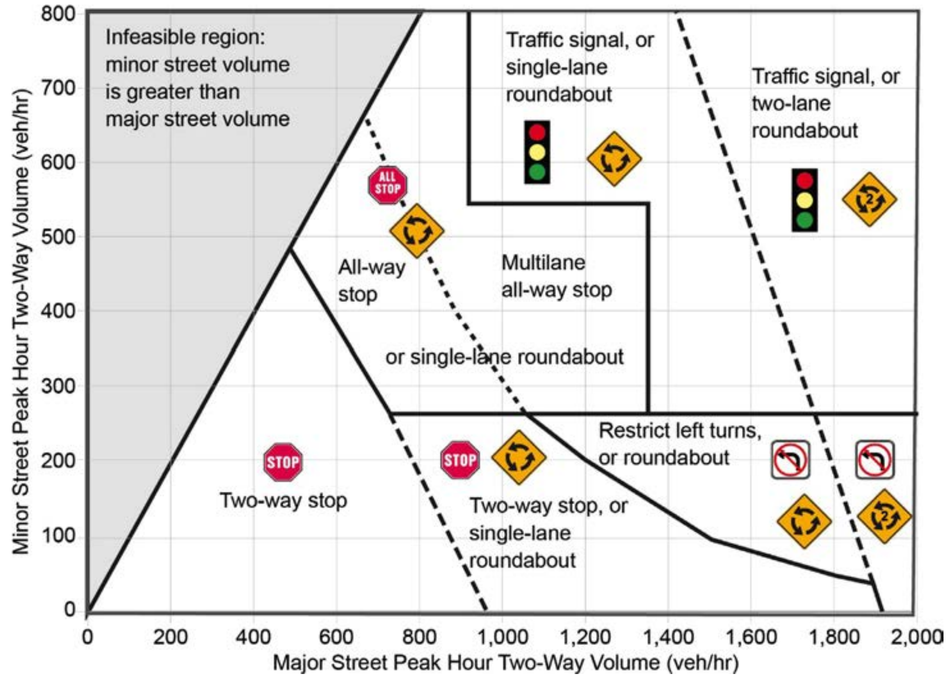
NOTE: Practical capacity is assumed to be 90 percent of maximum capacity. Conclusions not valid at planning level for conflicting flow rates above 1,250 veh/hr for a single-lane circulatory roadway and 2,300 veh/hr for a two-lane circulatory roadway. Values beyond these practical limits may be possible, but further analysis is recommended. SOURCE: Derived from HCM (*1*) and Lochrane et al. (*9*).

Exhibit 8.6. Planning-level sizing guide using peak period volume thresholds.

Sum of Peak Period Entering and Conflicting Flows (veh/hr)	Type of Roundabout and Number of Lanes
700 or less	Single-lane roundabout with traversable or non-traversable central island is likely sufficient
701 to 900	Single-lane roundabout with non-traversable central island is likely sufficient; single-lane roundabout with traversable central island may be sufficient
901 to 1,300	Single-lane roundabout with non-traversable central island may be sufficient
1,301 to 1,600	Two-lane entry into multilane roundabout is likely sufficient; detailed turning movement analysis recommended
1,601 to 2,300	Two-lane entry into multilane roundabout may be sufficient; detailed turning movement analysis recommended
Greater than 2,300	Three-lane entry into multilane roundabout may be sufficient; detailed turning movement analysis recommended

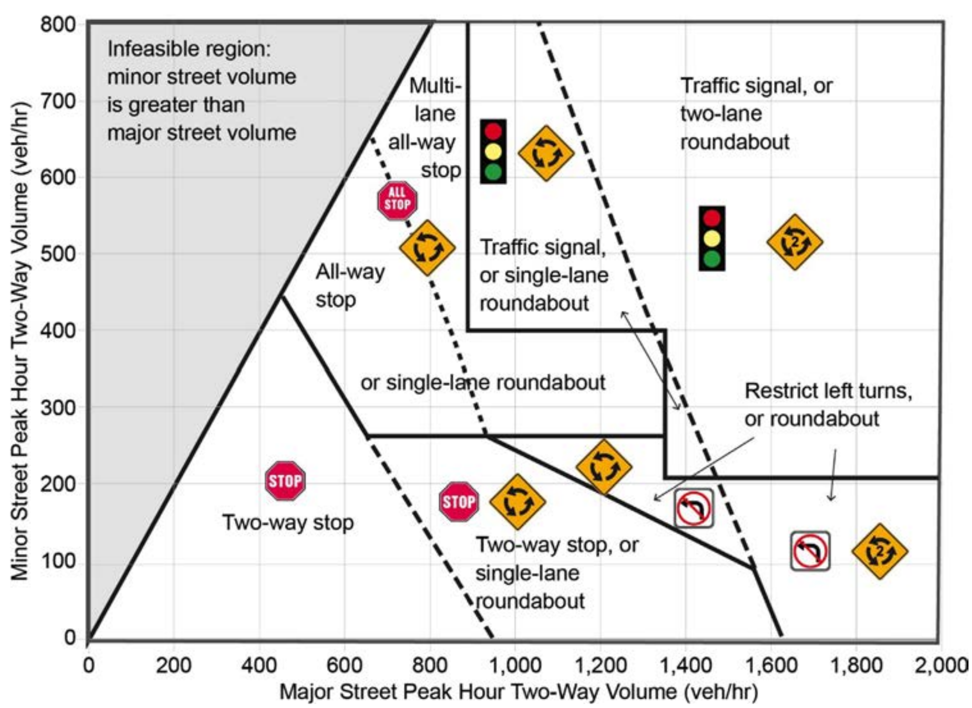
NOTE: Derived from Exhibit 8.5.

Exhibit 8.7. Intersection control type by operational performance, 50/50 volume distribution on each street.



NOTE: Mini-roundabouts and compact roundabouts are not included in this exhibit. Assumes eighth-highest-hour volumes equal 55 percent of peak hour volumes, peak hour factor equals 0.92, each approach has 10 percent left turns and 10 percent right turns, and each approach is a single lane in the base case. Derived from MUTCD 8-hour signal warrant, MUTCD all-way stop warrant, and HCM methods for two-way stop-controlled intersections and single-lane roundabouts. SOURCE: *NCHRP Report 825* (*10*).

Exhibit 8.8. Intersection control type by operational performance, 67/33 volume distribution on each street.



NOTE: Mini-roundabouts and compact roundabouts are not included in this exhibit. Assumes eighth-highest-hour volumes equal 55 percent of peak hour volumes, peak hour factor equals 0.92, each approach has 10 percent left turns and 10 percent right turns, and each approach is a single lane in the base case. Derived from MUTCD 8-hour signal warrant, MUTCD all-way stop warrant, and HCM methods for two-way stop-controlled intersections and single-lane roundabouts. SOURCE: *NCHRP Report 825* (*10*).

as the only determining factor, ignoring control delay for bicyclists and pedestrians as well as other performance measures, such as safety performance. **As such, Exhibit 8.7 and Exhibit 8.8 are not to be used as the sole factor for intersection selection.** Mini-roundabouts and compact roundabouts were not studied and are not represented in the exhibit. Refer to *NCHRP Report 825* for further details (*10*).

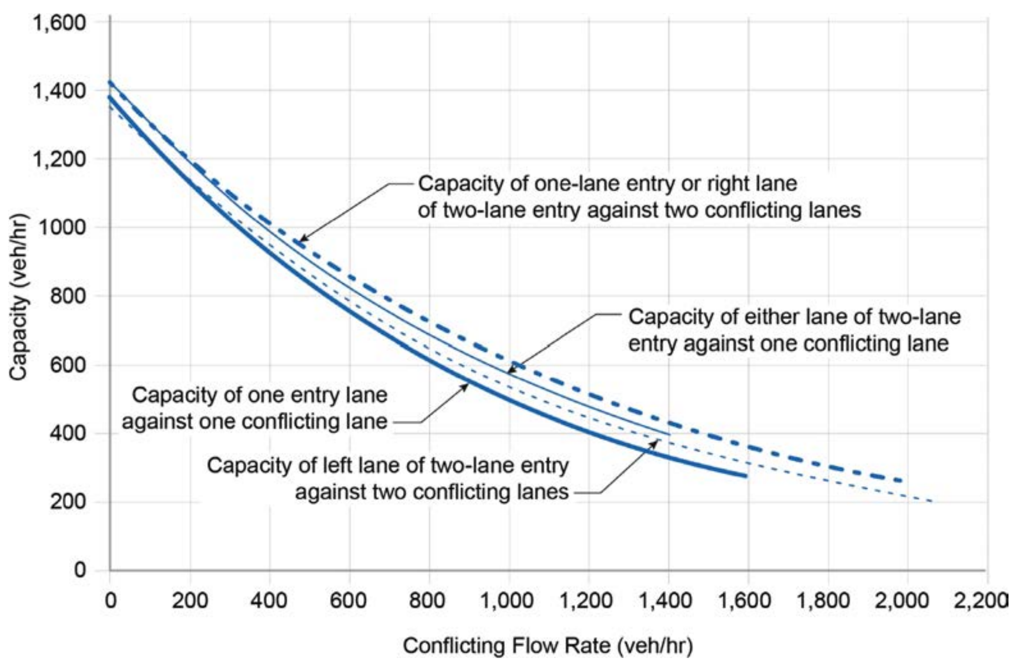
8.7 *Highway Capacity Manual* Analysis Techniques

The operational analysis method the HCM advises to analyze motor vehicles is based on a 2015 FHWA-sponsored update of the original *NCHRP Report 572* study of roundabout operations for US conditions and *NCHRP Report 772* for estimating corridor performance (*1, 6–8*). The procedures allow practitioners to assess the operational performance of an existing or planned one-lane or two-lane roundabout given traffic-demand levels. This Guide presents an overview of the HCM method but not the formulas or details, including techniques for calibration. Practitioners are encouraged to refer to the HCM for these details along with any updates approved by the TRB Committee on Highway Capacity and Quality of Service.

In accordance with national research, the HCM employs simple empirical regression models to reflect the capacity of roundabouts with up to two lanes, as shown in Exhibit 8.9. The HCM analyzes the performance of each entry lane, accounting for lane-use differences and different observed capacities. The HCM also includes models for estimating the performance of yield-controlled right-turn bypass lanes. The HCM does not have analytical models for other types of bypass lanes that merge at a low angle with exiting traffic or form a new lane adjacent to exiting traffic (non-yielding bypass lane). Further detail, including plots of data behind some of the capacity curves, can be found in the HCM, as well as the FHWA and NCHRP supporting research (*1, 6–8*).

For performance measures, the HCM estimates the volume-to-capacity ratio, the control delay, and the 95th-percentile queue on a lane-by-lane basis and assigns a LOS for each lane based on the control delay of that lane. The HCM also estimates control delay and LOS aggregated to the

Exhibit 8.9. HCM capacities of single-lane and multilane entries.



SOURCE: HCM (*1*).

approach level and the intersection level. For corridor segments that have roundabouts, the HCM estimates travel time.

The HCM identifies that its analytic methods have several key scope limitations for which it recommends using alternative tools, such as the methods described in the following sections of this chapter. These scope limitations include

- Pedestrian signals or hybrid beacons at roundabout crosswalks,
- Metering signals on one or more approaches,
- Adjacent signals or roundabouts,
- Priority reversal under extremely high flows,
- High pedestrian or bicyclist activity levels,
- More than two entry lanes on an approach, and
- Flared entry lanes, such as an entry that widens from one approach lane to two entry lanes over a short distance.

8.8 Other Deterministic Methods and Software Implementations

In addition to the HCM's software implementations, other deterministic operational analysis methods and software implementations are commonly used for roundabout analyses. The term *deterministic* means that a single set of inputs always produces the same set of outputs; no random variations (stochastic inputs) are part of the modeling process.

8.8.1 FHWA Tools

FHWA has developed analysis tools to aid ICE activities. This includes Cap-X, a spreadsheet-based tool to analyze a full range of intersection alternatives commonly considered during Step 1 of ICE activities (Cap-X includes several roundabout configurations) (*12*). Further detail on these tools can be found on FHWA's website.

8.8.2 Commercial Software

Several deterministic software methods implement HCM procedures and include methodologies anchored to international research and practice. The most common international methods used in the United States to date are based on Australian and British research and practice. These international methods are commonly sensitive to various flow and geometric features of the roundabout in ways not captured in the HCM, such as lane numbers and arrangements, as well as specific geometric dimensions (e.g., entry width, inscribed circle diameter). Some of these software implementations also capture capacity constraint effects; that is, the circulating flow downstream of an entry at capacity is reduced to account for flow unable to enter the roundabout. Some software implementations that also implement HCM methods may employ extensions beyond the original research implemented in the HCM.

International-based models and methods can bring value to the analysis process, but analysts must ensure that the procedure is applied appropriately. Common items to check for include the following:

- **Calibration to local driver behavior.** For analytical models, this calibration may involve using locally measured values for gap-acceptance parameters or applying global factors that shape the capacity model. For regression-based models, this may involve adjusting the intercept to match field-measured values of follow-up times. Calibration requires sufficient samples of roundabouts operating at capacity and are best established at the program level for a state or local region.

- **Calibration to effective geometry.** For regression-based models that employ continuous variables for key dimensions (e.g., entry width in feet or meters rather than in number of lanes), analysts will consider adjustments for effective geometry. This is especially true for single-lane entries that have curb-to-curb widths to accommodate large vehicles. Regression-based models do not recognize that a large single-lane entry has only one lane and may be modeled as a two-lane entry. A common adjustment in these cases is to assume that a single-lane entry has a maximum entry width of 14 ft or 15 ft (4.2 m or 4.5 m), regardless of the actual curb-to-curb width.
- **Lane use and assignment.** Some models are sensitive to lane use and assignment, including flares and short lanes; others are not. Adjustments need to account for lane configurations or system effects (e.g., downstream destinations, such as freeway on-ramps or other intersections) that might cause traffic to favor one lane over another, thus influencing capacity and performance measures. This procedure may employ lane utilization values other than the default values in the HCM or other models to reflect anticipated differences in the use of one lane versus another.

8.9 Simulation Techniques

A variety of simulation software packages are available to model transportation networks. Several are capable of modeling roundabouts, and their features change frequently. These models display individual vehicles and are sensitive to factors at that level: car-following behavior, lane-changing behavior, and decision making at junctions (e.g., gap acceptance). Such thoroughness, however, results in a microscopic level of detail for modeling operations, meaning that the software needs significantly more input and calibration than planning-level or HCM tools. Practitioners need to match their tools with the level of precision necessary for the stage of analysis.

Simulation models may be the most appropriate analysis tool for the following applications:

- **Modeling oversaturated conditions.** Oversaturated conditions occur when demand exceeds capacity over the analysis period. This causes queue growth throughout the analysis period. Depending on the simulation model, it may be possible to also model shifts in demand for each mode.
- **Interaction between traffic control devices at a roundabout.** Examples include metering signals, pedestrian signals, and at-grade rail crossings at or close to the roundabout.
- **Interaction between closely spaced roundabouts, other intersections, or freeway facilities.** Simulation models can show the queuing that may occur between closely spaced intersections and the effects of those queues on how the roundabout or other intersection operates. Applications can include corridor applications with a series of roundabouts, access management techniques for driveways with reduced access close to roundabouts, or other applications.
- **Unusual geometric or traffic control configurations.** Simulation models may be able to model atypical configurations that are not modeled using simpler techniques (e.g., unbalanced lane demands or unbalanced available lane storage).

As with the deterministic software methods described previously, practitioners need to verify that the simulation model is applied appropriately. Common items to check for include the following:

- **Calibration to local driver behavior.** Calibrating stochastic models is more challenging than calibrating deterministic models because some calibration factors, such as those related to driver aggressiveness, often apply globally to all elements of the network and not just to roundabouts. In other cases, the specific coding of the model can be fine-tuned to reflect localized driver behavior, including speeds, look-ahead points for gap acceptance, and locations for discretionary

and mandatory lane changes. Calibration to local behavior where roundabouts do not yet exist may not be possible; in these cases, regional or national guidance may be used.
- **Volume pattern checking.** For network models with dynamic traffic assignment, traffic volumes on a given link may not match what has been measured or projected.

Further guidance on applying simulation models, including the necessary calibration and validation processes, can be found on the FHWA Traffic Analysis Tools web page, particularly Volume III, *Guidelines for Applying Traffic Microsimulation Modeling Software* (*13*, *14*).

8.10 Assessment of Existing Roundabouts and Circular Intersections

Operational analysis of existing circular intersections may be needed for a variety of reasons. This section summarizes the techniques for obtaining traffic volume data and measuring existing operational performance.

8.10.1 Collecting Traffic Volume Data

Operational analysis of roundabouts requires either collecting existing or projecting future peak period turning movement volumes. Virtually all operational analysis techniques for roundabouts use turning movements as inputs into the methodology; these also facilitate analysis of other intersection forms and control types. As such, it is usually not enough to simply capture entering, circulating, and exiting volumes, even though these would be sufficient for planning-level and even some HCM techniques. The underlying turning movements (left turns, through movements, right turns, and U-turns from each entry) are needed for alternatives assessment.

For existing signalized or stop-controlled intersections, there are standard techniques for determining turning movements, such as the Institute of Transportation Engineers (ITE) *Manual of Transportation Engineering Studies* (*15*). For existing roundabouts or other circular intersections, turning movements are often more difficult to observe because of their delayed realization; through movements and left-turn movements often look identical until well after the driver enters the roundabout, and left-turn movements and U-turn movements are coincident for even longer. Roundabouts and other circular intersections are also typically larger than other intersection types, making it more difficult to observe motor vehicles, bicyclists, and pedestrians from a single vantage point.

Turning movements for motor vehicles at roundabouts or other circular intersections can be collected using a variety of techniques:

- **Live recording of turning movement patterns using field observers.** This is only feasible under low-volume conditions where the entire roundabout is visible from one location.
- **Video recording of the entire intersection followed by manual extraction of turning movements from the video.** This technique is feasible under any volume condition and usually requires all turning movements to be visible from one location. Multiple video locations can be used, but they must be synchronized for successful data extraction. While cameras from elevated viewpoints or mounted on tall poles or masts can be effective, drones are better equipped to get video footage of the entire roundabout.
- **Video recording of the entire intersection followed by automated extraction of turning movements from the video.** This technique has become increasingly viable given improvements in the algorithms used for video detection and analysis of trajectories.
- **Origin–destination survey techniques.** This technique is used most often when multiple intersections are being studied simultaneously and where overall travel patterns are needed. Mechanisms include probe data from mobile devices and license plate matching.

Other techniques, such as using link volumes and estimates of turning movements, may be useful for approximations but are not as accurate as these.

NCHRP Report 797: Guidebook on Pedestrian and Bicycle Volume Data Collection discusses methods and technologies for counting pedestrians and bicyclists as well as factors to consider when selecting a technique (*16*). These factors include adjustments for time periods, environmental factors, and land-use and facility types. The forecasting of future pedestrian and bicyclist demand is less developed in current practice, but it is still essential for reasonable comparisons of operational performance across all modes.

8.10.2 Field Measurement and Calibration of Operational Performance

Field measurement of an existing roundabout or circular intersection's operational performance can help practitioners confirm estimates from the existing conditions analysis. These field measurements are typically collected during peak periods, but they can extend to include off-peak periods to capture all-day performance.

The operational performance of a roundabout can be measured directly in the field using a variety of techniques:

- **Capacity.** During periods when an entry to an existing roundabout is operating at capacity with a continuous standing queue, the entry flow and conflicting circulating flow can be directly sampled. These samples are typically in 1- to 5-minute blocks of time during periods when queuing is continuous. These measurements can be graphed to determine a possible adjustment factor to the selected analysis model, most commonly as an intercept adjustment.
- **Control delay.** Practitioners can estimate control delay by measuring the average time vehicles take to travel between a control point upstream of the maximum queue in a lane and a point immediately downstream of the entry. The control delay is the difference between this measured travel time and the travel time needed by an unconstrained vehicle (one that did not queue or need to yield at entry). Control delay measurements include stopped delay as a component. Control delay can be measured for motor vehicles, bicyclists, and pedestrians.
- **Travel time.** Practitioners can measure travel time by collecting a sample of data between a designated origin point and designated destination point, with the travel between these points passing through each roundabout or circular intersection of interest. Travel time can be used to estimate geometric delay by comparing the travel time of an unconstrained vehicle passing through a roundabout with that needed by an unconstrained vehicle that does not pass through the geometric features of the roundabout (either measured before construction or estimated). Geometric delay is important when comparing travel times along a corridor. Travel time can be measured for motor vehicles, bicyclists, and pedestrians.
- **Yielding behavior of drivers to pedestrians.** This can be measured for calibrating the expected delay to pedestrians.
- **Queue length.** Queue length can be measured directly and is measured as part of the control delay estimation. With queue lengths taken at regular intervals, measures such as average queue length and 95th-percentile queue length can be directly determined from the field data.
- **Queue spillback.** When queue spillback extends into another intersection, practitioners can flag each occurrence and measure its duration. This can be useful for validating models of existing conditions (especially simulation models), whether for roundabouts or signalized intersections in a series or for the assessment of driveways that may be affected by existing roundabouts or signalized intersections.
- **Environmental performance data.** Probe vehicles may require specialized equipment to capture environmental performance data, such as tailpipe emissions. Therefore, emissions measurements

are typically only conducted for research purposes. Further discussion of these techniques can be found elsewhere (*17*).

Field measurement of performance measures may require significant sample sizes because of the inherent variability in delay measures. Further discussion on sample sizes and other aspects of field operational data collection can be found in the HCM and the ITE *Manual of Transportation Engineering Studies* (*1*, *15*).

8.10.3 Diagnostics of Operational Performance Issues

An existing or proposed roundabout or circular intersection may present operational challenges. Exhibit 8.10 provides some examples, along with potential remedies. The list of examples in Exhibit 8.10 is not intended to be exhaustive but illustrates that there is often more than one way to address an operational performance issue. For example, while adding lanes is often one potential solution to an operational problem, other options may be more appropriate for the given context.

Exhibit 8.10. Diagnostics of operational performance issues.

Operational Issue	Possible Causes	Possible Remedies
Large peak period motor vehicle delay for roundabout entry	Entry is over capacity because upstream entry is dominating circulating flow	Add a metering signal during peak periods for upstream entry
	Entry is over capacity because number of lanes is insufficient	Add right-turn bypass lane Add entry lane, which may require changing circulating and exiting lane configurations
Unbalanced queues across entry lanes	Insufficient lane configuration	Reconfigure entry lane assignment, which may require changing circulating and exiting lane configurations
	Traffic demand has a large peaking characteristic	Accept peak period delay to avoid creating unintended safety and accessibility challenges during off-peak periods and to encourage use of other time periods and modes
	Poor path alignment	Adjust geometry
Unacceptable peak period pedestrian delay at crosswalk	Insufficient gaps or yielding by drivers	Raised crosswalk Active traffic control device (beacon or signal)
Queue from roundabout blocks left turns out from upstream driveway	Driveway too close to roundabout	Restrict driveway turning movements to right in, right out Close driveway or relocate farther from roundabout Accept peak period delays and queues caused by undesirable impacts from other remedies
Queue from roundabout extends into upstream roundabout or signalized intersection	Inadequate capacity	Add or reassign lanes at roundabout
	Adequate capacity but insufficient queue storage	Add one or more lanes to distribute queue Meter upstream roundabout to reduce peak period flows at downstream roundabout

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CHAPTER 9

Geometric Design Process and Performance Checks

Contents

This chapter introduces and describes the design process and objectives, principles, and performance checks that guide the geometric design process. It details how to conduct performance checks fundamental to roundabout design while considering broader intended project outcomes. Three-dimensional roadway design discussions are presented in Chapter 10: Horizontal Alignment and Design and Chapter 11: Vertical Alignment and Cross-Section Design. This chapter supports iterative roundabout planning and design activities that optimize intersection configuration for each project condition and context.

Appendix: Design Performance Check Techniques details a variety of design performance check techniques that can facilitate the check process discussed in Chapter 9: Geometric Design Process and Performance Checks. The techniques in the appendix are representative but not exhaustive of all possible techniques. Practitioners sometimes need to modify performance check techniques to meet a specific configuration; any modifications need to be compatible with the design principles in Chapter 9.

The geometric design process and associated performance checks aim to meet the identified users' needs via the approach presented in Chapter 3: A Performance-Based Planning and Design Approach. User needs and stakeholder considerations help practitioners establish a planning framework—both topics are addressed in Chapter 4: User Considerations and Chapter 5: Stakeholder Considerations, respectively. ICE activities, presented in Chapter 6: Intersection Control Evaluation, guide and inform intersection control and form evaluation and selection. Each previous chapter contributes to the performance metrics for evaluating roundabouts, designed in each project context.

Geometric design performance checks complement the safety and operations considerations that contribute to a roundabout's design. Roundabout concepts have to represent and integrate design principles commensurate with the level of detail appropriate for the project development stage. Even at the earliest stages of roundabout planning and design, it is vital that safety, operational, and user needs guide concept development. Poor concepts can lead to poor decision making at the feasibility stage and can make it more difficult to generate substantial changes to a design during later stages.

This chapter supports ICE process activities and will help designers evaluate and optimize new roundabouts for a given project context. Performance checks are foundational to assessing existing circular intersections as part of in-service reviews. This chapter supports practitioners in assessing existing circular intersections, potentially quantifying existing issues, and using that information to consider possible countermeasures. The performance considerations connect integral concepts presented in Chapter 7: Safety Performance Analysis and Chapter 8: Operational Performance Analysis.

9.1 Design Process

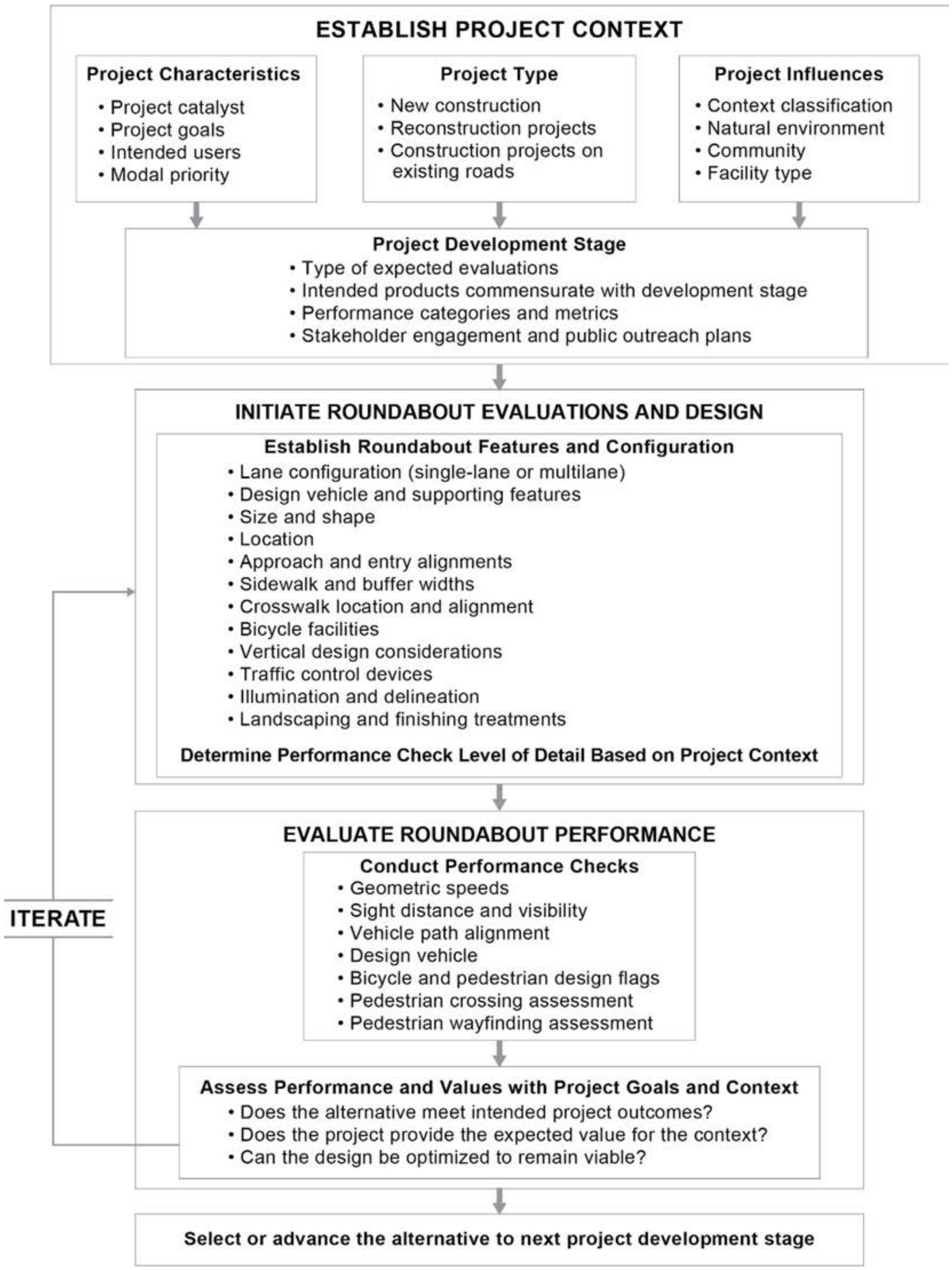
Roundabout design is a process of assessing anticipated users and then determining an appropriate balance of safety and operational performance, user quality of service, and ways to serve identified design vehicles. This process requires balancing several competing objectives while working within site-specific constraints. As a result, roundabout design is iterative, often customizing a design to the site conditions rather than relying on a template.

Although the principles are common across all roundabout types, many of the design techniques discussed in later chapters are substantially different for single-lane roundabouts than for roundabouts with two or more lanes. Subsequent chapters provide ranges of typical values for many of the different geometric elements as suggested starting points for designing a roundabout. However, design approaches and techniques may vary and depend on site-specific constraints and context.

Design values outside the ranges presented in subsequent chapters do not necessarily reflect unsafe conditions, provided the design principles presented in this chapter can be achieved. Similarly, individual geometric values falling within the ranges presented do not ensure a "good" design. The overall combination and composition of the various individual geometric elements are key to achieving the desired performance.

Exhibit 9.1 outlines the design process, illustrating the iterative nature of project planning, preliminary design, and final design. Information from the operational analysis determines the required number of lanes for the roundabout (single or multilane), which dictates the required size and many other design details. The basic design needs to be based on the principles identified in

Exhibit 9.1. Roundabout design process.



Section 9.2 to a level that verifies the layout will meet the design and performance objectives. The key is to conduct enough work to be able to check the design and identify whether adjustments are necessary.

Once enough iteration has been performed to identify an optimum size, location, and set of approach alignments, additional detail can be added to the design based on more specific information provided in Chapter 10: Horizontal Alignment and Design and Chapter 11: Vertical Alignment and Cross-Section Design. Performance checks continue as the alternative is refined through final design.

Geometric performance checks must happen at each project development stage, but they are most effective at the concept development stage. The level of detail and analysis at each stage will vary, with sketch-level checks to identify screening-level issues or concerns at the concept stage and comprehensive checks during preliminary design as more details develop.

9.2 Design Principles and Objectives

This section describes the design principles and objectives common to all roundabouts. Some features of multilane roundabout design are significantly different from single-lane roundabout design—so much so that some techniques used in single-lane roundabout design may not directly transfer to multilane design. Planning-level sizing and space requirements begin with the consideration of lane configurations, design users, design vehicles, control vehicles (e.g., OSOW trucks), speed management, path alignment, and sight distance. Roundabout planning and design therefore focuses on optimizing the configuration consistent with the context of a location, the performance outcomes of design decisions, and unique opportunities and constraints at a location, including the right-of-way.

Exhibit 9.2 shows the principles that guide roundabout design.

Each principle affects user safety, operational performance, and quality of service. When developing a design, practitioners must assess the trade-offs of safety performance, capacity, quality of service, footprint, cost, and other project considerations throughout the design process.

Favoring one design component may negatively impact another. For example, using large entry radii to favor truck movements could have the unintended consequence of allowing higher-than-desired entry speeds for passenger vehicles, which can impact safety performance and adversely affect pedestrians and bicyclists. Each user can be served at a roundabout; however, iteration may be necessary to achieve a balanced design with geometric features that integrate each user while attaining overall performance objectives.

Exhibit 9.2. Principles of roundabout design.

Overarching Principles
• Design for target vehicular speeds (e.g., 15 mph to 25 mph [25 km/h to 40 km/h]) throughout the roundabout, with maximum entering design speeds of 25 mph to 30 mph (40 km/h to 48 km/h), depending on lane configuration.
• Design specifically to meet the needs of pedestrians, bicyclists, and micromobility users.
• Establish appropriate lane numbers and lane assignments to achieve balanced performance to best serve the combined needs of each user.
• Design for and accommodate identified design vehicles.
• Provide channelization that is intuitive to drivers and results in vehicles naturally using the intended lanes, with signing and pavement marking to complement good geometrics.
• Provide sight distance (stopping, intersection, and decision) and visibility sufficient for users to recognize the intersection and observe other users.

9.3 Performance Checks Overview

Roundabout performance checks evaluate how well a design meets its performance objectives. Checks begin at the earliest stages of roundabout planning and design, including during sketch-planning efforts. The performance checks are repeated as concepts are developed and refined during ICE activities and other geometric approval steps. As the horizontal alignment becomes established (commonly near 30 percent completion), performance checks are used in subsequent steps to confirm the appropriateness of any modifications made in the final design process. Substantively modifying a design becomes increasingly more difficult and expensive at later design stages. Performance checks are therefore critical to early planning and design activities.

Performance checks and principles are excellent tools and methods for conducting roundabout peer reviews (objective evaluations conducted by a third party) and in-service assessments. The performance checks presented here can diagnose possible factors contributing to undesirable safety or operational performance.

Exhibit 9.3 presents the primary roundabout performance checks that support planning and design decisions and can be used to assess existing circular intersections and roundabouts.

9.4 Geometric Speeds

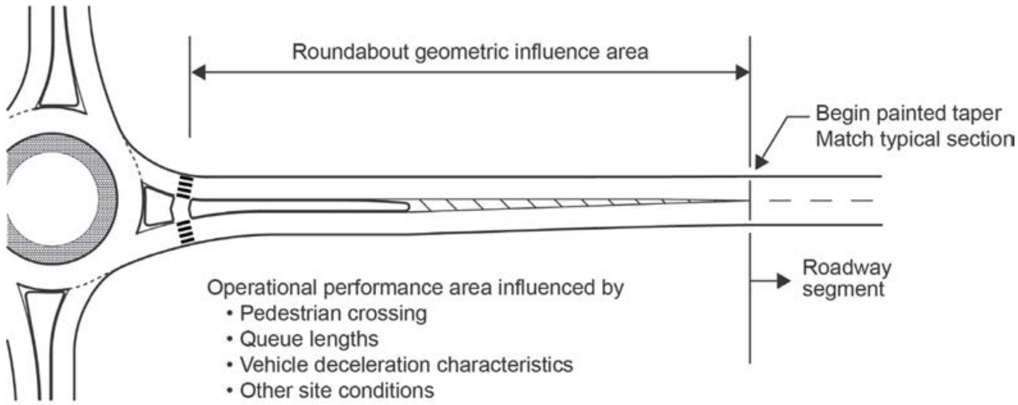
Vehicular speed is foundational to roundabout safety performance and is a product of roundabout geometry, resulting in what is termed *geometric speeds*. Achieving appropriate geometric speeds entering and traveling through the roundabout is a critical design objective, as speed affects safety performance for all users. Crash frequency is most directly tied to vehicular volume, whereas crash severity is most directly tied to vehicular speed. Speeds at roundabouts also improve the likelihood of drivers yielding to bicyclists and pedestrians and reduce the severity of any crashes, should they occur. Therefore, achieving appropriate roundabout speeds is fundamental to attaining target safety performance (*1*). This section describes geometric speed concepts approaching, entering, and navigating a roundabout, as well as how to develop a roundabout's fastest paths and estimate the associated speeds from those paths.

A well-designed roundabout reduces vehicle speeds upon entry and minimizes differences in the relative speeds between conflicting traffic streams. This results from the curved path each driver takes when navigating the roundabout. Roundabout approaches and entry design are also influenced by roadway approach speeds. Roundabouts have an operational and geometric influence area—a *functional area*—just like other intersections; this concept is illustrated in Exhibit 9.4. The *geometric influence area* begins at the point the typical section of approach roadway segment changes to begin the transition to the roundabout. The *operational influence area* is defined as the location where drivers must begin to decelerate to the back of the queue (or to the pedestrian crossing area if the queue does not extend that far).

Exhibit 9.3. Roundabout performance checks.

Performance Checks
• Geometric speeds
• Sight distance and visibility
• Vehicle path alignment
• Design vehicles
• Bicyclist and pedestrian design flags
• Pedestrian crossing assessment
• Pedestrian wayfinding assessment

Exhibit 9.4. Functional area of roundabout approach.



Low speed on entry reduces crash frequency and severity and helps to reduce speeds throughout the roundabout. *R* values refer to the radii of various roundabout fastest paths defined in the next section. R_1 is the roundabout entry path radius. The maximum recommended entering design speeds (based on a theoretical fastest path) are as follows:

- 25 mph (40 km/h) at all single-lane roundabouts and bypass lanes and for movements at multilane roundabout left-turn or right-turn paths. For entry paths that have positive superelevation of e = +0.02, this results in an R_1 value of approximately 175 ft (52 m).
- 30 mph (48 km/h) at multilane roundabout entry and exit paths. For typical entry paths that have positive superelevation of e = +0.02, this results in an R_1 value of approximately 280 ft (85 m).

Roundabout speed estimates need to account for the conditions and context on the approach roadways, not be viewed in isolation. For example, adjacent development and roadway features in the roundabout vicinity may naturally contribute to slower approach speeds. For some roundabouts, roadway approach geometry or downstream features may contribute to slower entry or exit speeds. An entry coming from a parking lot may have a lower observed entry speed than an entry coming from a roadway segment, even with the same entry geometry. Similarly, an approach curve before the entry (with radius R_0) may govern the speed that can be reached at the entry. Speed transition design is presented in Chapter 10: Horizontal Alignment and Design.

If target speed performance is not achieved in the first design iteration, roundabout size, location, or approach alignment and entry geometry (lane width, outside radius, and entry angle) are the primary design influences to consider when revising. Roundabout design is iterative, and performance checks need to be conducted after each modification until the design is optimized for the location and user needs. Further details on potential modifications are discussed in Chapter 10.

9.4.1 Assessing Geometric Speed Using Fastest Paths

Fastest paths provide a surrogate for the potential safety performance of a design, and they provide design values for other design checks. Fastest paths are evaluated to estimate the theoretical maximum speeds that a passenger vehicle can negotiate through a roundabout that is unconstrained by anything but raised features—the geometry of the roundabout.

The speeds predicted by fastest paths are higher than the average speeds exhibited at a roundabout because drivers react to other vehicles and traffic control devices. *NCHRP Report 572: Roundabouts in the United States* documented that fastest paths can reasonably represent anticipated 85th-percentile speeds for free-flowing vehicles (vehicles not influenced by other vehicles) (*1*). Even for free-flowing vehicles, actual speeds can vary substantially on the basis of vehicle suspension, individual driving abilities, and driver tolerance for gravitational forces.

Exhibit 9.5 illustrates the five critical path radii for each roundabout approach. These vehicular path radii are influenced by (but are independent of) roundabout curb radii:

- R_1, the *entry path radius*, is the minimum radius on the fastest through path before the entrance line.
- R_2, the *circulating path radius*, is the minimum radius on the fastest through path around the central island.
- R_3, the *exit path radius*, is the minimum radius on the fastest through path into the exit.
- R_4, the *left-turn path radius*, is the minimum radius on the path of the left-turn movement. This is typically the slowest of the paths.
- R_5, the *right-turn path radius*, is the minimum radius on the fastest path of a right-turning vehicle. At some roundabouts, this path may be faster than the through movement.

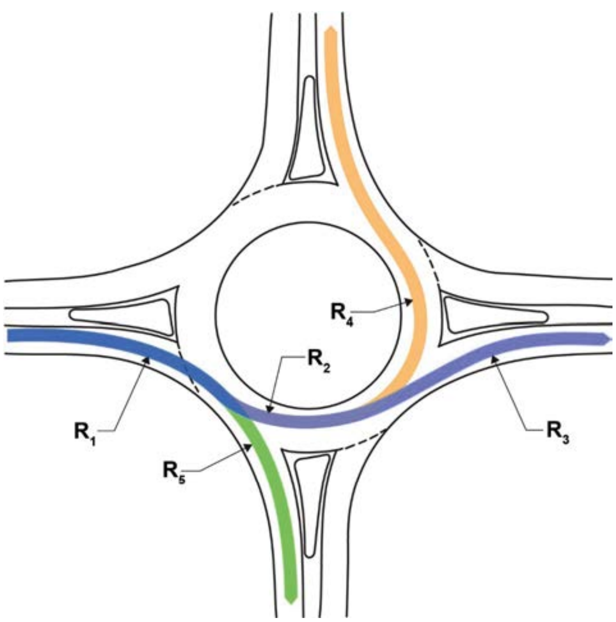
The R_1 through R_5 radii measured in this procedure represent the vehicle centerline in its path through the roundabout. A vehicle is assumed to be 6 ft (1.8 m) wide and maintain a minimum clearance of 2 ft (0.6 m) from its outer wheelpath to a perceived conflict, such as a roadway centerline or concrete curb. Where there is no perceived conflict, such as with a painted edge line, the outer wheelpath is assumed to be flush with the line.

The centerline of the vehicle path is drawn with the following distances to various geometric features, also shown graphically in Exhibit 9.6:

- 5 ft (1.5 m) from a raised curb face,
- 5 ft (1.5 m) from a roadway centerline, and
- 3 ft (0.9 m) from a painted edge line where there is at least 2 ft (0.6 m) of shoulder beyond the painted edge line.

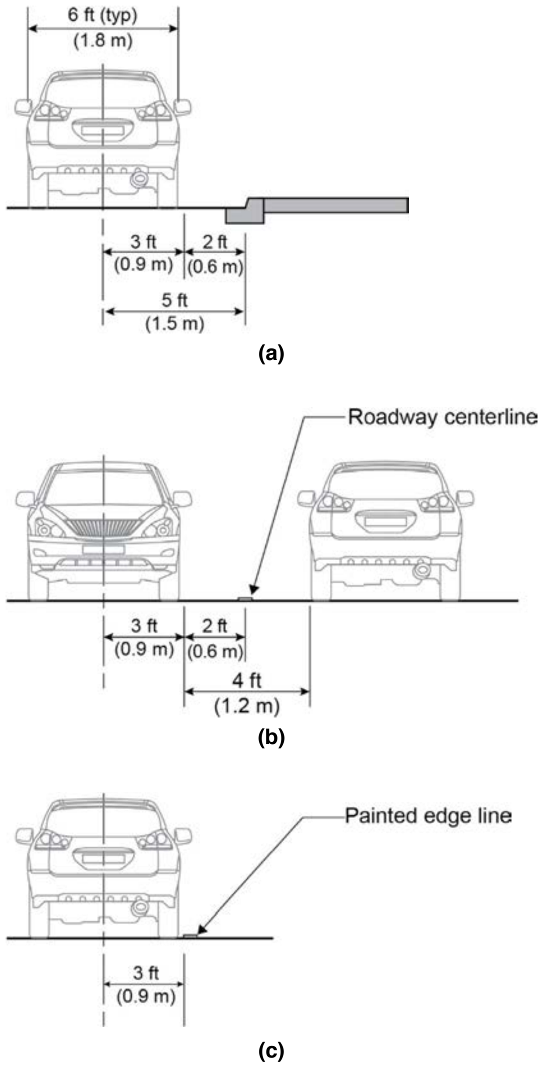
This assumes that drivers stay away from raised fixed objects and opposing traffic. For evaluation purposes, the curb face should be considered the constraint even if it is part of a curb and gutter.

Exhibit 9.5. Vehicle path radii.



SOURCE: Adapted from *NCHRP Report 672* (*2*).

Exhibit 9.6. Vehicle path distances from (*a*) curb, (*b*) roadway centerline, and (*c*) painted edge line.



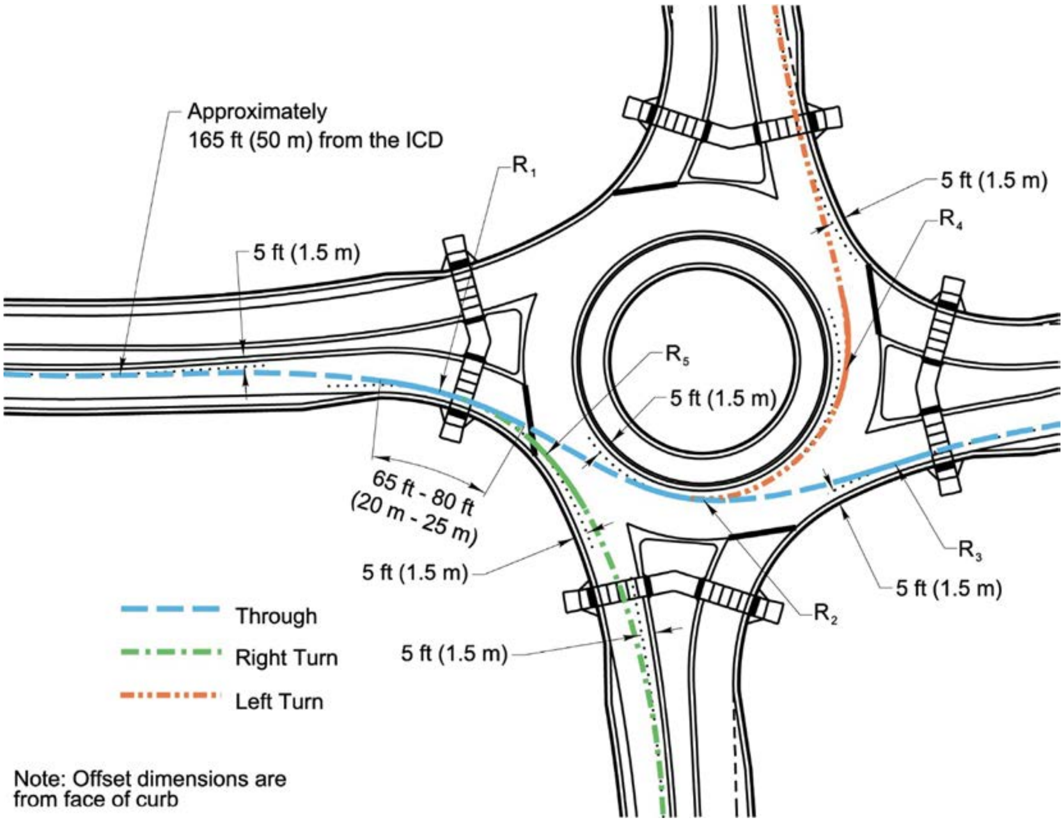
Limited relief vertical curb lips, rolled curbs, and other curb and gutter forms that are less concerning for a driver could lead to actual driving paths that infringe on the assumed buffer of 2 ft (0.6 m) to the curb face.

9.4.2 Developing Fastest Path Alignments

A variety of techniques for fastest path evaluations are available, ranging from hand sketch methods that support concept development to a variety of computer-assisted drafting (CAD) methods. Regardless of the process, the principles of driver behavior and the operational effects of roundabout geometrics are foundational to estimating roundabout speeds. Details for several examples of these techniques are provided in Appendix: Design Performance Check Techniques.

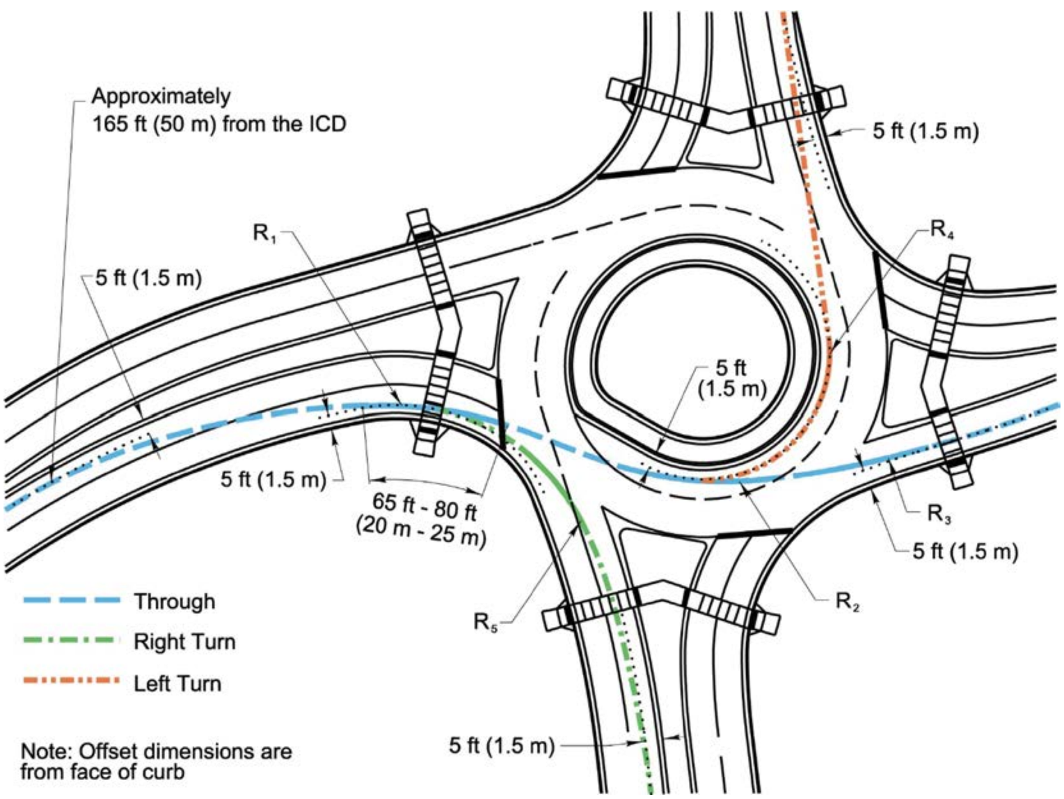
Exhibit 9.7 and Exhibit 9.8 illustrate the general construction of the fastest vehicle paths at a single-lane and a multilane roundabout, respectively. The fastest path needs to be drawn and

Exhibit 9.7. Fastest paths at a single-lane roundabout.



SOURCE: Adapted from Georgia Department of Transportation (*3*).

Exhibit 9.8. Fastest paths at a multilane roundabout.



SOURCE: Adapted from Georgia Department of Transportation (*3*).

checked for all approaches to the roundabout. Each path is unique, and a given entry path for a through movement may be distinctly different than for a right-turning movement.

Once fastest paths are constructed, each path is reviewed to assess whether the path reflects likely driver behavior. The path in Exhibit 9.8 may not represent the probable actual path. In this case, the 5-ft (1.5 m) offset is serving as a pass-through point. However, actual drivers may be farther from the (left or right) curb on the exit and hug the curb line farther downstream. The actual exiting speeds between these two paths might not result in substantive predicted speed performance differences.

Similarly, establishing right-turn (R_5) paths and speeds may require objectively assessing each path. Each right turn is unique, and, in some cases, the fastest path may have a driver hug the right edge line. In other cases, the fastest path may be closer to the truck apron and splitter islands on the driver's left side. Practitioners need to understand the principles of the fastest path performance checks to determine the assumed fastest path.

The entry path radius, R_1, is a measure of the deflection imposed on vehicles before they enter the roundabout. The ability of the roundabout to control speed at the entry is a proxy for the safety of the roundabout and whether drivers are likely to yield to circulating vehicles (*4*).

9.4.3 Estimating Speeds from Fastest Paths

The relationship between travel speed and horizontal curvature is documented in the Green Book (*5*). Superelevation and side friction factors affect vehicle speed. Side friction varies with vehicle speed and can be determined per AASHTO guidelines. The side friction factors vary with the design speed, from 0.38 at 10 mph (0.40 at 15 km/h) to about 0.15 at 45 mph (70 km/h), with 45 mph (70 km/h) considered to be the upper limit for low speed and speeds above 45 mph considered to be high speed. The AASHTO simplified curve formula is in Equation 9.1 and Equation 9.2; these can be used for any value of superelevation.

US Customary	Metric
Equation 9.1 $$f = \frac{V^2}{15R} - e$$ where f = side friction factor, V = predicted speed (mph), R = radius of curve (ft), and e = superelevation (ft/ft) (e.g., 0.02).	Equation 9.2 $$f = \frac{V^2}{127R} - e$$ where f = side friction factor, V = predicted speed (km/h), R = radius of curve (m), and e = superelevation (m/m) (e.g., 0.02).

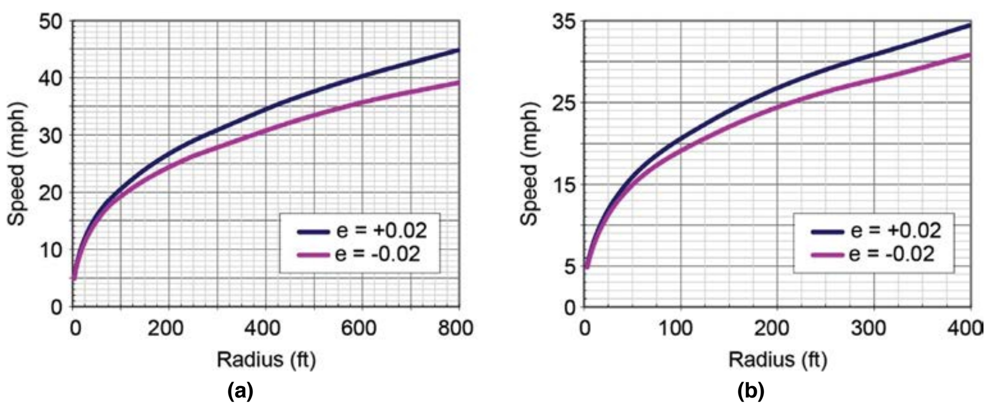
For roundabout planning and design in a low-speed environment, the most common superelevation values are +0.02 and –0.02, corresponding to cross slopes of 2 percent pointing down in the direction of the curve and against the direction of the curve, respectively. Equation 9.3 and Equation 9.4 provide a simplified relationship based on a regression fit between speed and radius for these two common superelevation rates, as reported in *NCHRP Report 572* (*1*). These regression curves were developed for radii less than or equal to 400 ft (120 m). Equation 9.5 and Equation 9.6 provide converted equations for metric units.

US Customary	Metric
Equation 9.3 $V = 3.4415R^{0.3861}$, $for\ e = +0.02, R \leq 400\ ft$	Equation 9.5 $V = 5.5374\left(\frac{R}{0.3048}\right)^{0.3861}$, $for\ e = +0.02, R \leq 120\ m$
Equation 9.4 $V = 3.4614R^{0.3673}$, $for\ e = -0.02, R \leq 400\ ft$	Equation 9.6 $V = 5.5693\left(\frac{R}{0.3048}\right)^{0.3673}$, $for\ e = -0.02, R \leq 120\ m$
where V = predicted speed (mph), R = radius of curve (ft), and e = superelevation (ft/ft).	where V = predicted speed (km/h), R = radius of curve (m), and e = superelevation (m/m).

Exhibit 9.9 and Exhibit 9.10 illustrate the speed–radius relationship. Exhibit 9.9 presents speeds and radii below 35 mph (60 km/h) and 400 ft (120 m). This range pertains primarily to roundabout evaluating speeds at the roundabout itself, where low speeds are expected. Exhibit 9.10 extends the speed–radius relationship to higher speeds and larger radii to support design evaluations for higher-speed environments and speed transitions between the roadway approach and the roundabout entry. Side friction values change above 45 mph (70 km/h), and users need to refer to AASHTO guidance for speed and curve computations above 45 mph (70 km/h). Larger versions of these exhibits are provided in Appendix: Design Performance Check Techniques.

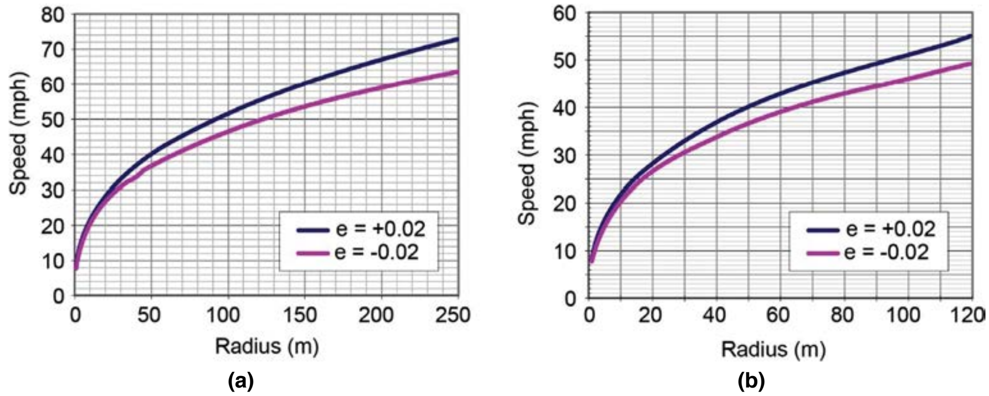
Some roundabout configurations may have exit paths with large radii or tangential alignments. The theoretical speed of the exit (e.g., a tangent) would not represent actual predicted speeds. When identifying the predicted speed for an exit with a large R_3 radius or tangential fastest path, the acceleration effect of a vehicle has to be accounted for in the estimate of exit speed. Chapter 10: Horizontal Alignment and Design provides details on entry and exit design methods.

Exhibit 9.9. Speed–radius relationship, US customary.



SOURCE: Based on Green Book, 7th edition, Equation 3-7, and side friction factors assumed for design (AASHTO Figure 3-4) (*5*).

Exhibit 9.10. Extended speed–radius relationship, metric.



SOURCE: Based on Green Book, 7th edition, Equation 3-7, and side friction factors assumed for design (AASHTO Figure 3-4) (*5*).

Tangential exits do not inherently result in excessive exit speeds compared with curvilinear exits, provided circulating speeds are low and the distance to the point of interest on the exit (typically the crosswalk) is short. Providing some degree of curvature on the exit allows drivers to focus on navigating to the exit and considering crosswalk locations at the roundabout exits. Research from *NCHRP Report 572* indicates that such curvature does not appear to always be the controlling factor for exit speeds (*1*). Exit speeds (e.g., V_2) can be influenced by upstream paths (e.g., R_2) and can be estimated using Equation 9.7 for US customary units and Equation 9.8 for metric units. **The exit speeds predicted by Equation 9.7 and Equation 9.8 are based on *NCHRP Report 572* research conducted on free-flowing vehicles at roundabouts where no pedestrians or active traffic control devices at the crosswalk were present to influence driver behavior at the time of speed measurement. As such, these equations may overestimate acceleration in the presence of pedestrians or in the presence of active traffic control devices.**

US Customary	Metric
Equation 9.7	Equation 9.8
$$V_3 = min\begin{Bmatrix} V_{3p} \\ \frac{1}{1.47}\sqrt{(1.47V_2)^2 + 2a_{23}d_{23}} \end{Bmatrix}$$	$$V_3 = min\begin{Bmatrix} V_{3p} \\ \frac{1}{0.278}\sqrt{(0.278V_2)^2 + 2a_{23}d_{23}} \end{Bmatrix}$$
where	where
V_3 = exit speed (mph),	V_3 = exit speed (km/h),
V_{3p} = V_3 speed predicted on basis of path radius (mph),	V_{3p} = V_3 speed predicted based on path radius (km/h),
V_2 = circulatory speed for through vehicles predicted on basis of path radius (mph),	V_2 = circulatory speed for through vehicles predicted based on path radius (km/h),
a_{23} = acceleration between the midpoint of V_2 path and the point of interest along V_3 path (6.9 ft/s^2), and	a_{23} = acceleration between the midpoint of V_2 path and the point of interest along V_3 path (2.1 m/s^2), and
d_{23} = distance along the vehicle path between midpoint of V_2 path and point of interest along V_3 path (ft).	d_{23} = distance along the vehicle path between midpoint of V_2 path and point of interest along V_3 path (m).

9.5 Sight Distance and Visibility

The visibility of the roundabout as a driver approaches the intersection includes sight distance for viewing pedestrians or other users at the crosswalk and vehicles already operating within the roundabout. The major types of sight distance of interest at roundabouts are common with other intersection forms and include

- **Stopping sight distance.** The distance along a roadway required for a driver to perceive and react to an object in the roadway and brake to a complete stop before reaching that object.
- **Intersection sight distance.** The distance required for a driver without the right-of-way to perceive and react to the presence of conflicting vehicles.
- **Decision sight distance.** The distance needed for a driver to detect and respond to an unexpected, or otherwise difficult to perceive, information source or condition in a roadway environment.
- **View angle.** The angle between the trajectory of the subject vehicle and the oncoming vehicle from the left.

Although sight distance is often thought to be influenced only by static features—horizontal curvature, vertical curvature, and fixed obstructions (e.g., walls, bridge abutments, and buildings)—sight distance can also change with time, depending on the selection and maintenance of landscaping in the vicinity of sight triangles. As a result, sight distance is to be verified during the landscaping plan development in addition to the development of horizontal and vertical alignments. This is discussed further in Chapter 14: Illumination, Landscaping, and Artwork.

9.5.1 Stopping Sight Distance

The Green Book provides the formulas given in Equation 9.9 and Equation 9.10 for US customary and metric units, respectively, for determining stopping sight distance (*5*).

US Customary	Metric
Equation 9.9 $$d = 1.47Vt + 1.075\frac{V^2}{a}$$ where d = stopping sight distance (ft), V = design speed (mph), t = perception–brake reaction time (assumed 2.5 s), and a = driver deceleration (assumed 11.2 ft/s^2).	Equation 9.10 $$d = 0.278Vt + 0.039\frac{V^2}{a}$$ where d = stopping sight distance (m), V = design speed (km/h), t = perception–brake reaction time (assumed 2.5 s), and a = driver deceleration (assumed 3.4 m/s^2).

Exhibit 9.11 gives design values provided by AASHTO that are based on the above equations. Other details about stopping sight distance, including assumed driver eye height, object height, and modifications for grade and trucks, are discussed further in the Green Book (*5*).

Stopping sight distance is required throughout a roundabout, as it is with other intersection forms. The following critical locations at roundabouts are common controlling factors to be checked for stopping sight distance:

- Stopping sight distance to the crosswalk and pedestrian waiting areas on approach (or to the entrance line if no pedestrian crossing is provided), illustrated in Exhibit 9.12.

Exhibit 9.11. Design values for stopping sight distance on level roadways.

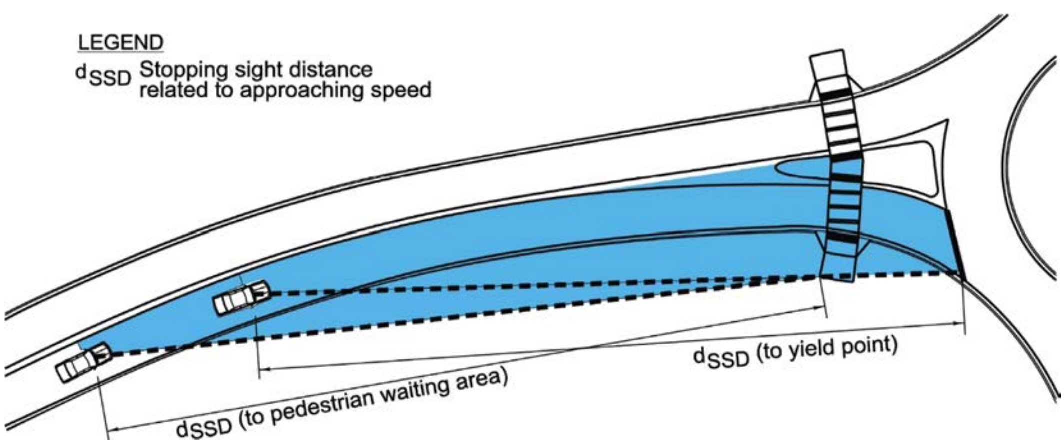
Design Speed (mph)	Design Stopping Sight Distance (ft)	Design Speed (km/h)	Design Stopping Sight Distance (m)
15	80	20	20
20	115	30	35
25	155	40	50
30	200	50	65
35	250	60	85
40	305	70	105
45	360	80	130
50	425	90	160
55	495	100	185

SOURCE: Green Book, Table 3-1 (*5*).

- Stopping sight distance to the crosswalk and pedestrian waiting areas at a right-turn bypass lane (or to the entrance line if no pedestrian crossing is provided), illustrated in Exhibit 9.13.
- Stopping sight distance for any approach curvature, illustrated in Exhibit 9.14.
- Stopping sight distance along the circulatory roadway measured to the truck apron curb, illustrated in Exhibit 9.15.
- Stopping sight distance to the crosswalk and pedestrian waiting areas on exit, illustrated in Exhibit 9.16.
- Any other locations where the combination of horizontal curvature, vertical curvature, and lateral obstructions may restrict stopping sight distance.

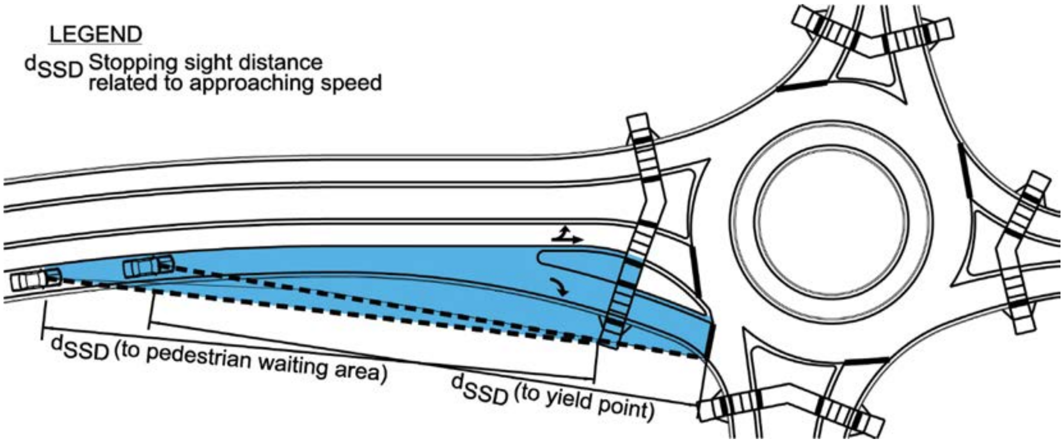
Stopping sight distance is measured using an assumed height of the driver's eye of 3.50 ft (1.080 m) and an assumed height of the object of 2.00 ft (0.60 m). Further details are provided in the Green Book (*5*).

Exhibit 9.12. Stopping sight distance to the pedestrian crossing and entrance line on the approach.



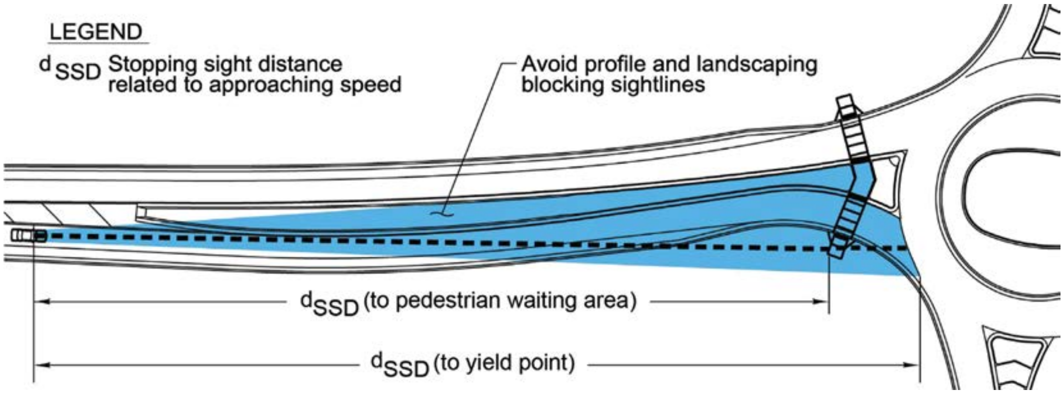
SOURCE: Adapted from Georgia Department of Transportation (*3*).

Exhibit 9.13. Stopping sight distance for a right-turn bypass lane.



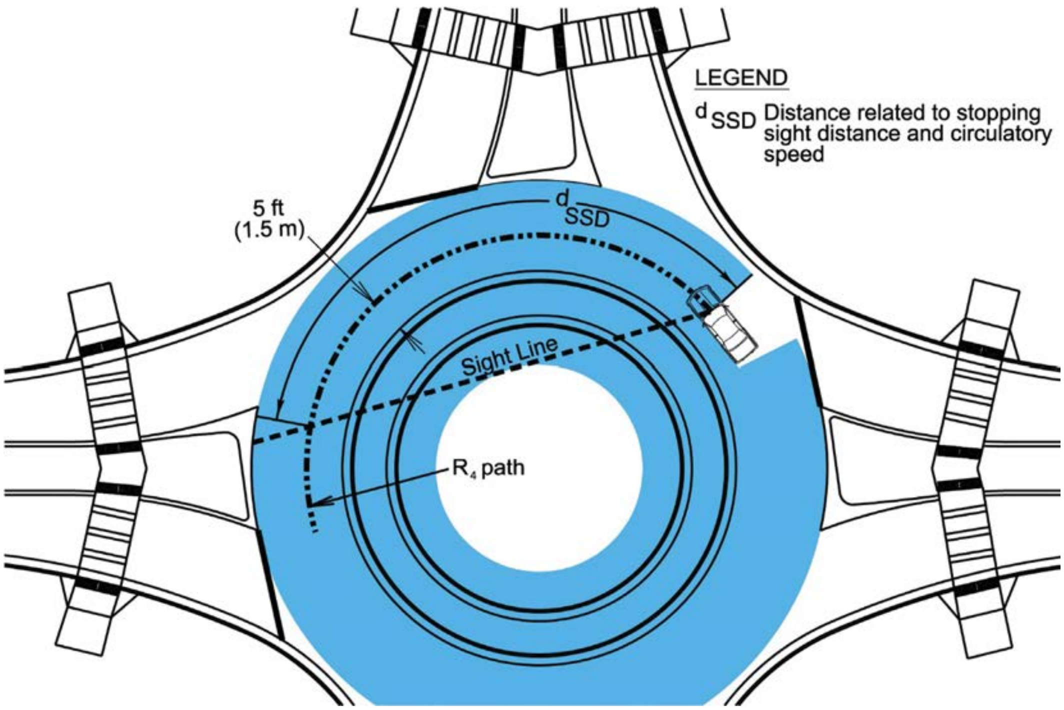
SOURCE: Adapted from Georgia Department of Transportation (*3*).

Exhibit 9.14. Stopping sight distance for approach curvature.



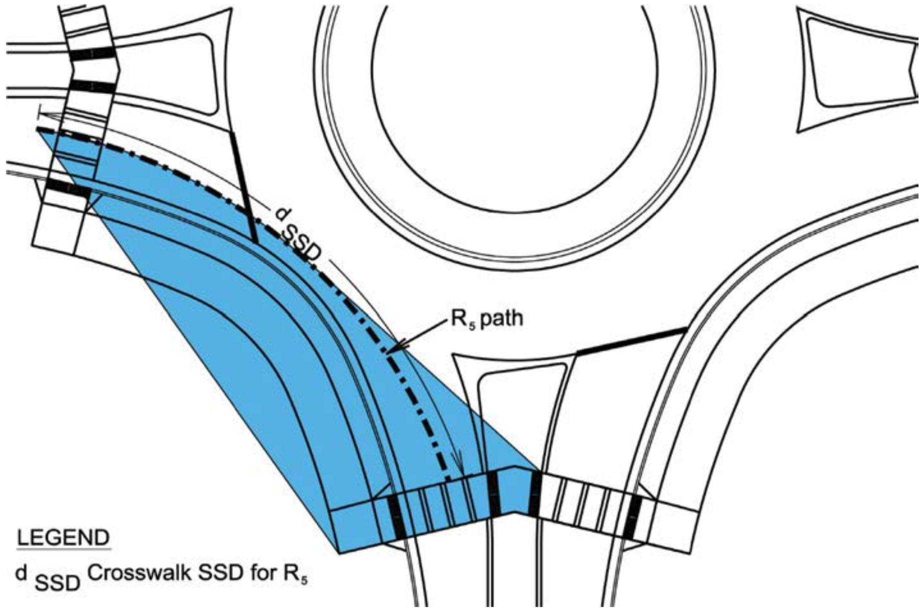
SOURCE: Adapted from Georgia Department of Transportation (*3*).

Exhibit 9.15. Stopping sight distance on circulatory roadway.



SOURCE: Adapted from Georgia Department of Transportation (*3*).

Exhibit 9.16. Stopping sight distance to crosswalk on exit.



SOURCE: Adapted from Georgia Department of Transportation (*3*).

9.5.2 Intersection Sight Distance

Intersection sight distance needs to be established at each roundabout entry. Intersection sight distance is measured for vehicles entering the roundabout and considers conflicting vehicles traveling along the circulatory roadway and entering from the immediate upstream entry.

Evidence suggests it is advantageous to provide no more than the minimum required intersection sight distance on each approach (*6*). Excessive intersection sight distance can lead to higher vehicle speeds that increase crash risk and severity for all road users (motorists, bicyclists, pedestrians). For roundabouts with raised central islands, landscaping, berming, or some types of raised features within the central island can effectively restrict sight distance to the minimum requirements. Central island treatments have the added benefit of creating a *terminal vista* on the approach to improve visibility of the central island from a distance. For all types of roundabouts, including roundabouts with fully traversable central islands, raised features on the sides and medians of the approaches can limit sight distance to only that which is needed.

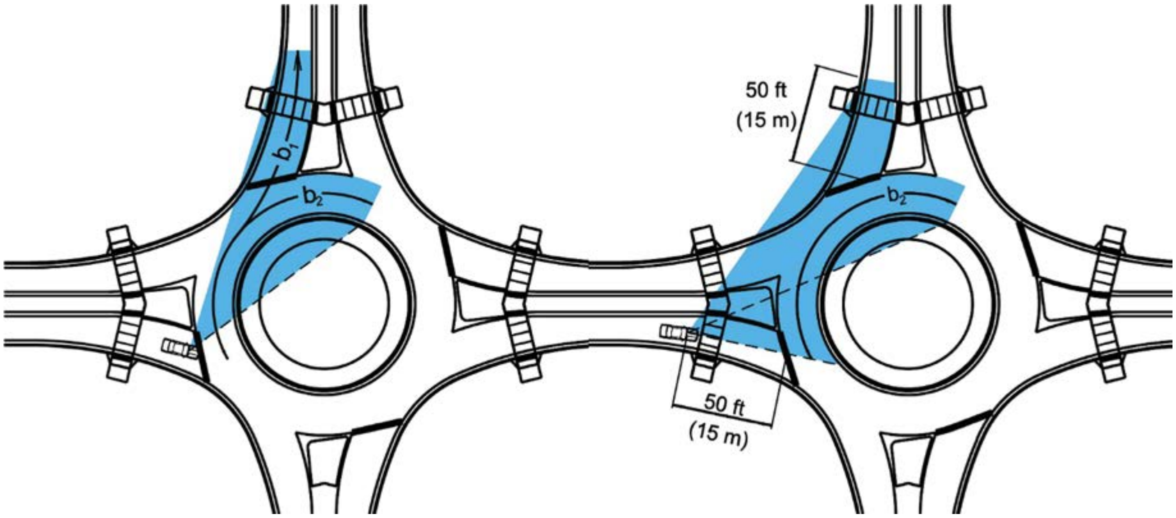
Intersection sight distance is measured by determining *sight triangles*. This triangle is bounded by a length of roadway defining a sight distance limit away from the intersection on each of the two conflicting approaches and by a line connecting those two limits. For roundabouts, these "legs" may be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

Intersection sight distance is measured using an assumed height of the driver's eye of 3.50 ft (1.08 m) and an assumed height of the object of 3.50 ft (1.08 m). Further details are provided in the Green Book (*5*).

Exhibit 9.17 and Equation 9.11 through Equation 9.14 provide the method for determining intersection sight distance. The sight distance triangle has two conditions that are to be checked independently:

- **Intersection sight distance at the entry.** A vehicle waiting at the entry faces conflicting vehicles within the circulatory roadway and on the immediate upstream entry. As such, the conflicting

Exhibit 9.17. Intersection sight distance.



SOURCE: Adapted from Georgia Department of Transportation (*3*).

leg of the sight triangle has two branches: one that extends up the immediate upstream entry, b_1, and one that extends around the circulatory roadway, b_2. The lengths of the two conflicting branches are calculated as shown in Exhibit 9.17 using Equations 9.11 and 9.12, respectively.

- **Intersection sight distance in advance of the entry.** For a vehicle approaching the roundabout, the length of the approach leg of the sight triangle and of the conflicting branch for the immediate upstream entry, b_1, are both to be limited to 50 ft (15 m). The length of the conflicting branch on the circulatory roadway, b_2, is calculated as previously described. The value of 50 ft (15 m) is consistent with British and French practice and with British research on sight distance, which found that excessive intersection sight distance results in a higher crash

US Customary	Metric
Equation 9.11 $$b_1 = 1.47V_{ent}\,t_g$$	Equation 9.13 $$b_1 = 0.278V_{ent}\,t_g$$
Equation 9.12 $$b_2 = 1.47V_{circ}\,t_g$$	Equation 9.14 $$b_2 = 0.278V_{circ}\,t_g$$
where	where
b_1 = length of entering branch of sight triangle (ft);	b_1 = length of entering branch of sight triangle (m);
b_2 = length of circulating branch of sight triangle (ft);	b_2 = length of circulating branch of sight triangle (m);
V_{ent} = speed of vehicles from upstream entry for the conflicting through movement, assumed to be average of V_1 and V_2 (mph);	V_{ent} = speed of vehicles from upstream entry for the conflicting through movement, assumed to be average of V_1 and V_2 (km/h);
V_{circ} = speed of circulating vehicles, assumed to be V_4 (mph); and	V_{circ} = speed of circulating vehicles, assumed to be V_4 (km/h); and
t_g = design headway (s, assumed to be 5.0 s).	t_g = design headway (s, assumed to be 5.0 s).

frequency (*7*). If the combination of sight distance along the approach leg and the immediate upstream entry leg of the sight triangle exceeds these recommendations, it may be advisable to add landscaping to restrict sight distance to the minimum requirements.

Exhibit 9.18 shows the computed length of the conflicting leg of an intersection sight triangle using an assumed value of design headway, t_g, of 5.0 s (*2*). This design headway is based on the amount of time required for a vehicle to safely enter the conflicting stream. This is an assumed value based on observational data for critical headways from *NCHRP Report 572* and observational data from FHWA research (*1*, *8*). Some state transportation agencies use smaller values for design headway for locations with restricted sight distance.

During design and review, practitioners need to check roundabouts to verify adequate stopping and intersection sight distance. Checks for each approach are overlaid onto a single drawing to illustrate the unobstructed vision areas for the intersection. This guides the appropriate locations for various types of landscaping or other treatments and provides checks against bridge abutments, berms, and other roadway features that may be present. Objects such as low-growth vegetation, poles, signposts, and narrow trees may be acceptable within some of these areas. However, those objects need to be designed appropriately for the speed environment and not significantly obstruct the visibility of other vehicles, bicyclists, pedestrians, the splitter islands, or other key roundabout components. In 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. Sight triangles that extend over right-of-way lines may present situations that require maintenance agreements, easements, or other modifications.

9.5.3 Decision Sight Distance

Drivers sometimes must interpret the roadway and complete navigation tasks in complex environments. At roundabouts, this includes multilane scenarios in which drivers must select the correct lane on the basis of their intended destination. In these cases (and others), a need for increased perception-reaction time may require longer distances than those required for stopping sight distance. As such, stopping sight distance is always required, and decision sight distance may also be needed for certain cases.

Decision sight distance is the distance needed for a driver to detect, interpret, and respond to an information source or condition in the roadway environment that is unexpected or otherwise difficult to perceive. In this situation, a driver must be able to recognize the condition, select an appropriate speed and path, and initiate and complete needed maneuvers. Because decision sight distance offers drivers an additional margin for error—it affords them sufficient length to maneuver their

Exhibit 9.18. Computed length of conflicting leg of intersection sight triangle.

Conflicting Approach Speed (mph)	Computed Distance (ft)	Conflicting Approach Speed (km/h)	Computed Distance (m)
10	73.4	20	27.8
15	110.1	25	34.8
20	146.8	30	41.7
25	183.5	35	48.7
30	220.2	40	55.6

NOTE: Computed distances are based on a critical headway of 5.0 s.

vehicles rather than to just stop—its values are substantially greater than stopping sight distance. If it is not practical to provide decision sight distance because of horizontal or vertical curvature or if relocating decision points is not practical, practitioners can consider suitable traffic control devices to provide adequate warning.

Exhibit 9.19, adapted from the Green Book, presents decision sight distances that could provide values for sight distances at critical locations or be used to evaluate the suitability of available sight distances (*5*). The Green Book provides additional information about the equations used to generate the table.

9.5.4 View Angles

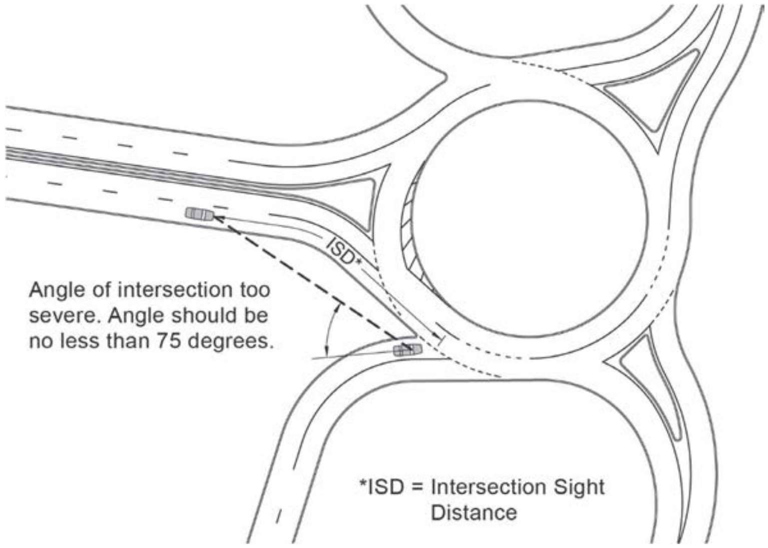
A *view angle* is the angle to the left, measured between the trajectory of the subject driver's vehicle and the line of sight for the driver to see an oncoming vehicle. A driver's ability to turn their head to the left is limited by human anatomy and becomes more difficult for older drivers and drivers with mobility limitations. From the driver's perspective, the maximum recommended view angle is 105 degrees to the left, measured from the trajectory of the subject driver's vehicle to the farthest point of the intersection sight distance triangle. This maximum is based on guidance for designing for older drivers and pedestrians at intersections, which recommends using 75 degrees as a minimum intersection angle for similar reasons (*9*). Although intersection angle, or the angle

Exhibit 9.19. Decision sight distance.

Design Speed (mph)	Decision Sight Distance for Avoidance Maneuver A (ft)	Decision Sight Distance for Avoidance Maneuver B (ft)	Decision Sight Distance for Avoidance Maneuver C (ft)	Decision Sight Distance for Avoidance Maneuver D (ft)	Decision Sight Distance for Avoidance Maneuver E (ft)
30	220	490	450	535	620
35	275	590	525	625	720
40	330	690	600	715	825
45	395	800	675	800	930
50	465	910	750	890	1,030
55	535	1,030	865	980	1,135
Design Speed (km/h)	**Decision Sight Distance for Avoidance Maneuver A (m)**	**Decision Sight Distance for Avoidance Maneuver B (m)**	**Decision Sight Distance for Avoidance Maneuver C (m)**	**Decision Sight Distance for Avoidance Maneuver D (m)**	**Decision Sight Distance for Avoidance Maneuver E (m)**
50	75	155	145	170	195
60	95	195	170	205	235
70	115	235	200	235	275
80	140	280	230	270	315
90	170	325	270	315	360
100	200	370	315	355	400

NOTE: Avoidance Maneuver A: Stop on road in a rural area; t = 3.0 s. Avoidance Maneuver B: Stop on road in an urban area; t = 9.1 s. Avoidance Maneuver C: Speed/path/direction change on rural road; t varies between 10.2 and 11.2 s. Avoidance Maneuver D: Speed/path/direction change on a suburban road or street; t varies between 12.1 and 12.9 s. Avoidance Maneuver E: Speed/path/direction change on urban, urban core, or rural town road or street; t varies between 14.0 and 14.5 s.
SOURCE: Green Book (*5*).

Exhibit 9.20. Example design with severe angle of visibility to left.



SOURCE: *NCHRP Report 672* and Tian et al. (*2, 6*).

between intersecting roadway centerlines, is different from view angle, the concepts are similar and are derived from the same human factors research. Some agencies have used a measurement of "phi" as a surrogate for driver view angle. There is no direct relationship between "phi angle" and view angle.

Common locations where view angles can be critical include

- **Consecutive entries into the roundabout.** Consecutive entries commonly occur at freeway interchange ramp terminals between the off-ramp and the cross street to the left, especially if the off-ramp leg is not perpendicular to the cross street.
- **Yield-controlled right-turn bypass lanes.** A driver must be able to comfortably see the roundabout exit and adjacent circulatory roadway immediately to their left to be able to judge gaps in exiting traffic.

Corrections to the view angle may require changes in the entry alignment as well as the ICD if the spacing between consecutive entries cannot otherwise be addressed. Exhibit 9.20 shows an example design with a severe angle of visibility to the left, and Exhibit 9.21 shows a possible correction.

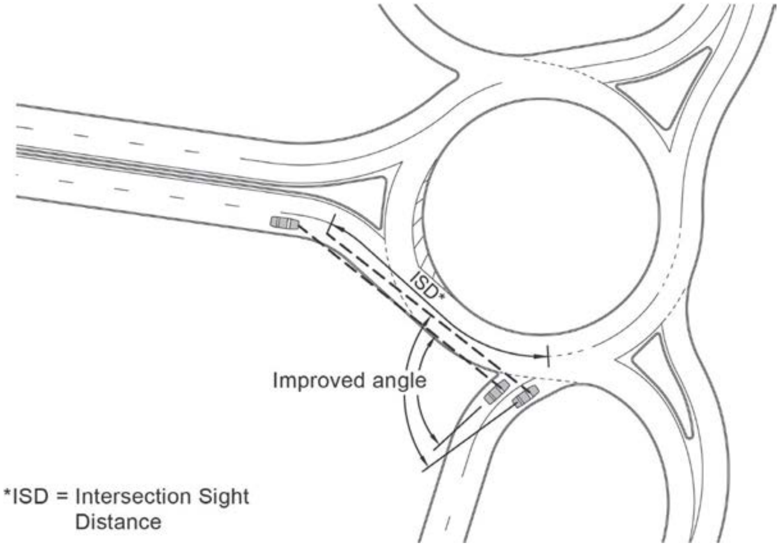
Performance checks conducted early in roundabout planning and design help inform these types of design decisions and trade-offs.

9.6 Vehicle Path Alignment

Like fastest paths at a multilane roundabout, vehicle path alignment is a specific performance evaluation that applies to multilane configurations. The *natural vehicle paths* are the paths approaching vehicles will take through the roundabout geometry, guided by their speed and orientation in the presence of other vehicles. These are illustrated in Exhibit 9.22.

The most common type of poor vehicle path alignment is when vehicles in the right entry lane are naturally aligned into the left circulating lane. A similar situation can occur on the exit,

Exhibit 9.21. Roundabout with realigned ramp terminal approach to provide better angle of visibility to the left.

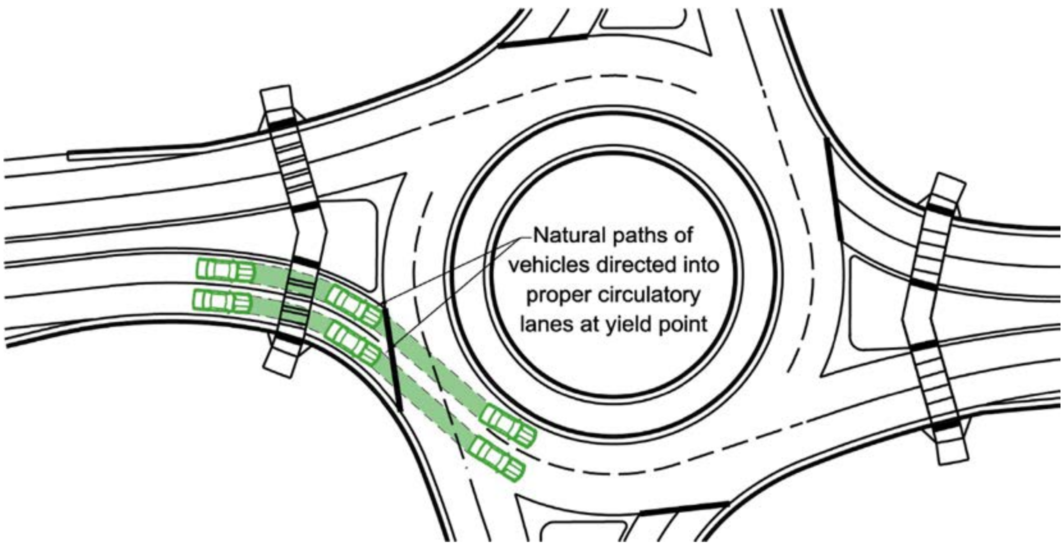


SOURCE: *NCHRP Report 672* and Tian et al. (*2, 6*).

where a vehicle in the left circulating lane is naturally aligned into the right exit lane. These two cases are shown in Exhibit 9.23. These examples of poor vehicle path alignment can cause lane imbalance as regular users avoid the left entry lane because of the increased conflicts. Even if crashes do not occur, the traffic operational performance observed may not match that of the models. Additional examples of poor path alignment are shown in Exhibit 9.24.

Further details on designing for good vehicle path alignment are provided in Chapter 10: Horizontal Alignment and Design. Examples of methods for checking vehicle path alignment are provided in Appendix: Design Performance Check Techniques.

Exhibit 9.22. Natural vehicle path through roundabout.



SOURCE: Adapted from Georgia Department of Transportation (*3*).

Exhibit 9.23. Examples of poor vehicle path alignment at a multilane roundabout.

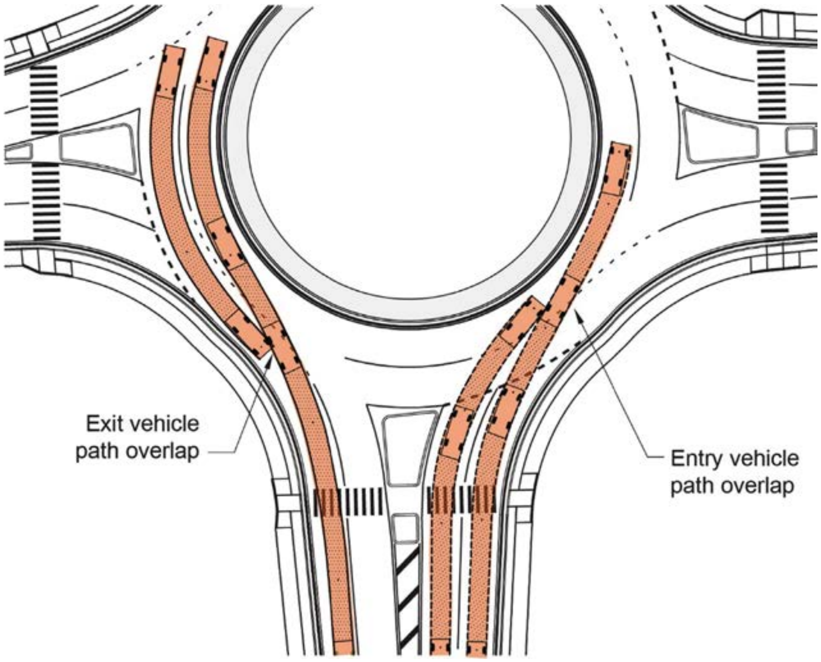


Exhibit 9.24. Examples of poor vehicle path alignment at a multilane roundabout.

(a)

(b)

(c)

SOURCE: Brian Ray.

9.7 Design Vehicles

Practitioners need to establish design vehicles early in roundabout planning and design. Design vehicles, in addition to the AASHTO range, may include emergency vehicles, OSOW vehicles, and farm equipment. Recreational routes are often frequented by motor homes and other recreational vehicles. Agricultural areas are frequented by tractors, combines, and other farm machinery. Manufacturing areas may see oversized trucks. The design vehicle may vary by movement; for example, the major street through movements may have a design vehicle different from other turning movements.

Practitioners need design vehicle performance checks to assess the roundabout layout, both during the initial concept stages and throughout the design process. Design vehicle performance checks are often the most critical checks that affect the size and footprint of the roundabout, thus significantly affecting the alternative selection process in its early stages.

Although some design decisions manifest themselves over time with safety or operational performance, the consequences of neglecting design vehicles are often not fully realized until after opening. Turning paths that are overly constrained do not appropriately serve the design vehicle. This may result in some trucks encroaching past the curb, which may damage landscaping or intrude into pedestrian areas. Exhibit 9.25 and Exhibit 9.26 show evidence of vehicle encroachment at a roundabout.

9.7.1 Types of Design Vehicle Checks

As discussed in Chapter 4, the design vehicle check process has two components:

- **Designing for trucks.** This process, using what can be described as the *design vehicle*, is the primary design check for trucks. A roundabout is designed to allow the design vehicle to travel through the roundabout between curbs, with some movements possibly using a truck apron.
  For single-lane roundabouts, two common scenarios are considered:
  - **Vehicles that stay in their lane without using the truck apron or traversable central island.** For most roundabouts, the largest anticipated passenger vehicle should not need to use the truck apron to avoid jostling passengers. This is commonly a bus design vehicle (e.g., BUS-40).

Exhibit 9.25. Evidence of vehicle encroachment on exit.

LOCATION: Old Frankfort Pike/Alexandria Drive, Lexington, Kentucky.
SOURCE: Lee Rodegerdts.

Exhibit 9.26. Evidence of vehicle encroachment in the central island.

LOCATION: SR 13/Old SR 13/NW 435 Road, Warrensburg, Missouri.
SOURCE: Lee Rodegerdts.

  - **Vehicles that use the truck apron or traversable central island.** For trucks with trailers, it is preferred that the cab of the trailer stay within the circulatory roadway and not mount curbs, with only the trailer using the truck apron. This has been common practice throughout the United States and meets the expectations of most truck drivers. For roundabouts with traversable central islands, both the cab and trailer can be assumed to use the traversable island. Vehicles that can be assumed to use the truck apron or traversable central island include trucks and emergency vehicles.

  For multilane roundabouts, the design vehicle may operate under one of the following two design cases:

  - **Straddle lanes.** For this type of multilane design, the design vehicle is assumed to use the entire curb-to-curb width for entering, circulating, and exiting plus the truck apron as needed. Both trucks and large passenger vehicles (e.g., buses) may straddle lanes.
  - **Stay-in-lane.** For this type of design, the design vehicle is assumed to stay in-lane on entry, while circulating, and while exiting, using the truck apron as needed. Large passenger vehicles (e.g., buses) should stay in-lane without using the truck apron.

- **Accommodating trucks**. This process is based on serving a less frequent but larger control vehicle (or *check vehicle*). The check vehicle is an anticipated but infrequent user of the roundabout that needs only to travel through. The check vehicle may require design features such as additional truck aprons along the exterior, hardened surfaces beyond the curb, passageways through splitter islands or the central island, removable signs, or other treatments. A check vehicle driver may be required to drive their cab onto the truck apron to complete some movements.

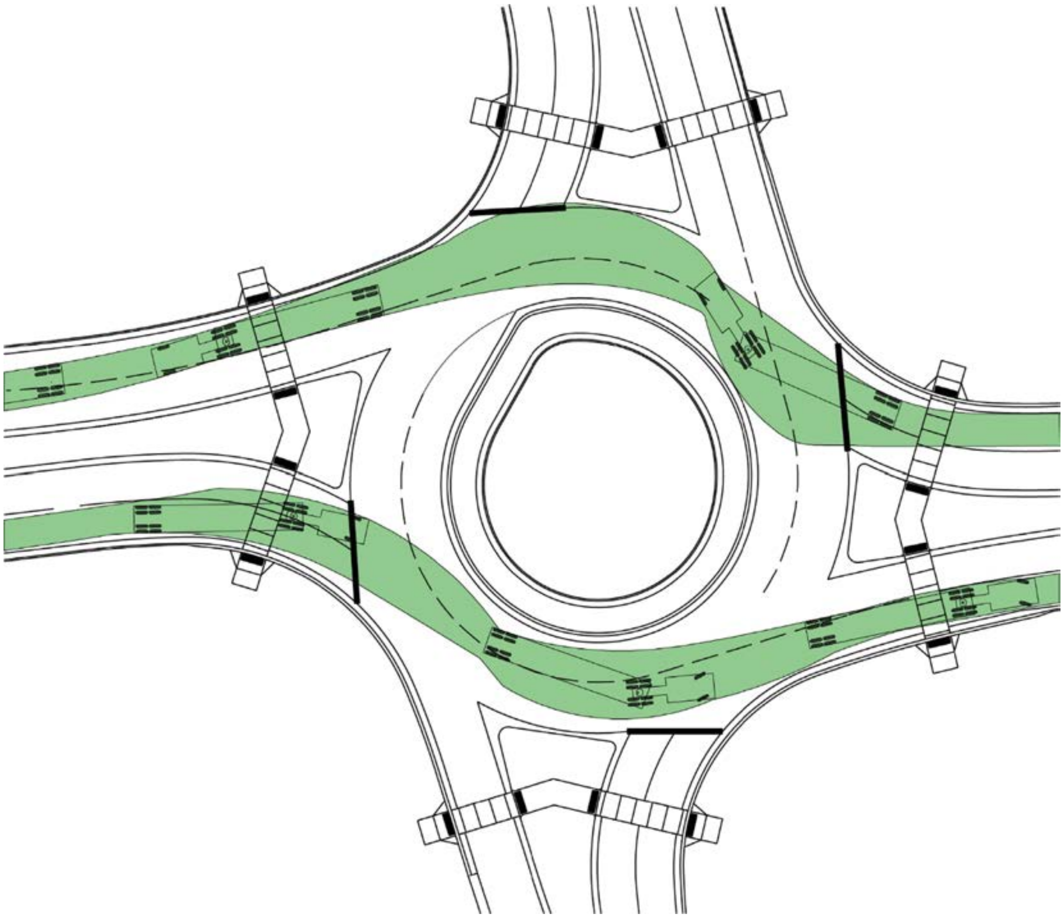
The associated geometric details and traffic control devices to support these two design cases are presented in Chapter 10 and Chapter 12, respectively.

9.7.2 Evaluating Design Vehicle and Check Vehicle

The most common process for determining design vehicles and checking vehicle performance uses CAD-based software. For the design vehicle, AASHTO recommends providing 1 to 2 ft (0.3 to 0.6 m) of shy distance between vehicle path and curb to accommodate variations in drivers and provide a reasonable margin for error (*5*). Buses need to be accommodated within the circulatory roadway without tracking over the truck apron (*4*).

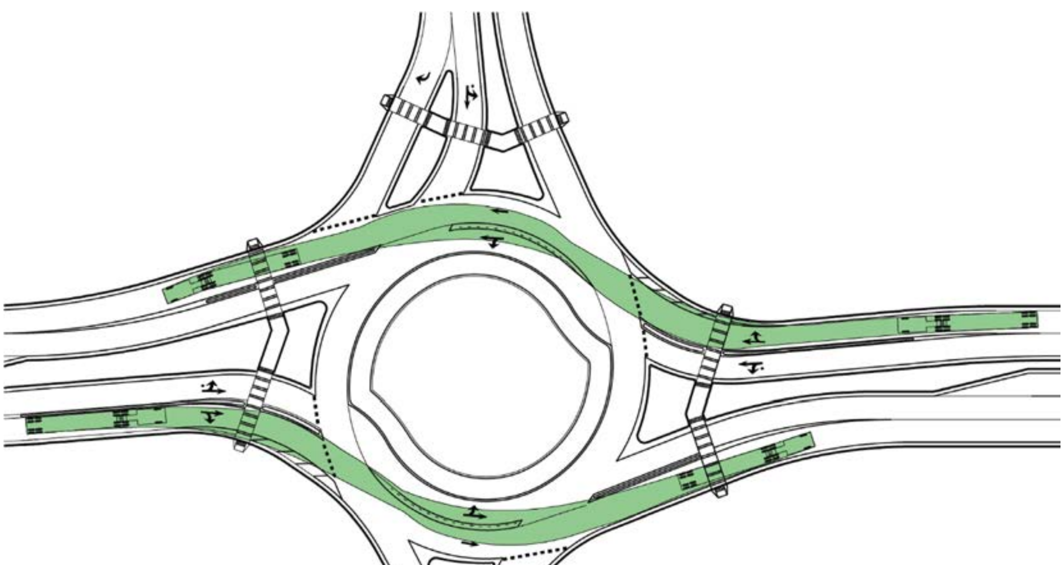
Exhibit 9.27 and Exhibit 9.28 demonstrate typical swept paths for through movements for the cases of straddling lanes and staying in-lane, respectively. Swept paths are to be drawn and

Exhibit 9.27. Turning movement swept paths straddling lanes.



SOURCE: Adapted from Georgia Department of Transportation (*3*).

Exhibit 9.28. Turning movement swept paths staying in entry lanes.



SOURCE: Adapted from Georgia Department of Transportation (*3*).

evaluated for each turning movement. Frequently, right-turn movements are critical for truck movements, particularly at single-lane roundabouts. When preparing design vehicle checks, practitioners need to construct a smooth vehicle path reflecting how a driver would realistically travel. The cab of a tractor trailer design vehicle is typically assumed to stay within the travel lanes and not mount curbs, with truck aprons supporting off-tracking of only the trailer.

Additional detail on design vehicle and check vehicle processes is provided in Appendix: Design Performance Check Techniques.

9.8 Bicycle and Pedestrian Wayfinding and Crossing Assessment

Bicycle facilities, pedestrian facilities, and facilities designed for shared bicyclist and pedestrian use are fundamental considerations in roundabout planning and design. Existing land uses and roadway context may change during a roundabout's service life. Even if sidewalk and crossing facilities may not be constructed initially, it is prudent to consider right-of-way needs and grading to serve potential future facilities. Splitter islands and right-turn channelization, to the extent practical, are developed to not preclude future crossings.

Pedestrians who use personal assistive devices or who are blind or have low vision have unique crossing needs. *NCHRP Research Report 834: Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities: A Guidebook*, explains how to apply crossing solutions at roundabouts for pedestrians who are blind or have low vision (*10*). Designs that serve pedestrians with vision or mobility disabilities benefit all pedestrians, and wayfinding and crossing assessments are integral parts of optimizing roundabout performance for these users.

Exhibit 9.29 presents a summary of wayfinding and crossing activities at roundabouts.

The rest of Section 8 presents more detailed methods that can be used at various stages in the project development process to assess facilities for bicyclists and pedestrians.

9.8.1 Bicyclist and Pedestrian Design Flag Assessment

A method for evaluating pedestrian and bicyclist safety and comfort at intersections is documented in *NCHRP Research Report 948: Guide for Pedestrian and Bicyclist Safety at Alternative and Other Intersections and Interchanges* (*13*). The guide provides an assessment method that focuses on emerging intersection forms, but it is useful for all types of intersections and interchange ramp terminal intersections, including roundabouts. The method allows practitioners to evaluate and compare alternatives concerning bicyclist and pedestrian safety and comfort at a planning level, with the type of data typically available in Stage 1 of an ICE. The assessment method helps practitioners integrate pedestrian and bicycle safety through planning, design, and operations.

Each design flag is correlated with degraded safety performance or comfort. The presence of a flag therefore provides a surrogate evaluation of each outcome. The guide and the details for implementing the flags are reproduced in Exhibit 9.30. Of the 20 design flags presented, 7 are eliminated by the roundabout's basic design. When designers assess and compare intersection performance, the design flags could be used to consider and compare various intersection features, attributes, and user considerations. The flags may help designers discern differences between various intersection forms. In assessing roundabout planning and design attributes, the flags that apply to roundabouts may help inform designers about roundabout-specific features that promote bicyclist and pedestrian comfort and safety performance. Appendix: Design Performance Check Techniques provides further detail for assessing these design flags at roundabouts.

Exhibit 9.29. Wayfinding and crossing activities at roundabouts.

Wayfinding and Crossing Activities	
Determining the appropriate crossing location	This aspect of wayfinding focuses on a person's ability to navigate from an approaching sidewalk to the appropriate crossing location. For a person who is blind or has low vision, this involves tactile detection of the curb ramp and determining whether it leads to the intended crossing. Installing a tactile guidance surface to aid in locating hard-to-find crosswalks at roundabouts can help pedestrians detect the curb ramp (*9*, *10*).
Aligning to cross (establishing the correct heading across the crosswalk)	This aspect of wayfinding focuses on a person's ability to orient themselves and initiate a crossing within the desired crosswalk while facing in the direction to cross. For a person who can see, this involves examining the marked or unmarked crossing location. For people who are blind or have low vision, this involves determining alignment from physical cues and the sounds of parallel and perpendicular motor vehicle traffic. Commonly used physical cues and vehicular sounds are absent or misleading at roundabouts. Installing a tactile guidance surface can help people accurately align themselves to cross (*11*, *12*). Making a full crossing at a roundabout entry or exit typically requires aligning to cross at multiple points, such as at bicycle lanes, vehicle lanes, and splitter islands.
Determining when to cross	The crossing decision is not a wayfinding task. It is a real-time, risk-based decision based on traffic and other ambient conditions at the time of crossing. It involves the person deciding whether a gap in conflicting vehicular traffic is available and acceptable and whether each conflicting vehicle is yielding the right-of-way. The accuracy of crossing decisions varies significantly depending on a person's senses and cognitive ability. These decisions are especially challenging for people who are blind or have low vision for several reasons, including • **Sound masking.** The sound of circulating traffic masks the audible cues pedestrians who are blind or have low vision use to identify the appropriate time to enter the crosswalk (both gap detection and yield detection). It may be impossible to determine by sound alone whether a vehicle or bicycle has stopped or intends to stop. This is especially problematic at roundabout exits because, without visual confirmation, it is difficult to distinguish a circulating vehicle or bicycle from an exiting vehicle. The problem will get worse as the proportion and number of electric vehicles and bicycles increases. • **Multiple threats.** At multilane roundabouts, this problem is magnified by the need to assess traffic traveling in multiple lanes. Even if a vehicle in one lane has stopped and a person who is blind or has low vision can discern this, the person will likely have difficulty assessing whether motorists have stopped in all lanes at a crosswalk. For this reason, the proposed PROWAG require active traffic control at multilane roundabout crossings.
Maintaining heading while crossing	This aspect of wayfinding focuses on how a person navigates from one side of the street to the other, often through one or more islands and sometimes through a change in alignment within an island. For people who are blind or have low vision, this requires traveling straight across each roadway or bicycle lane, detecting each intended pedestrian refuge along the crossing alignment, and realigning if needed (e.g., at staggered crossings).

9.8.2 Pedestrian Wayfinding Assessment

Assessing pedestrian wayfinding is a performance check complementary to reviewing pedestrian crossings at roundabouts. The guiding principles for providing quality of service and accessibility for pedestrians at roundabouts are common to all intersection forms. A person using an intersection must be able to make wayfinding decisions to navigate around the roundabout or cross an entry or exit. Wayfinding needs are common to pedestrians of varying capabilities, but they are most acute for people who are blind or have low vision. Providing for people with disabilities can also better serve pedestrians of all abilities.

Exhibit 9.30. Summary of design flags for pedestrian and bicycle intersection assessment.

Design Flag	Flag Description	Bicyclists or Pedestrians?	Comfort or Safety?	Typically Apply to Roundabouts?
Motor vehicle right turns	Permissive motor vehicles right turns across pedestrian paths	Pedestrian	Comfort, Safety	No
Uncomfortable/tight walking environment	Pedestrian facilities of narrow width	Pedestrian	Comfort	Yes
Nonintuitive motor vehicle movements	Motor vehicles arriving from unexpected direction	Pedestrian	Comfort, Safety	No
Crossing yield or uncontrolled vehicle paths	Yield or uncontrolled pedestrian crossings	Bicyclist, Pedestrian	Comfort, Safety	Yes
Indirect paths	Paths resulting in out of direction travel	Bicyclist, Pedestrian	Comfort, Safety	Yes
Executing unusual movements	Movements that are unexpected given local context	Bicyclist, Pedestrian	Comfort	No
Multilane crossings	Crossing distances of significant length across multiple lanes	Bicyclist, Pedestrian	Comfort, Safety	Yes
Long red times	Excessive stopped delay at signalized crossings	Bicyclist, Pedestrian	Comfort, Safety	No
Undefined crossing at intersections	Unmarked paths through intersections	Bicyclist, Pedestrian	Comfort	Yes
Motor vehicle left turns	Left turns across pedestrian and bicycle paths	Bicyclist, Pedestrian	Comfort, Safety	No
Driveways and side streets at or near intersection	Driveways or streets within intersection area of influence	Bicyclist, Pedestrian	Comfort, Safety	Yes
Sight and auditory distance for gap acceptance movements	Providing adequate distance to conflict points	Bicyclist, Pedestrian	Safety	Yes
Grade change	Vertical curves adjacent to intersections	Bicyclist, Pedestrian	Comfort, Safety	Yes
Riding or walking in mixed traffic	On-street bicycle facilities on high speed/volume roads, or shared bicycle–pedestrian paths	Bicyclist, Pedestrian	Comfort, Safety	Yes
Bicycle clearance times	Bicycles require longer clearance times than vehicles at signals	Bicyclist	Comfort, Safety	No
Lane change across motor vehicle travel lane(s)	Lane changes by bicycles across motor vehicle lanes	Bicyclist	Comfort, Safety	Yes
Channelized lanes	Bicyclist traveling in channelized lane adjacent to motor vehicles	Bicyclist	Comfort, Safety	Yes
Turning motorists crossing bicycle path	Lane changes by motor vehicles across bicycle facility	Bicyclist	Comfort, Safety	No
Riding between travel lanes, lane additions, or lane merges	Bicycle lanes with motor vehicle lanes on both sides	Bicyclist	Comfort, Safety	Yes
Off-tracking trucks in multilane curves	Tendency of trucks to swing into bicycle lanes while turning	Bicyclist	Comfort, Safety	Yes

SOURCE: Adapted from *NCHRP Research Report 948* (*13*).

NCHRP Research Report 834 documents a wayfinding assessment methodology that includes a checklist and set of questions (*10*). A fundamental consideration of wayfinding is whether the design is intuitive for users and provides design features that promote navigating the roundabout and accessing crossing locations. Wayfinding performance checks need to be conducted jointly with crossing assessment, given the close relationship between these activities and associated design features. Details on wayfinding performance checks adapted from *NCHRP Research Report 834* for roundabouts are provided in Appendix: Design Performance Check Techniques.

9.8.3 Pedestrian Crossing Assessment

The ADA requires that new or altered roundabouts be accessible to and usable by people with disabilities. Crossing is significantly more challenging for a person who is blind or has low vision if they must cross more than one lane of vehicular traffic at a time. Not only does the person face the potential for a multiple threat collision (as do all pedestrians in this environment), but the person also has more difficulty assessing whether each lane is clear, considering the increased number of sound sources and masking vehicles. This challenge reinforces that adding lanes to improve vehicle capacity can increase challenges for pedestrians of varying abilities.

NCHRP Research Report 834 documents a crossing assessment methodology based on performance checks that help describe the accessibility of a site (*10*).

The pedestrian crossing assessment is based on an evaluation of three performance measures:

- Crossing sight distance,
- Estimated level of crossing delay, and
- Expected level of risk for travelers who are blind or have low vision.

Practitioners can use this methodology to identify the performance of various crossing treatments, including horizontal geometry, raised crossings, RRFBs, and PHBs or pedestrian signals. Further details on these treatments are provided in Chapter 10: Horizontal Alignment and Design, Chapter 11: Vertical Alignment and Cross-Section Design, and Chapter 12: Traffic Control Devices and Applications. Crossing sight distance has been integrated into the sight distance checks presented in Section 9.5. Details for assessing crossing performance using crossing delay and expected level of risk are provided in Appendix: Design Performance Check Techniques.

9.9 Retrofitting Existing Circular Intersections

As roundabouts have become more common in the United States, practitioners have learned a great deal about roundabout safety, operations, and design principles. In some cases, existing roundabouts may have qualities that compel agencies to retrofit the circular intersection. This section specifically addresses how performance check fundamentals for new intersections also apply to existing circular intersections. Existing intersections are often assessed for factors that may lead to a documented safety or operational performance issue.

Rotaries, other circular intersections, and roundabouts that are not performing to expectations may be considered for a retrofit. Retrofitting could be completed as a result of in-service reviews or as part of maintenance projects that present opportunities to improve signing and pavement markings; curb configurations can similarly be improved as part of resurfacing projects. Small-scale improvement projects are also opportunities to include signing, pavement markings, and minor curb modifications. Large-scale retrofit projects might involve reconstructing the entire intersection, reducing the diameter, or significantly realigning one or more legs.

Retrofitting existing roundabouts or circular intersections is often more difficult than new construction. Project constraints can limit the scope of major geometric changes to the intersection. Design choices and remedies being considered will focus on the measured benefit attained from worthwhile safety and operational performance enhancements compared with the existing condition. There is a natural tendency to focus on how far a design configuration differs from the ideal design scenario. However, an improved, yet suboptimal, roundabout may still offer safety and operational performance benefits that exceed those of the existing configuration or other intersection forms.

Exhibit 9.31 and Exhibit 9.32 show the performance checks, contributing factors to undesirable performance, and typical modifications that may address identified issues. As shown, some factors

Exhibit 9.31. Example of performance checks, contributing factors, and typical retrofit modifications, Part 1 of 2.

Performance Check	Contributing Factors to Undesirable Performance	Possible Modifications to Address Issue
Geometric speed	• Skew • Inadequate deflection (combination of size, placement, or approach alignment) • Wide lanes • Excessively large entry curb radii	• Add raised crosswalks to enhance entry and exit speed control. • Modify the entry horizontal geometry to increase deflection. • Alter the approach alignment to the left to lengthen entry arcs and increase deflection. • Reduce the number of lanes. • Reduce lane widths. • Include or increase raised features, such as splitter islands and truck aprons.
Sight distance	• Skew • Excessive raised features (limits intersection sight distance) • Limited raised features (excessive sight distance promotes higher speed) • Excess approach reverse curvature limiting approach stopping sight distance	• Modify the entry horizontal geometry. • Add or remove raised features (e.g., landscaping or fencing within the splitter islands and the central island). • Improve fastest path speed control to reduce the required size of intersection sight distance triangles. • Reduce posted speeds. • Shift the yield point farther away from the circulatory roadway. • Consider an elliptical layout of the roundabout related to approach stopping sight distance.
View angles	• Skew • Right-turn yielding bypass lanes improperly aligned with receiving roadway leg	• Shift the yield point farther away from the circulatory roadway. • Adjust the entry geometry or adjacent exit alignment.
Design vehicle	• ICD, entry widths, circulatory width, entry radii, exit radii, and apron size	• Modify lane widths or curb locations. • Consider alternate paths for OSOW (e.g., median crossovers). • If multilane, use painted vane for off-tracking where entry lane discipline for trucks is desired. • Provide external truck aprons to provide pavement support for areas of known design vehicle or OSOW off-tracking.
Path alignment	• Entry and circulating lane misalignment • Excessively small radii on exit • Speed controlling radius too close to the entry • Alignment of exits at skewed intersections caused by distance between entry and downstream exit. Frequently the result of overly large ICD.	• Modify or add striping. This may include reducing the inside circulating lane width or adding gore striping between entry lanes. • Modify the horizontal geometry to better align entering vehicles to their intended circulatory lanes (e.g., increase the entry radius, move the controlling radius farther back from the entry, or introduce offset-left alignment of the approach). • Modify lane configuration.

Exhibit 9.32. Example of performance checks, contributing factors, and typical retrofit modifications, Part 2 of 2.

Performance Check	Contributing Factors to Undesirable Performance	Possible Modifications to Address Issue
Pedestrian wayfinding assessment	• Locations of pedestrian crossings not evident to pedestrians who are blind or have low vision • Running slopes of curb ramps not aligned with direction of travel on crosswalks	• Add tactile guidance surfaces.
	• Grade break at bottom of curb ramps does not intersect roadway at 0 degrees	• Reconstruct curb ramps.
	• Detectable warnings missing on curb ramps, raised crosswalks, or cut-through islands	• Install detectable warning surfaces.
Pedestrian crossing assessment	• No active traffic control for multilane roundabout	• Install active traffic control.

that lead to adverse performance can be assessed using several performance checks. Ideally, these issues can be mitigated early in the design process by identifying design features (e.g., skewed alignments) that contribute to fastest path and view angle challenges.

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PART IV

Horizontal, Vertical, and Cross-Section Design

PROJECT DEVELOPMENT PROCESS

	Part I: Introduction to Roundabouts	Chapter 1: Introduction Chapter 2: Roundabout Characteristics and Applications
Planning	*Part II: Planning and Stakeholder Considerations*	Chapter 3: A Performance-Based Planning and Design Approach Chapter 4: User Considerations Chapter 5: Stakeholder Considerations Chapter 6: Intersection Control Evaluation
Identify and Evaluate Alternatives	*Part III: Roundabout Evaluation and Conceptual Design*	Chapter 7: Safety Performance Analysis Chapter 8: Operational Performance Analysis Chapter 9: Geometric Design Process and Performance Checks
Preliminary Design	***Part IV: Horizontal, Vertical, and Cross-Section Design***	**Chapter 10: Horizontal Alignment and Design** **Chapter 11: Vertical Alignment and Cross-Section Design**
Final Design Construction, Operations, and Maintenance	*Part V: Final Design and Implementation*	Chapter 12: Traffic Control Devices and Applications Chapter 13: Curb and Pavement Details Chapter 14: Illumination, Landscaping, and Artwork Chapter 15: Construction and Maintenance
Supplemental Appendix		Appendix: Design Performance Check Techniques

CHAPTER 10

Horizontal Alignment and Design

Contents

This chapter addresses roundabout horizontal alignment considerations and design guidance. Roundabout planning and design stems from an understanding of each project's context at the earliest stages of roundabout planning and design. This understanding includes documenting the project characteristics and project type as well as considering other project influences. Identifying users' needs via the approach presented in Chapter 3: A Performance-Based Planning and Design Approach is foundational to roundabout design. User needs and stakeholder considerations help practitioners establish a planning and design framework that informs initial configurations. This chapter supports context-sensitive designs that are developed iteratively and supported by performance checks to meet design vehicle, path alignment, and speed objectives.

This chapter is complemented by Chapter 11: Vertical Alignment and Cross-Section Design and ties directly into the performance checks in Chapter 9: Geometric Design Process and Performance Checks, which support an iterative approach to intersection configuration optimization for each project condition and context. The performance considerations connect integrally to concepts presented in Chapter 7: Safety Performance Analysis and Chapter 8: Operational Performance Analysis. This chapter supports readers in each project development stage and covers horizontal design elements, including roundabout approaches, entries, exits, splitter islands, and right-turn lane design.

Roundabout planning and design occur at two levels: **broad design considerations** associated with roundabout size, location, and approach geometry as applied to early planning and design evaluations (e.g., ICE), and **design details and refinement** that support each mode of travel through the roundabout. Design level of detail can vary with each project development stage or

Exhibit 10.1. Project context considerations.

level of ICE. Concepts meeting performance outcomes outlined in Chapter 9 support efficient evaluations and reduce the risk of surprise in later preliminary and final design stages. Project context considerations from Chapter 9 are presented again in Exhibit 10.1.

Practitioners need to establish broad design configurations during planning and early concept development. This is consistent with the level of effort conducted in ICE activities or other project evaluations to determine intersection form. Design details are best considered early, as they become increasingly relevant as a project moves through project approval and geometric approval. The details become most relevant as a design moves through the early stages of final design and construction plan preparation.

10.1 Optimal Design for Project Context and User Type

Roundabout safety and operational performance depend on practitioners attaining geometrics that reduce vehicle speeds and create smooth transitions for vehicles between successive geometric elements (i.e., curves and tangents) approaching, entering, circulating, and departing the roundabout. Optimal roundabout design for each location is informed by roundabout performance evaluations that compare and assess how that performance best meets each anticipated user need. For example,

- Land-use context and context classification (existing or future) influence the speed environment.
- High-speed roadways may need longer splitter islands or other cross-section or horizontal alignment changes farther from the roundabout compared with lower-speed environments.

Facility type, roadway context classification, and development patterns set the context for roundabout design. Highway environments with high truck traffic, OSOW trucks, and few bicyclists and pedestrians may result in different geometry because of an emphasis on different combinations of performance objectives compared with a roundabout on an urban collector with more pedestrian and bicycle activity and low anticipated tractor-trailer volume.

Roundabout applications are scalable and adaptable to each project context. For example,

- Design choices for new construction may differ from those for reconstruction of an existing intersection or location of a roundabout in a constrained location.
- The design process and performance evaluations for reconstruction of an existing intersection may focus on optimizing a configuration to best adapt to the constraints or needs at a given location.

Roundabouts may offer distinct safety performance benefits compared with non-roundabout forms. **The design principles presented in this chapter will help optimize a roundabout's**

potential safety performance; however, a roundabout design that is less than ideal could still provide superior safety and operational performance over other alternatives.

Geometric performance checks are most important during the concept development stage, when they can have the greatest influence on major design decisions. However, roundabout performance checks apply at each project development stage as the configuration advances to final design.

- Conducting planning-level roundabout geometric design checks is commensurate with conducting planning-level traffic operations evaluations.
- Early evaluations could include using fundamental ICD ranges corresponding to anticipated design vehicles and generalized approach leg alignments and treatments to estimate longitudinal impacts approaching a roundabout.
- For roundabouts that advance to the next level of project planning to develop a site-specific concept, continued performance checks verify speed control, truck accommodation, and pedestrian and bicycle features integral to the roundabout design.
- Performance must be re-checked as the design is iteratively refined and adjusted, along with additional checks related to sight distance, pedestrian and bicycle accommodations, vertical design, and other considerations as the design progresses.

10.2 Design Process and Principles

Design begins early—even during planning—after practitioners establish the project context. A roundabout's basic form and features are influenced by its location, desired capacity, available space, required lane configurations, design vehicle, and other geometric attributes unique to each site. Documenting and establishing agreement on the site context and design element needs reduces the amount of potential re-design as the project moves from concept to final design.

Initial designs need to be based on meeting the performance objectives presented in Chapter 9: Geometric Design Process and Performance Checks to a level that verifies the layout will meet the design objectives. Roundabout design elements must integrate bicycle and pedestrian features (or at least not preclude them later). This includes considering splitter island design widths where future crossings may be located, considering drainage locations, and establishing a roadway and intersection cross section that could support a future sidewalk.

Roundabout design principles are common across all roundabout types. Roundabouts in low-volume (e.g., below 15,000 ADT), low-speed (i.e., less than 45 mph [70 km/h]), or constrained reconstruction locations may include combinations of traversable and non-traversable features, including splitter islands and central islands. These configurations may require special consideration compared with roundabouts with non-traversable central island features.

Roundabout performance, rather than specific design values or dimensions, is meant to guide decision making on design. Design values may vary from site to site and are to be treated as guidance. Applying design values outside the provided ranges does not necessarily result in an undesirable or unsafe condition if performance metrics can be achieved. Similarly, using individual geometric values that fall within the desired ranges does not necessarily provide an acceptable design. In roundabout design, the overall combination and composition of the various individual geometric elements is key to achieving the desired performance.

10.3 Horizontal Design Performance Influences

Exhibit 10.2 presents core horizontal roundabout design features and performance influences. Establishing design values and dimensions at the start of roundabout design is based on attaining the target performance metrics in Chapter 9: Geometric Design Process and Performance

Exhibit 10.2. Horizontal design performance influences.

Horizontal Design Performance Influences
• Roundabout size and shape o Lane configuration o Design vehicle o Approach alignment
• Roundabout location
• Roundabout approach and entry
• Facilities for pedestrians and bicyclists

Checks. A constrained location may require a smaller ICD with a fully traversable central island to meet anticipated design vehicles. Offset intersections or skewed approach alignments may lead to considering an elliptical, oval, peanut-shaped, or other configuration. Attaining performance targets forms the basis for advancing and approving configurations.

Construction needs and traffic sequencing may influence horizontal design elements beyond traffic operations and lane configurations. For example, construction material choices, such as pavement type, could affect the location of the roundabout, as portions could be constructed off existing roadway alignment to allow for concrete placement and curing. Locating the roundabout based on material type must not come at the expense of roundabout entry configurations that do not meet target performance objectives.

Achieving the various roundabout design principles and objectives involves selecting and combining individual geometric elements. Roundabout design involves optimizing several design decisions to create a layout that best meets the intended project outcomes and performance objectives. At a high level, three major design decisions influence a roundabout's overall performance:

- Size and shape
- Location
- Approach alignment and entry

The optimum combination of these three major features is based on project site constraints, adequate control of vehicle speeds, large vehicle traffic, other modes of transport, and overall design objectives.

10.3.1 Roundabout Size and Shape

Roundabout size and shape result from balancing trade-offs within a range of possible sizes for a given context. Over time, roundabout implementation in the United States has led to increasingly smaller footprints that have adapted to project needs as well as site conditions and settings.

Roundabouts may be considered in a variety of locations, ranging from neighborhood and suburban streets and rural intersections to high-volume urban locations and low- and high-capacity freeway ramp terminal intersections. Roundabout size and shape are greatly influenced by right-of-way and site conditions. Adapting a roundabout to a location is based on meeting target performance.

Roundabout size is typically described by the ICD, which is determined by several design objectives, including accommodating the design vehicle and providing speed control. Roundabout ICD is measured to the outer edge of the traveled way of the circulatory roadway. Exhibit 10.3 presents common ICD ranges for each roundabout configuration. These ranges overlap between

Exhibit 10.3. Common inscribed circle diameter ranges.

Roundabout Configuration	Typical AASHTO Design Vehicle	Common ICD Range[a]
Mini-roundabout	SU-30	45 ft to 90 ft (14 m to 27 m)
Compact roundabout	BUS-40 WB-40 WB-62 or WB-67[b]	65 ft to 120 ft (20 m to 37 m)
Single-lane roundabout (non-traversable central island)	BUS-40	90 ft to 120 ft (27 m to 37 m)
	WB-40	100 ft to 130 ft (30 m to 40 m)
	WB-62 or WB-67	120 ft to 180 ft (37 m to 55 m)
Multilane roundabout (2 lanes circulating)[c]	WB-40	135 ft to 160 ft (41 m to 49 m)
	WB-62 or WB-67	140 ft to 180 ft (43 m to 55 m)
Multilane roundabout (3 lanes circulating)[c]	WB-62 or WB-67	190 ft to 240 ft (58 m to 73 m)

[a]Assumes 90-degree angles between entries and no more than four legs. List of possible design vehicles is not comprehensive.
[b]Serving WB-62 or larger vehicles as through movements. Right turning may require other special considerations for approach and splitter island design.
[c]Common ICD ranges depend on whether the design vehicle will straddle or stay in-lane. Does not account for special vehicles or OSOWs.

roundabout configurations to demonstrate that roundabout sizes and configurations are a continuum, and the roundabout category is less important than the desired performance for a given location. Design vehicles in the table are presented in detail in the Green Book (*1*).

As shown in Exhibit 10.3, the design vehicle can have a significant effect on the size of the roundabout and is to be established early during roundabout planning activities. The distinction between designing for trucks versus accommodating trucks can influence roundabout size and is described in detail in Chapter 4: User Considerations. Roundabout configurations can be tailored to match specific patterns of truck movements, such as larger trucks for through movements along a major street and smaller trucks for turning movements. Roundabout ICD and approach design are influenced by the most common expected design vehicle. To a lesser extent, circle size or shape may be influenced by larger check or control vehicles, even when they are infrequent.

Large vehicles often dictate key roundabout dimensions by their swept path and their ability to turn at a minimum radius. Early planning and design assumptions for multilane roundabouts establish and document whether to have trucks straddle lane lines, to have trucks stay entirely in-lane, or to establish some combination thereof when entering, circulating, and exiting. This decision significantly affects the roundabout's key dimensions, including its diameter and associated footprint.

Design vehicles served on-pavement (i.e., not required to use inside or outside truck aprons) in the circulatory roadway often include fire trucks, emergency response vehicles, and transit or school buses. Practitioners need to confirm and verify design vehicle needs and assumptions through conceptual and final design layouts. Roundabouts serving OSOW trucks that require permits to travel on the roadway system may have unique needs, and practitioners need to address these vehicles during early project planning.

Many project factors affect roundabout size, shape, and location. Attaining target performance metrics for a given size, shape, and location can be influenced by roadway approach and roundabout entry alignments. The following are some general considerations for circle size:

- **Mini-roundabouts and compact roundabouts.** As subsets of single-lane roundabouts, these variations are defined by their smaller ICDs. This reduced footprint has been used in place of stop control or signalization at physically constrained intersections to improve safety performance and reduce delay. The small diameter is made possible by using a fully traversable central island to accommodate large vehicles. They may have traversable or non-traversable splitter islands. Fundamentally, this means mini-roundabout and compact roundabout central islands serve truck swept paths and cannot have signs placed in the central island. The small ICD of these reduced footprint roundabouts offers flexibility for constrained sites.

  Characterized by small diameter and often with traversable islands, mini-roundabouts and compact roundabouts are best suited to environments where roadway speeds are already low (i.e., 25 mph to 30 mph [40 km/h to 50 km/h]) and site constraints preclude using a larger roundabout with a raised central island. However, mini-roundabouts and compact roundabouts have been successfully applied on roadways with speeds greater than 30 mph (50 km/h). Those locations specifically incorporate speed management treatments (e.g., extra signs, rumble strips, raised pavement markers, delineators, flashers, longer splitter islands) on the roadway approaches because entry speed control is not reinforced by the non-traversable central island and truck apron.
- **Single-lane roundabouts.** The ICD for a single-lane roundabout largely depends on the turning requirements of the design vehicle, particularly for right-turn movements. If larger design vehicles are limited to through movements, ICDs in the lower range are often adequate. The diameter must be large enough to accommodate the design vehicle while maintaining adequate speed control to provide lower speeds for smaller vehicles. However, the circulatory roadway width, entry and exit widths, entry and exit radii, entry and exit angles, and overall skew of the intersection also play significant roles in accommodating the design vehicle and providing speed control.

  Offset-left alignments (described in detail in Section 10.3.3) can promote speed control on roundabouts with ICD values at the smaller end of the ICD range. In some cases, reverse curvature on approaches is an outcome of offsetting left and getting adequate entry deflection. In other cases, approach reverse curvature can be applied to achieve target speeds.

  Serving right-turning trucks can also affect roundabout size. Although through and left-turning movements may use the truck apron, serving a right-turn movement at a small roundabout can result in a wide area in the corner of the circulatory roadway or require an outside apron. A larger ICD can mitigate these issues.
- **Multilane roundabouts.** The size of a multilane roundabout is influenced by the number of lanes, strategy for serving trucks (straddling lanes versus staying in-lane), and site context. Size is also a byproduct of achieving target performance metrics. This often occurs by balancing the need to achieve speed control, providing adequate space for trucks and intended lane discipline, and promoting good vehicle path alignments. Typically, achieving the performance objectives requires a slightly larger diameter than those of single-lane roundabouts.

Roundabouts can take non-circular shapes to fit the geometry between adjacent intersection legs. Non-circular roundabouts may result from a need to attain entry speed control for intersections with legs of varying widths or offset centerlines. The necessary separation between approaches at intersections with more than four approaches can often be provided by using a non-circular shape.

Exhibit 10.4 depicts a partial single-lane roundabout in a residential environment. The roundabout has been configured to support a one-way cross street. In this slow-speed environment (20 mph [32 km/h]), a painted splitter island was used to maintain access to a driveway located near the entry. Section 10.6.1 discusses trade-offs associated with flush splitter islands, and Section 10.11.2 discusses issues with driveways in proximity.

Exhibit 10.5 depicts an elliptical roundabout. The elliptical shape helps provide geometric speed control in the presence of skewed angles between intersecting roadways.

Exhibit 10.4. Example of partial single-lane roundabout.

LOCATION: Southern Avenue/Whitfield Street, Boston, Massachusetts.
SOURCE: Kittelson & Associates, Inc.

Non-circular configurations may also help address skewed or offset intersections where the central island extends between both intersections. Left-turn movements and U-turn movements travel around both ends of the roundabout. The circular shape ends and narrowing in the middle often result from attaining a curvilinear alignment to promote slow speeds. However, roundabouts may be constructed without narrowing the central island between entry points. The design and shape for the central island need to be adapted to project site conditions and meet performance objectives outlined in Chapter 9: Geometric Design Process and Performance Checks.

Exhibit 10.6 through Exhibit 10.8 depict various non-circular roundabouts.

Exhibit 10.5. Example of elliptical roundabout.

LOCATION: US 319/1st Street NE/Sylvester Way, Moultrie, Georgia.
SOURCE: Georgia Department of Transportation.

Exhibit 10.6. Example of non-circular roundabouts.

LOCATION: SW Industrial Way/SW Wall Street and SW Industrial Way/ SW Bond Street, Bend, Oregon. SOURCE: Google Earth.

Exhibit 10.7. Example of non-circular roundabout.

LOCATION: US 395 (Main Street)/E Hawthorne Avenue/Railroad Avenue/ S Washington Street, Colville, Washington. SOURCE: Brian Walsh.

Exhibit 10.8. Example of non-circular roundabout.

LOCATION: W Hill Road/N 36th Street/W Catalpa Drive, Boise, Idaho. SOURCE: Google Earth.

A roundabout's size and shape also depend on the required lane configuration. Some considerations of lane configuration can affect the roundabout size, shape, and entry and exit geometry:

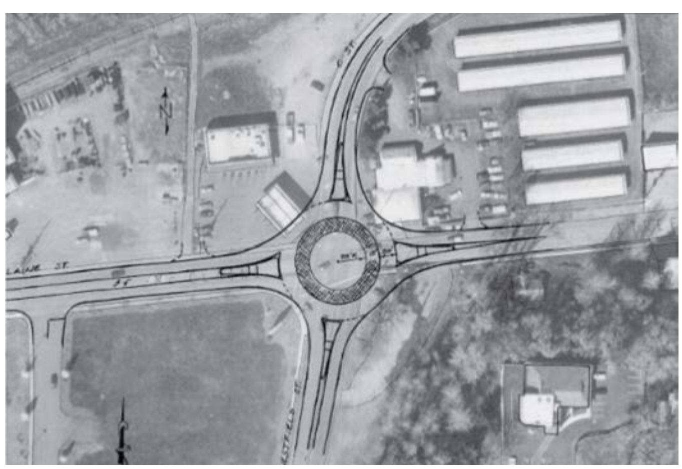
- Roundabouts requiring exclusive left-turn lanes may require spirals in the circulatory roadway so drivers can maintain appropriate lane assignments while traversing the circulatory roadway. Applying spirals (presented in Section 10.7.7) will typically result in a non-circular central island shape.
- Roundabouts may have a combination of one-lane and two-lane circulatory roadway sections. This may result in a non-uniform ICD. When selecting the ICD dimension, the ICD value commonly refers to the diameter across the wider two-lane portion of the roundabout, although some operational analysis methods discussed in Chapter 8: Operational Performance Analysis may instead refer to a localized diameter at the entry.
- Right-turn bypass lanes may be configured differently. A yielding right-turn bypass lane may allow for a smaller ICD. In some locations, a smaller ICD may provide better view angles and more intuitive lane assignments for drivers. Right-turn bypass lanes are discussed further in Section 10.9.

10.3.2 Roundabout Location

Locating a roundabout's center and its relationship to approaches and alignments (as well as roundabout size) affects roundabout performance. There is likely more freedom for designing new facilities compared with locations on an existing alignment or at an existing circular intersection being retrofitted. Site constraints and considerations for traffic maintenance during construction may influence a roundabout's position, just as right-of-way constraints and other footprint impacts might. Roundabout position then affects predicted performance, which can be enhanced by possible changes to the size and approach alignment.

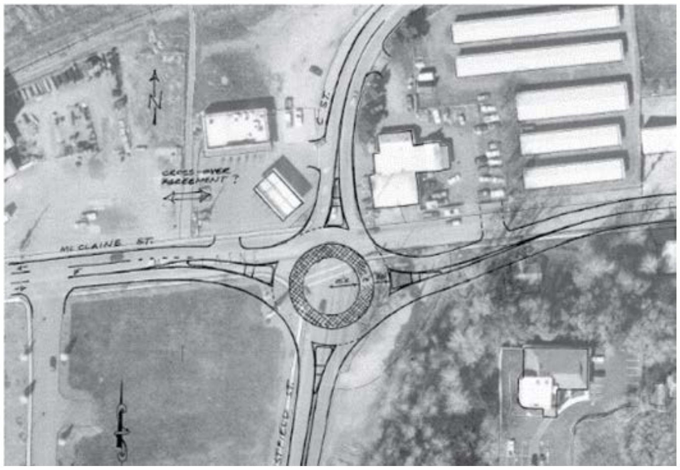
Exhibit 10.9, Exhibit 10.10, and Exhibit 10.11 provide an example of a design using three possible circle locations with the same ICD. Centering the roundabout on the existing intersection provides a baseline from which to consider project issues. The location as shown in Exhibit 10.9 affects developed properties in the northwest and northeast quadrants. Shifting to the south (shown in Exhibit 10.10) or to the east (shown in Exhibit 10.11) requires changes in approach alignment to control target entry speeds. This demonstrates that roundabout footprint and impact considerations go beyond the ICD and must be accounted for in early project planning.

Exhibit 10.9. Testing roundabout locations in early project planning—centered on existing intersection.



SOURCE: *NCHRP Report 672* (*2*).

Exhibit 10.10. Testing roundabout locations in early project planning—center shifted to the south.



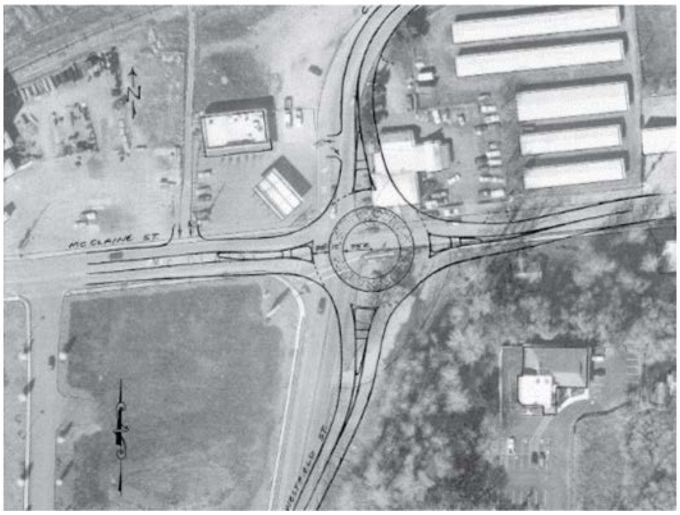
SOURCE: *NCHRP Report 672* (*2*).

Each roundabout location results in different performance outcomes, such as sight distance and impacts on the adjacent properties. Concept alternatives must consider performance outcomes to compare and assess design impacts between the alternatives being considered. Comparing and documenting performance differences between alternatives can increase confidence in the advanced alternatives and reduce the risk of needing to re-assess prior screened configurations. The optimal design will depend on the design criteria being emphasized. The goal is not to create a perfect balance between safety performance, capacity, and cost. Instead, the goal is to create an optimal configuration that does not unduly trade off any of the major design considerations.

10.3.3 Roundabout Approach Alignment

The roundabout approach includes the entry and the roadway approach alignment. A roundabout approach alignment affects speed control, the ability to serve design vehicles, and view

Exhibit 10.11. Testing roundabout locations in early project planning—center shifted to the east.



SOURCE: *NCHRP Report 672* (*2*).

angles. It can also mitigate the angle between approach legs. The roadway approach alignment can depend on the roundabout's size and location, which also affect the ability to attain the geometry's intended speed reduction effects. Roundabout approach and entry design complement size and location as key variables to attain target performance. Roundabout approach alignment is often influenced by the need to attain entry path alignment and entry speeds. It may influence the overall roadway departure geometry.

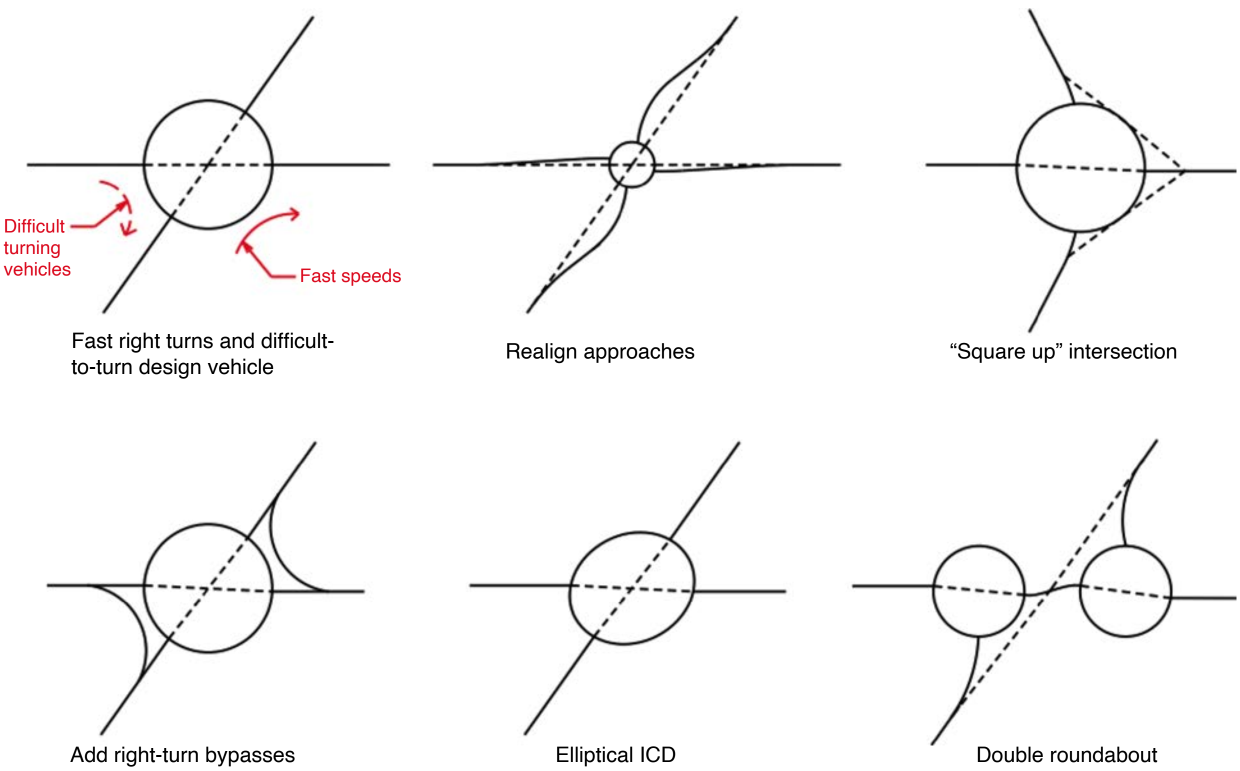
Intersection skew affects any intersection form, including roundabouts. As with other intersections, it is generally preferable for the approaches to intersect at perpendicular or near-perpendicular intersection angles. An acute skew angle can make navigation difficult for right-turning trucks and could necessitate a right-turn bypass. Practitioners need to keep in mind that the right-turn bypass creates an additional pedestrian crossing as well as additional conflicts for pedestrians and bicyclists. Obtuse skew angles can promote higher speeds.

Roadway approach geometry can mitigate the effects of intersection skew. By limiting the ICD size or location options at site-constrained locations, the roadway approach alignment can sometimes be established to attain desired performance. If the approach alignment is constrained, sometimes the roundabout's location and size can be iteratively adapted to attain the desired performance. Realigning one or more legs may be combined with other design features to mitigate the skew. In some locations, creating two roundabouts could be appropriate.

Exhibit 10.12 conceptually presents considerations for addressing intersection skew angles. In all cases and configurations, the primary consideration of design configuration is achieving target performance.

Integrating roundabouts into the surrounding roadway area affects right-of-way, access management, and other aspects. Practitioners can use a roadway approach *speed profile* to consider the transition between upstream segments and the roundabout. Speed profiles can

Exhibit 10.12. Considerations for addressing intersection skew angles.



SOURCE: Adapted from Georgia Department of Transportation (*3*).

guide roundabout approach horizontal alignments, including the transition length and range of horizontal curve radii leading from the approach to the roundabout entry. Accommodating the design vehicle can also influence roundabout approach alignment and entry.

The alignment of the approach legs affects the amount of deflection (speed control) achieved, the ability to accommodate the design vehicle, and the visibility angles to adjacent legs. The optimal alignment is generally governed by the size and position of the roundabout relative to its approaches.

A common starting point in design is to center the roundabout so that the centerline of each leg passes through the center of the inscribed circle, otherwise known as a radial alignment. This location typically allows the geometry of a single-lane roundabout to be adequately designed so that vehicles will maintain slow speeds through the entries and exits. The radial alignment also makes the central island more conspicuous to approaching drivers and minimizes any roadway modification required upstream of the intersection.

Another frequently acceptable alternative is to offset the centerline of the approach to the left (i.e., the centerline passes to the left of the roundabout's center point). This alignment will typically increase the deflection achieved at the entry to improve speed control. The inherent trade-off of a larger radius (or tangential) exit is speed control for the downstream pedestrian crossing. Geometry that provides low vehicular speed and good visibility to downstream pedestrian crossings reduces the pedestrian crash risk. Supplemental pedestrian crossing treatments augment pedestrian-focused exit designs.

Offsetting the centerline to the right of the roundabout's center point can decrease entry deflection and result in undesirable entry speeds. However, an offset-right alignment alone is not a fatal flaw in a design if speed control can be achieved by other means and other design considerations can be met. An offset-right alignment may be needed in some locations to reduce right-of-way impacts, improve view angles, or address issues associated with retrofitting existing circular intersections.

Various options for roundabout approach alignment are summarized in Exhibit 10.13. The optimal configuration is based on the project characteristics, type, and influences.

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 larger ICDs to achieve speed objectives. This means an ICD selected for roadways with skewed approaches could require other entry design adjustments and affect the location or shape of the circle to achieve speed objectives.

Exhibit 10.14 illustrates the fastest paths at a roundabout with perpendicular approach angles versus a roundabout with obtuse approach angles. Y-shaped intersection alignments have the potential for higher speeds than desired. Approaches that intersect at angles greater than approximately 105 degrees can be realigned to an offset-left configuration or by introducing curvature in advance of the roundabout to produce a more perpendicular intersection. Other possible geometric modifications include changes to the ICD or modifications to the shape of the central island to manage vehicle speeds. For roundabouts in low-speed, urban environments, the alignment of the approaches may be less critical.

Exhibit 10.15 and Exhibit 10.16 show images before and after installation, respectively, of a single-lane roundabout in a rural location. This configuration shows how each approach was designed to attain target performance within the context of this location. The alignment of the east leg was curved to the south to square up the intersection to nearly 90 degrees and better accommodate design vehicles making right turns. The north leg applies a slightly offset-left design, while the south leg is closer to the alignment through the center (i.e., radial).

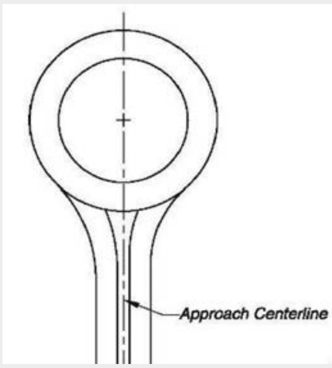
The roundabout addressed safety performance needs with a resulting alignment that better serves design vehicles. A secondary benefit is successive curves on the approach alignment that

Exhibit 10.13. Roundabout approach and entry alignment considerations.

Design Principle

The approach alignment does not have to pass through the center of the roundabout. The optimal approach alignment and entry design provides adequate speed control while providing appropriate view angles and balancing property impacts and costs.

Alignment Through the Center of the Roundabout



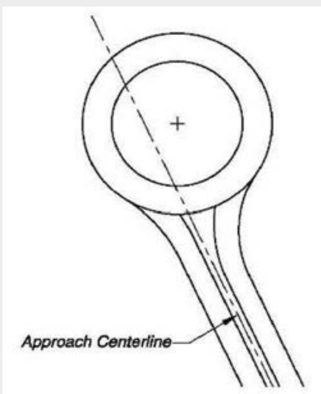
When It Might Be Appropriate

- Reduces amount of alignment changes along the approach roadway to keep impacts more localized to the intersection
- Allows for some exit curvature to encourage drivers to maintain slower speeds through the exit

Trade-Offs

- Curvilinear alignment resulting from the exit radius increases geometric control of exit speeds
- May require a slightly larger ICD (compared with offset left design) to provide the same level of speed control

Offset Alignment to the Left of Center



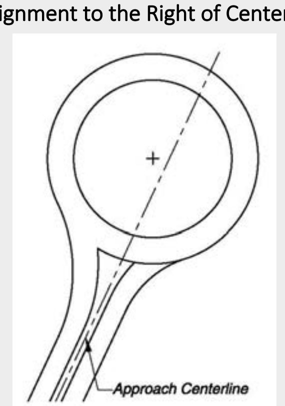
When It Might Be Appropriate

- Allows for increased entry speed control
- Accommodates large trucks with smaller ICDs—allows for larger entry radius while maintaining deflection and speed control
- May reduce roadway right-side impacts

Trade-Offs

- Increased exit radius or tangential exit reduces geometric control of exit speeds and could increase acceleration through crosswalk area
- May create greater impacts to the left side of the roadway

Alignment to the Right of Center



When It Might Be Appropriate

- Could be used for larger ICD roundabouts where speed control objectives can still be met
- In rare instances (if speed objectives are met), may minimize impacts or improve view angles

Trade-Offs

- Often more difficult to achieve speed control objectives, particularly at small-diameter roundabouts
- Increases the amount of exit curvature that must be negotiated

SOURCE: Adapted from *NCHRP Report 672* (*2*).

Exhibit 10.14. Angle between legs.

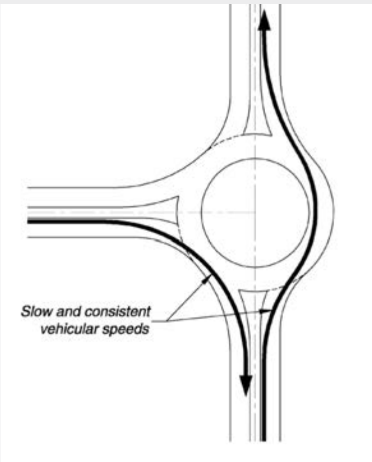
Question

Is it acceptable to have a skewed angle between intersection legs, or do the angles always need to be perpendicular?

Design Principle

The angle between legs may affect the ability to achieve slow fastest path speeds, impact navigation of large vehicles, and complicate signing and marking. In general, it will be easier to achieve the design objectives if the approach legs are nearly perpendicular to each other. However, perpendicular approaches are not a design requirement. Acceptable designs can be achieved with skewed angles between approaches, along with corresponding adjustments to other design components.

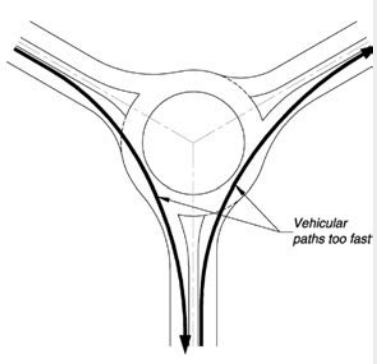
Perpendicular Legs



Perpendicular approach angles generally provide slow and consistent speeds when combined with other appropriately sized design features. Achieving acceptable fastest path speeds is often easier to accomplish with a perpendicular approach angle than with a skew.

Where the intersecting roadways are skewed under existing conditions, realignment of one or more approach legs would be required to achieve this "ideal" condition. The ability to realign a leg may depend on other site constraints and may not be feasible in all locations. Realigning to achieve an angle as close to 90 degrees as practical is generally desirable.

Large Angle Between Legs



In situations involving a large angle between legs, it is desirable to realign one or more legs to achieve a more perpendicular condition. Large angles make it difficult to provide adequate deflection and may result in fast vehicle speeds, particularly for right-turning movements.

Options to achieve adequate speed control without realigning the approaches include

- Increasing the ICD,
- Offsetting the approach centerline to the left of the roundabout's center, and
- Reducing entry widths and entry radii.

SOURCE: Adapted from *NCHRP Report 672* (*2*).

Exhibit 10.15. Example of intersection before installation of single-lane roundabout.

LOCATION: Powell Butte Highway/Neff Road/Alfalfa Market Road, Deschutes County, Oregon. SOURCE: Google Earth.

support speed reduction in this rural environment. This reinforces the idea that roundabout footprint considerations can occur beyond the intersection.

Attaining appropriate entry and exit path alignment is a fundamental objective in multilane configurations. In some cases, attaining appropriate entry design can lead to changes in the roundabout approach alignment. Exhibit 10.17 shows a multilane roundabout with an entry design that provides the path alignment needed to achieve performance objectives at multilane roundabouts. As a byproduct of attaining the proper entry alignment, the roundabout approach alignment passes south of the existing roadway and is needed to attain target roundabout entry speeds. A secondary benefit is a curvilinear alignment that promotes speed reduction.

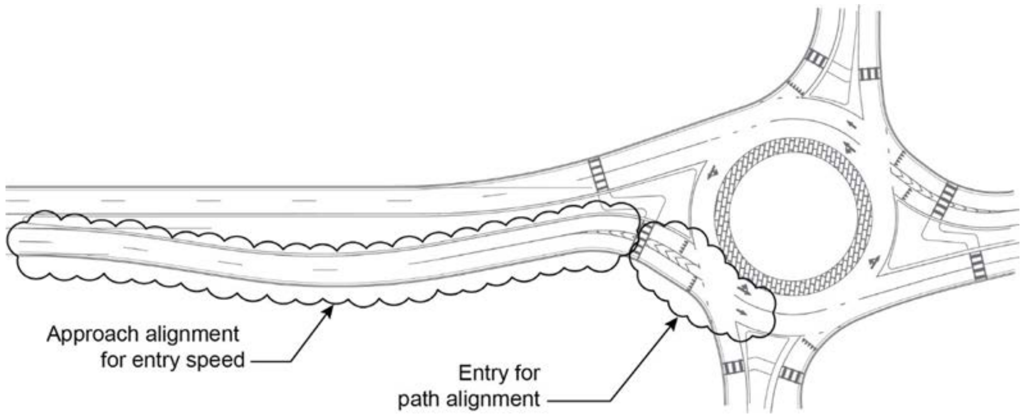
10.3.4 Facilities for Pedestrians and Bicyclists

Design elements that affect people walking (including those with disabilities) and biking include pedestrian and bicycle facility types, buffers and separations, crossing locations, sidewalk treatments, splitter islands, wayfinding treatments, and curb ramps. Pedestrians and bicyclists are to be treated as equal users and accounted for at the earliest planning and design activities, not as an afterthought. This means including adequate space and features for people walking and biking.

Exhibit 10.16. Example of intersection after installation of single-lane roundabout.

LOCATION: Powell Butte Highway/Neff Road/Alfalfa Market Road, Deschutes County, Oregon. SOURCE: Google Earth.

Exhibit 10.17. Example of multilane roundabout approach alignment.



Safety performance, connectivity, and accessibility are a priority. Bicycle and pedestrian facilities at a roundabout will connect to broader bicycle and pedestrian networks. If bicycle or pedestrian activity is anticipated in the future, approaches and splitter islands are to be designed with room for future facilities.

The type of bicycle and pedestrian facilities and associated buffers directly affect the quality of service, comfort, and accessibility for people walking and biking at a roundabout. To provide accessibility for all pedestrians, buffers that are detectable underfoot or by use of a long cane are needed between the circulatory roadway and the pedestrian path or between bicycle facilities and the pedestrian path. Bicycle facilities that are separated from pedestrian facilities improve the quality of service for both bicyclists and pedestrians but require more space than shared-use facilities. Shared-use facilities create challenges for pedestrians who may be unable to see or hear bicyclists or may be unable to move out of the path quickly. Additional buffer space may be needed behind the pedestrian path for lighting, signs, and other objects that would otherwise reduce the usable width for bicyclists and pedestrians.

10.4 Design for People Walking and Biking

This section provides an overview of designing pedestrian and bicycle facilities at roundabouts, including accessibility requirements and recommendations, sidewalk and path facilities, transition areas and pedestrian–bicycle conflict zone design, and crossings. Chapter 4: User Considerations provides an overview of the characteristics of people walking and bicycling, including a range of abilities, experience, and associated comfort levels.

As discussed in Chapter 4, people using pedestrian facilities, whether walking or using wheeled mobility devices, experience varying comfort levels. Comfort as a concept need not be construed as safety performance. However, using pedestrian comfort to guide pedestrian facility design tends to result in pedestrian facilities that provide beneficial safety performance outcomes. People of all ages and abilities walk along the public rights-of-way. People walk with children and use canes, walkers, and wheelchairs. Meeting such pedestrian needs through design leads to an equitable solution.

Similarly, as discussed in Chapter 4, people biking also experience varying comfort levels. A key component of a bicyclist's comfort is the connectivity of the bicycle network, including the stress level of intersections on the network. Therefore, bicycle facilities around roundabouts must provide connectivity while also matching or exceeding the safety and comfort levels between planned or existing bicycle facilities on the approach legs.

As with other intersection forms, roundabouts are often the focal point for determining the overall comfort, safety performance, accessibility, and usability of a facility for walking and bicycling. As such, the pedestrian and bicycle facilities through and around a roundabout need to match or exceed the safety performance, comfort, and stress levels of planned or existing pedestrian or bicycle facilities on the segments leading to the roundabout. This section provides guidance on planning and designing pedestrian and bicycle facilities to allow people walking and biking to travel through or around a roundabout.

As discussed in Chapter 4, pedestrian facilities in the United States are also governed by the ADA (*4*). The US Access Board has published proposed PROWAG (*5*), with an amendment for shared-use paths (*6*). Accessibility features at roundabouts include sidewalks and crosswalks that meet the appropriate surface, slope, and clearance requirements; ramps connecting sidewalks and crosswalks; detectable warning surfaces at curb ramps and splitter islands; detectable edge treatments between sidewalks and roundabout vehicular lanes to guide pedestrians to crosswalks (such as landscaping adjacent to the curb line); and signalized pedestrian crossings.

FHWA has issued a memorandum stating that "the Draft Guidelines [i.e., proposed PROWAG] are the currently recommended best practices and can be considered the state of the practice that could be followed for areas not fully addressed by the present ADAAG standards" (*7*). Regardless of the proposed PROWAG's status, the absence of regulations that mandate minimum technical standards does not absolve a state or local government from meeting ADA requirements.

This section focuses on aspects of design for walking and biking at roundabouts. For details not provided in this Guide, refer to the latest editions of the AASHTO *Guide for the Development of Bicycle Facilities* (*8*); AASHTO *Guide for the Planning, Design, and Operation of Pedestrian Facilities* (*9*); the National Association of City Transportation Officials (NACTO) *Urban Bikeway Design Guide* (*10*), the NACTO *Urban Street Design Guide* (*11*), the FHWA *Improving Intersections for Pedestrians and Bicyclists Informational Guide* (*12*), and proposed PROWAG (*5*, *6*).

10.4.1 General Design Principles for Walking and Biking

A set of design principles is a starting point for identifying design options that provide connectivity and comfort levels appropriate for people of all ages and abilities. These principles, based on domestic and international research and guidance documents related to bicycle facility planning and design, include the following:

- Minimize exposure to conflicts,
- Reduce speeds at conflict points,
- Clearly define areas of potential conflict,
- Separate modes,
- Clearly communicate right-of-way priority,
- Provide predictable, simple, direct alignments,
- Provide adequate sight distance,
- Provide comfortable spaces for waiting and decision making,
- Minimize person delay,
- Provide connectivity or usable connections for each mode to the existing and future networks, and
- Provide continuity or quality of service for each mode at the roundabout comparable with that of connecting segments.

The latter two points are especially important when considering the roundabout as part of a system. Bicycle and pedestrian facilities at a roundabout need to be integrated into the existing and future surrounding pedestrian and bicycle network. Not all connecting segments need to be of the same quality of service; people walking and biking around a roundabout can experience different pedestrian and bicycle facilities and design treatments between intersection legs depending on the approach facilities and characteristics of the local pedestrian and bicycle network. However, if a mix of separated and shared pedestrian facilities is provided, people who are blind or have low vision may be unaware that bicycles could share their path.

Single-lane roundabouts are simpler than multilane roundabouts for pedestrians and bicyclists because of lower design speeds, fewer conflict points, and no lane changing for bicyclists traveling in the travel lane. In addition, at single-lane roundabouts, motorists are less likely to cut off bicyclists when exiting the roundabout. The pedestrian and bicycle facilities through and around a roundabout need to match or exceed the safety performance, comfort, and stress levels of planned or existing pedestrian or bicycle facilities on the roundabout approaches. When separated pedestrian and bicycle facilities are provided or planned on roundabout approaches, it is often advantageous to maintain exclusive pedestrian and bicycle facilities throughout the roundabout. Typically, this includes maintaining the same facility width and degree of separation around the roundabout as those found on the segments leading to the roundabout.

10.4.2 Geometric Features for Accessibility

All new or altered pedestrian treatments at intersections in the United States, including roundabouts, must be accessible to and usable by people with disabilities per the ADA. This section presents geometric design details for accessible pedestrian treatments specific to roundabouts. The proposed PROWAG provide a more complete discussion of accessibility features, including curb ramp specifications and other features (*5*, *6*). Chapter 4: User Considerations details how people who have disabilities travel along segments and at intersections; these human factors form the basis for the recommendations in this section.

Buffers between pedestrian facilities and the circulatory roadway, such as landscape buffers or other detectable edge treatments, are essential components of the design. These buffers provide many benefits, including increased comfort for people walking, room for signs and other street furniture, snow storage, and space for the overhang of large vehicles as they navigate the roundabout. At roundabouts, buffers provide essential tactile guidance for people who are blind or have low vision to identify the correct crossing location, and buffers discourage walking into the circulatory roadway. The proposed PROWAG include a requirement to provide a detectable edge treatment between sidewalks and curbs in locations at the roundabout (such as bike ramps) where pedestrian crossings are not intended (*5*).

The minimum horizontal buffer width required for accessibility is 2 ft (0.6 m); a buffer width of at least 5 ft (1.5 m) provides viable space for landscaping. Low shrubs, grass, or other tactile material (e.g., river rock or other stone that is distinct underfoot from a typical walking surface) is needed in the area between the sidewalk and the curb for accessibility. Materials such as colored concrete, stamped concrete, brick pavers, or other common walking surfaces are not reliably detectable by people who are blind or have low vision and are not advised for this buffer space. An example of a buffer at a shared-use path is given in Exhibit 10.18.

In locations where a buffer of at least 2 ft (0.6 m) in width cannot be provided, fencing or other barriers may be necessary to guide people who are blind or have low vision to the crosswalks. Fencing may also be advantageous in areas where high numbers of pedestrians make pedestrian entry into the circulatory roadway more likely (e.g., on a college campus or near a transit station). Exhibit 10.19 shows an example of a location with a curb-tight sidewalk and fencing to provide a detectable buffer for pedestrians between crosswalks. This example provides only a minimum width for pedestrians and would not be sufficient to serve as a shared-use path for bicyclists and pedestrians; other options might include replacing the right-turn-only lane with a larger path.

Exhibit 10.18. Example of buffer between shared-use path and circulatory roadway.

SOURCE: Lee Rodegerdts.

Detectable boundaries are also needed between separated and adjacent bicycle and pedestrian facilities for people who are blind or have low vision. There are three types of boundaries:

- **Horizontal separation.** A buffer at least 2 ft (0.6 m) wide provides a detectable separation like that used between the pedestrian facility and circulatory roadway.
- **Vertical separation.** If bicycle and pedestrian facilities abut one another, either vertical separation or a tactile warning indicator must be detectable by people who are blind or have low vision. Vertical separation needs to be at least 2.5 inches (60 mm) between the abutting bicycle and pedestrian facilities to be readily detectable to people who are blind or have low vision (*13*, *14*). A beveled or mountable curb is advised to minimize pedal strikes when the vertical separation is greater than 3 in. (75 mm).
- **Tactile warning indicator.** If horizontal or vertical separation is not provided between abutting bicycle and pedestrian facilities, a tactile warning indicator is advised. These are presented in Section 10.4.3.

Exhibit 10.19. Example of roundabout with curb-tight sidewalk and fencing.

LOCATION: Hillsborough Street/Pullen Road, Raleigh, North Carolina.
SOURCE: Lee Rodegerdts.

10.4.3 Tactile Walking Surface Indicators for Accessibility

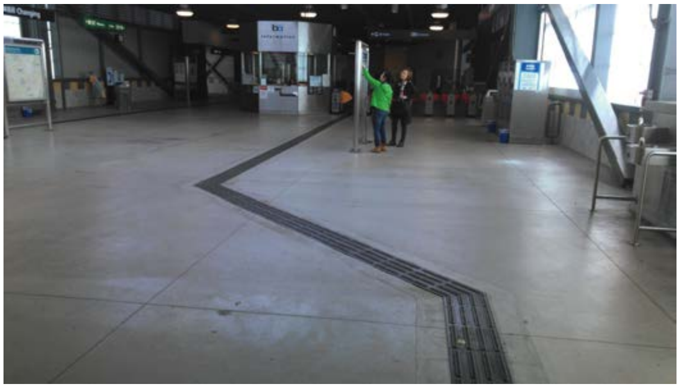
In addition to geometric treatments, tactile walking surface indicators (TWSIs) are used to aid wayfinding by people who are blind or have low vision. These indicators have been demonstrated to be readily detectable under foot and with a long cane. They should provide visual contrast with the surrounding surface (i.e., light-on-dark or dark-on-light). Some of these indicators are required for use at roundabouts and other intersections; others show promise in making a configuration accessible. These indicators can be classified into several types:

- **Detectable warning surface.** A detectable warning surface (DWS) is a standardized surface, first required by the US DOT 2006 ADA standards and standardized in 2010 in the ADA Accessibility Guidelines (*15*, *16*). It consists of truncated domes indicating the boundary between a pedestrian path of travel and a vehicular way where there is a curb ramp or blended transition as well as at the edge of transit boarding platforms. When people who are blind or have low vision encounter a DWS, they should stop, determine whether there is a street or platform edge in front of them, and prepare to cross or board. The DWS is not a reliable cue for aligning to cross the street. The most comprehensive specifications for installation are in proposed PROWAG (*5*, *6*). Exhibit 10.20 shows an example application.
- **Tactile directional indicator.** A tactile directional indicator (TDI) consists of raised, parallel, flat-topped, elongated bars in a strip that is 12 inches (300 mm) wide. When people who are blind or have low vision encounter a TDI, they should understand that this is a surface they can follow. They can choose to cross it or to follow it on either side. The TDI does not imply that there is any danger and cannot be used as a delineator between bicyclists and pedestrians. There are no established standards in the United States for TDIs, but many installations used to date for transit platforms conform to the international standard for a guidance pattern, ISO 23599:2019 (*17*).
  - **TDIs for delineating path of travel.** This surface indicates an unobstructed path of travel where there are no natural guidelines, such as edges of sidewalks, walls, or curbs, and where other directional cues, such as traffic, may be missing or ambiguous. In this application, raised bars are oriented **parallel** to the direction of travel. Exhibit 10.21 shows an example application for use in delineating a path of travel.
  - **TDIs for locating hard-to-find crossings.** Another application of the TDI surface that initial research suggests is effective is to indicate hard-to-find street crossings and other transit-related applications. This application consists of a strip that is 24 inches (600 mm) wide and installed across the width of the sidewalk with the raised bars oriented **perpendicular** to the direction of travel on an associated crosswalk. Initial research indicates that TDIs with

Exhibit 10.20. Example of DWS.

LOCATION: Records Avenue/Elden Gray Street, Meridian, Idaho.
SOURCE: Lee Rodegerdts.

Exhibit 10.21. Example of TDI (raised bars) for delineating path of travel.



LOCATION: Dublin/Pleasanton Bay Area Rapid Transit Station, Dublin, California. SOURCE: Beezy Bentzen.

bars oriented perpendicular to the path of travel across associated crosswalks significantly improve the efficiency of locating crosswalks (*18*). For people with mobility disabilities (using a variety of aids) TDIs also require less effort and result in less instability when crossing than raised bars oriented parallel with the direction of travel on the associated crosswalk (*19*). Exhibit 10.22 shows an example application for use in establishing crossing alignment.

– **TDIs for establishing crossing alignment.** This application is an extension of the use of TDIs for locating hard-to-find crossings. The bars of TDIs, when they are oriented **perpendicular** to the direction of travel across the crosswalk, have been shown to significantly improve the accuracy of establishing a heading (aligning) for crossing (*20*). At corner crossings, a square of TDI, 24 inches by 24 inches (600 mm by 600 mm) with the raised bars oriented perpendicular to the direction of travel on an associated crosswalk, is sufficient to result in significantly more accurate alignment (*20*). This application is anticipated to be effective at roundabouts where crossing alignments change, including within splitter islands. The TDIs for establishing alignment are placed near the end of the DWS farthest from the center of the intersection as an alignment cue for crossings where other cues are missing or ambiguous. Exhibit 10.23 shows an example application for use in establishing alignment for crossing at a corner.

- **Tactile warning delineator.** A tactile warning delineator (TWD) is a surface that initial research suggests is effective for helping people differentiate vehicular (bicycle, motor vehicle,

Exhibit 10.22. Example of TDI for locating hard-to-find crossings.

LOCATION: Main Street/Orange Avenue, Sarasota, Florida. SOURCE: Beezy Bentzen.

Exhibit 10.23. Example of TDI for establishing alignment for crossing.

LOCATION: Alexandria, Virginia. SOURCE: Beezy Bentzen.

or both) and pedestrian facilities that abut at the same grade (*21*). It consists of a raised linear surface that is 0.75 inches (19 mm) in height and trapezoidal in cross section that delineates the boundary between a pedestrian access route and a separated bicycle lane or the shared zone in a shared street. When people who are blind or have low vision encounter a TWD and they are walking on the portion farther from bicycles or motor vehicles, they should understand not to cross this surface because there is danger of a crash with a bicycle or motor vehicle on the other side. Initial research suggests that the TWD should be highly detectable under foot or with a long cane, accurately identifiable under foot, and crossable by people with mobility disabilities using a variety of aids. Initial research also indicates that TWDs have no adverse consequences for bicyclists under wet or dry conditions (*21*). There are no established standards in the United States for TWDs. Exhibit 10.24 shows an example application.

Exhibit 10.24. TWD (raised trapezoid).

SOURCE: Beezy Bentzen.

10.4.4 Design for Bicyclists to Use Travel Lane

In some contexts, it may be possible to allow bicyclists to use the travel lanes with motor vehicles and reserve sidewalks for pedestrians only. These contexts include low-speed, low-volume residential environments. The minimum sidewalk width to allow two-way traffic by people with mobility disabilities is 5 ft (1.5 m), but this width may not be sufficient for pedestrian demand and does not permit shared use with bicyclists if shared use is intended. Traffic furniture and other obstacles cannot infringe on the pedestrian travel areas. Sidewalks need to be as wide as necessary in areas with heavy pedestrian volumes, such as schools or highly urban areas; 10 ft (3.0 m) or wider is common in these applications. State or local laws may prohibit bicyclists from riding on sidewalks.

Where the sidewalk is too narrow for shared use, a bicycle facility on a segment leading to the roundabout has to end before the roundabout and begin again beyond the roundabout exit. When ending bike lanes in advance of the roundabout, a full-width bike lane normally has to end at least 50 ft to 200 ft (15 to 60 m) in advance of the crosswalk. Terminating the bike lane helps remind people biking that they need to merge and indicates to drivers that people biking will be entering the travel lane. A taper rate of 8:1 is commonly used to serve a design speed of 20 mph (32 km/h).

10.4.5 Design for Bicyclists and Pedestrians Using Shared-Use Paths

Shared-use paths, also known as *multiuse paths*, *sidepaths*, or *off-street trails*, are intended for the combined and exclusive use by pedestrians, bicycles, and micromobility (e.g., e-bicycles, e-scooters). Some shared-use paths also allow equestrian users. Motorized vehicles are typically prohibited (except for maintenance vehicles). Because shared-use paths are intended for bicyclists and pedestrians of all abilities, they are typically relatively level and are constructed with a relatively smooth surface. As discussed in Chapter 4: User Considerations, shared-use facilities are more challenging to use for people who are blind or have low vision.

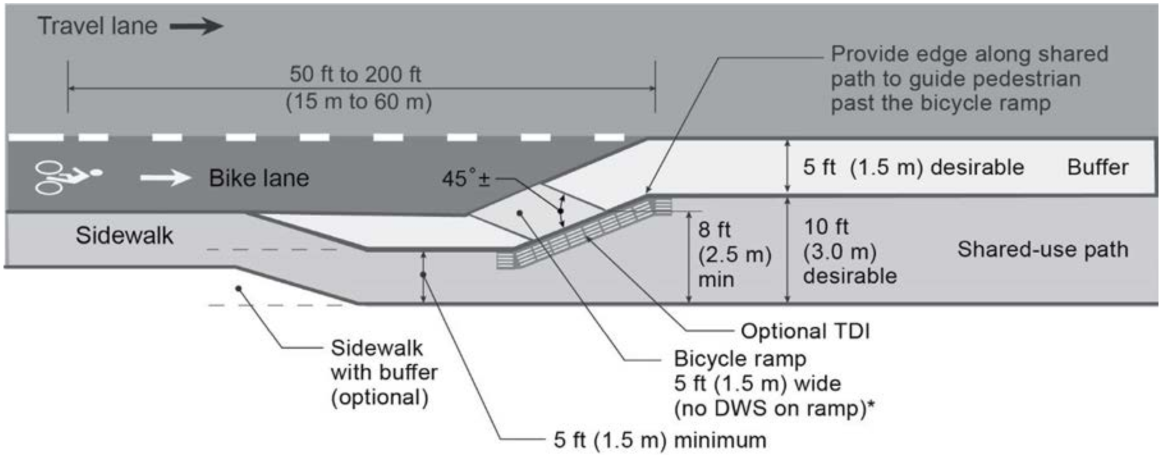
Where shared use by both bicyclists and pedestrians is intended, the desirable shared-use path width is at least 10 ft (3 m). If facilities around the perimeter of a roundabout are less than 8 ft (2.4 m) wide, they are too narrow for shared use and are treated as pedestrian-only facilities; see Section 10.4.4.

For roundabouts where on-street bicycle lanes connect to shared-use paths around the roundabout, bicycle ramps provide network continuity for bicyclists, and their design details need to minimize potential conflicts between people walking and biking (particularly with pedestrians who are blind or have low vision). Bicycle ramps would be placed either at the end of the full-width bike lane, where the taper for ending the bike lane begins, or within the tapered area near the beginning of the tapered section. Bicycle ramps would be placed at an angle appropriate for the transition between the approach and traversing bicycle facilities in these locations.

When transitioning to a shared-use path around the roundabout, an angle of approximately 45 degrees is appropriate. Wherever possible, bicycle ramps are placed entirely within the planting strip between the sidewalk and the roadway. Bicycle ramps can have slopes as high as 20 percent; slopes that are steeper than pedestrian ramps are preferred to distinguish bicycle ramps from pedestrian ramps. Exhibit 10.25 shows a bicycle ramp transition from an on-street bike lane to a sidewalk that has been widened to a shared-use path around the roundabout.

Bicycle ramps from a shared-use path onto an on-street bicycle lane need to be built with similar geometry and placement as the ramps at roundabout entries. Bicycle ramps would be placed at least 50 ft (15 m) beyond the crosswalk at the roundabout exit. Exhibit 10.26 shows the transition from the widened shared-use path to the on-street bicycle lane on the departure roadway and the shared-use path narrowing to a sidewalk.

Exhibit 10.25. Transition from on-street bike lane to shared-use path.

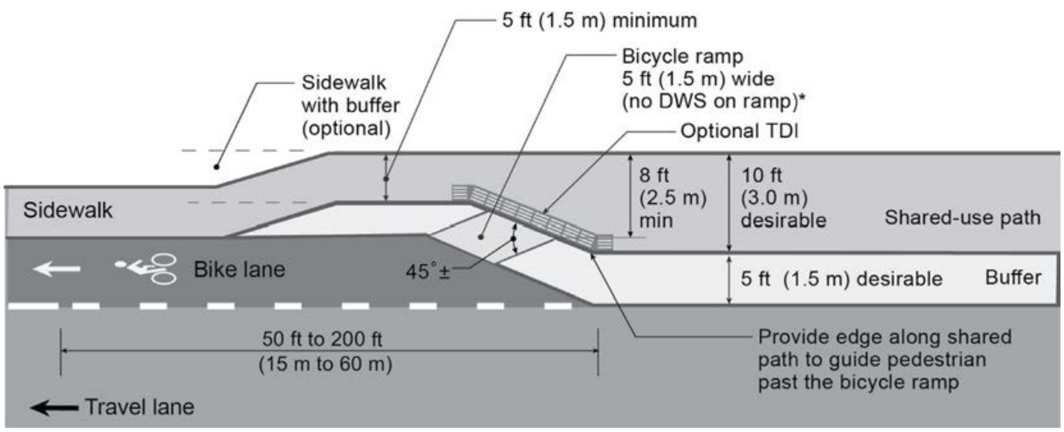


*DWSs are no longer recommended on bicycle ramps. If desired, optional TDIs can be used to delineate the desired path for pedestrians near the ramp. See FHWA (*12*).

Bicycle ramps can be challenging for people who are blind or have low vision. DWSs at the top of bicycle ramps have been recommended in past guidance and used in practice, but DWSs could be misinterpreted as a place to cross. Because of the potential ambiguity, current best practice emphasizes using the geometric configuration of the sidewalk as positive guidance for the desired walking path. This allows a person who is blind or has low vision to use the detectable edge of the sidewalk closest to the curb to maintain the correct alignment, with the bicycle ramp diverging at a distinct angle point and steeper slope. A TDI may also help guide pedestrians along the sidewalk in the vicinity of the bicycle ramp. The FHWA *Improving Intersections for Pedestrians and Bicyclists Informational Guide* further discusses the use of TDIs at intersections (*12*).

For single-lane roundabouts without sidewalks or where the sidewalk provided around the roundabout is not able to be widened for shared use (at least 8 ft [2.4 m] wide), bicyclists choosing to ride through the roundabout are served by the travel lane. In general, bicyclists who are comfortable riding on collector roadways can navigate low-speed, single-lane roundabouts without much difficulty. Bicyclists and motorists will travel at approximately the same speed through the roundabout, making it easier for bicyclists to merge with other vehicular traffic and take the lane

Exhibit 10.26. Transition from shared-use path to on-street bike lane.



*DWSs are no longer recommended on bicycle ramps. If desired, optional TDIs can be used to delineate the desired path for pedestrians near the ramp. See FHWA (*12*).

within the roundabout itself; encouraging these actions promotes positive safety outcomes for bicyclists in a roundabout but may be uncomfortable for less experienced riders. Because typical on-road bicycle travel speeds are between approximately 12 mph and 20 mph (20 km/h and 30 km/h), roundabouts designed to constrain motor vehicle speeds to similar values will minimize the relative speeds between bicyclists and motor vehicles, thereby improving bicyclists' perceived safety performance and comfort. Details about pavement markings for these applications can be found in Chapter 12: Traffic Control Devices and Applications.

If bicycle use is not permitted around the perimeter of the roundabout because its width is insufficient for shared bicyclist-pedestrian use, bicycle ramps are not placed directly in line with the bicycle lane or in a manner that suggests the sidewalk is the recommended bicycle path of travel through the roundabout. Instead, the bicycle lane is terminated to encourage bicyclists to take the travel lane to circulate through the roundabout. When bicycle lanes end in advance of the roundabout, a full-width bicycle lane normally ends at least 50 ft to 100 ft (15 to 30 m) in advance of the crosswalk. Terminating the bicycle lane reminds people biking that they need to merge. It also indicates to drivers that people biking will be entering the travel lane. A taper rate of 8:1 is advised to accommodate a design speed of 20 mph (30 km/h), which is appropriate for people biking and drivers approaching the roundabout.

10.4.6 Design for Separated Bicycle Facilities

A separated bicycle lane is a facility for exclusive use by bicyclists, located within or directly adjacent to the roadway, and physically separated from motor vehicle traffic with a vertical element. The combination of lateral buffer distance and vertical separation elements (such as flexible delineators, curb or height differences, or vehicle parking) can alleviate some on-street biking stressors. This section discusses separated bicycle facility features at roundabouts and does not cover all aspects of separated bicycle facilities. General guidance on separated bicycle facilities can be found in the NACTO *Urban Bikeway Design Guide* (*10*).

Separate bicycle facilities can be classified into three categories:

- **Separated bicycle lanes.** Also known as protected bicycle lanes, these are one-way bicycle facilities that use various methods for physical protection from adjacent motor vehicles. The minimum desired width for a separated bicycle lane is 5 ft (1.5 m). In areas with high bicyclist volumes or uphill sections, the desired width needs to be at least 6.5 ft (2.0 m) to allow bicyclists to pass each other. The desired width for a parking buffer is 3 ft (0.9 m), which allows for passenger loading and prevents door collisions. The buffer space is to be used to locate bollards, planters, signs, or other forms of physical protection. In the absence of a raised median or curb, the minimum desired width of the painted buffer is 3 ft (0.9 m).
- **Two-way separated bicycle lanes.** Also known as cycle tracks, these are physically separated facilities that allow bicycle movement in both directions on one side of the road. Two-way separate bicycle lanes share some design characteristics with one-way separated bicycle lanes but may require additional considerations at driveways and crossing locations. Two-way separated bicycle lanes can be used on one-way streets to reduce out-of-direction travel or on streets where there is not enough room for a one-way separated bicycle lane on both sides of the street. The desirable two-way cycle track width is 12 ft (3.6 m), with a minimum width of 8 ft (2.4 m) in constrained locations.
- **Raised bicycle facilities.** These are vertically separated from motor vehicle traffic and can be one-way or two-way. Raised cycle tracks may be at the level of the adjacent sidewalk or set at an intermediate level between the roadway and sidewalk to segregate the cycle track from the pedestrian area. A raised cycle track needs to include a raised or mountable curb, street furnishings, low vegetation, or parking to separate it from the adjacent motor vehicle lane.

When connecting from on-street bicycle lanes to a separated bicycle facility around the roundabout, a ramp angle of 20 degrees to 45 degrees is appropriate. The larger angle is preferred to minimize the likelihood of people who are blind or have low vision inadvertently traveling down the ramp and into the roadway. Wherever possible, bicycle ramps are to be placed entirely within the planting strip between the sidewalk and the roadway. Bicycle ramps can have slopes potentially as high as 20 percent; steeper slopes are preferred to distinguish from pedestrian ramps.

10.4.7 Pedestrian and Shared-Use Crossings

There are three basic crossing types at roundabouts: exclusive pedestrian crossings (crosswalks), exclusive bicycle crossings, and shared-use paths. At all crossing types, adequate sight distance must be provided so motor vehicle drivers entering or exiting the roundabout and pedestrians and bicyclists approaching the crossing can recognize a potential conflict and yield or stop as required. The information provided in Section 10.4.7 and Section 10.4.8 provides pedestrian and bicycle crossing considerations and highlights details and approaches to serving these users. Splitter island design details beyond the crossings are presented in Section 10.6.1. Details for crossings at bypass lanes are provided in Section 10.9.

Pedestrian crosswalk placement at roundabouts is based on providing pedestrian convenience, reducing pedestrian crash risk, and maximizing driver likelihood of stopping for or yielding to pedestrians:

- **Pedestrian convenience.** Pedestrians desire crossing locations as close to the roundabout as possible to minimize out-of-direction travel. The farther the crossing is from the roundabout, the more likely pedestrians are to choose a shorter route that may increase their crash risk. Placing crosswalks approximately vehicle length increments away from the entrance line reduces the chance that queued vehicles will stop within the crosswalk and block convenient pedestrian crossing movements.
- **Pedestrian safety performance.** Crossing distance and crossing location affect pedestrian crash risk. Crossing distance needs to be minimized to reduce pedestrian exposure to vehicular conflicts. Because of flared entries at most roundabouts, placing the crosswalk 20 to 25 feet (6.0 to 8.0 m) back from the entrance line reduces pedestrian crossing distance. This location also helps drivers focus on the pedestrian crosswalk before moving forward to look left for gaps in the circulating traffic stream.
- **Driver stopping or yielding.** Because drivers must stop for or yield to pedestrians in the crosswalk (or about to start crossing, depending on state law), crosswalk locations can affect vehicular operations, particularly at exits. A queuing analysis at the exit crosswalk may determine that a crosswalk location of more than one vehicle length may be desirable to reduce the likelihood of queuing into the circulatory roadway, thus improving a driver's willingness to yield or stop. Additional space on exit may also provide drivers with more time to perceive and react to pedestrians in the crossing and any active traffic control devices that may be present (see Chapter 12: Traffic Control Devices and Applications). Pedestrians may be able to better distinguish exiting vehicles from circulating vehicles at crosswalks located farther from the roundabout. The crosswalks need to be balanced with any associated out-of-direction travel for pedestrians that may unreasonably increase pedestrian travel time or potentially induce crossing movements between the designated crossing and the roundabout. *NCHRP Research Report 834: Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities: A Guidebook* provides further discussion (*22*).

Pedestrian crossings are commonly located in whole passenger car–length increments away from the edge of the circulatory roadway (or the yield line if one is provided). A typical minimum crosswalk setback of one passenger car length, or 20 ft (6.0 m), is advised, measured at the shortest dimension between the crossing and the yielding point for cars (which depends on pavement marking selection). At some roundabouts, particularly multilane roundabout exits, crosswalks are placed two car lengths (45 ft [14 m]) or three car lengths (70 ft [21 m]) away from the edge of the circulatory roadway, including a gap of 5 ft (1.5 m) between queued vehicles. This allows additional room for vehicular queuing and provides better visibility of active traffic control devices. The approach and exit geometry at roundabouts often make it impractical to keep the crosswalk setback at a consistent distance from the edge of the circulatory roadway.

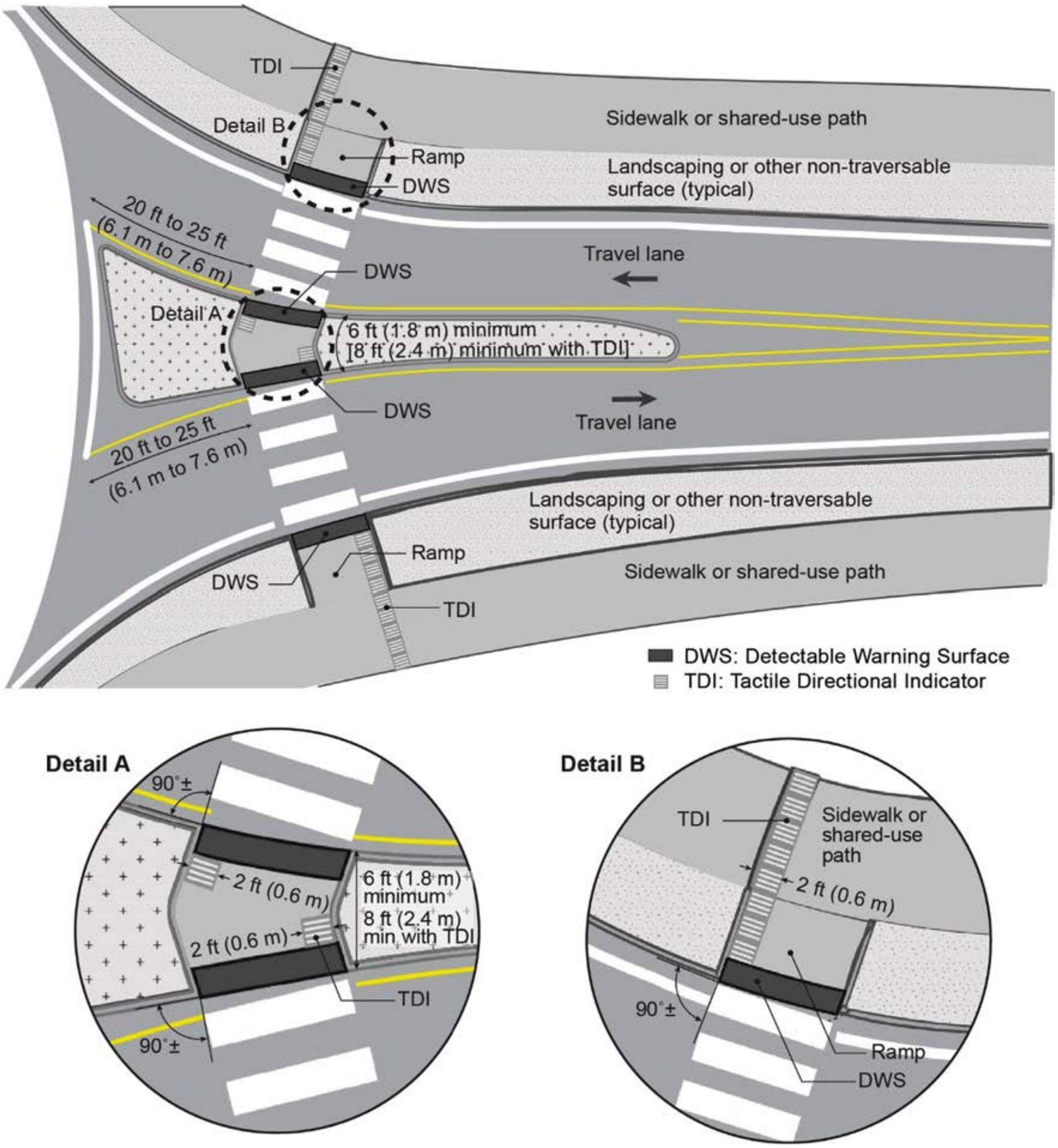
All roundabout pedestrian crossings have features in common:

- Ramps connect to the sidewalks at each end of the crosswalk.
- Ramps need to be the same width as the pedestrian crossing.
- Wherever sidewalks are set back from the roundabout with a buffer, ramps do not need flares and need curbed edges aligned with the crosswalk. This provides alignment cues for pedestrians, especially those who are blind or have low vision.
- DWSs are applied at the base of the ramp across its full width.
- If the splitter island is intended for use as a pedestrian refuge to allow two-stage pedestrian crossings, detectable warning surfaces are also applied along the full width of the path through the splitter island. The detectable warning surface on splitter islands begins at the curb line and extends into the cut-through area for 2 ft (0.6 m) in the direction of pedestrian travel. This results in a minimum of 2 ft (0.6 m) of clear space between detectable warning surfaces on a splitter island and an effective minimum splitter island width of 6 ft (1.8 m).
- A splitter island that is wider than the minimum requirements is highly desirable to accommodate groups of people, people pushing strollers, people on cargo bicycles or bicycles with trailers, equestrians, or other anticipated users. This provides a better quality of service for both pedestrians and bicyclists.

There are three common options for aligning a pedestrian crossing at a roundabout:

- **Place each leg of the crossing approximately perpendicular to the outside curb of the circulatory roadway for both the entry and exit lanes.** This creates an angle point in the walkway across the splitter island. This design is advantageous because it creates the shortest possible total crossing distance and makes it easier to build wheelchair-accessible ramps to the sidewalk (having the grade break at the gutter perpendicular to the curb). However, the resulting angle point in the splitter island may be too shallow to be detected by a person who is blind or has low vision, thus increasing the potential for veering over the length of the crossing. Exhibit 10.27 shows this option. This exhibit also includes a possible arrangement of optional tactile directional indicators as discussed in Section 10.4.3.
- **Place the entire crossing perpendicular to the centerline of the approach roadway. This results in angled crossings of the entry and exit lanes.** This design is advantageous because it offers a shorter overall walking distance for pedestrians and less variability in the distance between the edge of the circulatory roadway and the crosswalk. However, this can result in long and overly skewed crosswalks at roundabouts where the entry or exit lanes are angled significantly at the crosswalk location. In addition, since the curb ramp still needs to be perpendicular to the curb for people who use wheelchairs, the curb ramp may not be aligned parallel with the crosswalk and may not provide accurate alignment cues to people who are blind or have low vision. Exhibit 10.28 shows this option. Although not shown in the exhibit, optional tactile directional indicators may be used, as discussed in Section 10.4.3.
- **Stagger the crossing so that the exit side of the crossing is farther from the circulatory roadway than the entry side of the crossing.** This type of crossing supports supplemental crossing treatments for people who are blind or have low vision, increases driver sight distance and reaction time to pedestrians and active traffic control devices on exit, and increases space for vehicle queuing on the exit. Vehicle speeds may be higher on the exit side of a staggered crossing

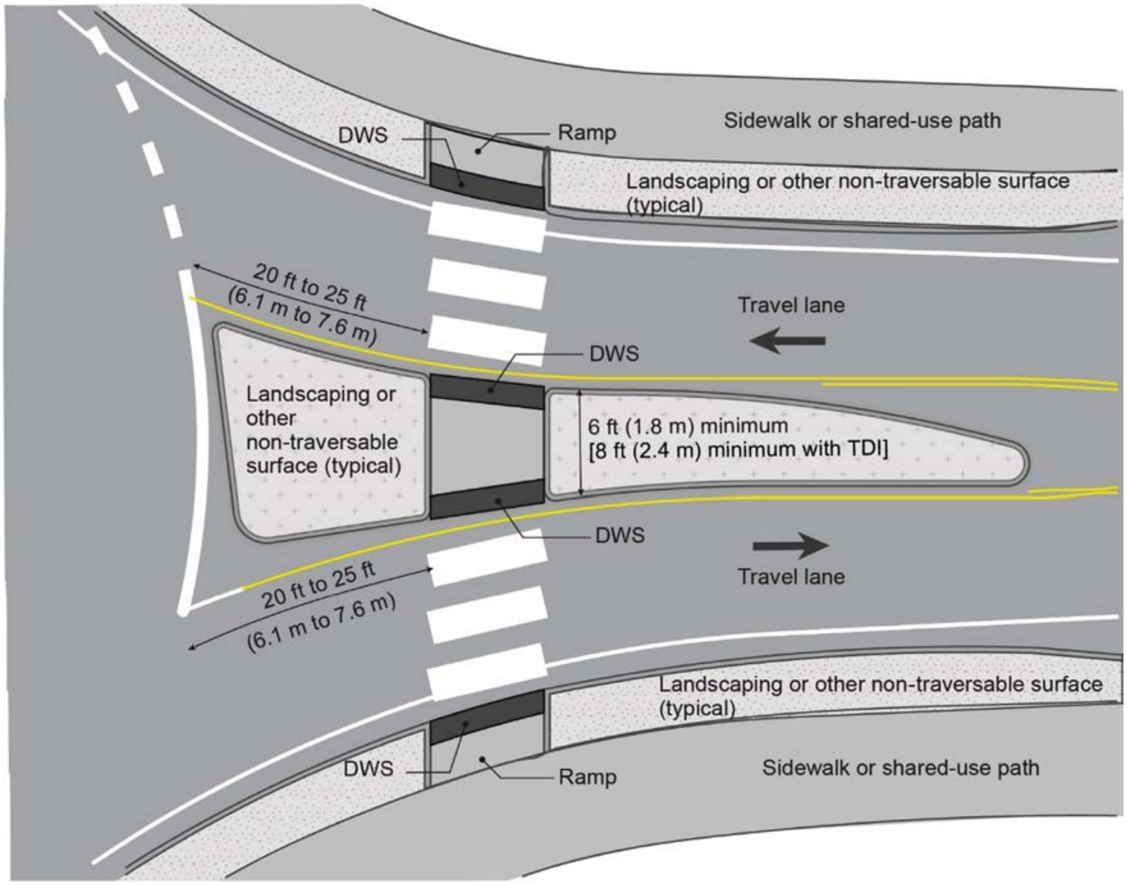
Exhibit 10.27. Typical features and dimensions of angled crossing.



unless supplemental treatments are used to control driver speeds, such as a raised crossing, as discussed later in the section, or active traffic control devices, as discussed in Chapter 12: Traffic Control Devices and Applications. A staggered design often requires a wider and longer splitter island to provide enough width for the staggered pedestrian crossing. Exhibit 10.29 shows this option. Although not shown in the exhibit, optional tactile directional indicators may be used, as discussed in Section 10.4.3.

The vertical design of the pedestrian crossing affects its horizontal design. It is generally desirable and more common for the walkway through the splitter island to be cut through instead of ramped. This is less cumbersome for wheelchair users and allows the cut-through walkway to align with the crosswalks, which provides guidance for all pedestrians, particularly those who are blind or have low vision. The cut-through walkway needs to be approximately the same width as the crosswalk, ideally a minimum width of 10 ft (3.0 m) to allow shared use by pedestrians and

Exhibit 10.28. Typical features and dimensions of straight crossing.

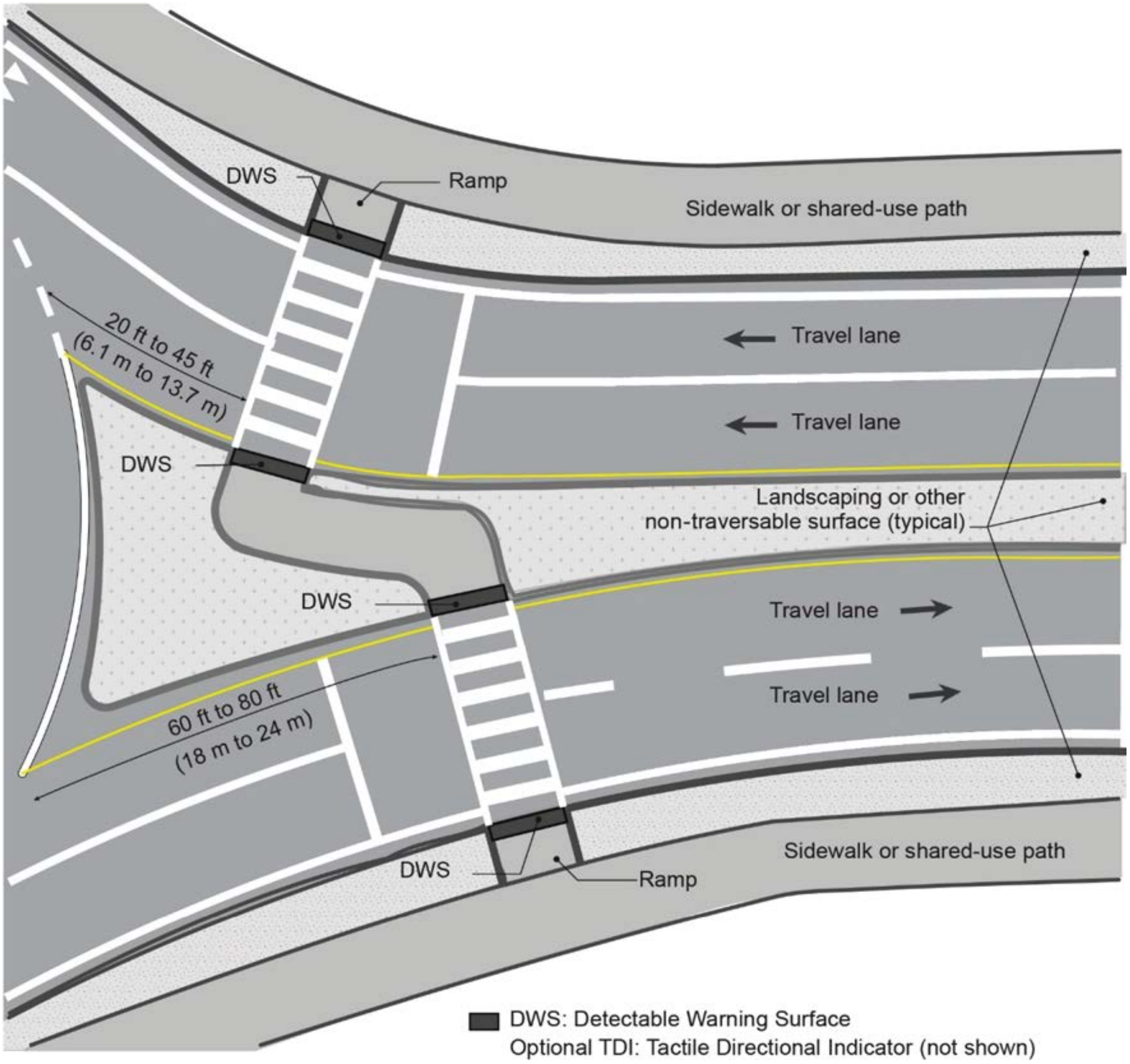


bicyclists. If separated bicycle and pedestrian crossings are provided, the pedestrian walkway can be narrower, to a minimum of 6 ft (1.8 m), to provide better wayfinding for people who are blind or have low vision. Exhibit 10.30 provides design details for splitter island pedestrian refuges for cut-through (preferred), mid-height, and full-height options. Some agencies adjust the edges of pedestrian passageways to facilitate winter maintenance; this is discussed further in Chapter 13: Curb and Pavement Details.

Raised crosswalks, or speed tables with pedestrian crossings on top, are another option for pedestrian crossings and can be applied to any of the alignment options presented previously. Raised crosswalks can encourage slow vehicle speeds where pedestrians cross and can also encourage enhanced driver yielding behavior. Raised crosswalks may reduce vehicle speeds at any location where vehicle speeds are higher than desirable at crosswalk locations. Raised crosswalks make crossings easier to navigate for people with mobility disabilities—who will not need to go up and down ramps—and people who are blind or have low vision to improve the likelihood of drivers yielding. Raised crosswalks need detectable warning surfaces (see Section 10.4.3) to delineate the edge of the street. Raised crossings need to be checked for possible conflicts with low-clearance vehicles (see Chapter 11: Vertical Alignment and Cross-Section Design) and maintenance (see Chapter 15: Construction and Maintenance).

Raised crossings can have drainage issues if not accounted for in the design. For raised crosswalks being installed into an existing drainage system, the provision of drainage may be costly or prohibitive.

Exhibit 10.29. Typical features and dimensions of staggered crossing (Z-crossing).

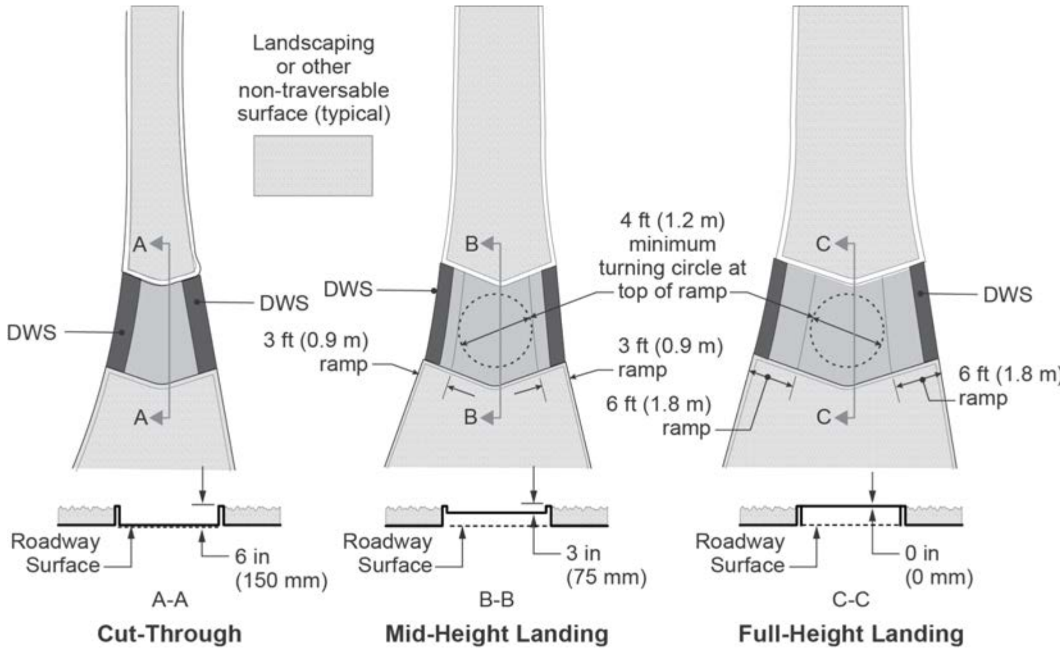


In all cases, determining the crossing configuration early in planning and design helps establish the roundabout footprint. For example, a staggered crossing placement at the exit and associated wider splitter island could result in a straighter alignment for motor vehicles that results in higher vehicle speeds than what might be present with an angled crossing alignment. On the other hand, the staggered crossing placement may be beneficial for pedestrian accessibility because it provides better visibility of traffic control devices or a raised crossing used for pedestrian accessibility to offset the higher potential speed. Therefore, establishing crossing locations and alignments early in the design process is critical to serving pedestrians while balancing other design objectives.

10.4.8 Crossings with Separated Bicycle and Pedestrian Facilities

When people walking and biking are separated on segments leading to the roundabout, it can be desirable to separate them at the roundabout. There are many possible configurations of separate bicycle and pedestrian crossings at a roundabout, and these depend on the context, facility type, and the location of the facilities at the roundabout. This section illustrates possible configurations along with associated advantages and disadvantages. The principles presented here can be used to evaluate other possible configurations. While bicycle crossings are typically located inside

Exhibit 10.30. Splitter island pedestrian refuge design details.



Source: Adapted from Minnesota Department of Transportation (23).

pedestrian crossings to match the configuration on segments leading to the roundabout, it may be preferable in some cases to reverse this by placing the pedestrian crossing inside the bicycle crossing. The examples below discuss this further.

Raised crossings can be beneficial over at-grade crossings because they can improve the likelihood for drivers to yield to bicyclists and pedestrians. Raised crossings need to maintain the raised area through pedestrian and bicycle crossings, and the downslope has to be flatter than the upslope to allow drivers to queue on the downslope. This helps shorten the distance between the raised crossing and a downstream yielding point, such as at the roundabout entry.

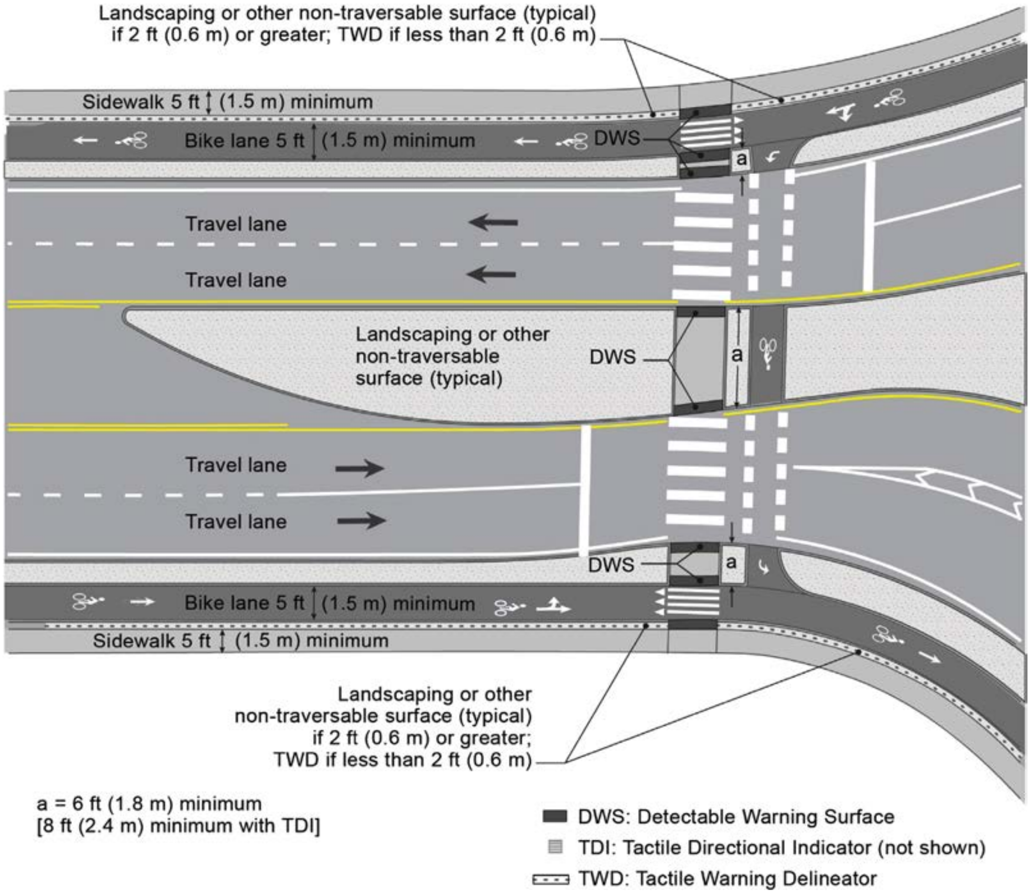
The separated bike lane approach to the bicycle crossing needs to result in bicyclists arriving at the queuing area at a perpendicular angle to approaching motorists. Channelizing islands would maintain separation between the bicycle and pedestrian crossings. When a separated bicycle crossing or a wider crossing with a mix of people walking and biking is provided, a wider splitter island that is 10 ft (3.0 m) wide or more is preferred, as it provides additional bicycle storage and more space for users to wait.

Exhibit 10.31 illustrates a possible arrangement of separated bicycle and pedestrian crossing, where the bicycle crossing is one-way, connects to one-way separated bicycle facilities, and is located inside the pedestrian crossing.

Advantages of this arrangement:

- Pedestrians and bicyclists are separated from each other, minimizing conflicts between modes and maximizing accessibility to the pedestrian crossing.
- Both crossings are straight, resulting in the fewest turns for bicyclists and pedestrians.
- The narrow separation between the bicycle and pedestrian crossings creates a single yielding point for drivers at each crossing. On the exit side, the crossings are located to provide visibility of traffic control devices and storage for one to two vehicles in each lane.
- The bicycle crossing is closer to the roundabout, resulting in less out-of-direction travel for some bicyclist movements.
- The alignment allows the bicycle and pedestrian crossings to be operated as a one-stage crossing to minimize delay for bicyclists and pedestrians.

Exhibit 10.31. Separate bicycle and pedestrian crossings with one-way separated bicycle lanes at multilane roundabout.



Disadvantages of this arrangement:

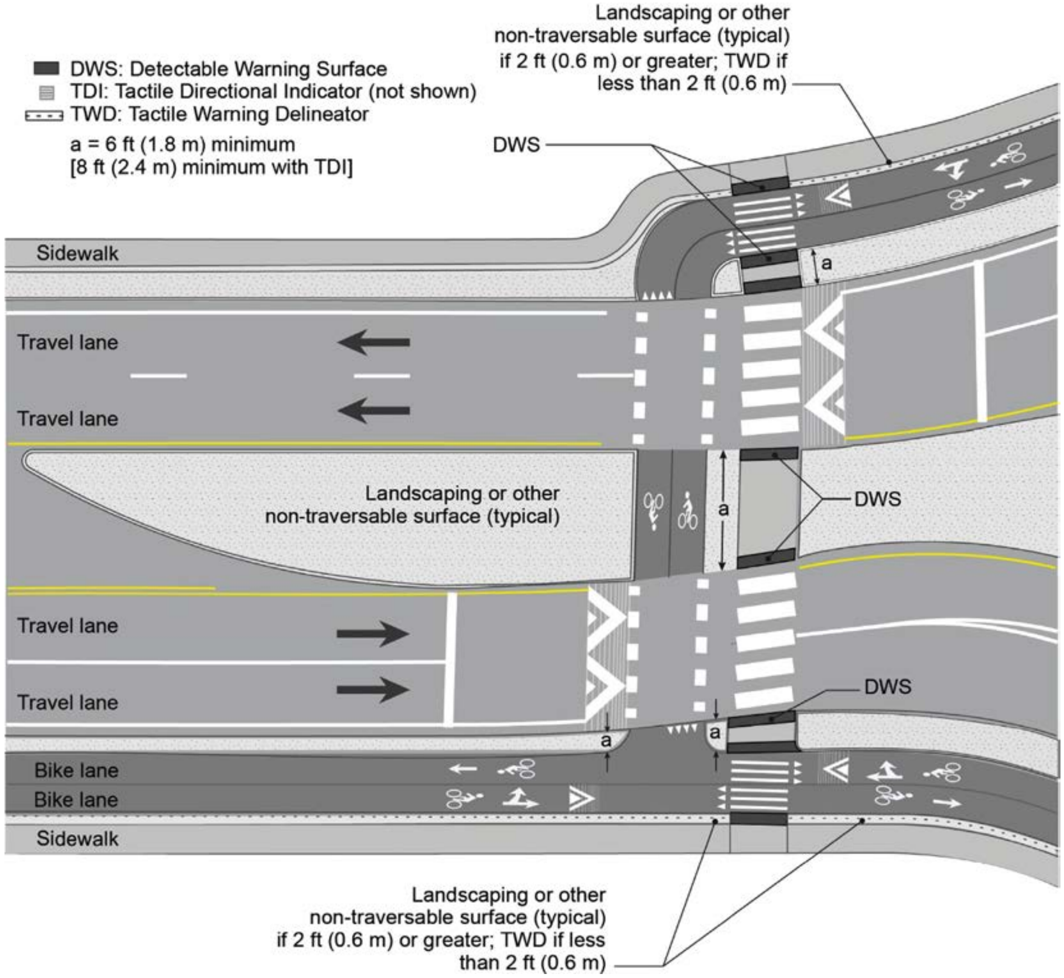
- The pedestrian crossing is farther from the roundabout, resulting in more out-of-direction travel for some movements.
- Depending on the overall length of the crossing, the pedestrian clearance time under one-stage operation is much longer than a typical two-stage crossing because of the additional travel time for both crossing and within the splitter island. This may increase vehicular queuing at the crossings, which may require shifting the crossings further from the roundabout to avoid extended interruptions within the circulatory roadway.
- If active traffic control devices are used with two-stage operation, the two-stage operation for bicyclists and pedestrians may not be obvious given the linear alignment of crossings. This may result in confusion to bicyclists and pedestrians over which display controls each crossing (including accessible pedestrian signals).

Exhibit 10.32 illustrates a possible separated bicycle and pedestrian crossings arrangement where the bicycle crossing is two-way and located outside the pedestrian crossing.

Advantages of this arrangement:

- Pedestrians and bicyclists are separated, minimizing conflicts between modes and maximizing accessibility for the pedestrian crossing.
- Both crossings are straight, resulting in the fewest turns for bicyclists and pedestrians.
- The narrow separation between the bicycle and pedestrian crossings creates a single yielding point for drivers at each crossing. On the exit side, the crossings are located to provide visibility of traffic control devices and storage for one to two vehicles in each lane.

Exhibit 10.32. Separate pedestrian and bicycle crossings at a multilane roundabout entry with two-way cycle track.

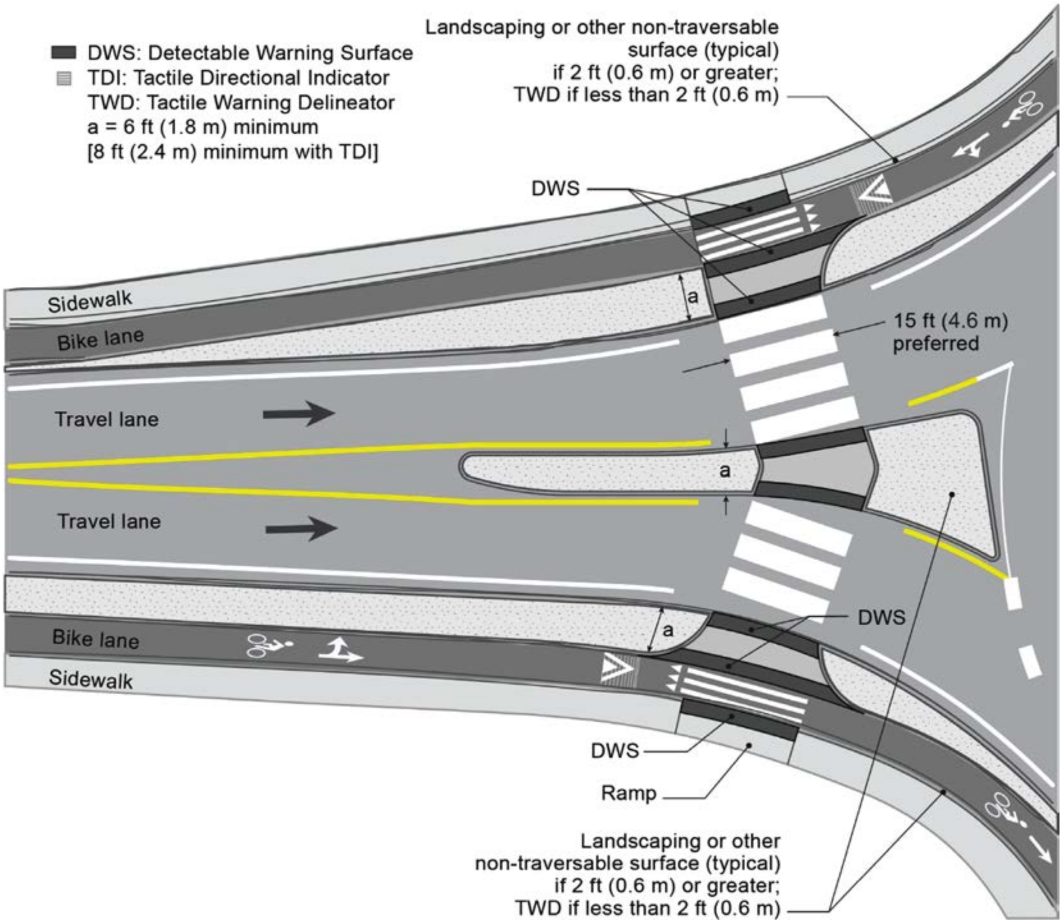


- The pedestrian crossing is closer to the roundabout, resulting in less out-of-direction travel for some movements.
- The alignment allows the bicycle and pedestrian crossings to be operated as a one-stage crossing to minimize delay for bicyclists and pedestrians.

Disadvantages of this arrangement:

- The bicycle crossing is farther from the roundabout, resulting in more out-of-direction travel for some movements.
- Depending on the overall length of the crossing, the pedestrian clearance time under one-stage operation is much longer than a typical two-stage crossing because of the additional travel time for both crossing and within the splitter island. This may increase vehicular queuing at the crossings, which may require shifting the crossings further from the roundabout to avoid extended interruptions within the circulatory roadway.
- If active traffic control devices are used with two-stage operation, the two-stage operation for bicyclists and pedestrians may not be obvious given the linear alignment of crossings. This may confuse bicyclists and pedestrians over which display controls each crossing (including accessible pedestrian signals).

Exhibit 10.33. Widened and shared-use crossing at roundabout.



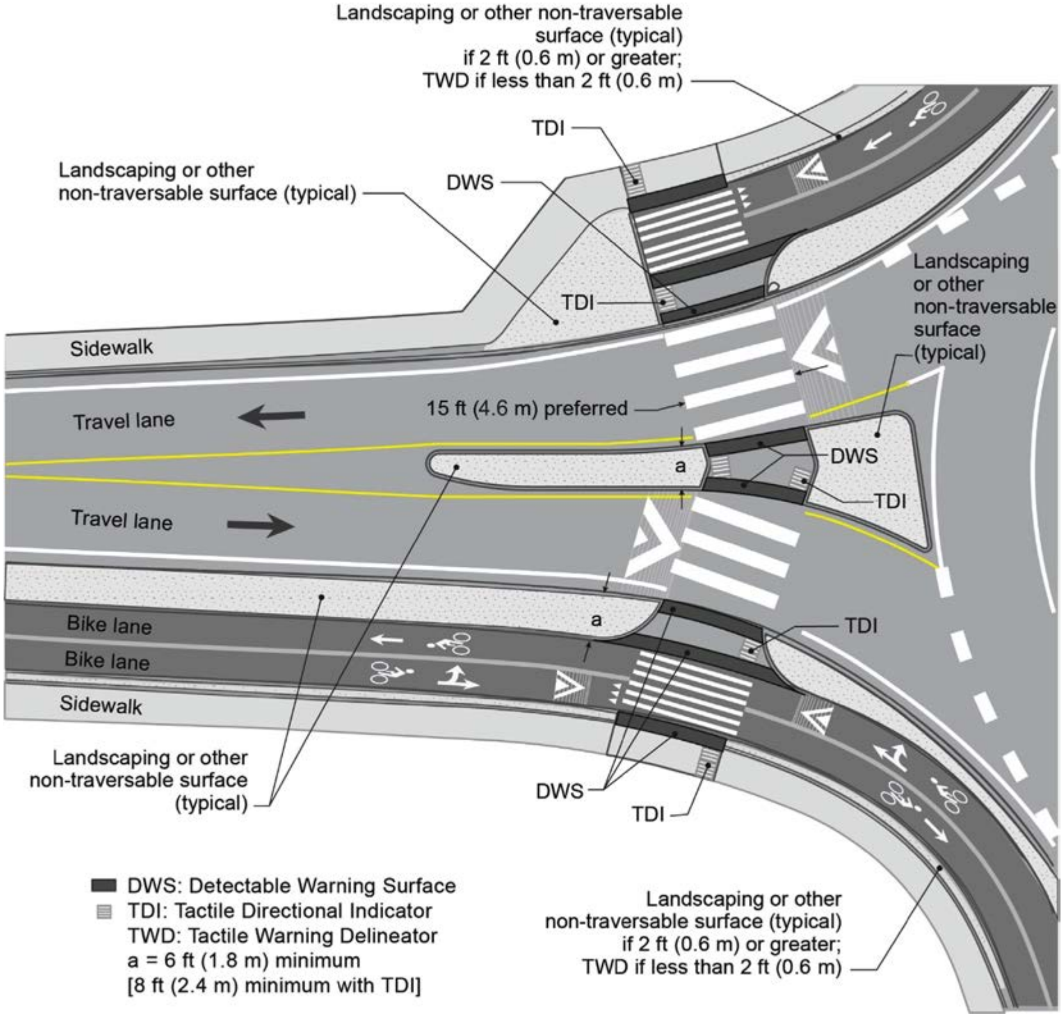
In constrained locations with separated bicycle and pedestrian facilities between roundabout approaches, it may not be possible to provide separate pedestrian and bicycle crossings because of space constraints, the inability to provide adequate separation between the crossings, or narrow splitter island widths. In these cases, a wider (at least 15 feet [4.6 m]) crossing is preferred. When a wider crossing is used, the curb ramp must be clearly differentiated from a driveway. This discourages drivers from using the curb ramp. An appropriate alignment needs to facilitate accessible crossing for all users, particularly people who are blind or have low vision. Exhibit 10.33 and Exhibit 10.34 provide examples. Details for crossings at bypass lanes are provided in Section 10.9.

10.5 Design for Large Trucks

Designing roundabouts for large trucks includes many common considerations between single-lane and multilane roundabouts. The principles associated with establishing design vehicle needs early in the project process apply to all roundabouts. This section builds on concepts presented in other portions of this Guide, including Chapter 4: User Considerations, for serving various user needs and considering target performance for large vehicles as the means of making roundabout design decisions.

The site configuration and other factors that influence the roundabout and roadway approaches also influence how well trucks are served. Roundabout design activities must jointly consider

Exhibit 10.34. Widened, shared, and raised shared-use crossing with two-way cycle track.



horizontal, vertical, and cross-section design needs. Attaining target performance often means iteratively considering and testing three-dimensional design elements. Horizontal design cannot be assessed in isolation.

For any roundabout configuration, practitioners must determine the design vehicle and how it will travel through the roundabout between curbs, with some movements possibly using a truck apron for trailer off-tracking. In addition, the larger, but less frequent, control (or check) vehicle must be selected. A variety of techniques can accommodate this vehicle, including hardened surfaces or aprons beyond the curb, passageways through splitter islands or the central island, removable signs, or other treatments. For some vehicle movements, the truck driver may have to drive their cab onto the truck apron.

For trucks with trailers, the roundabout needs to be designed for the cab of the truck to stay within the traveled way and not mount curbs, with only the trailer using the truck apron. This has been common practice throughout the United States and meets the expectations of most truck drivers. For roundabouts with traversable central islands, the cab and trailer can be assumed to use the traversable island. Vehicles assumed to use the truck apron or traversable central islands include trucks and emergency vehicles.

10.5.1 General Considerations

The design vehicle is a significant controlling factor for many single-lane roundabout dimensions. In particular, the choice of design vehicle and what larger vehicles need to be accommodated affect the ICD, entry width, entry radius, and circulatory roadway width. For example, in areas with high truck volumes (e.g., a freeway ramp terminal intersection, industrial areas, warehousing, or intermodal ports), a larger diameter better serves large vehicles and minimizes the widths for the entries, exits, and circulatory roadway. However, smaller-diameter roundabouts with appropriate entry and exit configurations may adequately serve high truck volumes. In general, a fundamental design objective may be to provide the smallest roundabout possible (commensurate with the project context). This includes the project characteristics, project type, and project influences.

Design vehicle volumes and patterns can greatly influence roundabout planning and design decisions. Large vehicles traveling as *through* vehicles can readily be served by roundabouts in the lower ICD range. Truck routes and designated routes for permitted vehicles can support design choices. Minor intersection approaches may be designed differently than the major roadway. For reconstruction projects with constrained right-of-way, it might be reasonable to configure the intersection so that single-unit trucks and buses can easily make all movements. For example, a minor approach serving a residential area may serve the occasional moving truck. The right turns to and from the minor leg might be designed to accommodate the rare larger truck. However, if other access to the area is available, these accommodations may be less critical.

A fundamental consideration of single-lane roundabout design is whether a central island is to include a non-traversable portion (i.e., a landscaped or hardscaped area) or if design vehicles may traverse the entire central island. As ICD becomes smaller, it becomes more likely that a roundabout will require a fully traversable central island along with potential partially or fully traversable splitter islands. In this situation, landscape areas, signs, or street furniture may have to be positioned out of the expected truck path to accommodate larger vehicles.

Practitioners may configure the roundabout to serve specific design vehicles. Passenger buses need to be accommodated within the circulatory roadway without tracking over the truck apron, which could jostle bus occupants. Buses and motor coach dimensions can vary significantly between type and configuration. Recreational routes are often frequented by motor homes and other recreational vehicles. Agricultural areas are frequented by tractors, combines, and other farm machinery. Manufacturing areas may see oversize trucks. Each of these special design vehicles needs to be incorporated into the design process early, as they can affect fundamental design decisions about size, position, and approach alignment.

At single-lane roundabouts, the right-turn movement is often the controlling intersection movement. This is especially true for locations with skewed approach alignments (less than a 90-degree angle between adjacent approach centerlines). To adequately accommodate the design vehicle, the corner radius may sometimes be increased to serve the vehicle swept path. This may result in a wide portion of entry and portion of the circulatory roadway. This wide area may be marked with striping (which may create geometric speed control challenges) or addressed via an external truck apron. Pedestrian waiting areas must be established outside the truck swept path.

Exhibit 10.35 depicts a single-lane roundabout in a rural location on a state highway. The right side of the splitter island at the entry was pulled away from the edge of the traveled way to accommodate a design vehicle larger than a WB-67. While this splitter island design serves large vehicles, it could also diminish the beneficial channelization effect that guides users onto the circulatory roadway as drivers tend to follow curb lines. While it does provide additional space, there may be other options available to serve large vehicles.

Mini-roundabouts and compact roundabouts require unique considerations compared with roundabouts with non-traversable central islands. The location and size of mini-roundabouts and compact roundabout central islands (and the corresponding width of the circulatory roadway)

Exhibit 10.35. Example of treatments to serve large vehicle.

LOCATION: OR 126/SW Tom McCall Road, Prineville, Oregon.
SOURCE: Kittelson & Associates, Inc.

are dictated primarily by passenger car swept path requirements. Passenger cars should be able to navigate through the intersection without traversing the central island.

Compact roundabouts may have fully traversable central islands (to serve design vehicles) with ICD dimensions that commonly allow for raised or mountable splitter islands. Mini-roundabout ICD dimensions are sometimes small enough to require the entire splitter island or the portion of splitter island between the circulatory roadway and the pedestrian crossings to be flush or fully mountable. For mini-roundabouts and some compact roundabouts, a small ICD often results in buses having to travel over the central island. For compact roundabouts with larger ICDs, it may be possible to accommodate the swept path of a bus vehicle within the circulatory roadway.

10.5.2 Truck Aprons

This section discusses truck aprons as they relate to horizontal alignments and features. Chapter 11: Vertical Alignment and Cross-Section Design discusses vertical considerations for truck aprons and other vertical design elements. Truck aprons may be constructed in a variety of ways and with varying materials. Chapter 13: Curb and Pavement Details discusses this in more detail.

A traversable truck apron on the central island is typical for most single-lane roundabouts to accommodate large vehicles while minimizing other roundabout dimensions. The width of the truck apron is based on the swept path of the design vehicle, with the remainder being the non-traversable portion of the central island. External truck aprons may be used on the external curb areas, preferably away from pedestrian crossings, to support truck swept paths while constraining the fastest path for smaller vehicles. Some agencies use truck aprons that are wider than the swept path of the design vehicle, such as to facilitate snowplow operations (the snowplow operator drives on the truck apron) or to allow for parking of a maintenance vehicle.

Truck aprons need to be traversable to trucks but elevated to discourage passenger vehicle drivers from using them. CAD-based vehicle turning path simulation software can determine truck apron width. Truck aprons commonly have the following characteristics:

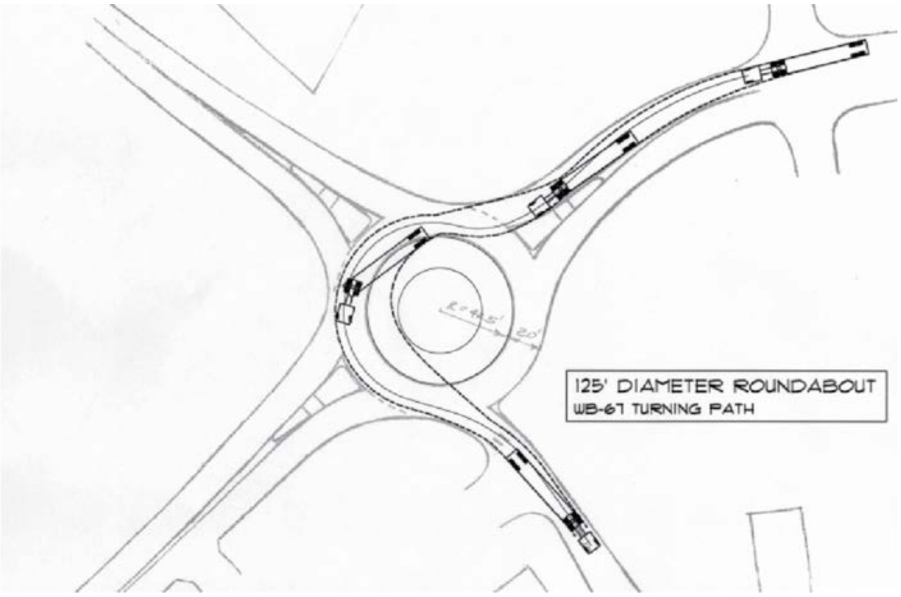
- Truck aprons may range in width from 3 ft to 15 ft (1.0 m to 4.6 m) and be configured as needed to serve the design vehicle. Some agencies use minimum truck apron widths of 10 ft to 12 ft (3.0 m to 3.6 m) to allow for maintenance vehicles and snowplows to access the roundabout. If truck aprons beyond 15 ft (4.6 m) in width are needed, this may be an opportunity to evaluate the benefit of a larger ICD or a smaller ICD with a fully traversable central island.

- The truck apron may benefit from being constructed from a different material than the circulatory roadway pavement to differentiate it from the roadway and the sidewalk. The apron may be colored to further differentiate it from roadways and sidewalks. However, a well-defined pedestrian circulation pattern with an appropriate buffer to the circulating roadway and clear crossing points may minimize the need for this distinction. Well-defined pedestrian circulation patterns and design features benefit all pedestrians, including people who are blind or have low vision.

Exhibit 10.36 and Exhibit 10.37 show sketches of the same roundabout with two different ICDs: 125 ft (38 m) and 140 ft (43 m), respectively. As illustrated in the exhibits, a wider truck apron is often required to accommodate a left-turning vehicle at a roundabout with a smaller ICD. This limits the amount of central island landscaping possible, which may then limit the visibility of the central island on the approach. Wider entries and larger entry radii are also typically required for a small-diameter roundabout to accommodate the design vehicle.

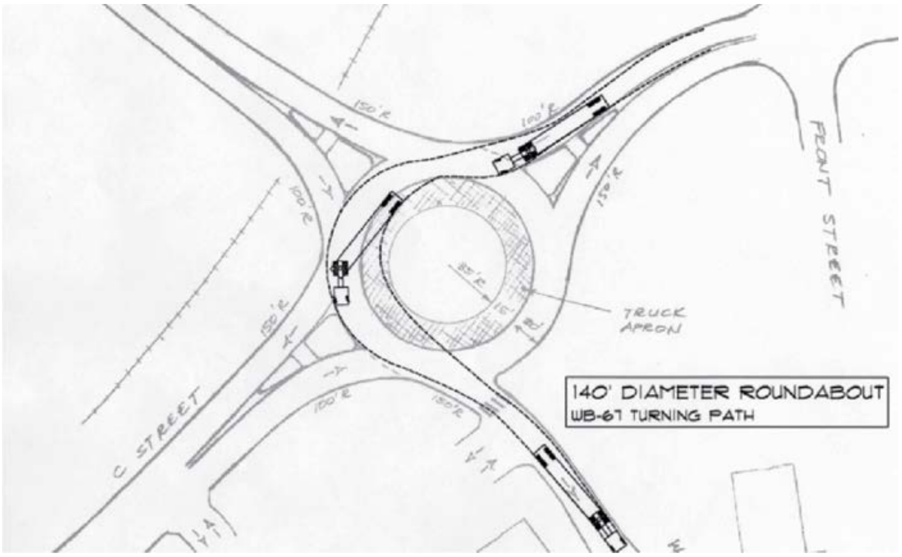
Truck aprons may also be used for maintenance vehicle parking or customized to serve swept paths for large trucks. Exhibit 10.38 shows a single-lane roundabout with a truck apron customized to meet the design vehicle through movement swept path. This configuration also depicts pavement behind a mountable curb that serves as an external truck apron. In this example, the external truck apron passes through the pedestrian crossing at each entry. This is to be avoided wherever possible; however, if unavoidable, the apron can be lowered to crosswalk level through the pedestrian crossing and then returned to its standard elevation after the crosswalk. This minimizes confusion for pedestrians with vision disabilities, who could otherwise mistake the truck apron for an appropriate place to wait. It is necessary to serve pedestrians with mobility disabilities by maintaining appropriate grades and cross slopes through the crossing.

Exhibit 10.36. Swept paths for WB-67 design vehicle at smaller-diameter roundabout.



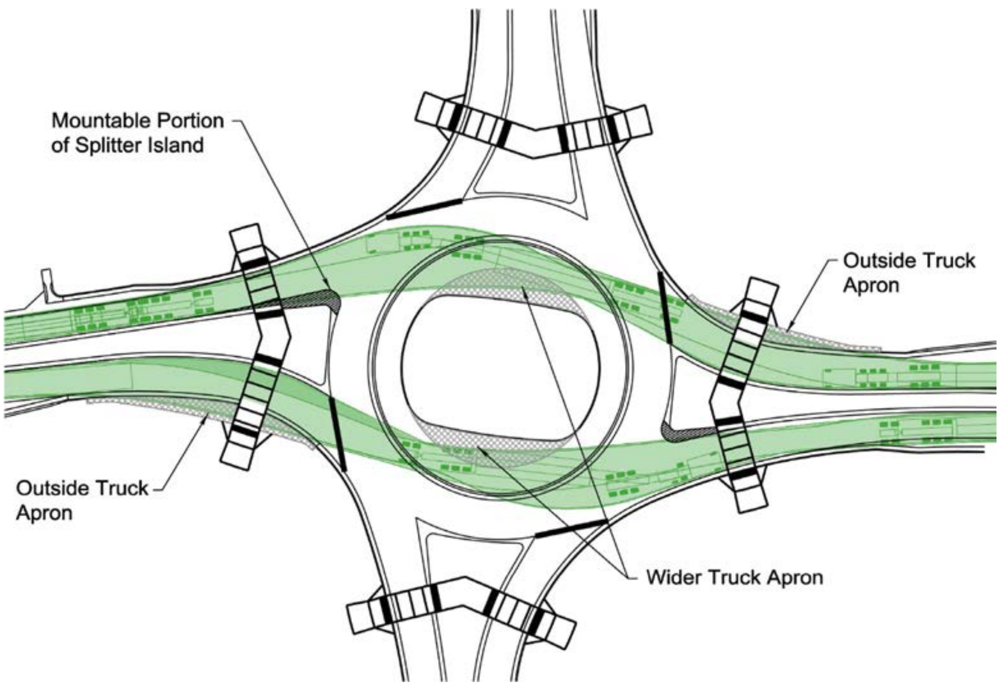
NOTE: Inscribed circle diameter of 125 ft (38 m).
SOURCE: *NCHRP Report 672* (*2*).

Exhibit 10.37. Swept path for WB-67 design vehicle at larger-diameter roundabout.



NOTE: Inscribed circle diameter of 140 ft (43 m).
SOURCE: *NCHRP Report 672* (*2*).

Exhibit 10.38. Truck apron customized for design vehicle and pedestrian crossings.



SOURCE: Adapted from Georgia Department of Transportation (*3*).

10.5.3 Design Vehicles in Multilane Roundabouts

Multilane roundabouts commonly have wider entries, circulating roadways, and exits compared with single-lane roundabouts. Multilane roundabout design vehicle considerations must consider the swept paths on entry, on exit, and within the circulatory roadway.

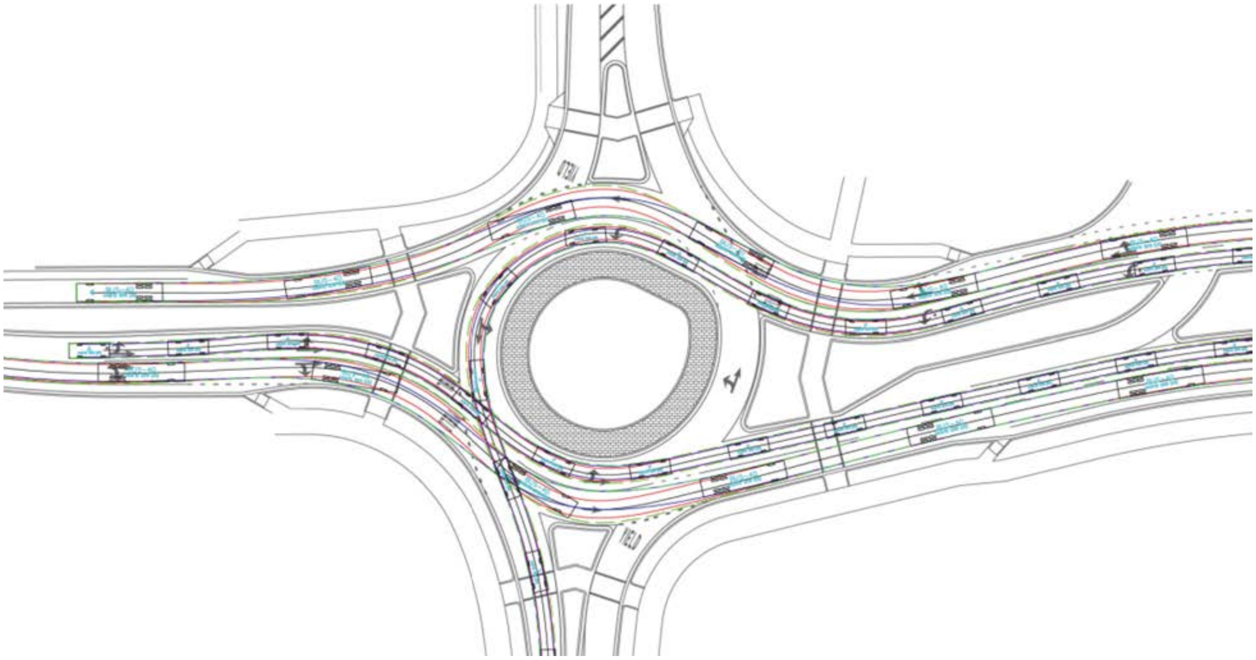
For multilane roundabouts, the design vehicle may operate under one of the following two design cases:

- **Straddle lanes.** For this type of design, the design vehicle is assumed to use the entire curb-to-curb width for entering, circulating, and exiting along with the truck apron as needed. Both trucks and large passenger vehicles (e.g., buses) may straddle lanes.
- **Stay-in-lane.** For this type of design, the design vehicle is assumed to stay in-lane on entry, while circulating, and while exiting. Truck aprons are commonly used to serve large vehicles in the inside lane, but they typically cannot be used by large vehicles in the outside lane. Large passenger vehicles (e.g., buses) should stay in either lane without using the truck apron.

The anticipated frequency of a particular design vehicle guides roundabout design. For instance, a location with expected infrequent use by a WB-67-size tractor-trailer may allow the occasional WB-67 to straddle lanes in the roundabout. A different location could have frequent bus service that would necessitate accommodating buses within their own lane to travel adjacent to a passenger car. Anticipated design vehicle volumes and patterns dictate design evaluations and decisions. A particular roundabout may have multiple design vehicles depending on the unique site characteristics; vehicle combinations beyond WB-62 and WB-67 vehicles may be applicable to serve a specific location's need. Exhibit 10.39 shows an example of side-by-side navigation for a bus and passenger car.

As noted in Chapter 4: User Considerations, some states have amended their vehicle codes to address trucks at roundabouts. An example of state-specific signs associated with these laws is provided in Chapter 12: Traffic Control Devices and Applications.

Exhibit 10.39. Side-by-side navigation for bus and passenger car.



SOURCE: Kittelson & Associates, Inc.

10.5.4 Designing for Oversize and/or Overweight Vehicles

This section presents the horizontal geometric aspects for accommodating OSOW vehicles; Chapter 11: Vertical Alignment and Cross-Section Design presents vertical aspects. Techniques for checking OSOW passage through a design—both CAD-based techniques and field test techniques—are like those used for other truck types and are provided in Chapter 9: Geometric Design Process and Performance Checks and Appendix: Design Performance Check Techniques. Additional information on international examples can be found in the *Kansas Roundabout Guide,* second edition (*24*).

OSOW vehicles, discussed in Chapter 4: User Considerations, are vehicles having one or more characteristics that require a permitting process to use the roadway system. This can include dimensions that exceed allowed parameters without a permit, such as length, height, width, or weight. Some of these vehicles also have low ground clearance. The inherent characteristics of roundabout design—using horizontal geometry to control vehicle speeds and separate movements—must be adapted to support the passage of an OSOW vehicle, which benefits from as straight an alignment as possible.

On roadway systems where OSOW vehicles are allowed, a successful roundabout design accommodates them under permitted conditions while meeting the performance objectives for the roundabout under regular operating conditions. A variety of techniques are available for successfully accommodating OSOW vehicles. Each depends on the site's context and the OSOW check vehicle's specific characteristics and intended travel patterns. An OSOW vehicle is typically treated as a check vehicle, not a design vehicle, because its passage requires permits for travel and is typically accompanied by pilot vehicles and flaggers. This creates circulation options unavailable to other vehicles.

One technique for accommodating OSOW vehicles is to provide bypass lanes for truck movements. This is different than a right-turn bypass for all vehicles. An example of this is shown in Exhibit 10.40 for a roundabout in Marion County, Kansas. This type of treatment may be feasible in rural environments, where sufficient land is available to provide the bypass lanes. These bypass lanes are preferably gated for authorized vehicles only and are not intended for general traffic use. If signs for authorized vehicles are provided instead of gates, the bypass lanes may be used

Exhibit 10.40. Example of OSOW bypass lanes.

NOTE: Gates are preferred over signs to control the bypass lanes to prevent unauthorized use.
LOCATION: US 56-K-150/US 77, Marion County, Kansas. SOURCE: Google Ea

by unauthorized drivers, thus adding unsignalized intersections as points of potential conflict. In some cases, the bypass lane can be part of construction staging to support the construction of the roundabout under traffic.

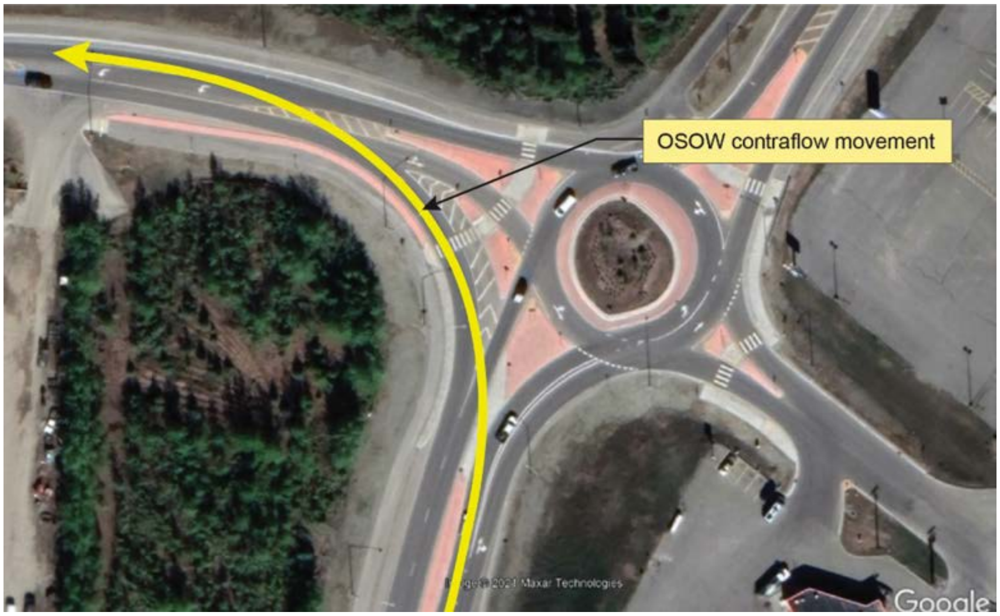
Another technique for accommodating OSOW vehicles is to use a bypass lane in either normal or contraflow patterns. This technique may be especially effective if the OSOW pattern is restricted to turns between two adjacent legs. An example of this is shown in Exhibit 10.41. The right-turn bypass lane is used in both directions for OSOW trucks. When a contraflow OSOW left-turn movement is needed, flagging is used to enable the OSOW vehicle to traverse the right-turn bypass lane in a contraflow direction using traversable sections in the median. While the contraflow bypass lane is used for the longest OSOW vehicles, standard trucks and shorter OSOW vehicles can circulate normally using straddle-lane operation with the extended truck apron.

For roundabouts where OSOW vehicles make through movements along only one axis (e.g., the major street), it may be desirable to provide a bypass lane through the central island. An example of this technique is shown in Exhibit 10.42. For example, this technique could be used along state highways as well as at interchange ramp terminal intersections where the OSOW vehicle must temporarily depart from the freeway because of bridge restrictions.

For most applications where OSOW vehicles can travel in either direction, a bypass lane that connects the two exits is preferred. Under flagging operation, the OSOW vehicle crosses over in advance of the splitter island, travels contraflow through the exit, passes through the central island, and then resumes travel along the exit as normal. The advantages of this method include:

- Roundabout exits usually have larger radii or tangents than roundabout entries, which are designed with geometric speed control as a primary objective.
- The central island immediately in front of the entry is retained for signs, landscaping, or other treatments to provide terminal vista for the roundabout entry.

Exhibit 10.41. Example of OSOW contraflow movement using a bypass lane.



LOCATION: Danby Street/Wembley Street, Fairbanks, Alaska. SOURCE: Google Earth.

Exhibit 10.42. Example of roundabout with OSOW truck accommodation diagonally across the central island.

LOCATION: L555/Hoeber-und-Mandelbaum-Straße, Waghäusel, Germany.
SOURCE: Google Earth.

- The bypass lane does not line up with normal operations, thus reducing the need for gated operation. Gated operation may still be preferred to prevent unauthorized access to the central island.

Exhibit 10.43 presents a roundabout with a gated central island cut through at a location in Green Bay, Wisconsin.

Another common treatment is to use an enlarged truck apron around the central island, external truck aprons on one or more entries or exits, or a combination. When using an enlarged truck apron, practitioners must verify that the roundabout's visibility to drivers approaching the intersection is appropriate for the context. Exhibit 10.44 and Exhibit 10.45 show examples of these applications. In these cases, sign placement, landscaping, and other treatments may be compromised.

Exhibit 10.43. Plan view of a roundabout with a gated central island cut through for OSOW vehicles.

LOCATION: Mid Valley Drive/Scheuring Road, Green Bay, Wisconsin.
SOURCE: Google Earth.

Exhibit 10.44. Enlarged truck apron for OSOW through movements.

LOCATION: GA 16/Holonville Road, Griffin, Georgia.
SOURCE: Georgia Department of Transportation.

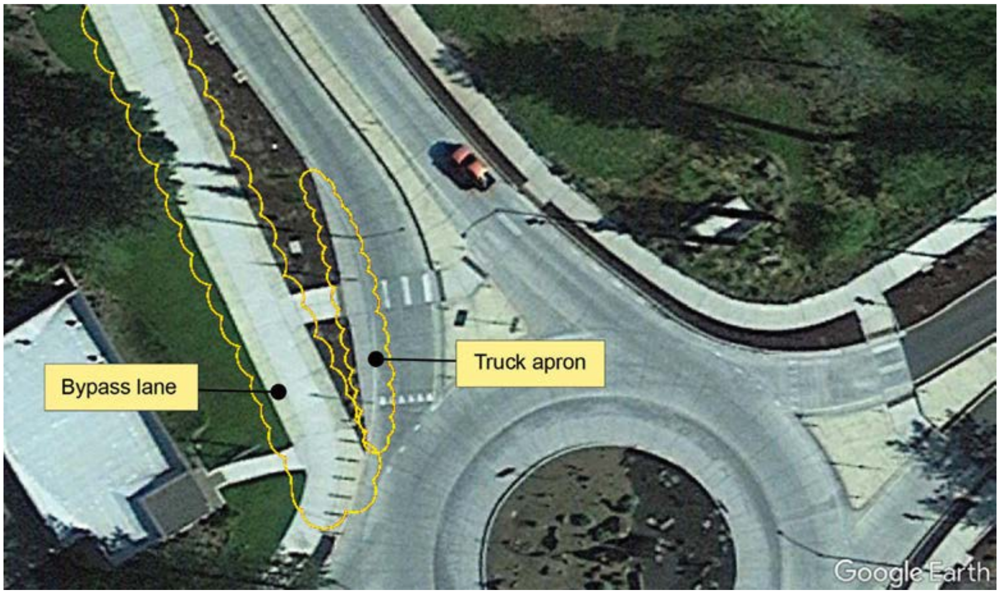
At interchange ramp terminal intersections or in other cases where OSOW travel is one-way, an extended truck apron lined up from entry to exit in the direction of OSOW travel may be preferable. In these cases, sign placement, landscaping, and other treatments may be compromised.

An external truck apron may serve OSOW vehicles for some applications. External truck aprons are to be avoided where they intersect pedestrian facilities because of the potential confusion they can create for people who are blind or have low vision. If the external truck apron crosses a pedestrian crossing, pedestrian accessibility must be maintained at the pedestrian crossing by

Exhibit 10.45. OSOW truck accommodation on one side of the central island.

LOCATION: County Road T/I-94 Westbound Ramps, Saint Croix County, Wisconsin. SOURCE: Google Earth.

Exhibit 10.46. Example of external truck apron and OSOW bypass lane.



LOCATION: US 20/West Barclay Drive, Sisters, Oregon. SOURCE: Google Earth.

dropping the external truck apron to the level of the crossing and then resuming after the crossing. Exhibit 10.46 shows an example of this application. A bypass lane reserved for OSOW use was also used during staged construction.

10.6 Single-Lane Roundabouts

This section presents parameters and guidelines for designing horizontal geometric elements at single-lane roundabouts. Many of the same principles also apply when designing multilane roundabouts, although techniques for designing multilane roundabouts are often different and more complex because of additional factors.

A fundamental part of single-lane roundabout design is whether a central island will include a non-traversable portion (i.e., a landscaped or hardscaped area) or if design vehicles may traverse the entire central island. A mini-roundabout or compact roundabout is well suited for constrained locations and could be considered in other applications. As presented in Chapter 2: Roundabout Characteristics and Applications, there is a continuum of single-lane roundabouts ranging from the smallest ICD with fully traversable features to larger ICD, single-lane forms with non-traversable features.

The design of a roundabout with a traversable central island applies the same principles as the design of a roundabout with non-traversable features in the central island. Key considerations include vehicle channelization, design vehicle paths, and intersection visibility. Given that the central islands for mini-roundabouts and some compact roundabouts are fully traversable, the entries need to guide drivers to the intended path. Sub-optimum designs may result in drivers turning left in front of the central island (or driving over the top of it), improperly yielding, or traveling at excess speeds through the intersection.

There are many ways to initiate a roundabout layout. One method is based on locating the roundabout and begins by assessing the intersection constraints and considering approach alignment and entry configurations that support speed control. This generally includes an iterated approach and entry configuration while considering the footprint of the roundabout. With an initial ICD and roundabout location established, the next step is to refine the roadway approaches, entries, and exits so they will serve design vehicles and manage entry speeds. While it may not be intuitive, establishing the pedestrian crossing, refuge space, and channelization needs of the painted taper and splitter island is an early activity that sets the foundation for configuring the entries and exits. Adapting the splitter island shape and length is part of attaining target speed control needs on the approach and at the entry.

Once channelization and pedestrian refuge needs are established, the roadway approaches, entries, and exits can be developed. Following this order establishes and protects the pedestrian crossing and refuge configuration and allows the entries and exits to meet speed and design vehicle performance needs. Starting from the inside and working outward (i.e., left edges of the traveled way to the right edges) eliminates the risk of having insufficient pedestrian refuge and waiting areas.

With each approach configured, performance checks can evaluate the design. Performance check results will support subsequent design iterations that can include adjusting the ICD, roundabout location, approach alignments, and entries and exits to best meet user needs and target performance for all users.

10.6.1 Splitter Island Types

Splitter islands (also called *separator islands*, *divisional islands,* or *median islands*) serve a variety of purposes:

- They can provide refuge for pedestrians if sized appropriately.
- They assist in controlling speeds.
- They guide motor vehicles with the correct direction of circulation to deter wrong-way movements.
- They physically separate entering and exiting traffic streams.
- They provide space for placing traffic control devices.

This section presents a discussion of the overall splitter island design. Section 10.4 discusses key features and considerations for serving pedestrians and bicyclists through the splitter island; Section 10.6.2 presents other splitter island dimensions; and Chapter 13: Curb and Pavement Details presents design details, such as curbing options, sloped noses, and other features.

The splitter island will be the first design consideration after sizing, positioning, and selecting each approach alignment. The size of the splitter island (i.e., length and width) is considered before designing the approach entries and exits. Practitioners can consider a painted taper that initiates the transition from the roadway segment (i.e., the typical section of the adjacent roadway segments) at the first iteration of the splitter island configuration. In some cases, the length of the splitter island may be an outcome of the approach alignment needed to support speed control (e.g., applying reverse curvature), such as with an offset-left approach configuration.

Early consideration of the full transition from the roadway segment to the roundabout entry allows the design to account for speed reduction (if needed) and a flowing and natural progression of geometric elements that communicate the appropriate driving demands (i.e., self-describing and self-enforcing roadway). Establishing control points for the splitter island envelope (i.e., width, length, and shape) before designing the entry and exit geometry greatly increases the success of establishing properly sized splitter islands as the first concepts. As the design is refined and adapted based on performance checks, the final raised island portion of the approach will eventually meet the appropriate dimensions (i.e., offsets, tapers, length, widths).

For mini-roundabouts and compact roundabouts, splitter islands serve the same purpose that they serve at other roundabout forms. They align entering and exiting vehicles, promote deflection

Exhibit 10.47. Splitter island types.

Design Aspect	Raised and Non-Traversable	Raised and Traversable	Flush and Painted
Overall recommendation	Preferred	Acceptable if needed	Least desirable
Design vehicle	All design vehicles can navigate the roundabout without tracking over the splitter island area.	Some design vehicles may safely travel over the splitter island area; truck volumes are low.	Vehicles are expected to travel over the splitter island area with relative frequency to navigate the intersection.
Pedestrian use	Provides refuge for two-stage pedestrian crossings if sized appropriately	Requires one-stage pedestrian crossings	Requires one-stage pedestrian crossings
Area	50 ft^2 (4.6 m^2) or greater	50 ft^2 (4.6 m^2) or greater	Less than 50 ft^2 (4.6 m^2)
Approaching motor vehicle speeds	All speeds	All speeds	25 mph (40 km/h) or less

and counterclockwise circulation, and provide pedestrian refuge. Splitter islands may be traversable or flush depending on the size of the island and whether design vehicles need to track over the top of the splitter island to navigate the intersection.

Splitter islands can be raised and non-traversable by motor vehicles, raised and traversable by motor vehicles, or flush and painted. In general, **raised islands are to be used where possible**, and flush or painted islands are generally discouraged. However, in some constrained locations, one or more splitter islands may need to be fully traversable or painted. Depending on site conditions and design vehicle travel patterns, some combinations of these splitter islands may be appropriate. For example, a splitter island may be flush or traversable between the ICD and the pedestrian crossing area but raised from the crossing upstream on the approach. Exhibit 10.47 presents a summary of design aspects for each type of splitter island.

Exhibit 10.48 depicts a single-lane roundabout that uses a painted splitter island on one leg to avoid a large underground utility. Raised islands are used on the other three legs.

Exhibit 10.48. Example of roundabout with one painted splitter island.

LOCATION: SW Bond Street/SW Wilson Avenue, Bend, Oregon.
SOURCE: Kittelson & Associates, Inc.

10.6.2 Splitter Island and Approach Taper Dimensions

This section discusses the overall dimensions of the splitter island and its associated approach taper if one is present. Section 10.4 discusses key dimensions for serving pedestrians and bicyclists through the splitter island; Section 10.6.1 presents a discussion of splitter island types; and Chapter 13: Curb and Pavement Details presents design details, such as curbing options, sloped noses, and other features.

The length of the raised island generally needs to be at least 50 ft (15 m), although 100 ft (30 m) or longer can be beneficial. Longer splitter islands may be beneficial on horizontal curves leading to the roundabout where the roundabout may not be visible from the upstream approach. Longer splitter islands are to be considered where a crest vertical curve obstructs the view of the roundabout. Extending the splitter island so that it is visible to approaching drivers helps with navigation and speed reduction. Longer islands may be beneficial with offset-left approach alignments that channelize reverse curves to support speed control on the approach and at the entry. Longer splitter islands may be beneficial in locations where approach speeds are 45 mph (70 km/h) or greater. Treatments for high-speed approaches are detailed in Section 10.14.

The painted taper transitioning from the roadway segment (i.e., the upstream typical section) to the nose of the splitter island is an additional length beyond the splitter island itself. The painted taper provides the initial indication that the roadway typical section is changing and the road user is entering the roundabout influence area. To determine taper length, practitioners may consult the MUTCD formulas or apply Green Book principles for freeway exit ramp diverges in constrained locations (*25, 1*). The design intent is to provide a smooth transition from the roadway segment to the roundabout splitter island.

The MUTCD formulas provide a smoother transition than the exit ramp model, and the two methods are provided to support design decisions commensurate with project opportunities and constraints. According to the MUTCD, the formulas for a shifting taper are as follows (*25*):

$$L = WS,\ for\ S \geq 45\ mph$$

$$L = \frac{WS^2}{60},\ for\ S < 45\ mph$$

where

L = the length of the taper (ft), subject to a minimum length of 100 ft in urban areas and 200 ft in rural areas and extended as required by sight distance conditions;
W = the offset distance (ft); and
S = the posted, 85th-percentile, or statutory speed (mph) (with 1 ft = 0.3048 m and 1 mph = 1.609 km/h).

For example, when developing one-half of a 14-ft (4 m) median or splitter island on a 45-mph (70 km/h) posted speed roadway, the painted taper length in advance of the splitter island would be approximately (7 × 45) = 315 ft (96 m). Therefore, a roundabout entry with a splitter island that is 100 ft (30 m) long and a painted taper that is 315 ft (96 m) long would match the typical section of the upstream roadway about 415 ft (127 m) from the ICD.

Practitioners may also consider the freeway exit ramp model in constrained site conditions. Freeway exit ramp diverge angles commonly range from 2 degrees to 5 degrees (29:1 and 12:1). Considering a 2.5-degree diverge (23:1), developing one-half of a 14-ft (4 m) median or splitter island on the roadway center line results in a 161-ft (49 m) painted taper length in advance of the splitter island. The painted taper could be approximated to 160 ft (49 m). Using this method, a roundabout entry with a splitter island that is 100 ft (30 m) long and a painted taper that is 160 ft (49 m) long would match the typical section of the upstream roadway about 260 ft (79 m) from the ICD.

Principles of channelization include 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. These features are consistent with themes for island delineation and approach treatment presented in the Green Book (*1*). Exhibit 10.49 shows typical splitter island nose radii and offset dimensions from the entry and exit traveled ways.

10.6.3 Approach Design

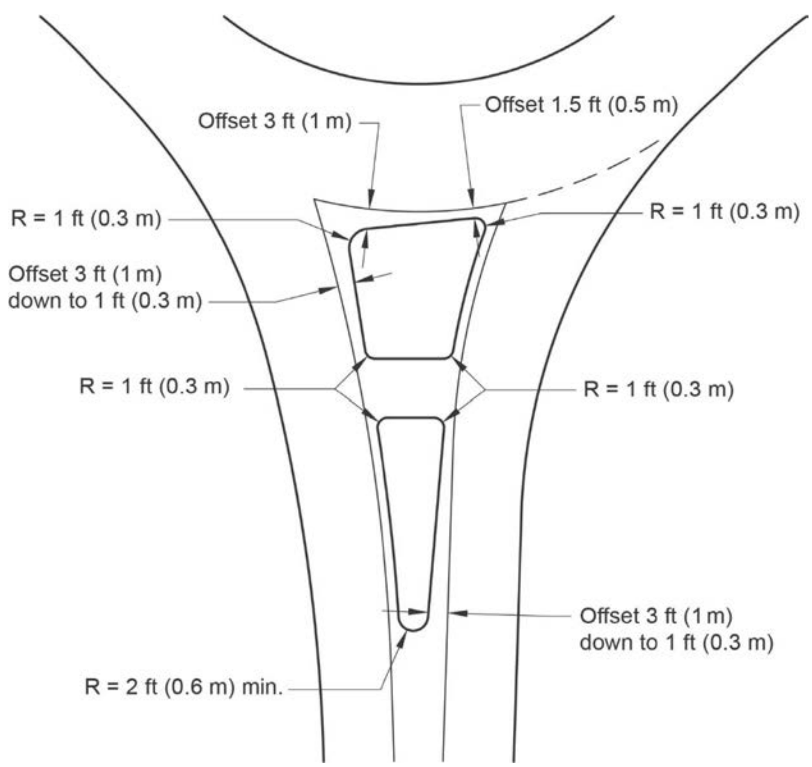
Approach design includes the horizontal geometry associated with roundabout approaches and the roundabout entry. Designs need to account for approach alignment, design speeds, and speed profiles between the upstream approach and the entry. Each combination of roundabout approach and departure is a unique alignment, and this provides significant design flexibility in customizing configurations to meet an array of project needs.

Roadway approach design works integrally with roundabout size and location to achieve target geometric performance. Approach, entry, and exit design can begin after the splitter island needs have been established. This includes identifying pedestrian waiting areas and refuges as well as longitudinal considerations that provide a painted taper and develop the splitter island length.

The roadway approach and departure horizontal alignment directly affect the speed performance of the roundabout entry and exits. Speed transition needs to be established between the upstream roadway segments and the roundabout entry. An overall objective is to provide horizontal curvature commensurate with the anticipated vehicle speeds at that location.

Roadways with travel speeds of 45 mph (70 km/h) or higher away from the roundabout may need speed transitions leading to the roundabout entry. Transition and deceleration lengths will

Exhibit 10.49. Typical splitter island nose radii and offsets.



SOURCE: Adapted from *NCHRP Report 672* (*2*).

influence the roundabout's geometric influence area (i.e., the transition from the segment typical section). For approaches on roadways with speeds 45 mph (70 km/h) or higher, longer painted gores (the painted area between the roadway typical section and the splitter island) and longer splitter islands support speed transitions. Reverse curvature (i.e., a chicane) may be used to support speed transitions. Tangent sections must be used between reverse curves. Treatments for high-speed approaches are covered in Section 10.14.

10.6.4 Entry Design

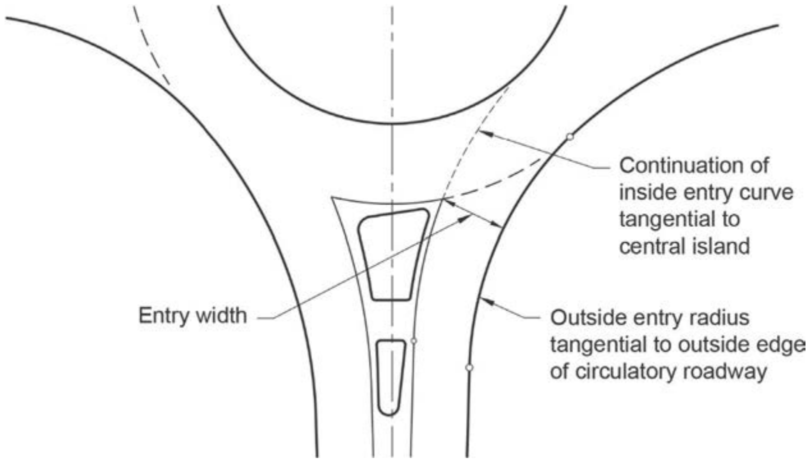
Roundabout entry design is founded on providing horizontal deflection that reduces vehicle speeds and provides curb radii and entry widths that meet design vehicle needs. Accommodating larger control or check vehicles requires considering the area outside the curb line and if there are special needs for landscaping, traffic furniture, signing, and truck aprons.

The roundabout entry is the area bounded by the curb or the edge of pavement consisting of one or more curves leading into the circulatory roadway. The roundabout entry is different from the entry path curve, which is defined by the fastest vehicular travel path through the entry geometry (measured by R_1). The entry curb radius, in conjunction with the entry width, the circulatory roadway width, and the central island geometry, controls the amount of deflection imposed on a vehicle's entry path.

Entry radii at urban single-lane roundabouts typically range from 50 ft to 100 ft (15 m to 30 m). A common starting point is an entry radius in the range of 60 ft to 90 ft (18 m to 27 m); however, a larger or smaller radius may be needed to accommodate large vehicles or serve small-diameter roundabouts, respectively. Curb radii greater than 100 ft (30 m) have a higher potential to produce faster entry speeds than desired but anecdotally may increase entry capacity under conditions with low conflicting flow rates. The entry curb radius can be reduced or increased as necessary in combination with the entry width and alignment to produce the desired entry path radius.

There are various ways to configure the roundabout entry. For each, the outside curb line of the entry is commonly designed curvilinearly tangential to the outside edge of the circulatory roadway. One method projects the inside (left) edge of the entry roadway curvilinearly tangential to the central island. This configuration promotes positive guidance and is often a starting point that may need to be adapted to serve the design vehicle. Exhibit 10.50 shows a typical single-lane roundabout entrance design with the continuation of the entry curve tangential to the central island.

Exhibit 10.50. Single-lane roundabout entry design with the entry curve tangential to the central island.



SOURCE: Adapted from *NCHRP Report 672* (*2*).

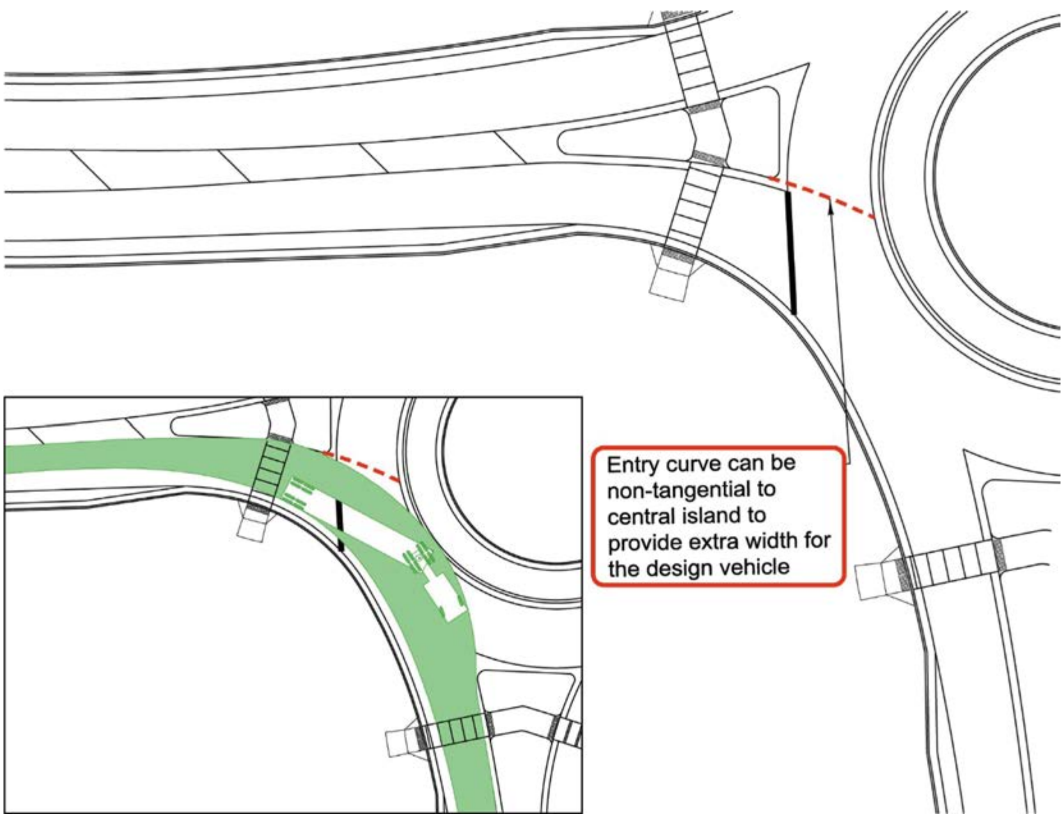
Exhibit 10.51 shows a typical single-lane roundabout entrance design with the entry curve tangential to the central island while having the edge of the splitter island cut back to serve large vehicles. This shows the projection of the left edge of the splitter island non-tangential to the central island. Drivers follow curbing, and this configuration diminishes the positive channelization of the splitter island as a means of serving right-turning large vehicles. However, this configuration could be a potential design approach in constrained site conditions.

The entry geometry needs to provide adequate horizontal curvature to channelize drivers into the circulatory roadway to the right of the central island. It is also often desirable for the splitter island to have enough curvature to block a direct path to the central island for approaching vehicles. This helps avoid vehicles errantly hitting the central island and further discourages drivers from making a wrong-way, left-turn maneuver.

Entry design is also based on attaining intersection and stopping sight distance and appropriate view angles. The view angle to the left must be adequate for entering drivers to comfortably view oncoming traffic from the immediate upstream entry or from the circulatory roadway. Chapter 9: Geometric Design Process and Performance Checks discusses these principles further.

Typical entry widths for single-lane entrances range from 14 ft to 18 ft (4.2 m to 5.5 m) at the ICD; these are often flared from upstream approach widths and to the circulatory roadway width. Entry width is measured from the point where the entrance line intersects the left edge of the traveled way to the right edge of the traveled way along a line perpendicular to the right curb line. Each entry width is commonly dictated by serving the design vehicle while meeting speed management and pedestrian crossing needs.

Exhibit 10.51. Single-lane roundabout entry design serving the design vehicle.



SOURCE: Adapted from Georgia Department of Transportation (*3*).

A nominal entry width of 15 ft (4.6 m) is a common starting value for a single-lane roundabout. Where entry widths are nominally greater than 18 ft (5.5 m) or wider than the circulatory roadway width, drivers may interpret the wide entry to be two lanes when there is only one receiving circulatory lane. If curb-to-curb widths must be that wide for design vehicles, pavement markings may help provide a narrower travel lane. Chapter 12: Traffic Control Devices and Applications discusses this further.

10.6.5 Exit Design

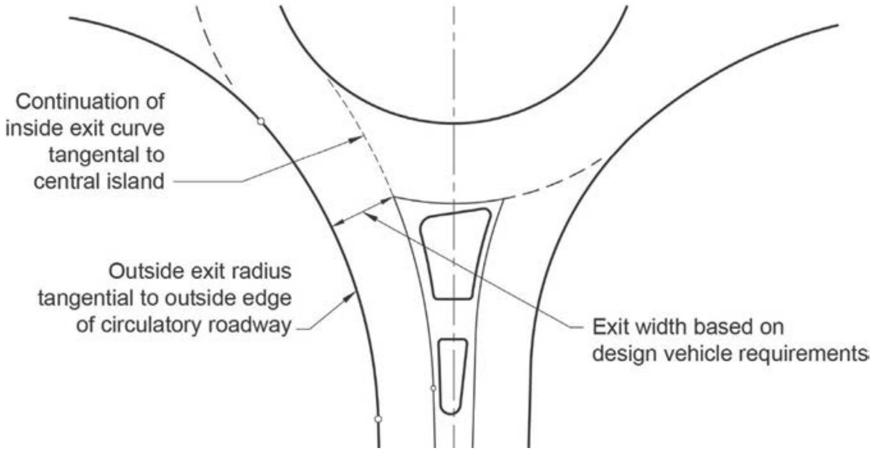
The exit curb radii are usually larger than the entry curb radii. The exit design is influenced by the design environment (i.e., land-use environment, context classification, and project type), pedestrian demand, design vehicle, and physical constraints. Each exit on a given roundabout needs to be customized to the project context and site-specific needs.

Generally, exit curb radii are to be no less than 100 ft (30 m), with common values ranging from 200 ft to 400 ft (60 m to 120 m). The exit curb is commonly designed to be curvilinearly tangential to the outside edge of the circulatory roadway. Likewise, the projection of the inside (left) edge of the exit roadway is commonly curvilinearly tangential to the central island and outside of the splitter island envelope that was established earlier.

Exit path radii are influenced by the exit curb radii. Exit widths and curbs need to accommodate the design vehicle paths within the curb lines. Slower exit speeds are preferable because higher exit speed configurations reduce yielding rates to pedestrians and increase the severity of pedestrian crashes. However, if adequate deflection is achieved at the entry and maintained in the circulatory roadway, resulting in lower circulating speeds, the exit geometry can use flatter curves or tangents.

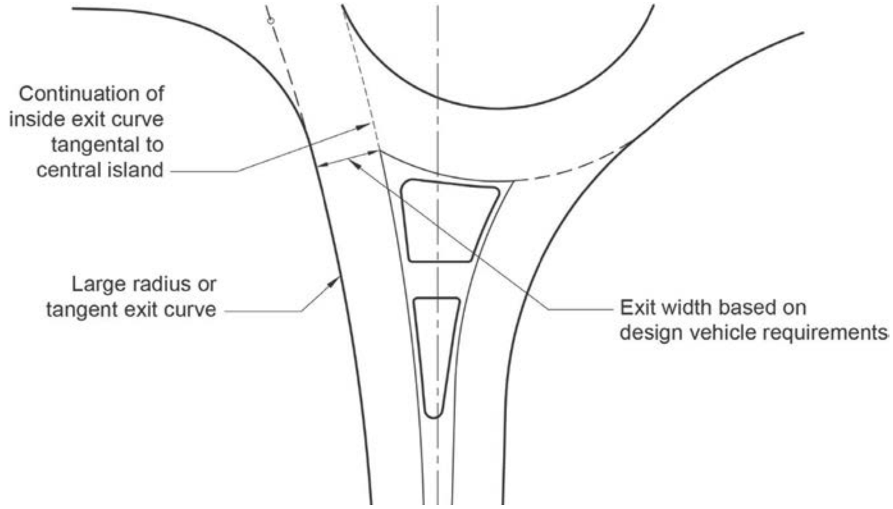
Single-lane exit curb-to-curb widths may range from 18 ft to 20 ft (5.5 m to 6 m) to serve design vehicles. The exit lanes taper in width from the ICD to the typical traffic lane widths downstream of the exit curb line radius. The exit curvature provides a natural location to begin the narrowing. This narrowing also corresponds to the decreasing width of a truck swept path as the trailer begins tracking directly behind the tractor. Exit lane transition widths are to be developed in conjunction with design vehicle checks and the transition from the ICD to the selected standard lane width based on serving the design vehicle swept path. A curvilinear exit configuration is illustrated in Exhibit 10.52.

Exhibit 10.52. Single-lane roundabout curvilinear exit design.



SOURCE: Adapted from *NCHRP Report 672* (*2*).

Exhibit 10.53. Single-lane roundabout large radius exit design.



SOURCE: Adapted from *NCHRP Report 672* (*2*).

Offset-left designs can result in tangent or near-tangent exits. For configurations using an offset-left approach alignment, the exit design may require much larger radii, ranging from 300 ft to 800 ft (90 m to 250 m) or greater. Larger exit radii may also be desirable in areas with high truck volumes to reduce the potential for trailers to track over the outside curb. Exhibit 10.53 presents an exit configuration with tangential or large exit radius qualities commonly associated with offset-left entry configurations.

Exhibit 10.54 presents the exit and entry of a roundabout with an offset-left entry. Of note is the curvature on the roadway approach to support the offset-left entry design. This configuration results in an exit configuration with a large radius or tangent alignment.

10.6.6 Circulatory Roadway Width

The circulatory roadway and central island design are directly influenced by the selected ICD and design vehicle. If the site is constrained and smaller ICD values are selected, the central island

Exhibit 10.54. Example of single-lane roundabout large radius exit design.

SOURCE: Georgia Department of Transportation.

may need fully traversable features, depending on the design vehicle. Roundabouts with fully traversable features in the central island (i.e., mini-roundabouts and compact forms) may be appropriate. Section 10.3.1 explains the variety of context considerations that affect these choices.

The required width of the circulatory roadway is determined from the design vehicle's turning requirements. Except opposite a right-turn-only lane, the circulating width is typically at least as wide as the maximum entry width. Typical circulatory roadway widths range from 16 ft to 20 ft (4.8 m to 6.1 m) for single-lane circulatory roadways. This width usually remains constant throughout the roundabout. Single-lane circulatory roadway widths greater than 20 ft (6.1 m) may lead drivers to assume two vehicles are allowed to circulate side by side.

The circulatory roadway width needs to be wide enough to accommodate a design vehicle up to a bus without using a truck apron. A truck apron will often need to be provided within the central island to accommodate larger design vehicles (including the WB-62 [WB-19] or WB-67 [WB-20] design vehicles) while maintaining a relatively narrow circulatory roadway to adequately constrain smaller vehicle speeds.

Section 10.5.2 discusses truck aprons further. Appropriate templates or a CAD-based computer program can determine the swept path of the design vehicle through each of the turning movements. Usually, the right-turn movement is the critical path for determining circulatory roadway width. This assumes truck drivers making a right turn will not drive their cabs onto the truck apron. In accordance with AASHTO policy, a minimum clearance of 1 ft (0.3 m) (preferably 2 ft [0.6 m]) is provided between the outside edge of the vehicle's tire track and the curb line to allow for variations in driver performance and truck dimensions.

10.6.7 Central Island Design

The central island is the area bounded by the circulatory roadway. It may include a non-traversable central area surrounded by a traversable truck apron. The central island shape of a single-lane roundabout typically matches the overall diameter or shape of the roundabout. The diameter of the central island depends on the ICD and the required circulatory roadway width. The resulting island is typically configured or includes features to enhance driver recognition of the roundabout upon approach.

Raised central islands for single-lane roundabouts are preferred over depressed central islands, as depressed central islands are more difficult for approaching drivers to recognize and may have drainage challenges. Central islands for mini-roundabouts and compact roundabouts may be fully traversable. Raindrop-shaped islands may be used where certain movements do not exist, such as service interchange ramp terminal intersections.

10.6.8 Mini-Roundabout and Compact Roundabout Design

Mini-roundabouts and some compact roundabouts have fully traversable central islands. The location and size of a mini-roundabout or compact roundabout's central island (and the corresponding width of the circulatory roadway) are dictated primarily by passenger car swept path requirements. The central island needs to allow all movements to be served at the intersection with counterclockwise circulation. Designing the central island size and location to provide deflection through the roundabout encourages proper circulation and reduced speeds through the intersection.

The central island may either be domed, which is common for mini-roundabouts, or it may be raised with a mountable curb and flat top for larger islands, which is common for compact roundabouts. More detail is provided in Chapter 11: Vertical Alignment and Cross-Section

Design. Flush central islands are generally discouraged to maximize driver compliance but may be used on roadways with speeds of 25 mph (40 km/h) or less and appropriate signs and pavement markings. Longer painted tapers, splitter islands, curbs, and other features (e.g., advance signing, pavement markings, reflecting delineators, or illumination) may be applicable in locations with approach speeds of 45 mph (70 km/h) and greater. Although fully traversable and relatively small, the central island needs to be clear and conspicuous. Islands with a mountable curb are to be designed similarly to truck aprons at other roundabouts.

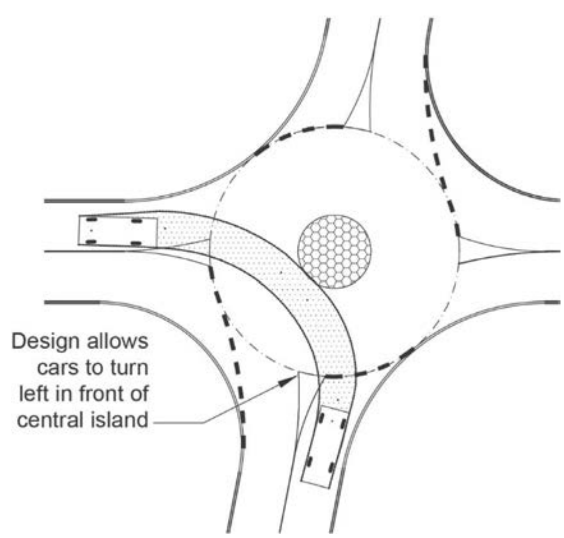
The central island size and location of the entrance line affect mini-roundabout design. Placing the entrance line at the outer edge of the inscribed circle diameter, which is common practice for single-lane and multilane roundabouts, allows for a larger central island. However, this may promote left turns in front of the central island.

Exhibit 10.55 illustrates an undesirable configuration that allows passenger cars to turn left in front of the central island. This may be aggravated by the intersection skew angle, small central island, small splitter islands, and relatively large circulatory roadway width. Possible design improvements are illustrated in Exhibit 10.56 and Exhibit 10.57. These include simultaneously enlarging the central island, reducing the circulatory roadway width, and advancing the entrance line forward (in effect, reducing the ICD).

Another option for reducing left turns in front of the central island is enlarging the ICD. Enlarging the ICD allows for a larger turning radius for the design vehicle, which also reduces the width of the vehicle swept path. This allows for a larger central island and narrower circulatory roadway. The larger ICD promotes the counterclockwise travel path around the central island. The larger ICD may require moving curb lines to create the larger roundabout.

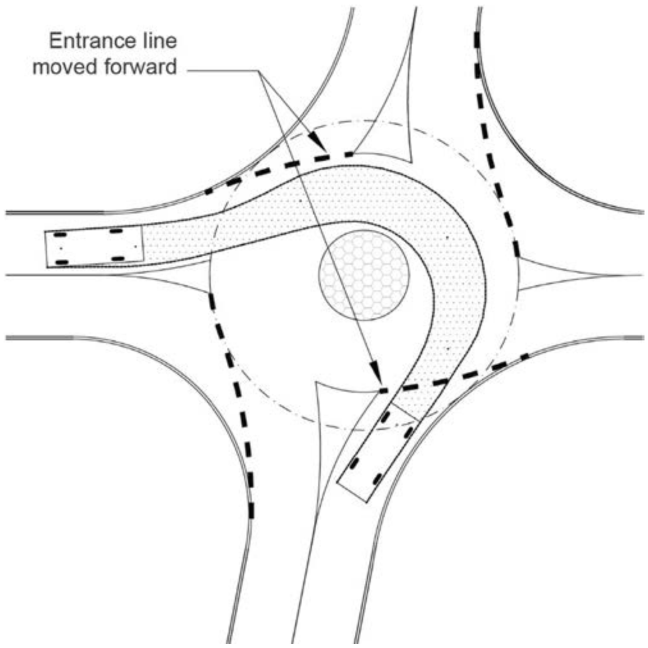
If this is possible, the central island could be developed with mountable (i.e., rolled, chamfered, or rounded top corner) curb and a raised flat central island. **As the mini-roundabout's size increases from within the curb line, the roundabout moves along the design continuum toward a compact design.** Exhibit 10.58 depicts a mini-roundabout with the outside curb line shifted outward.

Exhibit 10.55. Undesirable mini-roundabout configuration that promotes improper left turns.



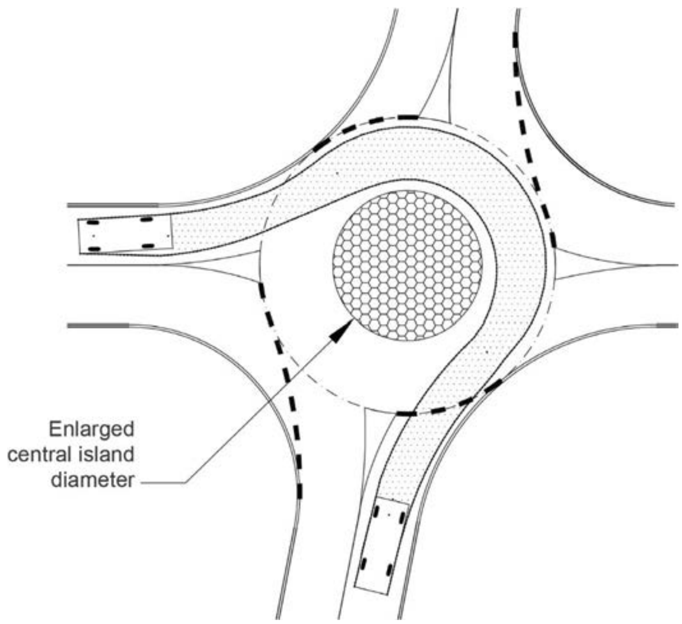
SOURCE: Adapted from *NCHRP Report 672* (*2*).

Exhibit 10.56. Mini-roundabout treatment of moving entrance line forward to discourage improper left turns.



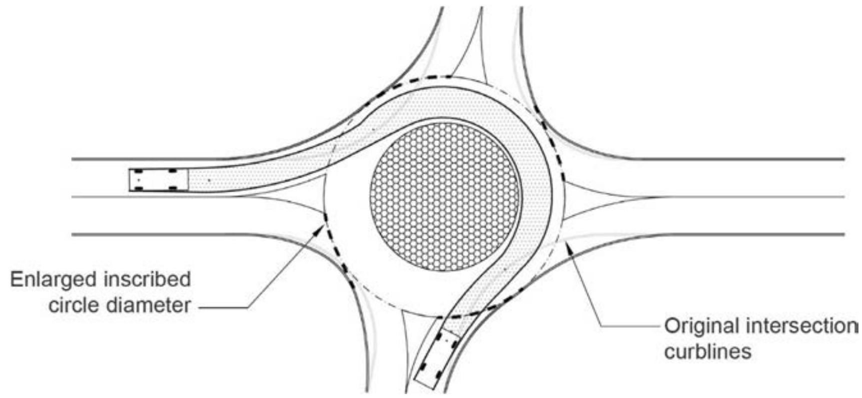
SOURCE: Adapted from *NCHRP Report 672* (*2*).

Exhibit 10.57. Mini-roundabout treatment of enlarged central island diameter to discourage improper left turns.



SOURCE: Adapted from *NCHRP Report 672* (*2*).

Exhibit 10.58. Mini-roundabout treatment of larger inscribed circle diameter to discourage improper left turns.



SOURCE: Adapted from *NCHRP Report 672* (*2*).

10.7 Multilane Roundabouts

Multilane roundabouts carry many of the same design attributes as single-lane roundabouts but introduce new aspects that complicate the design process. Multilane roundabouts include at least two circulating lanes in at least a portion of the circulatory roadway. They include roundabouts with entries on one or more approaches that flare from one to two or more lanes that circulate through the roundabout. In some cases, the roundabout may have a different number of lanes on one or more approaches (e.g., two-lane entries on the major street and one-lane entries on the minor street).

Multilane roundabouts introduce several design concepts that are not present with single-lane roundabouts:

- **Lane assignments in multilane sections.** Multilane roundabouts are multilane intersections with a central island. Because of this, the desired design establishes correct lane assignments for drivers **in advance** of the intersection and then facilitates those movements through the intersection without requiring drivers to change lanes. This requires attention to signs and pavement markings to communicate and facilitate the desired movements in advance of the roundabout and throughout each movement's passage through the roundabout.
- **Horizontal geometry that supports specific lane assignments.** This includes aligning vehicles at the entrance line into the correct lane within the circulatory roadway, positioning lanes within the circulatory roadway to facilitate smooth movements (including spiraling as needed, as discussed in Section 10.7.7), and minimizing the likelihood of drivers straying from their intended lane while circulating and exiting.
- **Continued attention to performance objectives.** The larger and more complex multilane footprint makes each performance objective more challenging to meet. These performance objectives, discussed in detail in Chapter 9: Geometric Design Process and Performance Checks, include
  - Geometric speed control with wider entries, exits, and circulatory roadway;
  - Truck circulation using the intended method (straddling lanes versus staying in-lane);
  - Path alignment for each lane through the roundabout; and
  - Providing the necessary measures to make bicycle and pedestrian crossings across multilane sections accessible to all users.

Each of these concepts requires strategic layout consideration as well as attention to design details that facilitate the intended strategy. Single-lane roundabout design principles and processes set the foundation for multilane roundabout design. However, multilane operations having vehicles adjacent to each other while approaching, navigating, and exiting a roundabout creates new complexities and risks that must be addressed in special design treatments and configurations.

In general, the size of the roundabout is influenced by the number and assignment of lanes, strategy for truck accommodations (straddling lanes versus staying in-lane), and site context. Size is also a byproduct of achieving target performance metrics. This often occurs by balancing the need to achieve geometric speed control with providing adequate space for trucks, intended lane discipline, and path alignment. Typically, achieving the performance objectives requires a larger diameter than that of a single-lane roundabout. As such, there is no single answer to the question: "What is the best ICD for a multilane roundabout?" Further discussion is provided in Section 10.7.5 for straddle-lane design and Section 10.7.6 for stay-in-lane design.

Multilane roundabout performance begins with appropriate geometric design paired with complementary and supporting traffic control devices. Multilane roundabout design tends to be less forgiving than single-lane roundabout design, with the potential for more frequent property damage crashes if the principles in this section are overlooked. Research for an FHWA Pooled Fund Study (*26*) has found the most common property damage crashes at some multilane roundabouts include

- Drivers in the outside entry lane failing to yield to a driver circulating in the inside lane,
- Drivers making left turns from the incorrect outside lane, and
- Drivers making right turns from the incorrect inside lane.

These crash patterns are influenced by a combination of geometry and traffic control devices (principally signs and pavement markings) and driver behavior. Other patterns commonly observed at multilane roundabouts are passenger car drivers straddling lanes and changing lanes through the entry or (especially) the exit.

For multilane roundabouts, the entry geometry is typically established first to identify a design that adequately controls entry speeds, provides appropriate path alignment, and accommodates the design vehicle. The splitter island is then developed in conjunction with the exit design to provide adequate median width for the pedestrian refuge and sign placement. The size and shape of the splitter island forming the left side of the entry, for example, helps with motor vehicle alignment at entry. The design also plays a critical role in providing for two-stage pedestrian crossings, with sufficient room in the splitter island where people may pause while crossing.

Many splitter island design aspects discussed for single-lane roundabouts also apply to multilane designs. However, because active traffic control devices are more common at multilane crossings to provide accessibility for all pedestrians, it is more common for multilane crossings to be designed to operate with two crossing stages. Section 10.4 discusses pedestrian and bicycle crossings further.

Single-lane roundabouts have some design elements (such as central islands and approach treatments) that apply to multilane roundabouts and are not described again in this section. Many aspects of single-lane roundabout design and general performance objectives also apply to multilane roundabout planning and design. However, single-lane roundabout design techniques may be problematic if applied to a multilane configuration.

10.7.1 Determining the Appropriate Lane Configuration

Determining the appropriate lane configuration for a roundabout is based on two interdependent aspects:

- The lane configuration needs of the roundabout itself to serve each mode.
- The roundabout's interaction with the surrounding roadway network.

In general, it is best that a roundabout (like any intersection) have as few lanes as possible while still achieving the desired performance. Providing additional lanes that are not needed for capacity purposes increases crash risk by increasing the number of conflict points. If additional lanes are needed for future conditions, practitioners can consider a phased design approach to allow for future expansion when conditions warrant, rather than initially overbuilding a roundabout and reducing safety performance. This is discussed further in Section 10.8.

A detailed study of field operations at a series of multilane roundabouts in the United States found that at some multilane roundabouts with a history of property damage crashes, turning movements from the incorrect lane were common contributors to erratic maneuvers, conflicts, and near-crashes (as seen in video observation) (*26*). These included improper left turns from the right entry lane and improper right turns from the left entry lane for entries with a typical shared left-through, shared through-right configuration. Among potential causes of improper turns, the study identified several that are system-related and became more prominent under heavier peak period conditions, including

- Closely spaced intersections that preclude lane changes between intersections.
- Upstream signals that release drivers in platoons, making it difficult for drivers to select the correct lane prior to entering the roundabout.
- Upstream origins or downstream destinations close to the roundabout. For close upstream origins, drivers would change lanes once they perceived the best opportunity, which was often while circulating or exiting. For close downstream destinations, drivers would either position themselves for the downstream destination before entering the roundabout and make an incorrect turning movement, or they would change lanes within the roundabout or while exiting to position for the downstream turning movement.

These system effects require considering more than the isolated operational analysis of the roundabout. In some cases, reducing the number of lanes may be the best option for mitigating these patterns, rather than relying solely on lane-use restrictions within the roundabout (e.g., with raised lane dividers), which may simply shift lane changing upstream or downstream of the roundabout.

10.7.2 Designing for the Needed Lane Configuration

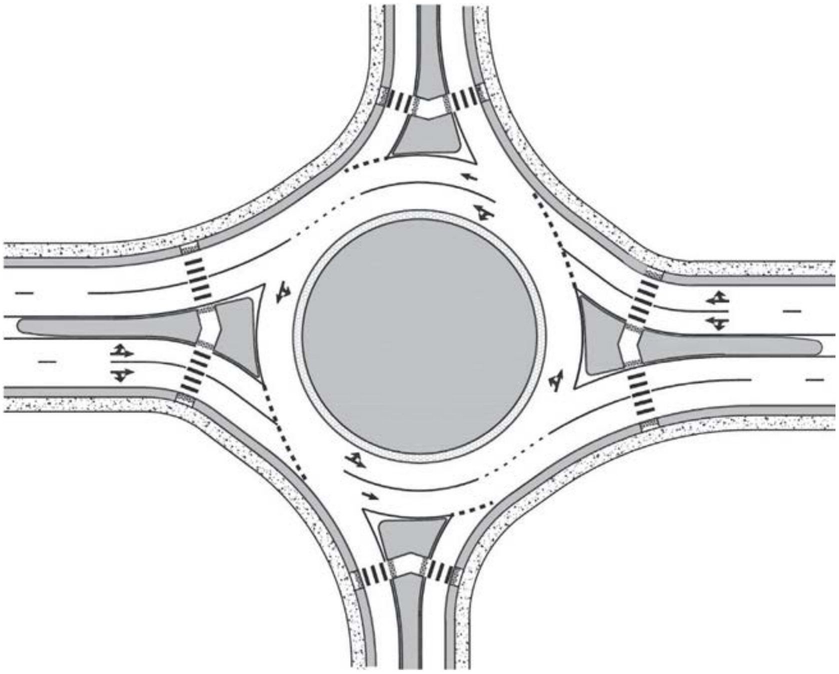
Because the lane configuration needed for each entry or exit may be different, it is often preferred to adjust the number of circulating and exiting lanes to match the needed entry lane configuration. As a result, the circulatory roadway width may vary throughout the roundabout based on the number of needed lanes.

This concept is illustrated with two examples. In the first example, shown in Exhibit 10.59, two through lanes are needed on the major street, with left-turn and right-turn movements operating as shared lanes with the through movements. Both minor approaches in this example need one lane to function acceptably. This is a common multilane roundabout configuration and is sometimes referred to as a *hybrid* or *2 × 1 (two-by-one)* roundabout.

When additional lanes are needed for turning movements, practitioners need to adjust the lane configuration throughout the roundabout to match. A complex example is shown in Exhibit 10.60, as two intersecting roadways each have heavy left-turn movements needing double left-turn lanes. To support this without requiring lane changes within the roundabout, an extra circulating lane in one quadrant and a circulating lane alignment that spirals to the outside is needed to enable all vehicles to reach their intended exits without changing lanes. The alignment of these spirals requires careful attention to geometric detail and is discussed further in Section 10.7.7.

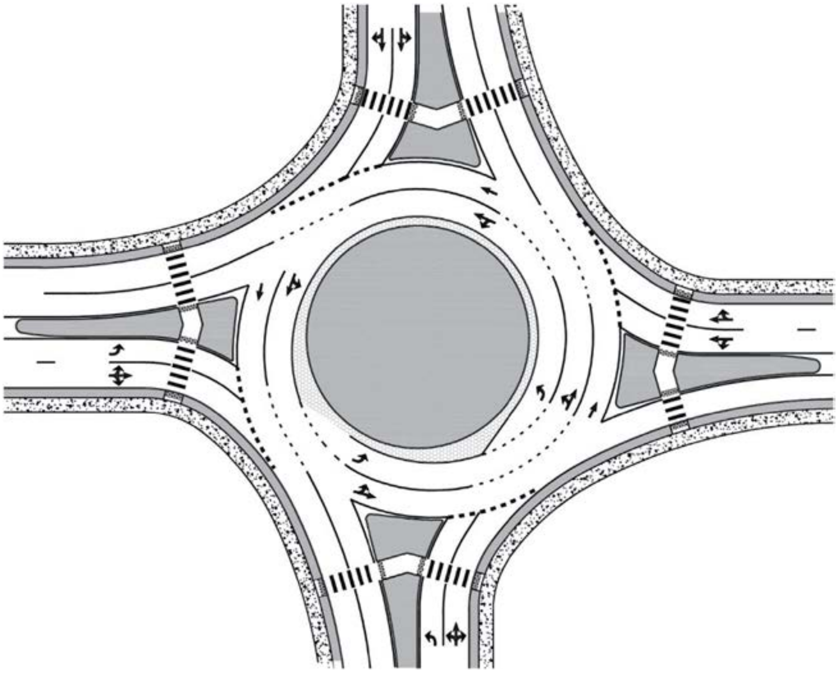
A roundabout can provide capacity by adding and dropping lanes before and after the roundabout. Exhibit 10.61 illustrates an example.

Exhibit 10.59. Multilane major street with single lane on minor street.



SOURCE: Adapted from *NCHRP Report 672* (*2*).

Exhibit 10.60. Two-lane roundabout with consecutive double-left turn movements.



SOURCE: Adapted from *NCHRP Report 672* (*2*).

Exhibit 10.61. Example of adding and dropping a lane upstream and downstream of a roundabout.

LOCATION: County Road G/Monroe Road, De Pere, Wisconsin.
SOURCE: Google Earth.

10.7.3 Managing Separation Between Legs

Separation between adjacent legs that creates sufficient distance resulting in circulating traffic merging and then diverging at the exits can increase crash risk. Roundabout entries need to be configured so that entering and circulating vehicles cross, rather than merge and diverge. At roundabouts where the design favors merging and diverging, research has found that drivers in the outside entering lane are less likely to yield to circulating traffic, which commonly results in an exit-circulating conflict downstream (*11*). This can occur in several situations:

- Roundabouts with an angle between two legs that is significantly greater than 90 degrees.
- Roundabouts at or near 90-degree angles between legs but with a large enough ICD to create a segment of circulatory roadway between legs.

Separations between legs have been shown to reduce the likelihood of drivers yielding to all circulating vehicles in front of the subject entry. Drivers in the outside lane may not perceive a conflict with traffic that is exiting at the next leg. As such, drivers in the outside lane enter the roundabout next to circulating traffic in the inside lane. This can create conflicts at the exit point between exiting and circulating vehicles (an **exit-circulating conflict**), as shown in Exhibit 10.62.

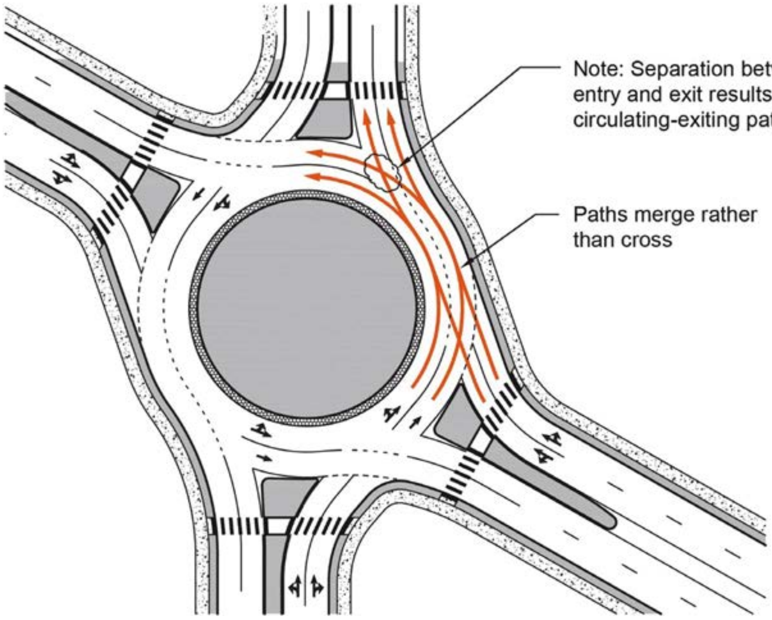
An overly large ICD can result in separation and create a pattern of exit-circulating crashes. Exhibit 10.63 shows an example of a multilane roundabout with an overly large ICD that results in a segment of circulatory roadway between legs. In addition, from the circulating driver's perspective, the exiting alignment of reverse curve with no tangent directly contributes to drivers naturally crossing the lane line while exiting. This concept, called *path alignment,* is discussed next.

Exhibit 10.64 illustrates an operational means of addressing the exit-circulating conflict by adjusting the lane configuration. This could be a possible low-cost design configuration that addresses the issue, but it may come at the expense of traffic operational performance. This may be an acceptable trade-off for a given site and context where exit-circulating crashes are documented. If the changes in traffic operations and safety performance of this configuration are not acceptable for the site and context, it may be necessary to realign the approach to minimize the segment of circulatory roadway between legs, as illustrated in Exhibit 10.65.

10.7.4 Vehicle Path Alignment

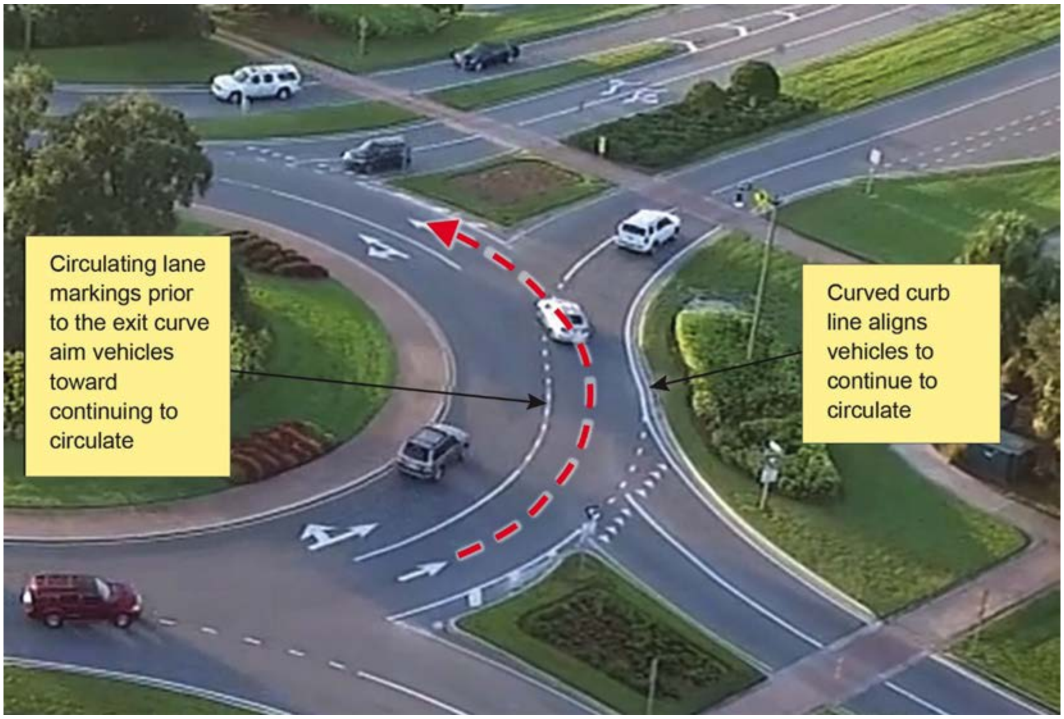
Multilane design focuses on aligning entering vehicles into the appropriate lane within the circulatory roadway and aligning exiting vehicles into the appropriate lane when exiting. These

Exhibit 10.62. Exit-circulating conflict caused by large angle between legs.



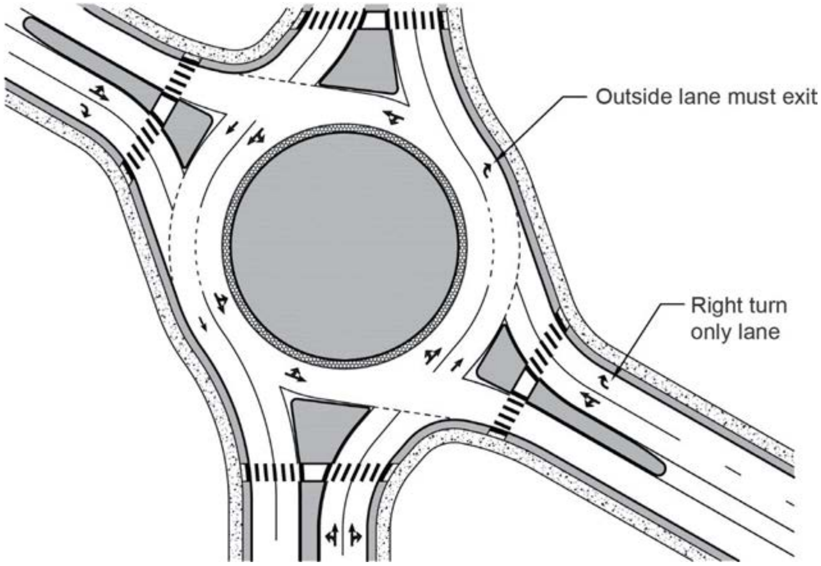
SOURCE: Adapted from Tian et al. and *NCHRP Report 672* (*27*, *2*).

Exhibit 10.63. Exit-circulating conflict caused by large inscribed circle diameter.



SOURCE: Medina et al. (*26*).

Exhibit 10.64. Possible lane configuration modifications to resolve exit-circulating conflicts.

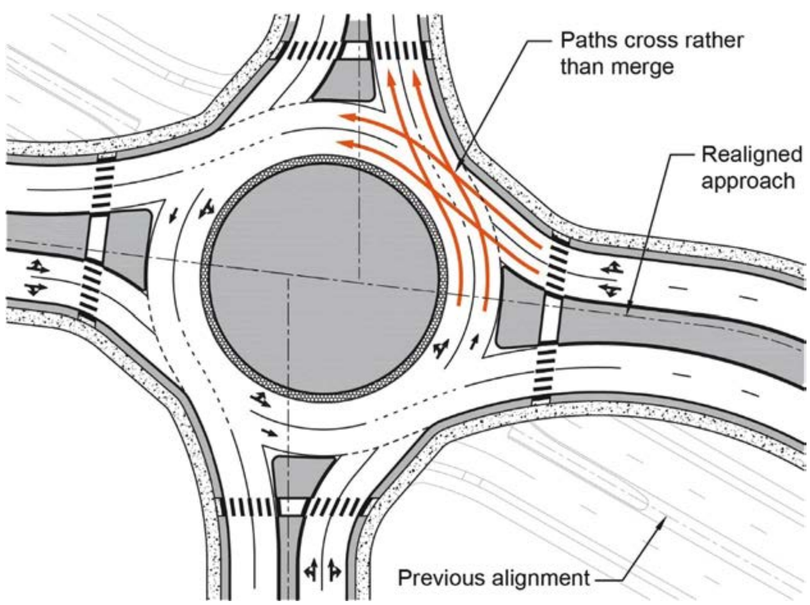


SOURCE: Adapted from Tian et al. and *NCHRP Report 672* (*27, 2*).

alignment considerations often compete with geometric speed objectives, but both are important: geometric speed objectives affect crash severity, while path alignment objectives directly address common property damage crashes. There are many ways to balance geometric speed control and path alignment, and these vary by site-specific conditions, project type, and project content and objectives. Because of this, no single technique will always work for a given context and location.

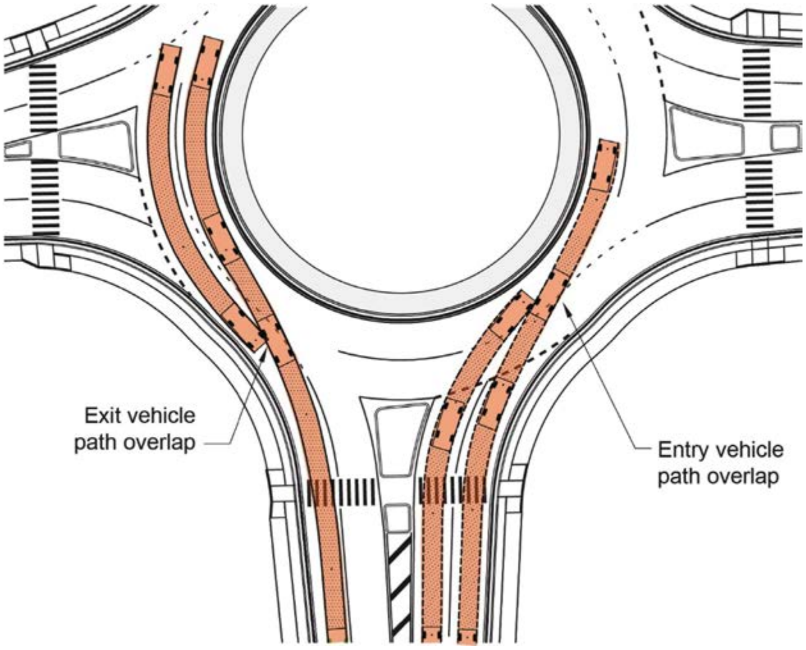
As discussed in Chapter 9: Geometric Design Process and Performance Checks, if proper vehicle path alignment is not attained, the paths of side-by-side entering, circulating, or exiting

Exhibit 10.65. Realignment to resolve exit-circulating conflicts.



SOURCE: Adapted from Tian et al. and *NCHRP Report 672* (*27, 2*).

Exhibit 10.66. Examples of poor path alignment.



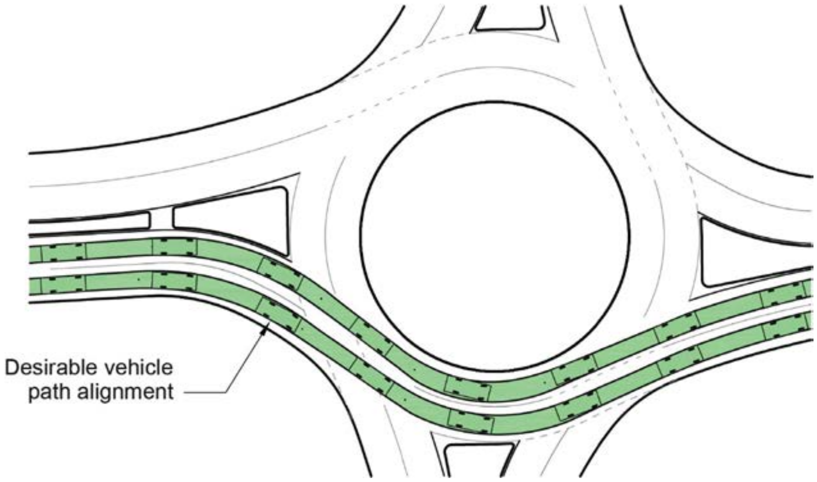
SOURCE: Adapted from *NCHRP Report 672* (*2*).

vehicles may overlap. A common case occurs at entries where the geometry of the right (outside) lane tends to lead vehicles into the left (inside) circulatory lane. Research for an FHWA Pooled Fund Study found that path alignment problems were common on exit and were either caused by poor geometry (the geometry tends to lead vehicles from the left-hand circulating lane into the right-hand exit lane) or by drivers changing lanes in preparation for a downstream turning movement (*26*). Exhibit 10.66 illustrates examples of path alignments that create path overlap.

The desired result of the entry design is for vehicles to be aligned into their correct lane within the circulatory roadway, as illustrated in Exhibit 10.67.

The techniques to address these challenges are best implemented early in the design process, given the strategic nature of design decisions that may affect the viability of an alternative.

Exhibit 10.67. Desirable vehicle path alignment.



SOURCE: Adapted from *NCHRP Report 672* (*2*).

Techniques for addressing path alignment vary depending on truck treatments and are discussed in the following sections.

10.7.5 Principles and Techniques for Straddle-Lane Design

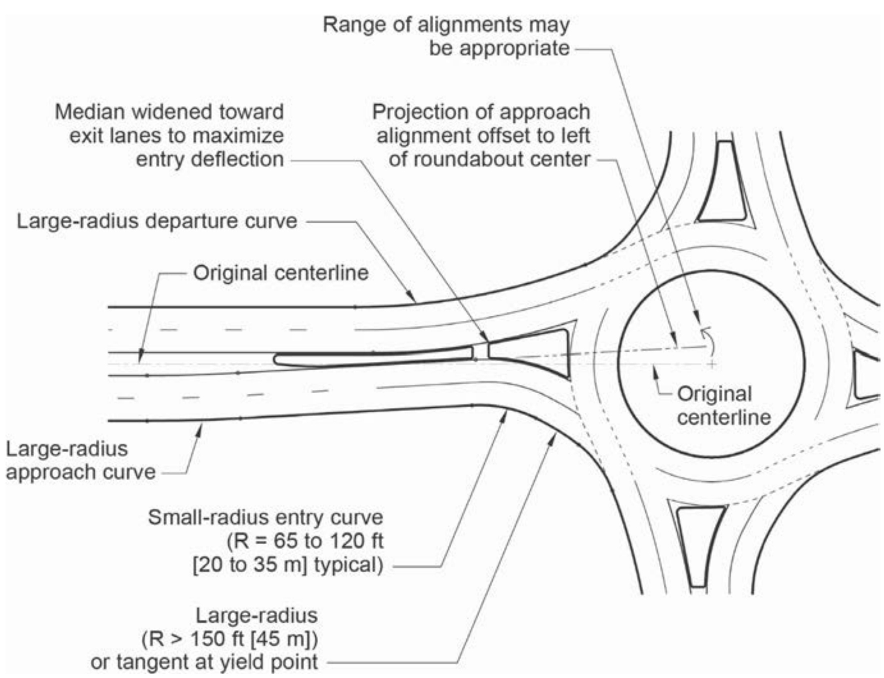
By definition, a straddle-lane design has trucks occupying more than one lane as needed when entering, circulating, and exiting. Passenger cars, however, form most of the motor vehicle stream, and multilane roundabouts need to be designed to maintain lane discipline by using target path alignment, as discussed in Chapter 9: Geometric Design Process and Performance Checks. As such, path alignment, along with the associated objective of acceptable view angles (also discussed in Chapter 9), are objectives for straddle-lane designs that require additional attention to detail beyond single-lane design. These two objectives are related:

- Each entering vehicle in each lane needs to be aligned with its receiving lane (path alignment).
- Each entering vehicle needs an alignment that provides a clear line of sight toward conflicting vehicles (view angle).

These two objectives require that vehicles be staggered at the entrance line so that vehicles in the outside lane can see in front of the vehicle in the adjacent lane to the left. There are many possible techniques to achieve good path alignment and view angles, and practitioners need to adapt them to the specific geometry and constraints of the roundabout under consideration. **Regardless of the technique, performance checks presented in Chapter 9 are necessary to confirm that each objective is met.**

Exhibit 10.68 shows a possible method to attain desired path alignment using a compound curve or tangent along the outside curb. The design consists of an initial small-radius entry curve set back from the edge of the circulatory roadway. A short section of a large radius curve or tangent is provided between the entry curve and the circulatory roadway to align vehicles into

Exhibit 10.68. Approach offset to increase entry deflection.



SOURCE: Adapted from *NCHRP Report 672* (*2*).

the proper circulatory lane at the entrance line. Finding the location of the entry curve from the entrance line is an iterative process. If it is located too close to the circulatory roadway, the entry may have path alignment issues. However, if the entry curve is located too far away from the circulatory roadway, it can result in inadequate geometric speed control.

For the method illustrated in Exhibit 10.68, entry curve radii commonly range from approximately 65 ft to 120 ft (20 m to 35 m) and are set back at least 20 ft (6 m) from the edge of the circulatory roadway. A tangent or large radius curve (greater than 150 ft [45 m]) is then fitted between the entry curve and the outside edge of the circulatory roadway.

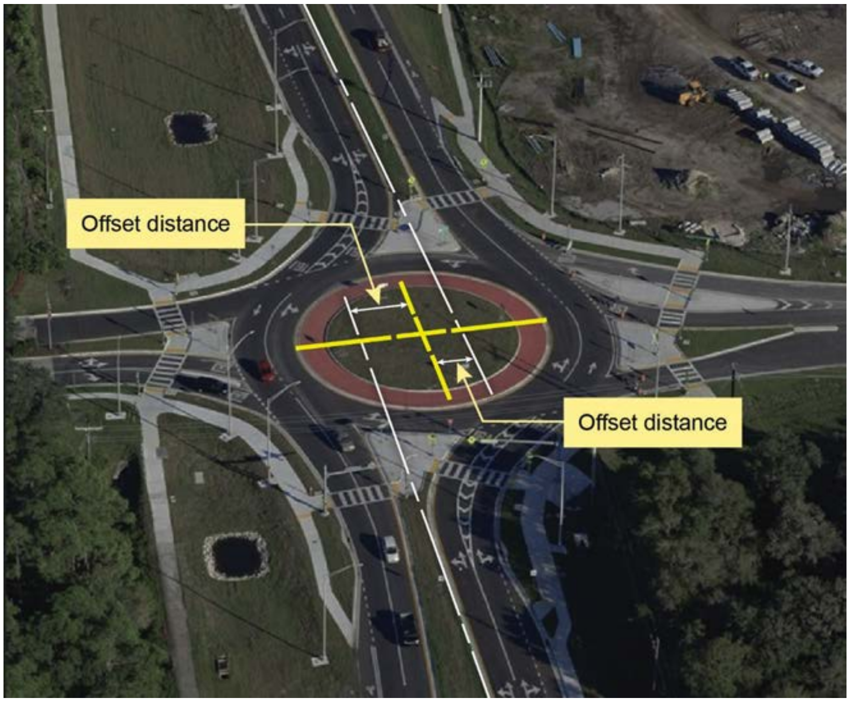
Exhibit 10.69 is an example of this method at a roundabout in Florida.

An alternative method for designing the entry curves to a multilane roundabout is to use a single radius entry curve rather than a small curve and tangent. In some ways, this is like a single-lane design; however, larger radii are typically required to provide adequate vehicle alignment. A single-entry curve configuration often helps with geometric speed control but may result in poor path alignment.

If the circulatory roadway is sufficiently wide relative to the entry, entry curves can be designed tangential to a design circle offset 5 ft (1.5 m) from the central island. This improves the curvature and deflection achieved on the inside (splitter island) edge of the entry. Regardless of the method, it is desirable for the inside (splitter island) curb to block the through path of the left lane to promote adequate deflection.

Achieving adequate geometric speed control on entry and meeting design objectives are independent of the control line (i.e., centerline or profile grade line) of the approaching roadways. The centerlines of approach roadways do not need to pass through the center of the inscribed

Exhibit 10.69. Example of approach offset.



LOCATION: SR 64/Greyhawk Boulevard/Pope Road, Manatee County, Florida.
SOURCE: Kinard and Stone.

circle. It is common design practice for multilane roundabouts to have an offset-left alignment. This may provide a useful method for achieving speed control and path alignment.

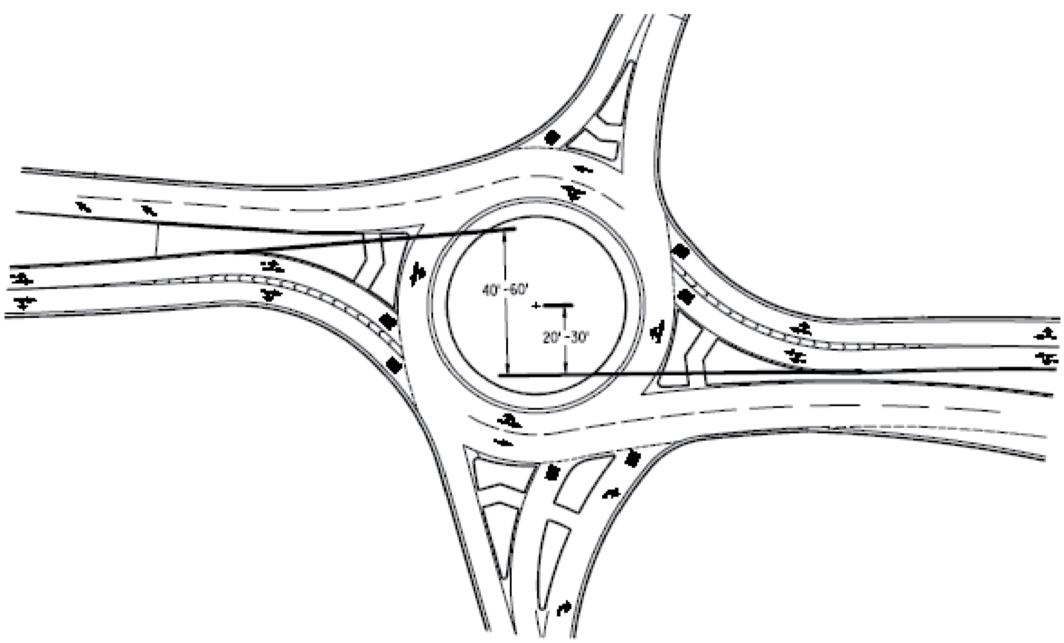
Exhibit 10.70 illustrates a design technique to enhance geometric speed control on the entry by shifting the approach alignment toward the left of the roundabout center. This technique can effectively increase entry geometric speed control; however, it is often at the expense of geometric speed control on the exit of the same leg.

The radii of exit curves are commonly larger than those at the entry because of factors such as entry alignment, diameter, and design vehicle tracking. Larger exit curve radii typically promote desired vehicle exit path alignment. The need to serve each of these elements often requires additional treatments beyond horizontal geometry to make the pedestrian crossing at the exit accessible to all pedestrians. These crossing treatments are discussed further in Section 10.4.5.

The exit side is perhaps more critical for path alignment, given that drivers may travel at faster speeds than at the entry. A tangent or large radius arc helps connect the circulatory roadway to the exit (see Exhibit 10.71). This reduces the likelihood of drivers drifting out of their lane when exiting, and it reduces the tendency of drivers continuing to circulate (i.e., making an improper left turn from the outer entry lane) rather than exiting from the outside lane. **This technique also promotes visibility of the entire crosswalk and associated traffic control devices on the exit, recognizing that it does not inherently provide geometric speed control.**

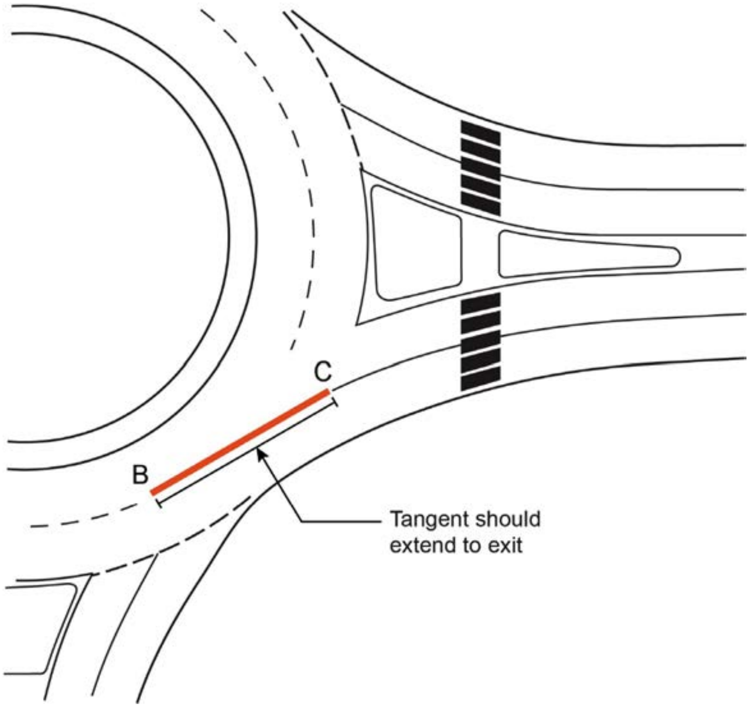
Some states have used a hybrid approach in which trucks share space between entry lanes under the presumption that trucks will not travel side by side (formerly known as Case 2 design). This shared space is often marked using a gore-striping technique sometimes used at freeway exit ramps, consisting of two white lines and chevrons between the lanes. Exhibit 10.72 illustrates this technique. The actual dimensions may vary depending on the individual design. For example, the New York State Department of Transportation has used two entry lanes that are 12 ft (3.6 m) wide and a gore area that is 6 ft (1.8 m) wide for a total width of 30 ft (9 m) (*29*).

Exhibit 10.70. Example of major approach offset.



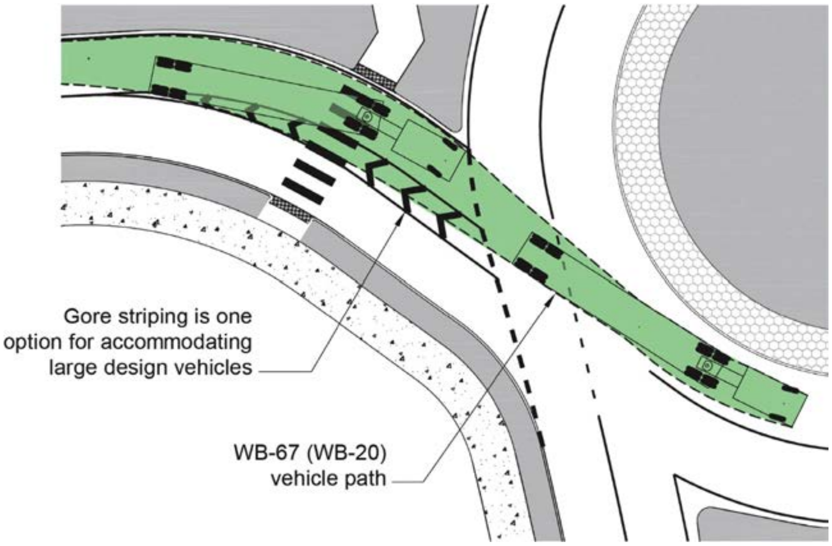
SOURCE: Wisconsin Department of Transportation and *NCHRP Report 672* (*28, 2*).

Exhibit 10.71. Exit vehicle path alignment.



SOURCE: Adapted from Wisconsin Department of Transportation (*28*).

Exhibit 10.72. WB-67 (WB-20) truck path with gore striping at entry.



SOURCE: Adapted from McCulloch and *NCHRP Report 672* (*29, 2*).

This technique does not represent true stay-in-lane operation because it requires truck drivers to understand three concepts:

- They must drive on the gore area to complete their movements.
- Only one truck can use the gore area at a time.
- In the circulatory roadway, the truck may have to straddle lanes.

Research conducted for this Guide suggests that this type of design is not universally understood by truck drivers (*30*). Truck drivers often occupy both lanes beyond the extent of the gore striping. **As such, this Guide advises designing for trucks straddling lanes as the default for most situations.**

The required entry width for a straddle-lane design depends on the number of lanes and the design vehicle. A typical entry width where trucks straddle lanes ranges from 24 ft to 30 ft (7.3 m to 9.1 m) for a two-lane entry and from 36 ft to 45 ft (11.0 m to 13.7 m) for a three-lane entry. Typical widths for individual lanes at each entry range from 12 ft to 15 ft (3.7 m to 4.6 m). It may be beneficial to retain the ability for smaller large vehicles (e.g., buses) to stay in-lane and allow side-by-side circulation with passenger cars.

Multilane circulatory roadway lanes in a straddle-lane design are commonly 14 ft to 16 ft (4.3 m to 4.9 m) wide. Using these values results in a total circulating width of 28 ft to 32 ft (8.5 m to 9.8 m) for a two-lane circulatory roadway segment and 42 ft to 48 ft (12.8 m to 14.6 m) total width for a three-lane circulatory roadway segment. The circulatory roadway width is usually governed by the types of vehicles that may need to be accommodated adjacent to one another through a multilane roundabout. For straddle-lane design, vehicles smaller than the design vehicle will form most of the traffic within the circulatory roadway.

If the entering traffic is predominantly passenger cars and single-unit trucks (AASHTO P and SU design vehicles, respectively) and semi-trailer traffic (e.g., WB-40 and larger) is infrequent, it may be appropriate to design the width for two P vehicles or a P and an SU truck side by side. If semi-trailer truck traffic is relatively frequent, it may be preferable to provide sufficient width for the simultaneous passage of a semi-trailer truck in combination with a P or SU vehicle. There is no available research on the quantity of truck traffic to define "relatively frequent."

10.7.6 Techniques for Designing for Trucks Staying In-Lane

For a roundabout that intends for trucks to stay in their own lane, several design considerations come into play. For stay-in-lane design, a larger ICD, larger entry and exit radii, and wider lanes may be required to accommodate the design vehicle while working to meet other performance objectives. However, these objectives conflict with one another. For example, larger entry and exit radii needed for truck movement make geometric speed control more difficult, as do the larger lane widths needed for truck tracking.

The circulatory roadway in stay-in-lane design commonly has a narrower inside lane—where trucks can also use the truck apron—and a wider outside lane—where trucks are unable to use the apron. Exact widths depend on the ICD, the specific design vehicle being served, and other site-specific factors. In general, the outside lane will be narrower with larger ICDs and wider with smaller ICDs because of the associated off-tracking of truck trailers. Some agencies have used striping to reduce the apparent width of the outside lane. The combination of vehicle types to be accommodated side by side depends on the specific site traffic conditions, and requirements for side-by-side design vehicles are to be established and documented in early project planning.

10.7.7 Spiraling in Multilane Roundabouts

A spiral is a circulating lane alignment needed for some multilane roundabout configurations. Spirals are common for straddle-lane designs with certain lane configurations and are an integral part of stay-in-lane designs. Spirals are commonly needed in the following situations:

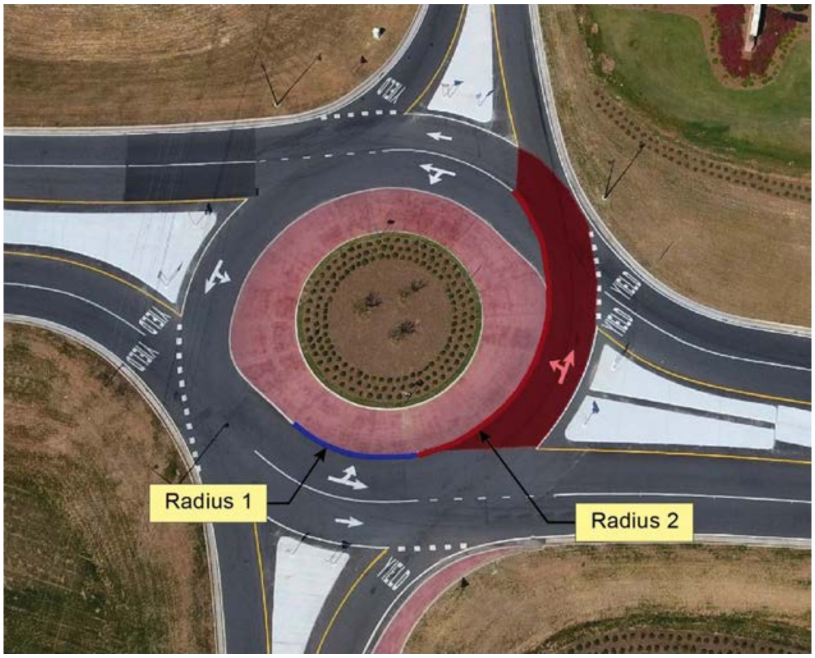
- Where one or more entries require exclusive left-turn lanes.
- Where a combination of entering and exiting lanes requires a spiral to maintain lane continuity.
- Where a circulating driver must shift to the outside lane when transitioning from single-lane to multilane portions of the circulatory roadway.
- At a 2 × 1 multilane design and similar configurations to improve the likelihood of entering drivers in the outside lane yielding at entry.

Exhibit 10.73 illustrates a 2 × 1 multilane roundabout with spirals. In the exhibit, Radius 1 is the original circle radius, and Radius 2 provides the spiral. The combination of Radius 1 and Radius 2 is a compound curve, not a true spiral with a continuously variable radius. However, when Radius 1 and Radius 2 are sufficiently similar, the net effect is to create a smooth path to help circulating drivers shift to the outside circulating lane and to reduce the likelihood of entering drivers in the outside lane from entering next to a circulating vehicle.

10.7.8 Turbo Roundabouts

Multilane roundabout design continues to evolve, with a variety of techniques developed around the world to achieve desirable roundabout performance. One technique initiated in the Netherlands for multilane roundabout design is called a *turbo roundabout* (*31*). As discussed in Chapter 2: Roundabout Characteristics and Applications, a turbo roundabout is a multilane roundabout that uses spiral road geometry and physical channelization to maintain driver lane discipline in the circulatory roadway.

Exhibit 10.73. Example of using spiral to shift circulating lane to the outside.



SOURCE: Georgia Department of Transportation.

Exhibit 10.74. Example of roundabout with turbo roundabout features.

LOCATION: University Boulevard/Merrill Road, Jacksonville, Florida.
SOURCE: Federal Highway Administration.

The Dutch turbo roundabout originates from a style of European multilane roundabout with perpendicular entries and no substantive channelization or raised lane dividers. This form has been found to have poor safety performance. The specific turbo roundabout version developed and implemented in the Netherlands to address undesirable operational characteristics has two key features that distinguish it from other multilane roundabouts around the world, including in the United States:

- Entries are perpendicular to the circulatory roadway, which is common practice for many roundabouts in northern Europe (both single lane and multilane).
- Raised lane dividers are used within the circulatory roadway to prevent lane changing and guide drivers to the appropriate exit.

Spiraling and lane dividers are used to discourage lane changes that may result in weaving conflicts within the circulatory roadway. Conceptually, the intent is to guide users to appropriate lanes before entering the roundabout, which eliminates lane changes while inside the roundabout. Other European countries have implemented variations of the Dutch turbo roundabout, typically with modifications to geometric alignment and the type of lane divider, such as mountable lane dividers, flush lane dividers, or solid pavement markings—all of which discourage lane changing and promote lane discipline. Further detail on turbo roundabout design practices can be found in FHWA's synthesis report, *Advancing Turbo Roundabouts in the United States* and FHWA's informational primer, *Turbo Roundabouts* (*32, 33*).

The specific combination of geometry and lane divider treatment used in the Netherlands is new to the United States. One of several proposed variations uses raised lane dividers and is shown in Exhibit 10.74. Another variation uses pairs of double white lines and raised pavement markers to separate circulating lanes and is shown in Exhibit 10.75. **The key to successful multilane roundabout design, as with all roundabout design, is achieving performance objectives while designing a roundabout appropriate for its context. The means (i.e., techniques) used are less important than the outcome (i.e., performance), and variations in techniques are possible if they achieve the desired performance.** Techniques used for turbo roundabouts may help achieve these objectives.

10.8 Design for Interim and Ultimate Configurations

This section illustrates a common technique for designing a single-lane roundabout configuration as an interim configuration. This section also discusses how practitioners can consider a future expansion to a multilane configuration. The techniques presented in this section can also apply

Exhibit 10.75. Example of roundabout with turbo roundabout features.

LOCATION: N Tamiami Trail/Fruitville Road, Sarasota, Florida.
SOURCE: Ken Sides.

to many other cases, such as conversion from a hybrid 2 × 1 configuration to an ultimate 2 × 2 configuration or between other combinations of multilane roundabouts.

When projected traffic volumes indicate that a multilane roundabout is required for future-year conditions, practitioners need to evaluate the duration of time that a single-lane roundabout would operate acceptably before requiring additional lanes. Where a single-lane configuration will be sufficient for much of the roundabout's design life, it may be appropriate to evaluate whether it is best to first construct a single-lane roundabout until traffic volumes dictate expanding to a multilane roundabout. Another reason to stage the construction of a multilane roundabout is the uncertainty of traffic predictions for a 10-year horizon year or 20-year design year, as discussed in Chapter 8: Operational Performance Analysis. Traffic predictions may never materialize because of the significant number of assumptions that practitioners must make when developing volume estimates for horizon or design years.

Single-lane roundabouts, as well as single-lane approaches to multilane roundabouts, are generally simpler for motorists to learn, are more readily accepted in new locations, and have fewer vehicle conflicts and crashes. This allows for a gradual transition into the ultimate multilane build-out of the intersection. Single-lane roundabouts also introduce fewer conflicts to bicyclists and pedestrians and provide increased safety benefits and usability to bicyclists and pedestrians by minimizing the crossing distance and limiting exposure time to vehicles while crossing an approach. Single-lane roundabouts are also safer and easier for bicyclists to use when circulating with motor vehicles, should that be desired.

When considering an interim single-lane roundabout, the practitioner needs to evaluate the right-of-way and geometric needs for both the single- and multilane configuration as well as future construction staging for the additional lanes.

There are many potential ways to expand from an interim to an ultimate configuration. The following sections illustrate two common ways: expanding to the inside and expanding to the outside.

10.8.1 Expanding to the Inside

Expanding to the inside involves adding any necessary lanes for the ultimate configuration to the inside of the interim roundabout configuration, with the outer curbs and ICD remaining the same in both the interim and ultimate configurations. This allows for setting the outer limits of the intersection during initial construction and limits the future construction impacts to surrounding properties during widening, as sidewalks and outer curb lines will not typically require adjustment.

The roundabout first needs to be configured for the ultimate multilane configuration. An interim single-lane design is established within the ultimate multilane configuration by providing wide splitter islands and an enlarged central island that occupy the space required for the inside travel lanes. Future expansion would be accomplished by narrowing the splitter island and widening the inside of the existing travel lanes. Typically, this could require replacing the splitter islands, central island curbing, and truck apron. However, cold pavement joints support removing only the unnecessary portion and adding new curbing.

This process typically requires short-term lane closures and, therefore, may be best accomplished by working on one approach at a time and implementing localized detours for the approach that is undergoing demolition. The remainder of the intersection can continue to operate. If demolition is staged from the entry lanes of the intersection, the exit on the leg where demolition is occurring may be able to remain open.

Once the original splitter island is removed, work on forming and pouring concrete for the new splitter island can be accomplished from the new inside lane developed as part of the demolition. This may allow for the original outside entry lane to be re-opened to traffic, subject to flagging or other necessary traffic control. Once the new splitter island has been constructed and the additional roadway pavement is placed for an approach, the new inside lanes may remain coned off until the remaining approaches have been completed and the final markings and signing have been placed for the full intersection.

10.8.2 Expanding to the Outside

Expanding to the outside involves adding lanes for the ultimate configuration to the outside of the interim roundabout configuration, with the central island and splitter islands built for the interim condition and retained for the ultimate configuration. Assuming the right-of-way was purchased for the ultimate design, the interim sidewalks and landscaping could also be constructed in their ultimate location.

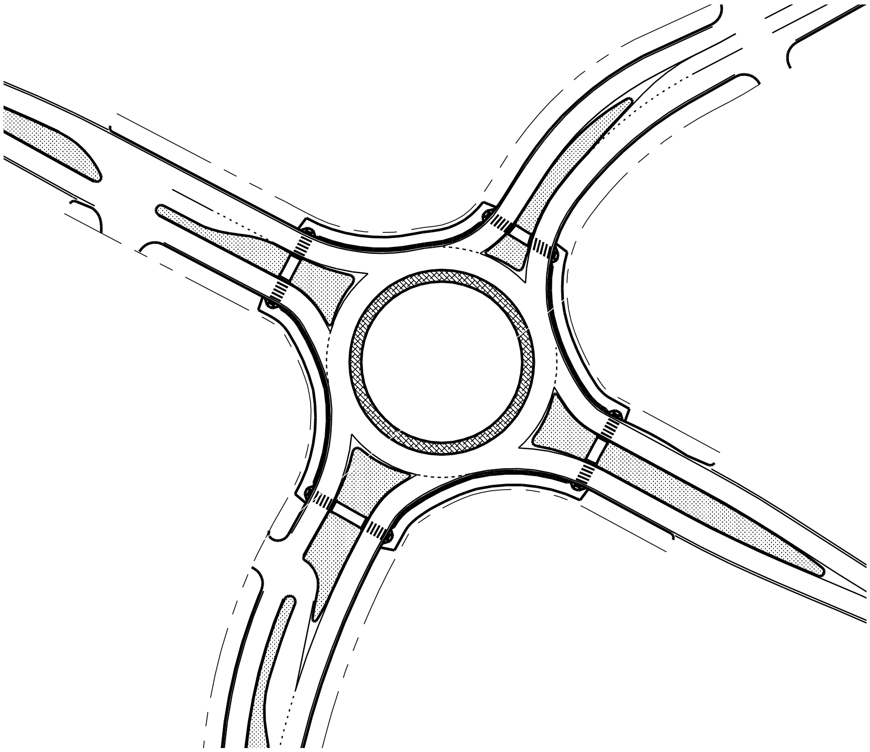
When using this option, the roundabout is first designed to meet the performance objectives for the ultimate multilane configuration. The interim single-lane design can be established within the ultimate configuration by adjusting the outer curb positions. The ultimate multilane design is needed for establishing right-of-way needs and reserving or purchasing what is needed for the ultimate roundabout footprint.

This method can be less disruptive to motor vehicle traffic since most of the improvements are added to the outside of the roadway. Expanding to the outside could result in the need to relocate drainage structures along with new outside curb lines. The original curb lines must be demolished and replaced with pavement. It is best to remove the original pavement markings; final markings and signs are then placed before the additional lanes of traffic are opened. In locations where concrete pavement is used, grinding pavement markings may leave a permanent mark on the roadway surface that could confuse drivers.

Exhibit 10.76 and Exhibit 10.77 provide interim and ultimate configurations, respectively, for an example of a staged multilane roundabout that is expanded to the inside.

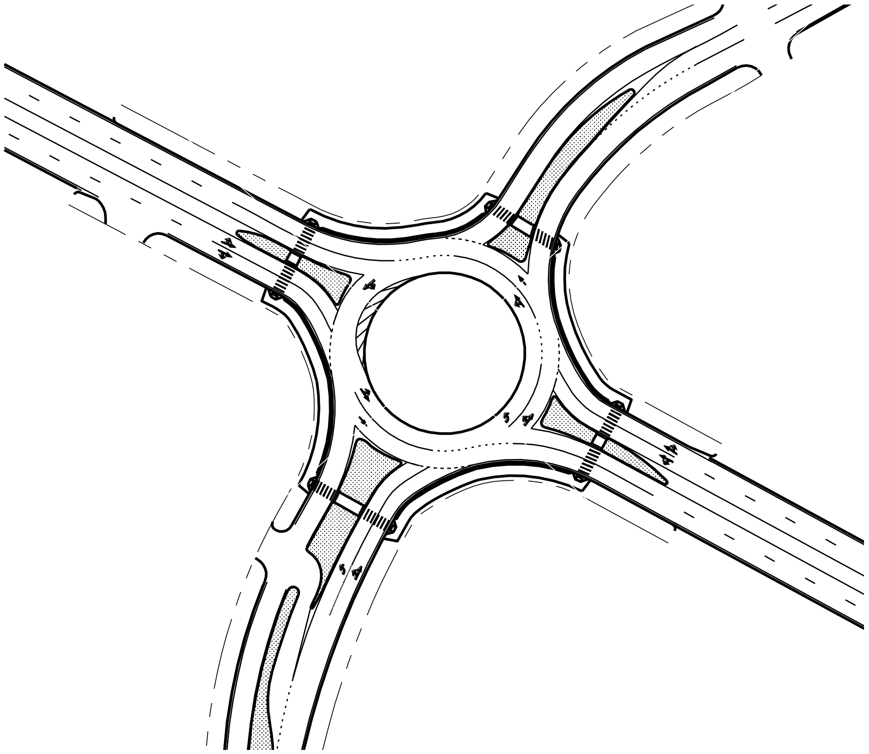
It may seem advantageous from a cost perspective to build curbs in their ultimate configuration and use signs and pavement markings to mark the interim configuration. However, research has

Exhibit 10.76. Staged multilane roundabout, interim configuration.



SOURCE: *NCHRP Report 672* (*2*).

Exhibit 10.77. Staged multilane roundabout, ultimate configuration.



SOURCE: *NCHRP Report 672* (*2*).

found that lanes and spiraling channelization that are designated solely with pavement markings and not with curbing are less effective and can contribute to poor safety performance (*26*, *34*). As such, definition of the interim configuration using curbing is preferred.

10.9 Bypass Lanes

Bypass lanes, sometimes called *channelized turn lanes* or *slip lanes*, may be included at any roundabout (as with any other type of intersection). The most common type of bypass lane at roundabouts is a right-turn bypass lane. However, at T-intersections, a through bypass lane is sometimes used across the top of the T. The principles presented in this section are the same for both types of bypass lanes, even though most examples are for right-turn bypass lanes.

If applied to single-lane configurations, design consideration for bypass lanes may include principles of multilane roundabout design as they relate to helping drivers select their lane in advance of the intersection. Extending the life of the single-lane roundabout (or precluding the need for a multilane roundabout) by incorporating a bypass lane may be desirable, as doing so gives the relative safety performance benefit of a single-lane roundabout. However, the bypass lane needs to be carefully designed to support safety for all modes, especially bicyclists and pedestrians. The following are some bypass lane considerations:

- A bypass lane creates one or two additional pedestrian crossings. The potentially higher speeds of bypass lanes and the lower expectation of drivers to stop may require active traffic control and increase the risk of pedestrian collisions. Bypass lanes also introduce additional complexity for pedestrians who are blind or have low vision navigating the intersection.
- The bypass lane creates additional conflicts on the exit between motor vehicles, depending on its configuration.
- The transitions to and from a bypass lane can create conflicts with bicycle facilities as well as conflicts at each crossing location.
- A bypass lane provides an opportunity to serve right-turning design vehicles on movements with acute angles between intersecting streets.

Providing a bypass lane allows right-turning traffic to bypass the roundabout, providing additional capacity for the through and left-turn movements at the approach. However, considering reverse traffic patterns during the opposite peak period is necessary to completely assess traffic operations during each peak period. A heavy right-turn volume during one peak period is often a heavy left-turn return volume during another peak period.

The radius of the right-turn bypass lane cannot be significantly larger than the radius of the fastest entry path provided at the roundabout. The goal is to create vehicle speeds for drivers decelerating into the bypass lane that are similar to speeds within the roundabout. A small radius also offers greater safety performance benefits for pedestrians who must cross the right-turn bypass lane.

Exhibit 10.78 and Exhibit 10.79 show examples of right-turn bypass lanes.

10.9.1 Yielding Bypass Lanes

The yielding bypass lane is the preferred bypass lane option whenever bicycle or pedestrian use is intended. The concept is illustrated in Exhibit 10.80. A common challenge is that the view angle for a driver in the right-turn-only lane may be insufficient, depending on overall roundabout geometry. In addition, the pedestrian crossing on the exit is located farther from the end of the right-turn-only lane to provide drivers with sufficient time to react to and stop for pedestrians.

Exhibit 10.78. Example of right-turn bypass lane.

LOCATION: Avon Road/I-70 Westbound Ramps, Avon, Colorado.
SOURCE: Lee Rodegerdts.

The advantage of a yielding bypass lane is that it may allow the roundabout to remain as a single-lane roundabout with a slower right-turn movement, which results in safer operation for all users.

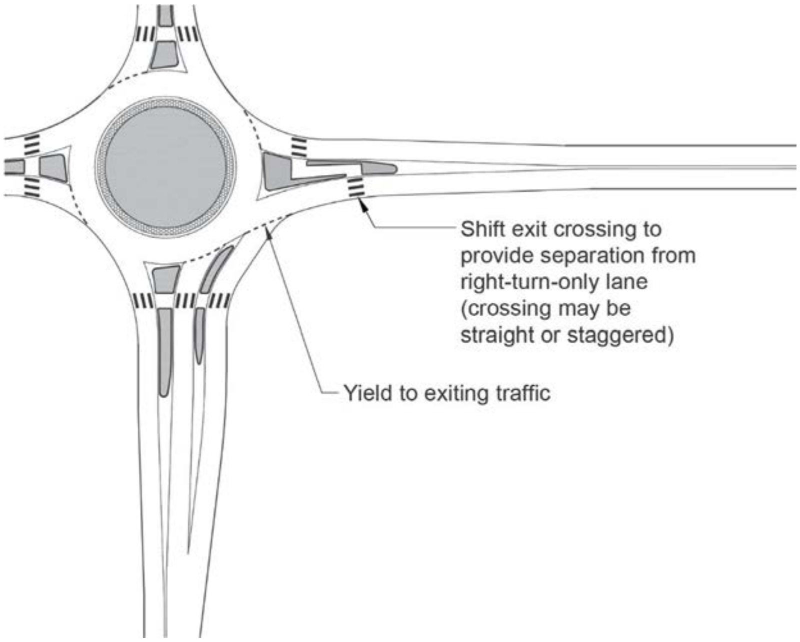
The disadvantage is that the crosswalk immediately downstream needs to be located far enough from the bypass lane yield point to allow drivers to shift their attention from conflicting traffic to the downstream crosswalk and provide enough time for them to react to and stop for pedestrians and bicyclists at the crossing. This may require a staggered pedestrian crossing, as discussed in Section 10.4.

In some cases, it may be desirable to use a right-turn-only lane rather than a separated right-turn bypass lane. Exhibit 10.81 shows two of these options, both of which are designed to have the right-turn-only lane terminate into the splitter island rather than aligning it partially or completely with the circulatory roadway. Without that design characteristic, drivers in the right-turn-only lane may more readily enter the circulatory roadway.

Exhibit 10.79. Example of right-turn bypass lane.

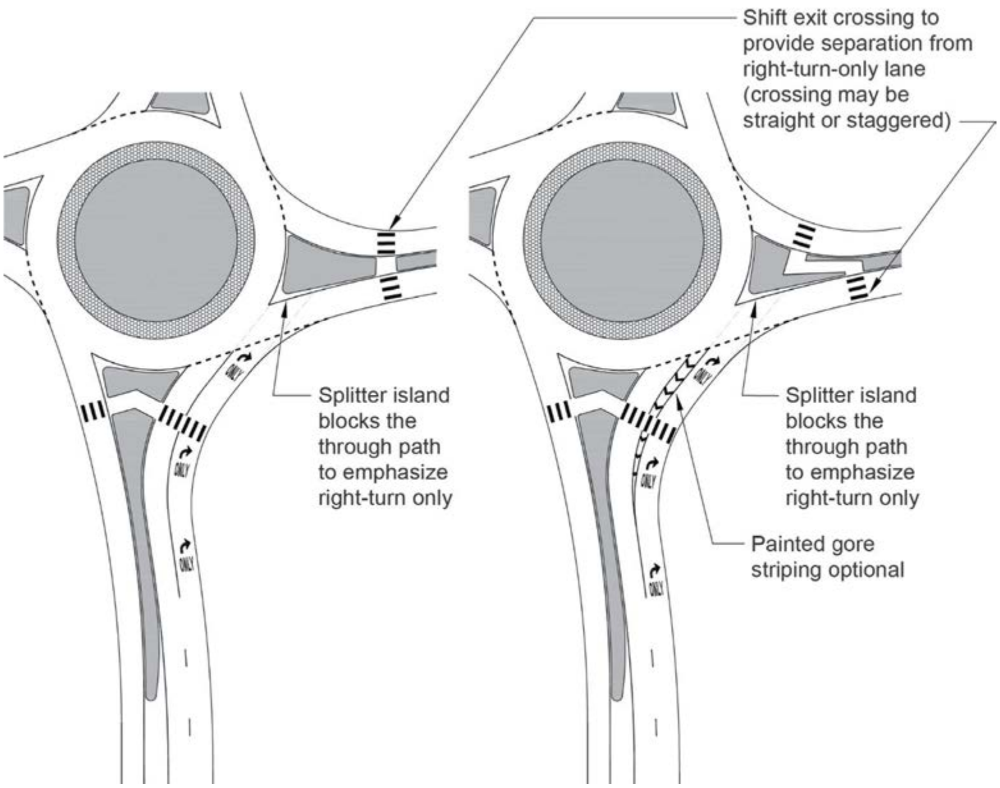
LOCATION: Main Street/Marlboro Street/Winchester Street, Keene, New Hampshire. SOURCE: Google Earth.

Exhibit 10.80. Yielding right-turn bypass lane.



SOURCE: *NCHRP Report 672* (*2*).

Exhibit 10.81. Yielding right-turn-only lane.



SOURCE: *NCHRP Report 672* (*2*).

The exhibits are conceptual only to reflect this bypass type. The view angle for a driver in the right-turn-only lane may be insufficient, depending on overall roundabout geometry. In addition, the pedestrian crossing on the exit needs to be located farther from the end of the right-turn-only lane to provide drivers with sufficient time to react to and stop for pedestrians.

A painted traffic separator between the through and right-turning lanes channels right-turning drivers and promotes a right turn for drivers yielding at the exit. This separation may also create space for the swept path of right-turning design vehicles. The right turn creates a multilane crossing for pedestrians on the entry that may require additional treatments for accessibility, such as raised crosswalks and active traffic control. It will also create a potential sudden conflict for pedestrians on the exit. As part of the design, the entry lane and right-turn-only lane are checked for adequate view angles to the left, following the principles presented in Section 10.7 for multilane design. The crossing on the exit is located away from the end of the right-turn-only lane so that drivers have time to react to and stop for pedestrians.

For right-turn lanes of all forms, it may sometimes be possible to develop the right-turn-only lane well in advance of the intersection and place a through bike lane to the left of the right-turn-only lane, similar to the standard design for conventional intersections. If this design is used, the through bike lane is then terminated or connected to a separated bicycle facility or multiuse path around the roundabout before bicyclists enter the roundabout (as with normal entry design for bicyclists). This would make the presence of a right-turn bypass lane less challenging for bicyclists.

10.9.2 Merging Bypass Lanes

Merging bypass lanes are designed for vehicles in the right-turn bypass lane to enter the exiting roadway at a shallow angle at similar speeds to exiting vehicles. Under this option, the bypass lane is carried alongside the main roadway for a sufficient distance to allow vehicles in the bypass lane and vehicles exiting the roundabout to accelerate to comparable speeds. The bypass lane is then merged at a taper rate according to AASHTO guidelines for the appropriate design speed (*1*). Merging bypass lanes are not advised in environments where bicycle and pedestrian use is intended (because motor vehicle speeds are higher in the bypass lanes) unless supplemental crossing treatments are used (such as raised crosswalks). An example of a merging bypass lane is illustrated in Exhibit 10.82.

Merging bypass lanes have two advantages:

- A merging bypass provides a higher motor vehicle capacity than a yielding bypass.
- The merging area reduces the departure roadway to a single lane, which is compatible with many two-lane highway cross sections.

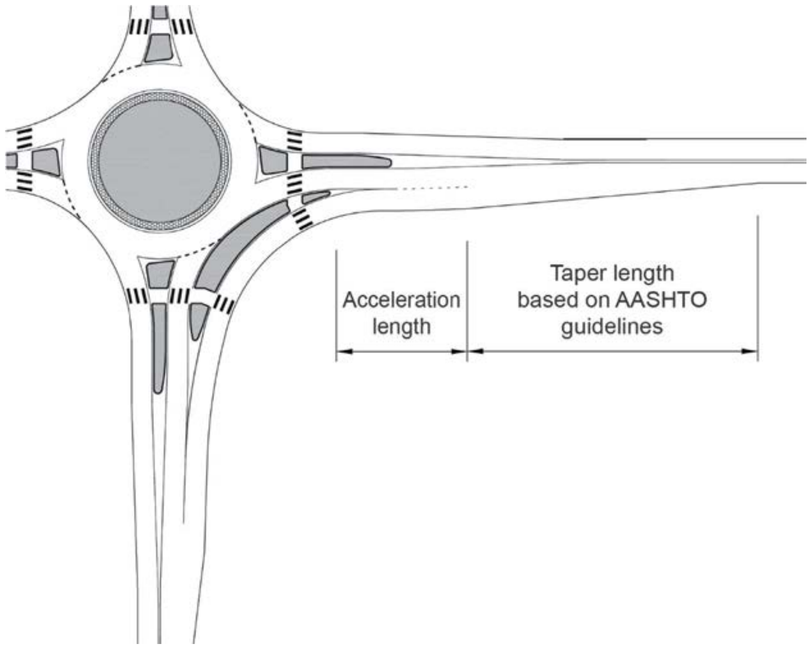
The arrangement has two disadvantages:

- The merging bypass lane generally promotes higher motor vehicle speeds than the yielding bypass option and creates additional conflicts for bicyclists and pedestrians.
- The downstream merge could create secondary conflicts if driveways or public streets are located beyond the merge where drivers may be decelerating to make a right turn.

10.9.3 Add-Lane Bypass Lanes

Add-lane bypass lanes may be desirable when the overall roadway cross section increases in number of lanes downstream of the roundabout. The geometry of the add-lane bypass lane in the vicinity of the roundabout is like that of a merging bypass lane. Add-lane bypass lanes are not advised in environments where bicycle and pedestrian use is intended (because motor vehicle speeds are higher in the bypass lane) unless supplemental crossing treatments are used (raised crosswalks, active traffic control, or both).

Exhibit 10.82. Merging right-turn bypass lane.



SOURCE: *NCHRP Report 672* (*2*).

The advantage of an add-lane bypass lane is that it provides the highest motor vehicle capacity.

The arrangement has several disadvantages:

- The add-lane bypass lane promotes the highest motor vehicle speeds of the three options.
- The high motor vehicle speed creates the potential for less yielding to pedestrians.
- The add-lane on the exit creates a weaving conflict for bicyclists exiting the roundabout who need to change lanes to enter whatever bicycle facility is provided on the outside of the departing roadway.
- The add-lane creates potential weaving conflicts for destinations immediately downstream of the roundabout, which may compromise its effectiveness in environments with nearby intersections or access points.
- If a downstream intersection or access point is located within the merge area, there are additional conflicts for motor vehicles and any bicyclists and pedestrians present.

10.9.4 Pedestrian and Bicycle Crossings for Bypass Lanes

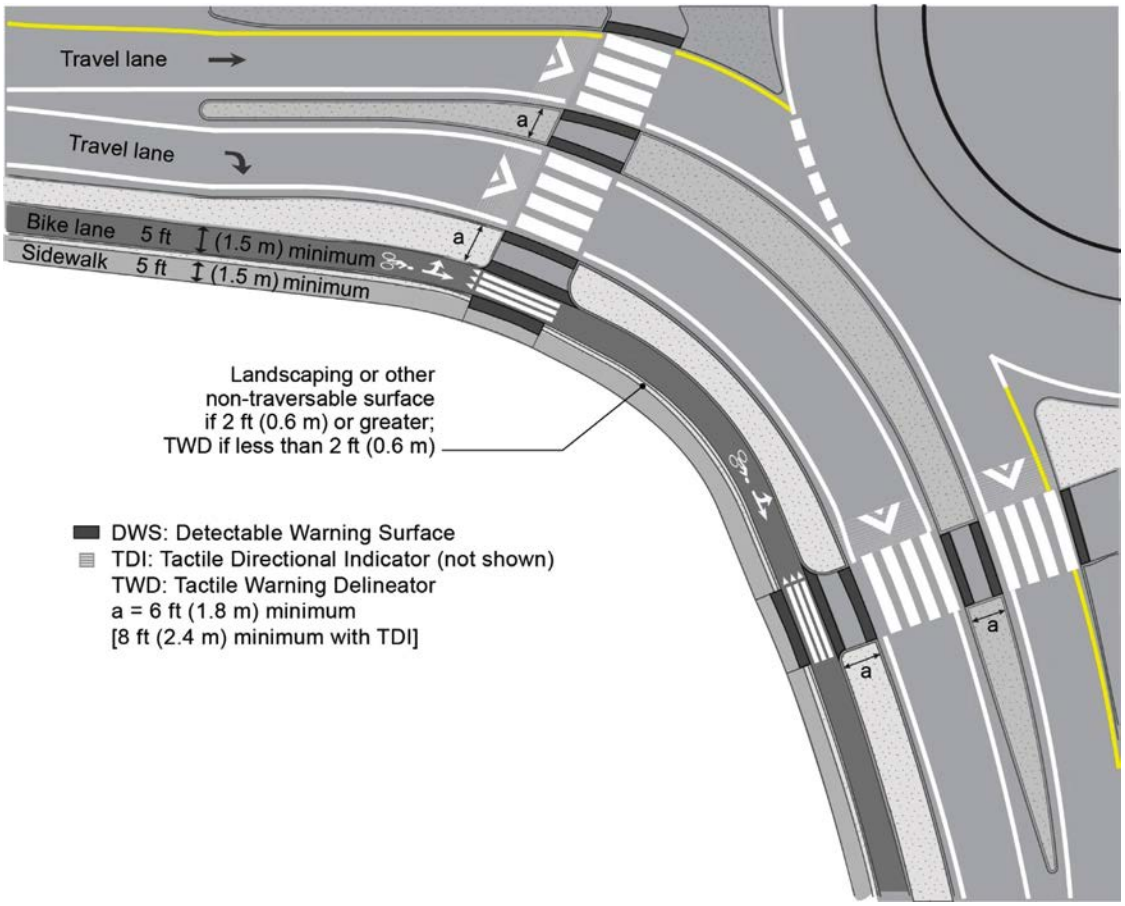
Section 10.4 presents a variety of concepts for designing for people walking and biking through a roundabout. The concepts in that section can be extended to bypass lanes. For yielding bypass lanes, the same range of options used at roundabout entries can be used across the yielding bypass lane.

As discussed previously, merging or add-lane bypass lanes are more challenging than yielding bypass lanes for bicyclists and pedestrians at roundabouts and other intersection forms, especially for people who are blind or have low vision. Because of these challenges, raised crosswalks can be beneficial to improve driver speed control and yielding behavior. Exhibit 10.83 illustrates an add-lane or merging bypass lane with a raised shared-use crossing.

This arrangement has several advantages:

- The raised crossing provides vertical geometric speed control for motor vehicles, provides greater driver visibility of people walking, and promotes better driver yielding behavior.

Exhibit 10.83. Pedestrian crossing with raised crosswalks at the roundabout entry with a right-turn bypass lane.



- The raised crossing has pairs of detectable warning surfaces for each interaction with vehicles.
- The raised crossing is straight, resulting in the fewest turns for bicyclists and pedestrians. This is especially helpful for people who are blind or have low vision.

However, it also has two disadvantages:

- Pedestrians and bicyclists use the same shared-use crossing. The shared-use crossing creates more conflicts between bicyclists and pedestrians than separated crossings, especially considering that the crossing is bidirectional for both bicyclists and pedestrians.
- The raised crossing may be more difficult to maintain during snow conditions and may introduce drainage challenges.

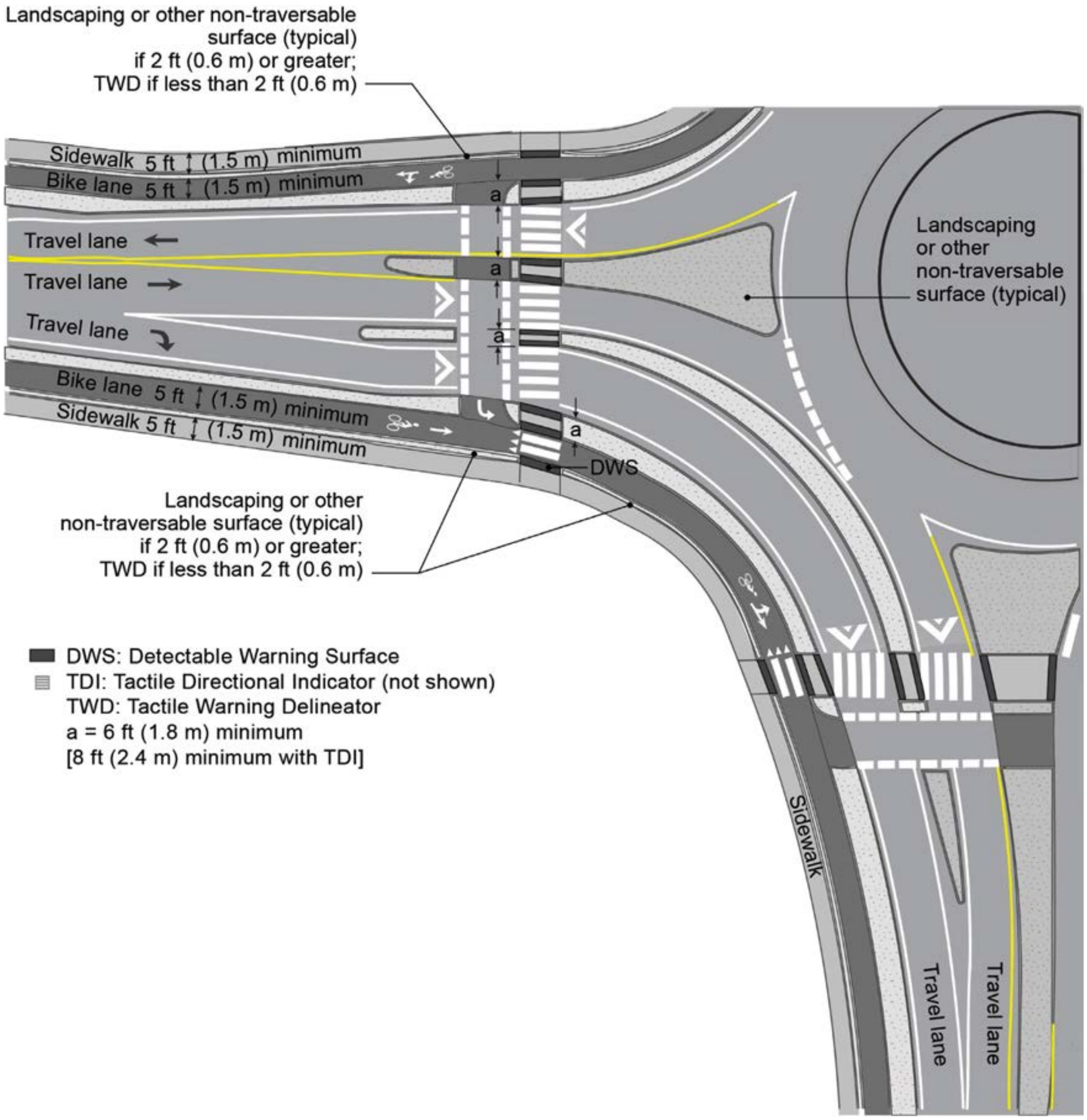
Other arrangements are possible by adapting the concepts used for shared-use crossings of roundabout entries and exits.

Exhibit 10.84 illustrates a roundabout bypass lane with a possible arrangement of separated bicycle and pedestrian crossings. Other variations are possible by adapting the concepts presented previously for entry and exit crossings.

Advantages of this arrangement:

- The raised crossing provides vertical geometric speed control for motor vehicles, provides greater driver visibility of people walking, and promotes better driver yielding behavior.
- The raised crossing has pairs of detectable warning surfaces for each interaction with vehicles.

Exhibit 10.84. Separate raised bicycle and pedestrian crossings with one-way separated bicycle lane at sidewalk level at roundabout with a right-turn bypass lane.



- Pedestrians and bicyclists are separated, minimizing conflicts between modes and maximizing accessibility for the pedestrian crossing.
- The raised crossing is straight, resulting in the fewest turns for bicyclists and pedestrians. This is especially helpful for people who are blind or have low vision.
- The narrow separation between the bicycle and pedestrian crossings creates a single yielding point for drivers at each crossing.
- The straight alignment facilitates the possibility of one-stage operation to minimize delay for bicyclists and pedestrians.

Disadvantages of this arrangement:

- The raised crossing may be more difficult to maintain during snow conditions and may introduce drainage challenges.
- Depending on the overall length of the crossing, the pedestrian clearance time under one-stage operation is much longer than a typical two-stage crossing because of the additional travel

time for both crossing and within the splitter island. This may increase vehicular queuing at the crossings, which may require shifting the crossings further from the roundabout to avoid extended interruptions within the circulatory roadway.

- If active traffic control devices are used with two-stage operation, the two-stage operation for bicyclists and pedestrians may not be obvious given the linear alignment of crossings. This may result in confusion to bicyclists and pedestrians over which display controls each crossing (including accessible pedestrian signals).

Other arrangements are possible by adapting the concepts used for separated crossings of roundabout entries and exits.

10.10 Interchanges

This section discusses roundabouts as part of interchanges. Interchanges involve grade separating one or more movements. They are most common on freeways but can occur on other facility types. Freeway interchanges include system and service forms. Service interchanges apply stop, yield, or signal control at the crossroad ramp terminal intersections. Roundabouts may be used at ramp terminal intersections and have been successfully applied at traditional diamond and partial cloverleaf forms. Roundabouts have also been applied at displaced left-turn forms that include transposed travel directions between ramp terminal intersections (i.e., a diverging diamond interchange). Roundabouts may take many shapes and forms as isolated intersections or connected forms.

Ramp terminal intersections have interdependency that requires practitioners to understand the roadway network's lane configurations and operational characteristics and needs, which allows for verifying that each intersection can operate effectively and serve each user. Ramp terminal intersection configuration selection may occur as part of an interchange selection process, a separate study (e.g., ICE), or a combination of the two. Regardless of the interchange type or the roundabout form, the fundamental performance objectives apply to roundabout ramp terminal intersections at interchanges.

10.10.1 Isolated Roundabouts

Roundabouts at service interchange ramp terminal intersections operate like other intersection forms. Roundabouts may be separated and operate independently; they are essentially isolated. U-turns are not traditionally provided along the arterial street at non-roundabout ramp terminal intersections for capacity and safety reasons as well as to discourage wrong-way movements on the freeway exit ramps. Interchanges are significant investments that intend to serve movements between the primary roadway (typically a freeway) and a secondary roadway (typically an arterial street). Arbitrarily providing U-turns to support access along the secondary roadway puts the burden on the interchange to serve third-order traffic (public or private access), which degrades the primary interchange function.

However, U-turns at roundabout ramp terminal intersections may be necessary to serve two-way frontage roads or connecting roadways and could be essential to an access management plan for the arterial. If U-turns are provided but are only occasional occurrences, drivers may become accustomed to not needing to yield to conflicting U-turning vehicles. In addition, the segment of circulatory roadway that serves only the occasional U-turn movement is more likely to accumulate road debris from a lack of use.

Exhibit 10.85 depicts a diamond interchange with isolated ramp terminal intersections. The configuration in Exhibit 10.85 uses a raindrop form at each ramp terminal intersection that does

Exhibit 10.85. Example of raindrop-shaped roundabouts at diamond interchange.

LOCATION: Dike Access Road/I-5 Ramps, Woodland, Washington.
SOURCE: Google Earth.

not allow cross-street U-turns. This configuration removes the yielding condition between the roundabouts and essentially eliminates the likelihood of queuing between the ramp terminals. This may be beneficial in reconstruction projects that retain the cross section on the minor roadway between the ramp terminal intersections.

One of the major concerns for rural service interchange locations is the potential for wrong-way movements on the freeway exit ramp. The raindrop configuration makes wrong-way movements into the off-ramps more difficult and removes impervious areas in the circulatory roadway.

Exhibit 10.86 depicts a two-quadrant partial cloverleaf form with isolated ramp terminal intersections. The configuration in Exhibit 10.86 allows U-turns.

Exhibit 10.87 depicts a trumpet interchange form with a single, isolated ramp terminal intersection. The configuration in Exhibit 10.87 allows U-turns as a byproduct of serving two-way traffic on the leg opposite the freeway exit ramp.

Exhibit 10.88 depicts a diverging diamond interchange (DDI) with an isolated ramp terminal intersection. The configuration in Exhibit 10.88 supports the crossover configuration that allows contraflow travel between the ramp terminal intersections. This DDI combines a

Exhibit 10.86. Example of circular roundabouts at an interchange.

LOCATION: Austin Chaney Road/US 74 Bypass Ramps, Monroe, North Carolina. SOURCE: Google Earth.

Exhibit 10.87. Example of isolated roundabout at an interchange that allows U-turns.

LOCATION: SR 68 / SR 1 Off-Ramp/17 Mile Drive, Monterey, California.
SOURCE: Google Earth.

roundabout at one ramp terminal intersection with a signalized intersection at the other ramp terminal intersection. A DDI could be configured with roundabouts located at each ramp terminal intersection.

10.10.2 Connected or Single Roundabouts

Roundabouts at service interchange ramp terminal intersections may also be connected and operate as a single roundabout, which may be appropriate at non-interchange locations. The name *connected* or *single* roundabout acknowledges the proximity of the two ramp terminal intersections and how they operate compared with the isolated forms. These forms have sometimes been informally called *raindrop*, *peanut*, *dumbbell*, or other names describing their shape.

When multilane roundabouts are connected to one another in proximity, there is an overarching need to guide drivers for key movements throughout the length of the roadway segments without the need to change lanes. The highest priority movements are those to and from the freeway ramps, and these should be served with minimal lane changing if intersections are closely spaced. This requires attention to many system-related details, including operational

Exhibit 10.88. Isolated roundabout as part of DDI.

LOCATION: MO 291/SW Blue Parkway/US 50 Ramps, Lee's Summit, Missouri.
SOURCE: Google Earth.

Exhibit 10.89. Example of diamond interchange with connected raindrop-shaped roundabouts.

LOCATION: W Main Street/US 31 Ramps, Carmel, Indiana.
SOURCE: Google Earth.

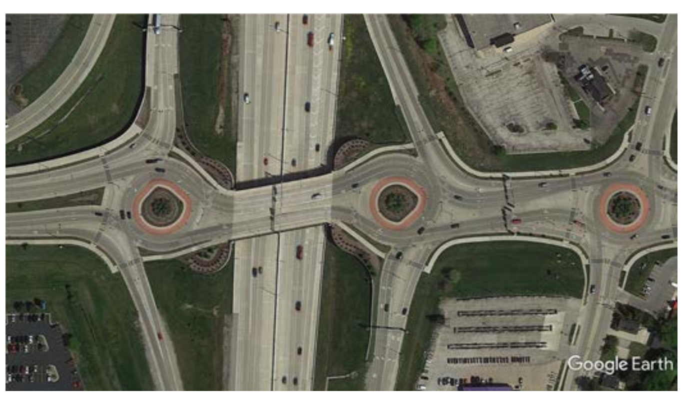
performance, coordinated signs and pavement markings, and geometric configurations that support the overall intended system operation. Further guidance on signs and pavement markings for these applications is provided in Chapter 12: Traffic Control Devices and Applications.

Exhibit 10.89 depicts a diamond interchange with connected ramp terminal intersections. The configuration does not allow U-turns. The configuration in Exhibit 10.90 has two isolated intersections that allow U-turns at the ramp terminal intersection. Each of these forms has the crossroad passing over the freeway and, coincidently, an adjacent roundabout on the crossroad. These interchange forms are also applicable where the freeway passes over the crossroad.

Exhibit 10.91 depicts a diamond interchange with connected ramp terminal intersections, with the freeway passing over the crossroad. The configuration does not allow U-turns and operates in the same manner as the form in Exhibit 10.89. This form allows single-span bridges on the freeway.

Exhibit 10.92 and Exhibit 10.93 present diamond interchanges where a crossroad has been configured as elongated roundabouts (oval shaped). These forms could also be configured as a single circular roundabout. Regardless of shape, the fundamental traffic operations are the same between the forms presented in Exhibit 10.89 through Exhibit 10.91. Roundabout capacity is based primarily on the lane configuration at each entry-circulating point; the size and shape of

Exhibit 10.90. Example of diamond interchange with separate circular-shaped roundabouts.



LOCATION: W Mason Street/I-41 Ramps, Green Bay, Wisconsin.
SOURCE: Google Earth.

Exhibit 10.91. Example of connected roundabouts with crossroad underpass.

LOCATION: E 191st Street/US 31 Ramps, Westfield, Indiana.
SOURCE: Google Earth.

Exhibit 10.92. Example of single roundabout with crossroad underpass.

LOCATION: E Broadway Street/I-135 Ramps, Newton, Kansas.
SOURCE: Google Earth.

Exhibit 10.93. Example of single roundabout with crossroad underpass.

LOCATION: S. Anderson Road/US 50 Ramps, Newton, Kansas.
SOURCE: Google Earth.

the circle have less effect, if any, on roundabout capacity relative to lane configuration. The oval or circular form may require four shorter bridges or two longer bridges, depending on its size. These forms could be used with the crossroad passing over the freeway, in which case the crossroad bridges would be curved rather than straight.

Regardless of the interchange type or the roundabout form, the fundamental performance objectives apply to roundabouts at interchanges.

10.11 Access Management

Roundabouts can be a useful tool within an access management plan. They can provide U-turn opportunities at intersections that may allow the number and location of full access points along the roadway to be reduced. Roundabouts offer the ability to serve U-turn movements more safely and efficiently than other intersection forms. This enables access points between roundabouts to be served by right-in, right-out movements or, in some cases, right-in, right-out, left-in movements. This promotes corridor operations and reduces crash risk by shifting the most difficult movements—left-out movements from access points—to U-turn movements at roundabouts.

Access points near a multilane roundabout can directly affect the operational and safety performance of the access point and the multilane roundabout. Research has found a likely link between the presence of nearby access points and improper lane use at a multilane roundabout, which is a key contributing factor to crash patterns at some multilane roundabouts (*26*). Where downstream access points are located close to a roundabout, drivers may pre-position themselves by choice in advance of the roundabout, in some cases turning from the incorrect lane to avoid a late lane change at the access point. Because of these potential interactions, access management is an important component of ICE activities, especially when determining the number and assignment of lanes at a roundabout and the connecting roadway system.

Access management at roundabouts follows many principles used for access management at conventional intersections. For public and private access points near a roundabout, two scenarios commonly occur:

- Access into the roundabout itself.
- Access near the roundabout.

This section addresses considerations for access into or near the roundabout and considerations for locating a full access near a roundabout.

10.11.1 Access into the Roundabout

In general, it is preferable to have private access points connect to the roadway system away from public intersections, including roundabouts. However, it may be possible to provide direct access from a private access point into a roundabout if the access point can be configured in a way that does not adversely affect the roundabout's safety or operation.

One objective during planning and design is to find alternatives to direct private access at the roundabout. This includes looking for potential alternative access points for the same property, options for shared access points, and other strategies. These are discussed in more detail in other references, including the TRB *Access Management Manual* (*35*).

If private access must be integrated into a roundabout, there are two primary considerations:

- If the access point is a low-volume generator with trips primarily by drivers familiar with the location, such as residents of one to three single-family homes, the access will take the form of a driveway. This reduces the likelihood of drivers on the public street misconstruing the private access as a public destination. However, traditional driveway configurations do not incorporate features to discourage wrong-way movements, as a splitter island does.

- If the access point is to be a more significant traffic generator (e.g., a commercial or retail property, larger residential use, or public or private institution) or trips are primarily taken by people less familiar with the location, the entry will be configured like a normal roundabout leg, with a full splitter island and other associated features.

Exhibit 10.94 depicts private driveway access to a college that has been configured to resemble a public access street.

Site constraints sometimes make it necessary to provide direct access into a roundabout. For a driveway to be located where it has direct access to the circulatory roadway of a roundabout, it needs to satisfy the following criteria:

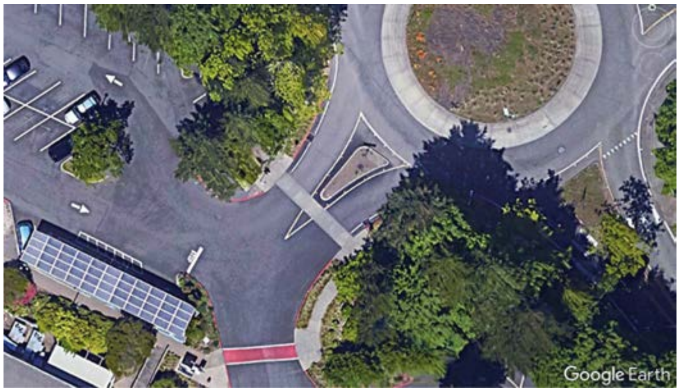
- No alternative access point is reasonable.
- Traffic volumes are sufficiently low to make the likelihood of errant vehicle behavior minimal. Driveways carrying the trip generation associated with a few single-family houses are typically acceptable; driveways with higher traffic volumes need to be designed as a regular approach with a splitter island. In addition, if a high proportion of unfamiliar drivers are expected at the driveway, the practitioner can consider providing more positive guidance.
- The driveway design enables vehicles to exit facing forward, with a hammerhead design or other area on site where vehicles can turn around. Driveways that only allow backing maneuvers into the roundabout are to be used only in low-volume environments.
- The driveway design enables proper intersection sight distance from the driveway location and adequate stopping sight distance for vehicles approaching the driveway and traveling along the primary roadway.
- The driveway designs are distinct from the circulatory roadway (e.g., concrete driveway aprons adjacent to an asphalt concrete circulatory roadway) to provide a clear visual indication that they are private driveways not to be confused with public roadways.
- Pedestrian and bicycle circulation across the driveway are maintained.

Exhibit 10.95 and Exhibit 10.96 depict examples of a private driveway accessing a roundabout.

10.11.2 Access Near the Roundabout

Public and private access points near an intersection can be common in reconstruction projects with existing or proposed development. In some cases, access must be provided near a roundabout

Exhibit 10.94. Private access configured as public street.



LOCATION: SW Terwilliger Blvd/S Palater Road, Portland, Oregon.
SOURCE: Google Earth.

Exhibit 10.95. Example of private driveway with direct access to a roundabout.

LOCATION: Alameda Padre Serra/Montecito Street/Salinas Street/Sycamore Canyon Road, Santa Barbara, California. SOURCE: Lee Rodegerdts.

and within the splitter island vicinity. Such locations will have restricted operations because of the splitter island. It is typically best to avoid these conditions, but the configurations are sometimes unavoidable and may be necessary if impact is expected to be minimal or no reasonable alternatives are available. Access considerations in the roundabout influence area may include

- Closing the access if it is redundant to other access points serving the properties,
- Shifting the access up or downstream to a location outside the splitter island,

Exhibit 10.96. Example of private driveway with direct access to a roundabout.

LOCATION: Route 85A (Maple Road)/Route 155, Voorheesville, New York. SOURCE: Google Earth.

Exhibit 10.97. Example of driveway located between crosswalk and roundabout.

LOCATION: SW Century Drive/SW Simpson Avenue, Bend, Oregon.
SOURCE: Lee Rodegerdts.

- Investigating crossover easements between adjacent parcels,
- Investigating alternative access roads to provide property access from a different location and serve the properties away from the roundabout, and
- Providing a break in the painted taper or splitter island to serve low-volume locations.

When access is developed near the roundabout, driveways are not to be located between the crosswalk and roundabout entrance or exit. Driveways between the crosswalk and the circulatory roadway complicate the pedestrian ramp treatments and introduce conflicts. They can be especially difficult for people with vision disabilities to correctly interpret. This can potentially increase crash risk, degrade traffic operations, or reduce accessibility.

Exhibit 10.97 and Exhibit 10.98 show examples of undesirable driveways located near a roundabout. Driveways blocked by the splitter island will be restricted to right-in and right-out movements.

Exhibit 10.98. Example of driveway improperly aligned with crosswalk.

LOCATION: NE Inglewood Hill/216th Avenue NE, Sammamish, Washington.
SOURCE: Lee Rodegerdts.

Exhibit 10.99. Example of driveway reconfiguration.

LOCATION: Mandalay Avenue/Acacia Street, Clearwater Beach, Florida.
SOURCE: Lee Rodegerdts.

Exhibit 10.99, Exhibit 10.100, Exhibit 10.101, and Exhibit 10.102 show examples of configurations that address access near the roundabout. These examples include relocating an access point or providing a break in the painted taper or splitter island to serve low-volume locations.

Research has found that access points near multilane roundabouts can significantly affect safety performance (*11*). For example, Exhibit 10.103 illustrates a multilane roundabout with a right-in, right-out access point (solid line at lower left corner) upstream of an entry.

Drivers exiting the access point to turn left are required by access management to instead turn right and make a U-turn at the roundabout. However, because the access point is close to the roundabout, drivers at the study location were frequently observed to make an incorrect

Exhibit 10.100. Example of splitter island broken to allow driveway access.

LOCATION: Route 85A (Maple Road)/Route 155, Voorheesville, New York.
SOURCE: Google Earth.

Exhibit 10.101. Example of painted taper broken to provide private driveway access.

LOCATION: Bradshaw Road/Sheldon Road, Elk Grove, California.
SOURCE: Google Earth.

Exhibit 10.102. Example of splitter island broken to allow driveway access.

LOCATION: Powell Butte Highway/Neff Road/Alfalfa Market Road, Deschutes County, Oregon.
SOURCE: Google Earth.

U-turn from the outer lane. This becomes more prevalent with increased volumes during peak periods. The driver making the improper U-turn creates a potential exit-circulating conflict with a through movement on the intersecting street. This type of pattern is possible in many permutations on the entry and exit where access points are close to multilane roundabouts. Major origins or destinations upstream or downstream of the roundabout, such as shopping center access points or freeway interchange ramps, can have similar effects.

These lane positioning challenges are not unique to roundabouts and can occur with similarly spaced signalized intersections. However, field research suggests that drivers appear to be more willing to make turning movements from incorrect lanes at multilane roundabouts, with poor safety performance over time as a result (*26*). Single-lane roundabouts eliminate these issues and are to be strongly considered where possible. If multilane roundabouts are necessary, the roundabout design needs to consider overall access needs and design influences. During corridor or intersection planning activities, creating an access management plan will inform the best lane configurations for the intersection and connecting roadways.

10.11.3 Locating Full Access Near a Roundabout

Locating an access point that allows all ingress and egress movements (hereafter referred to as *full access*) is influenced by four primary technical considerations. However, other issues and

Exhibit 10.103. Example of incorrect U-turn at multilane roundabout initiated from nearby access point.

SOURCE: Medina et al. (*26*).

needs may be influenced by optimizing the roundabout design for project context and user types, as outlined in Section 10.1. The location and level of access for access points in the vicinity of a roundabout, especially a multilane one, is a valuable part of ICE activities.

Factors to consider include

- **The capacity of the minor movements at the access point.** A standard unsignalized intersection capacity analysis is performed to assess the operational effectiveness of an access point with full access. Unlike the platooned flow typical downstream of a signalized intersection, traffic passing in front of an access point downstream of a roundabout will be more randomly distributed. As a result, an access point downstream of a roundabout may have less capacity and longer delay than one downstream of a traffic signal. Queuing from nearby intersections (the roundabout or others nearby) needs to be checked to see if the operation of the access point will be affected.
- **The need to provide left-turn storage on the major street to serve the access point.** For all but low-volume driveways, it is often desirable to provide separate left-turn storage for access points downstream of a roundabout to minimize the likelihood that a left-turning vehicle will block the major street traffic flow. A probability analysis can determine the likelihood of an impeding left-turning vehicle, and a queuing analysis can determine the length of the queue behind the impeding left-turning vehicle. If the number of left-turning vehicles is sufficiently small or the distance between the access point and the roundabout is sufficiently large, a left-turn pocket may not be necessary.
- **The available space between the access point and the roundabout.** Traffic operations or local criteria will dictate the minimum left-turn storage length and the bay taper length requirements. The distance to the full access point will include at least the minimum length roundabout splitter island and any additional requirements for a turn lane into the access point, if needed. In addition, access will be restricted along the entire length of the splitter island and left-turn pocket channelization.
- **Sight distance needs.** A driver at the access point needs to have proper intersection sight distance and to be visible when approaching or departing the roundabout.

10.12 Parking

Parking considerations on a roundabout approach or in a roundabout are like those of other intersections. Parking within a roundabout is prohibited. Some circular intersections have parking along the circulatory roadway, which creates friction and potential conflicts with circulating vehicles. While these conditions may be appropriate for the context, a circular intersection with parking along the circulatory roadway is not a roundabout and may not have the same safety performance and operational characteristics of a true roundabout.

Practitioners can discourage parking on the roadway approaches and departures to remove vehicle conflicts, friction, and other distractions from users navigating and crossing the roundabout. The traffic operational or geometric influence area of the roundabout may extend well upstream or downstream of the ICD. Parking on roadway approaches and departures is based on assessing and establishing the operational and geometric influence area of the roundabout, with a priority to provide no parking or to locate parking as far upstream or downstream as possible. The needs on each approach of the same roundabout may be unique. The following factors are considered when establishing parking near roundabout entries and exits:

- Parking maneuvers create friction along the roadway. These movements will preferably not interfere with bicycle, pedestrian, or motor vehicle movements at the roundabout.
- Parked vehicles can obstruct visibility of pedestrians and bicyclists.

- Parking along multilane roadways can introduce lane assignment problems similar to those for access points, as discussed in Section 10.11.
- State or local standards or guidelines may dictate a minimum parking setback from intersections. At roundabouts, this setback is be measured from the crosswalk or the point where bicyclists may be entering the travel lane—whichever is farther from the roundabout.

10.13 Bus Stop Placement

Bus stops are commonly located in the vicinity of roundabouts. To provide the best quality of service for bus passengers, bus stops are located as close to pedestrian crossings as possible to minimize out-of-direction travel. However, they also need to be located to be compatible with the roundabout, including having buses in the correct lane in a multilane roundabout. This section presents a discussion of possible options for bus stops.

If a bus stop on the entry side of the roundabout (a near-side stop) is chosen, it will be located and designed as follows:

- On a single-lane approach, the bus stop could be in the travel lane immediately upstream of the pedestrian crossing.
- On a multilane approach, a near-side bus stop in the travel lane is to be avoided because vehicles in the lane next to the bus may not see pedestrians and create a multiple-threat condition. A pullout compatible with the pedestrian and bicycle circulation system is instead used. However, a bus exiting the pullout may obscure the visibility between pedestrians and oncoming motor vehicles; a bus stop on the exit side may be preferable.

If a bus stop on the exit side of the roundabout (a far-side stop) is chosen, it will be located and designed as follows:

- Bus stops are located immediately beyond the pedestrian crossing to improve visibility of pedestrians to other exiting vehicles. Proximity to the crosswalk is preferable to minimize out-of-direction travel for pedestrians.
- Stops on the exit side result in the crosswalk being behind the bus, which helps drivers see pedestrians and allows the bus to depart while pedestrians are still crossing the street.
- Bus pullouts reduce the likelihood of queuing behind the bus into the roundabout. A bus pullout may create sight line challenges for the bus driver to see vehicles approaching from behind as the bus driver attempts to merge into traffic.

Bus stops cannot be located along the circulatory roadway for the following reasons:

- Bus stops along the circulatory roadway eliminate the detectable buffer that is required between the circulatory roadway and pedestrian path per proposed PROWAG. Detectable buffers are discussed further in Section 10.4.
- Bus stops within the circulatory roadway, either in-lane or in a pullout, introduce conflicts within the circulatory roadway that cannot be present at a roundabout.

10.14 Treatment for High-Speed Approaches

Roundabouts have been successfully located at the intersection of high-speed roadways. Roundabouts provide geometric features that create low speeds. However, roadway facility type, context, or context classification may create conditions at which additional treatments are beneficial for speed reduction in advance of the roundabout. For roadway approaches with posted speeds of 45 mph (70 km/h) or greater, the roundabout configuration may include treatments on those approaches. This could include considerations for possible transition treatments or features between the upstream segment and the roundabout to support speed reductions. When conducting in-service reviews at an existing circular intersection, the upstream roadway approach speeds could provide insights into the observed roundabout performance.

Intersections on rural roads often have higher approach speeds than urban or local streets. Most intersections on rural roads are two-way stop-controlled intersections, with the major street uninterrupted. As such, drivers may not expect to encounter speed interruptions or intersections that require stopping—as at an all-way, stop-controlled intersection—or potentially stopping—as at a roundabout or signalized intersection. The primary safety and operational needs at these rural intersections are making drivers aware of the impending intersection and providing ample distance to comfortably decelerate to the appropriate speed.

This challenge is not unique to rural roadways. Suburban roadways and some urban roadways may also have posted speeds of 45 mph (70 km/h) or higher. Creating driver awareness of speed reduction at roundabouts may be necessary. The same general principles apply to creating awareness and providing sufficient distance to reduce speed at the roundabout entries. Mini-roundabouts and compact roundabouts have less conspicuous central islands, so treatments on those approaches may be especially necessary to support desired roundabout safety and operational performance.

A fundamental principle associated with speed transitions is creating self-describing roadways that help an approaching driver interpret and react to the upcoming roundabout correctly and safely. Deceleration distances are provided in the Green Book (*1*); values provided include minimum lengths that represent rapid deceleration conditions that may be uncomfortable for passengers. The deceleration lengths provided in this section represent AASHTO values for comfortable deceleration lengths between an approach speed and roundabout target speeds.

Curvilinear alignments, also called *chicanes*, are not required for speed reduction but are acceptable. In some cases, curvilinear alignments may be a byproduct of the entry design to achieve appropriate entry speeds and other design performance objectives. However, curvilinear alignments can help support incremental speed reduction upstream of the roundabout entry. In constrained locations, however, curvilinear alignments may not be possible.

Geometric design and the transition zone established to meet target speed reduction may be based on the required deceleration length, which includes the painted taper and the splitter island. Geometric design is the foundation for speed transitions. However, signage, pavement markings, lighting, and other treatments (e.g., speed feedback signs, rumble strips, or flashing beacons) support deceleration to the roundabout. Exhibit 10.104 depicts a roundabout approach with a painted taper and extended splitter island as the primary feature supporting the speed transition. The approach also includes complementary optical speed bars to help drivers understand deceleration needs approaching a rural roundabout.

Exhibit 10.105 depicts a tangent roadway approach in a high-speed environment. Exhibit 10.106 depicts a curvilinear roadway approach in a high-speed environment.

10.14.1 Visibility

Visibility enables driver awareness of an approaching roundabout and positively contributes to safety performance. Providing visibility of the roundabout and approaches can reduce the potential for single-vehicle crashes. Where possible, the geometric alignment of approach roadways is constructed to maximize the visibility of the central island and the shape of the roundabout.

The central island of the roundabout and the geometric alignment and channelization on the approaches are primary features to support speed reduction. Cross-section elements, such

Exhibit 10.104. Example of geometric and supplemental features on a rural roundabout approach.

LOCATION: Powell Butte Highway/Neff Road/Alfalfa Market Road, Deschutes County, Oregon. SOURCE: Lee Rodegerdts.

Exhibit 10.105. Example of tangent alignment on approach roadway.

LOCATION: STH 65/80th Avenue/W Graham Street, Roberts, Wisconsin. SOURCE: Google Earth.

Exhibit 10.106. Example of curvilinear alignment on approach roadway.

LOCATION: Bullfrog Road/Suncadia Trail, Cle Elum, Washington. SOURCE: Google Earth.

as introducing curbing on the approach, help drivers interpret the transition from the roadway to the intersection. In addition, adding curbs and dropping shoulders reduces the cross-section width to promote positive guidance. All these features contribute to a self-describing roadway that encourages speed reduction.

Traffic control devices, reflective delineators, and roadway lighting supplement these geometric features to provide additional visibility approaching a roundabout. These are discussed further in Chapter 12: Traffic Control Devices and Applications and Chapter 14: Illumination, Landscaping, and Artwork.

10.14.2 Approach Speed and Speed Transitions

Assessing the influence of the approach roadway and transition lengths to the roundabout can follow operations and design principles for freeway exit ramp deceleration lengths. Practitioners can determine deceleration lengths by considering design or operating speeds at the exit ramp and an associated target speed. At a freeway exit ramp, the deceleration length is typically the distance to a downstream controlling curve or stop condition.

The deceleration distance for a roundabout is based on the assumed stop location and the distance upstream of the roundabout, where the approach speed has been established. Roundabout approach speeds can be the observed, posted, or design speed on the approach roadway. Deceleration lengths can be the distance to a potential stop condition at the roundabout crosswalk, the entry (if no crosswalk is provided), or the estimated back of queue on a given approach—whichever is farthest from the roundabout. The deceleration length includes the painted taper and the splitter island.

Exhibit 10.107 presents the deceleration length concept for a single-lane roundabout. This concept also applies at multilane entries.

Exhibit 10.108 presents minimum deceleration lengths to an assumed stopped condition for flat grades of less than 3 percent. The table and values are adapted from the Green Book, Table 10-6, for freeway exit ramp terminals. For grades greater than 3 percent, adjustment factors from AASHTO may be used to shorten or lengthen the deceleration distance (*1*).

The deceleration length values can inform planning and design decisions and are not intended to be absolute values or requirements. Many roadway, context, and land-use considerations may affect these decisions. For example, existing rural conditions could be evolving to more developed

Exhibit 10.107. Deceleration length roadway approach to crosswalk.

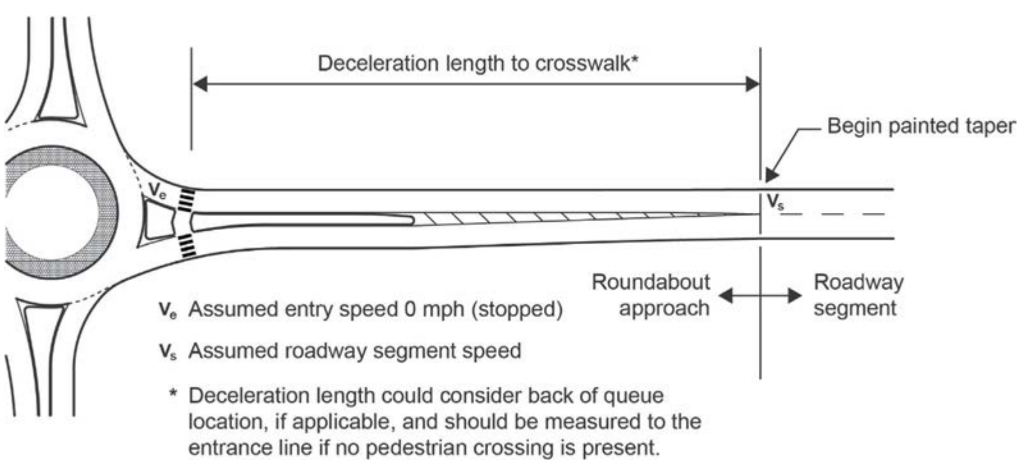


Exhibit 10.108. Minimum deceleration lengths for flat grades.

Approach Roadway Design Speed (mph)	Minimum Deceleration Length to an Assumed Stopped Condition (ft)	Approach Roadway Design Speed (km/h)	Minimum Deceleration Length to an Assumed Stopped Condition (m)
40	320	70	110
45	385	80	130
50	435	90	145
55	480	100	170
60	530	110	180
65	570	120	200
70	615	130	215
75	660		
80	705		

SOURCE: Adapted from Green Book, Table 10-6 (*1*).

conditions along the roadway or near the intersection. However, evaluating roadway approach speeds and speed transition needs early in project development can help identify footprint issues or other access considerations that support ICE activities or other project evaluations. Considering approach speeds may also support in-service roundabout review.

Extended splitter islands alert drivers to the changing condition of an impending roundabout. The splitter island is within the deceleration length that includes the painted taper. Splitter islands provide positive guidance and can aid in reducing approach speeds. Their configuration is based on a horizontal alignment that provides the desired speed transition.

Splitter island lengths of 150 ft to 200 ft (45 m to 60 m) or more have been commonly used to complement the painted taper for overall deceleration needs. Splitter islands need to be customized to each roundabout approach and to be consistent with the horizontal design of each approach. For example, at a roundabout on a rural highway approaching a community, longer splitter islands may be appropriate to support speed reduction on the high-speed approach, while shorter splitter islands may be appropriate for the other approaches with lower approach speeds.

10.14.3 Approach Curves

The change in speed from the upstream roadway segment to the roundabout entry can be established as a speed profile (i.e., speed over distance). The segment speed could be observed speed, posted speed, or design speed, and the assumed speed at the roundabout is a stopped condition. If approach curvature is to be used to manage speed or as a byproduct of desired roundabout entry design, the speed profile can provide insight into the curve radii to be used. A series of progressively sharper curves on the approach creates a self-enforcing roadway that slows motor vehicles to target entry speeds.

Transition alignments to roundabouts with speeds of 45 mph (70 km/h) or less are classified by AASHTO as *low speed* and may use superelevation rates presented in the Green Book, Table 3-13 (*1*). Tangents always need to be provided between reverse curves to support a flowing alignment to the roundabout entry. Because most of these speeds are in the low-speed category (i.e., 45 mph [70 km/h] or slower) a normal crown or reverse crown may be used in many cases. If there are other superelevation needs based on site conditions, practitioners can use published superelevation values based on the anticipated operating speeds along the speed profile, deceleration needs, and curve radii.

Approach curves are commonly reverse curves and need to be separated by a tangent. An initial horizontal curve is not required, and an angle point may be used. This is similar in concept to an angle point used at a highway exit ramp. Angle points may range from 2 degrees to 5 degrees, as presented in Section 10.6.2.

When approach curves are used, they are to match the desired speed along the roadway approach. A broad radius needs to be followed by a moderate radius before the entry radius. Actual speeds associated with these radii will vary by roadway approach speed and deceleration needs. The curve radii selected ideally will not introduce speed differentials of more than 10 mph to 15 mph (16 km/h to 25 km/h) between successive curves.

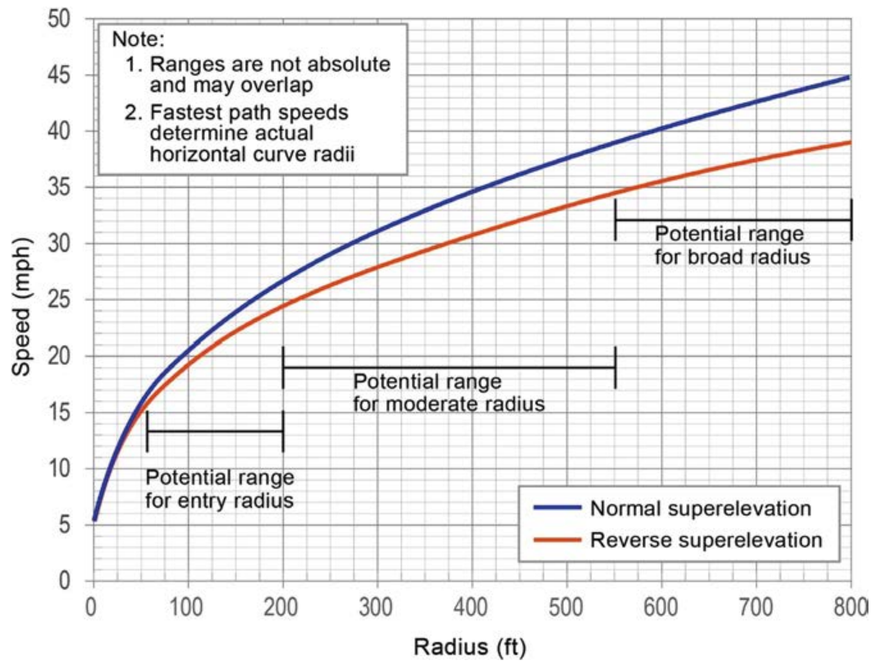
Exhibit 10.109 presents an example of speed-radius relationships for normal crown and reverse crown (i.e., +2 percent and −2 percent superelevation) for speeds of 45 mph (70 km/h) or less. The exhibit generally identifies a range of speeds for broad, moderate, and entry radii.

Exhibit 10.110 presents an example of a design detail for a curvilinear alignment for approach speeds 50 mph (80 km/h) or greater. As shown in the exhibit, these approach curves are progressively smaller radii to minimize the speed reduction between successive curves. The transition from large to small radii matches the speed profile and comfortable deceleration along the approach to the roundabout entry (or to the crosswalk or expected back of the queue).

10.14.4 Curbing

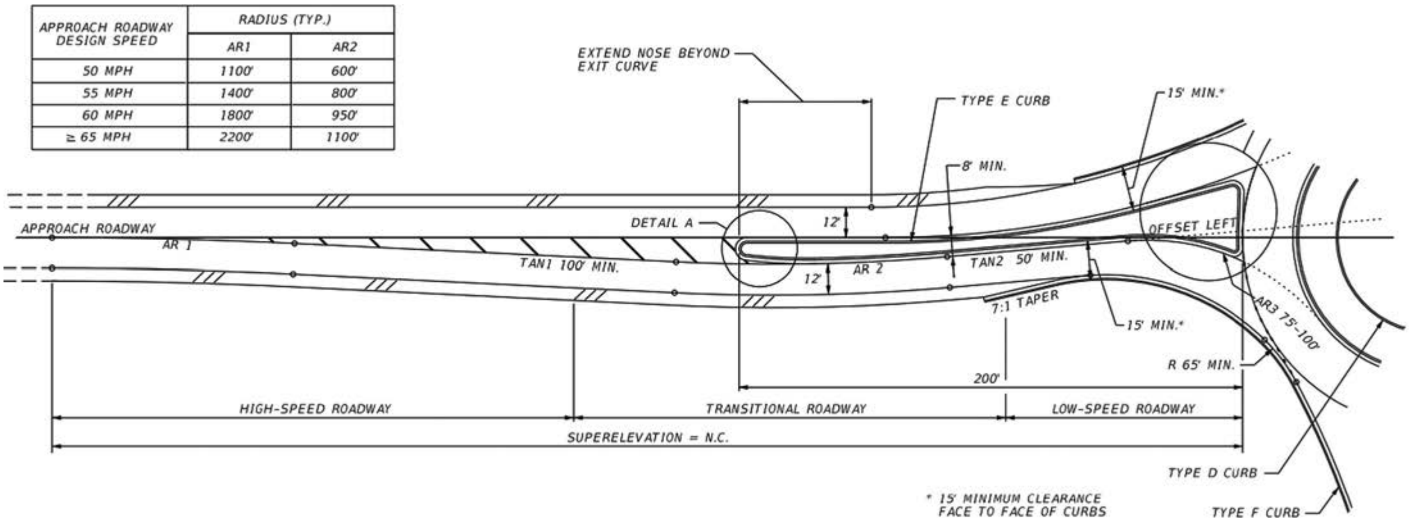
On roadways without curbs, adding outside curbs changes the roadway cross section and indicates a changing roadway and operational environment. Curbing can be introduced coincidentally with the painted taper on the roadway segment approaching a roundabout or coincidentally with the beginning of the splitter island. Curbing creates a funneling effect that supports a driver's

Exhibit 10.109. Example broad and moderate speed/curve relationships.



SOURCE: Adapted from Washington State Department of Transportation (*36*).

Exhibit 10.110. Example approach curve design.



APPROACH ROADWAY DESIGN SPEED	RADIUS (TYP.)	
	AR1	AR2
50 MPH	1100'	600'
55 MPH	1400'	800'
60 MPH	1800'	950'
≥ 65 MPH	2200'	1100'

SOURCE: Florida Department of Transportation (*37*).

recognition of the upcoming roundabout while providing positive guidance through the transition to the roundabout entry.

Rural highways typically have no outside curbs. Instead, they often have paved or gravel shoulders. Adding curbs on the outside edges of pavement provides drivers with a sense that they are entering a more controlled setting that supports speed reduction. Curbing does not necessarily require closed drainage systems. Open drainage can often remain if gaps are provided in the curbs so that stormwater may drain to adjacent drainage ditches. Mountable curbs, if used, are advised on high-speed approaches.

Exhibit 10.111 depicts a rural roundabout approach where curbing was introduced at the beginning of a splitter island on a high-speed approach. Exhibit 10.112 shows an example of a roundabout with gaps in curbing to support open drainage.

Exhibit 10.111. Example of external curbing introduced at the leading end of a splitter island.

LOCATION: Best Road/McLean Road, Mount Vernon, Washington.
SOURCE: Lee Rodegerdts.

Exhibit 10.112. Example of curbing with open drainage.

LOCATION: Best Road/McLean Road, Mount Vernon, Washington.
SOURCE: Lee Rodegerdts.

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CHAPTER 11

Vertical Alignment and Cross-Section Design

Contents

This chapter discusses *roundabout vertical design*. Roundabout vertical design represents a combination of roadway profiles, cross-section elements, and resulting three-dimensional surfaces that must consider the interrelationships of all elements. As with horizontal design, roundabout vertical design is an iterative performance-based process including checks for intersection sight distance, drainage, and user needs (such as pedestrians, trucks, vehicles with trailers, and snowplows).

The fundamentals of vertical design for roundabouts are similar to those for other intersections. However, for vertical alignment and cross-section development, roundabouts differ from other intersection types. Each roadway approaching a roundabout has a control line (also referred to as a *baseline of construction* or *profile grade line*)—which may or may not be in the center of the roadway—outside the roundabout influence area. The control line for each approach will intersect in the roundabout to establish the connection between the roadways and form the basis for subsequent vertical design. However, the control line that defines the approach roadways at roundabouts will differ into and through the circulatory roadway. A variety of design approaches are available to define control lines, for example, along the face of curb on either side of a median or along perimeter curb lines. Any approach a practitioner takes in the roundabout's vertical design should provide sufficient information to support design decisions and allow a contractor to construct the roundabout.

Because of the interrelationship between vertical alignment and cross section, a discussion of vertical alignments is followed by an overview of design goals and considerations related to the roadway cross section. This chapter discusses these elements as they relate to roundabout performance—visibility, drainage, driver comfort and safety, and accessibility—and the need for context-sensitive design. Finally, the chapter presents vertical considerations related to pedestrians, bicyclists, and trucks.

11.1 Profile and Cross-Section Relationships

Once a horizontal alignment is established, vertical design may proceed with the following goals:

- Serve design users:
  - Provide drivers with smooth longitudinal transitions into and out of the intersection.
  - Develop cross slopes and cross-slope transitions in line with speed control targets for the intersection.
  - Accommodate truck movements by minimizing likelihood of load shifting and vehicle rollovers.
  - Provide accessible pedestrian crossings.
  - Avoid under clearance conflicts for low-clearance vehicles with curbs, truck aprons, and circulatory roadways.
- Provide adequate stopping sight distance.
- Facilitate surface drainage and avoid icing in travel lanes.
- Provide a constructible design.

These goals may be associated with jurisdiction-specific requirements (e.g., minimum or maximum grades at certain locations). In general, roadways have to be designed with a cross slope and a longitudinal grade to support stormwater conveyance and to minimize the likelihood of icing. Minimum requirements may vary but are typically 0.5 percent (*1*). However, below 1 percent, contractors often struggle to maintain construction tolerances to attain positive drainage, which can result in ponding and sediment collection (especially at curbs).

Exhibit 11.1 presents a general overview of vertical design decisions and performance checks. The process addresses various components of vertical design and emphasizes adaptability to each project context. Context is key; early project planning and concept assessments may identify vertical design and drainage as critical project design drivers. In such cases, practitioners need to consider vertical elements early when developing horizontal design configurations.

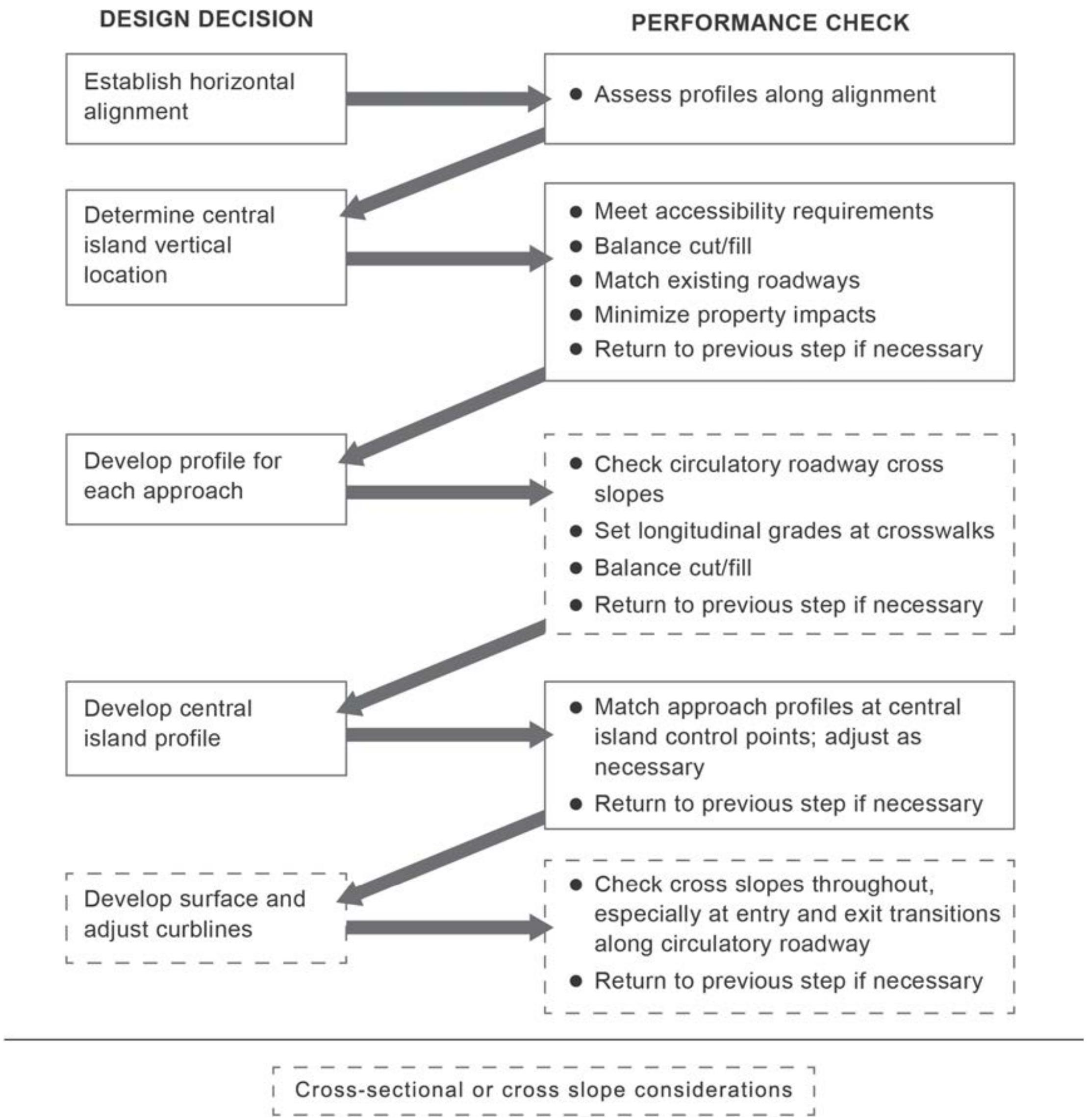
As Exhibit 11.1 demonstrates, the practitioner will iteratively evaluate grades, surfaces, and cross slopes resulting from alignment decisions through a series of assessments that inform vertical design choices. Exhibit 11.1 demonstrates the interconnected nature of these longitudinal and cross-slope considerations by showing decisions or performance checks that include cross-slope elements with a dashed border.

Section 11.2 provides the general approach for developing a profile that considers site context along with key design and performance targets.

11.2 Profile Development

Developing a roundabout profile to support a vertical design is an iterative process. This section presents a procedure that involves tying the elevations of each approach roadway profile along an established baseline into a smooth profile at the roundabout entry, around the central island, and to the exit that transitions to the departure roadway. These elevations, in turn, help guide external curb profiles. The travel paths for each entry, each exit, and the circulatory roadway are unique, each defined by interior and exterior curbs with their own profiles. Together, the profile elements support developing and refining a continuous surface that meets vertical design requirements.

Exhibit 11.1. Overview of vertical alignment development decisions and checks.



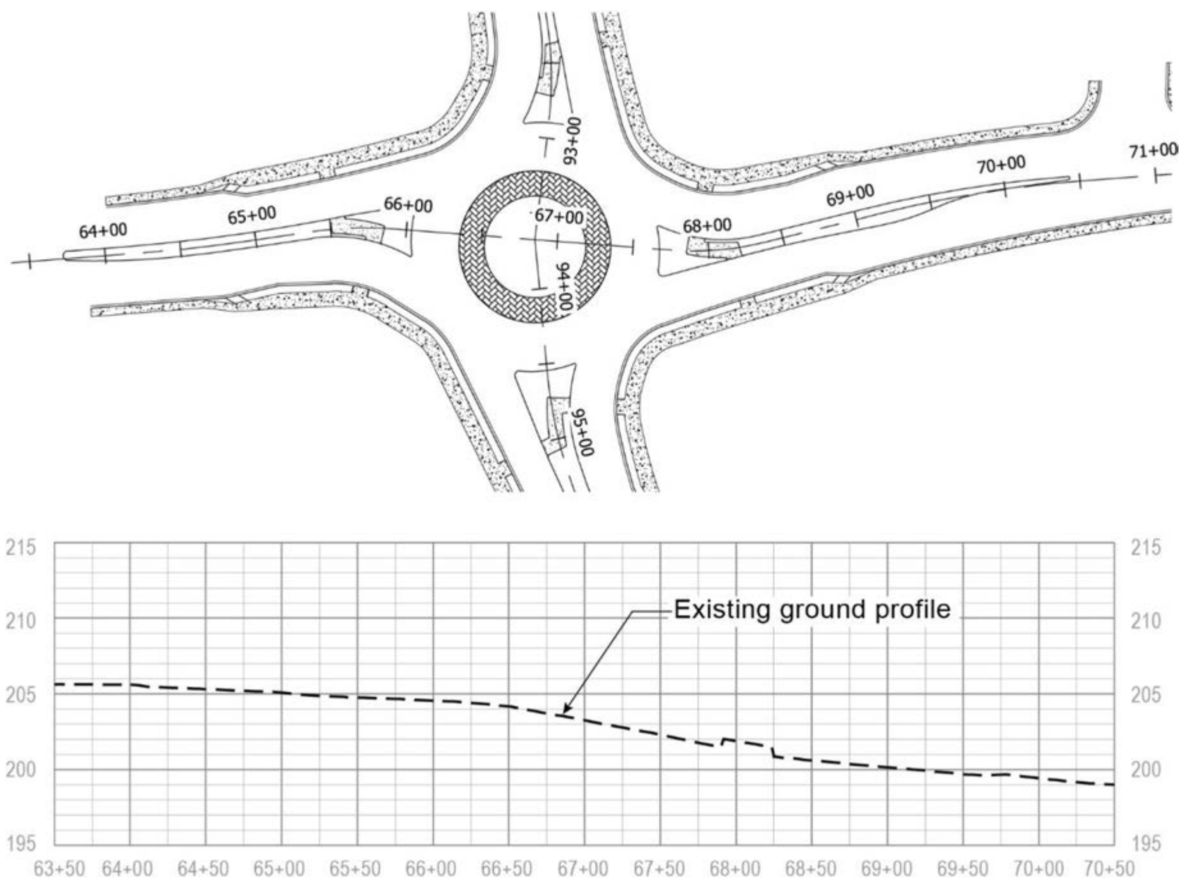
A general procedure to develop a profile is described below. The example is provided to emphasize design principles and intent, but a variety of techniques can be used to appropriately meet vertical design needs.

Vertical alignment design starts with overlaying a horizontal alignment onto the existing roadway approach profiles and assessing the context. The vertical alignment can be assessed along any desired profile grade line. A vertical alignment needs to reflect the natural terrain of the area. However, each design is unique. Constructing a roundabout that matches existing roadway features could mean using existing outside curb elevations and cross sections as design controls; this *outside-in* approach is described at the end of this section. Profile development proceeds as follows:

- **Establish horizontal alignment.** Chapter 10: Horizontal Alignment and Design explains how to develop a horizontal alignment. In reconstruction projects or projects along an existing alignment, the horizontal alignment of the roundabout will likely not match the centerline of the existing roadway. The construction alignment will follow the curvature of the roundabout, and the profile grade line will eventually be established along this horizontal alignment.

- **Assess existing ground profiles along the horizontal alignment.** A sample of existing elevations along each roadway's profile grade line provides the existing topography and roadway approach as well as departure grades. The existing ground profile allows practitioners to match the subsequent profile design decisions to the existing context and condition (to the extent possible). See Exhibit 11.2 for an existing ground profile matching a proposed horizontal alignment.
- **Determine central island vertical elevation.** Using the existing ground profiles as a reference (Exhibit 11.2), select an approximate elevation for the central island. For roundabouts with non-traversable central islands, the elevation of the truck apron's inner edge will be the basis for the vertical design of the non-traversable central island. For mini-roundabouts and compact roundabouts with fully traversable central islands, the established elevations will be the basis for the traversable central island (whether raised or flat). The following priorities will influence the vertical elevation:
  - Meet accessibility requirements at crosswalks (see Section 11.5).
  - Provide positive drainage.
  - Avoid low spots near crosswalks to minimize water ponding where pedestrians will cross.
  - Optimize cut and fill among approaches, either mathematically or visually.
  - Match existing roadway approaches.
  - Minimize impacts to adjacent properties, including any cut, fill, and need for retaining walls.
- **Develop the profile for each leg of the roundabout.** Using the roundabout elevation established in the previous step, practitioners will design a profile for each leg that ties into the existing grade at the extents of construction. The profiles will allow for adequate cross slopes through the circulatory roadway (see Section 11.4) and meet accessibility requirements at all pedestrian

Exhibit 11.2. Example of plan of roundabout alignment and existing ground profile.



crossings (see Section 11.5). Practitioners will then assess the balance of cut and fill again and iterate as needed to optimize the design. Roadway approaches with steep grades (see Section 11.3) may provide additional challenges. Exhibit 11.3 provides an example vertical alignment profile overlaid on an existing ground profile to show how the proposed alignment profiles relate to the existing condition.

- **Develop the central island profile.** Practitioners will design a profile along the truck apron that closely matches elevations with the roadway profiles established in the previous step. This may result in a *tilted* or *warped* circulatory roadway if one side of the roundabout is higher than the other. This is acceptable and often necessary when the existing grade varies on each approach (Section 11.4 discusses these concepts). The central island profile may have one low point and one high point around the circle—see Exhibit 11.4 for an example. Depending on the size of the roundabout, the assumed design speed of the circulatory roadway is between 15 mph and 25 mph (24 km/h and 40 km/h), as discussed in Chapter 9: Geometric Design Process and Performance Checks. Any crest and sag vertical curve values must be compatible with the design speed of the circulatory roadway. The approach profiles can be adjusted to match the outside edge of the circulatory roadway. Practitioners might need to adjust the profiles on the approaches, in the roundabout, or on the roundabout exit to smooth transitions. Practitioners will check vertical clearances (described in Section 11.6) for locations where vehicles may be prone to bottoming out and consider lengthening vertical curves to address low points and to smooth the profile.
- **Develop a continuous surface.** With the centerline and circulatory roadway profiles established, the roadway cross slopes can be laid out. Commercial software can model a continuous surface given the following inputs: a horizontal alignment, profile, and desired crown from the center of

Exhibit 11.3. Example of plan and profile for roundabout alignment.

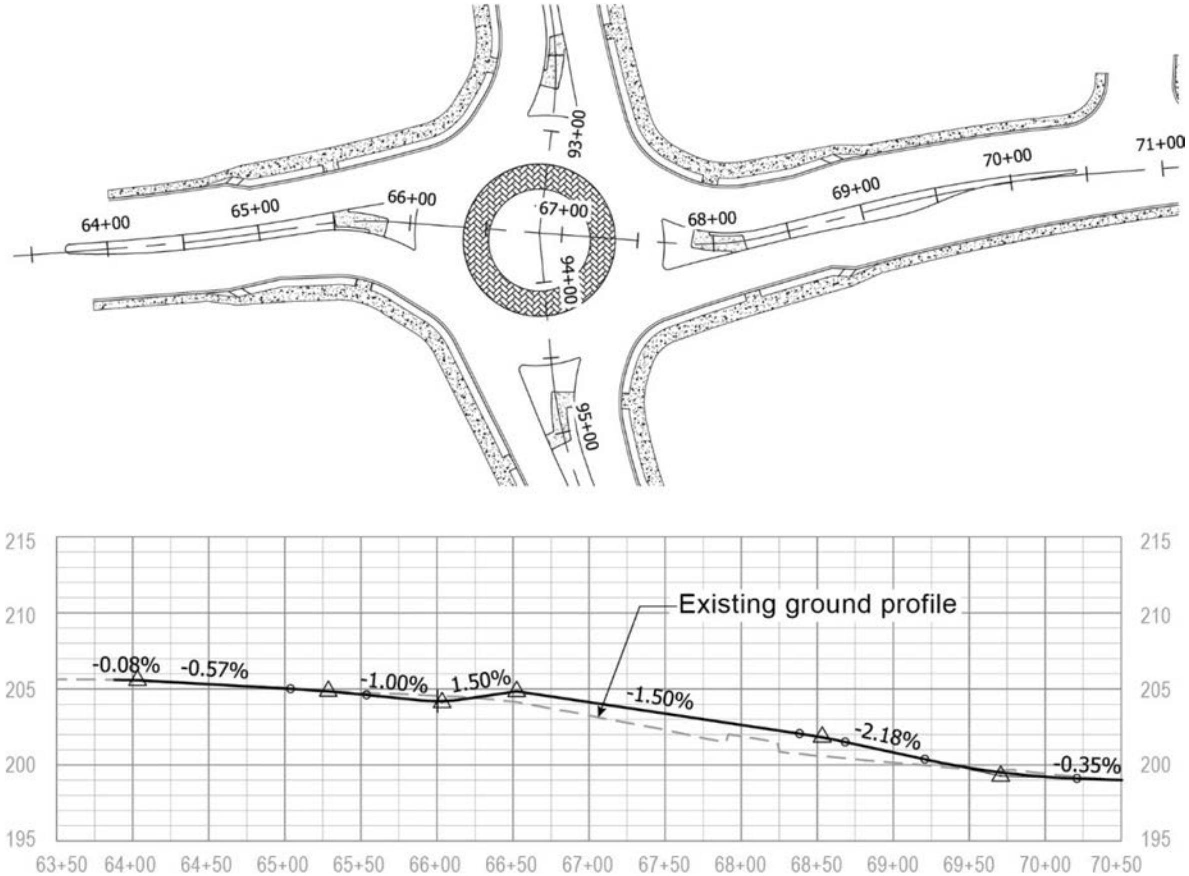
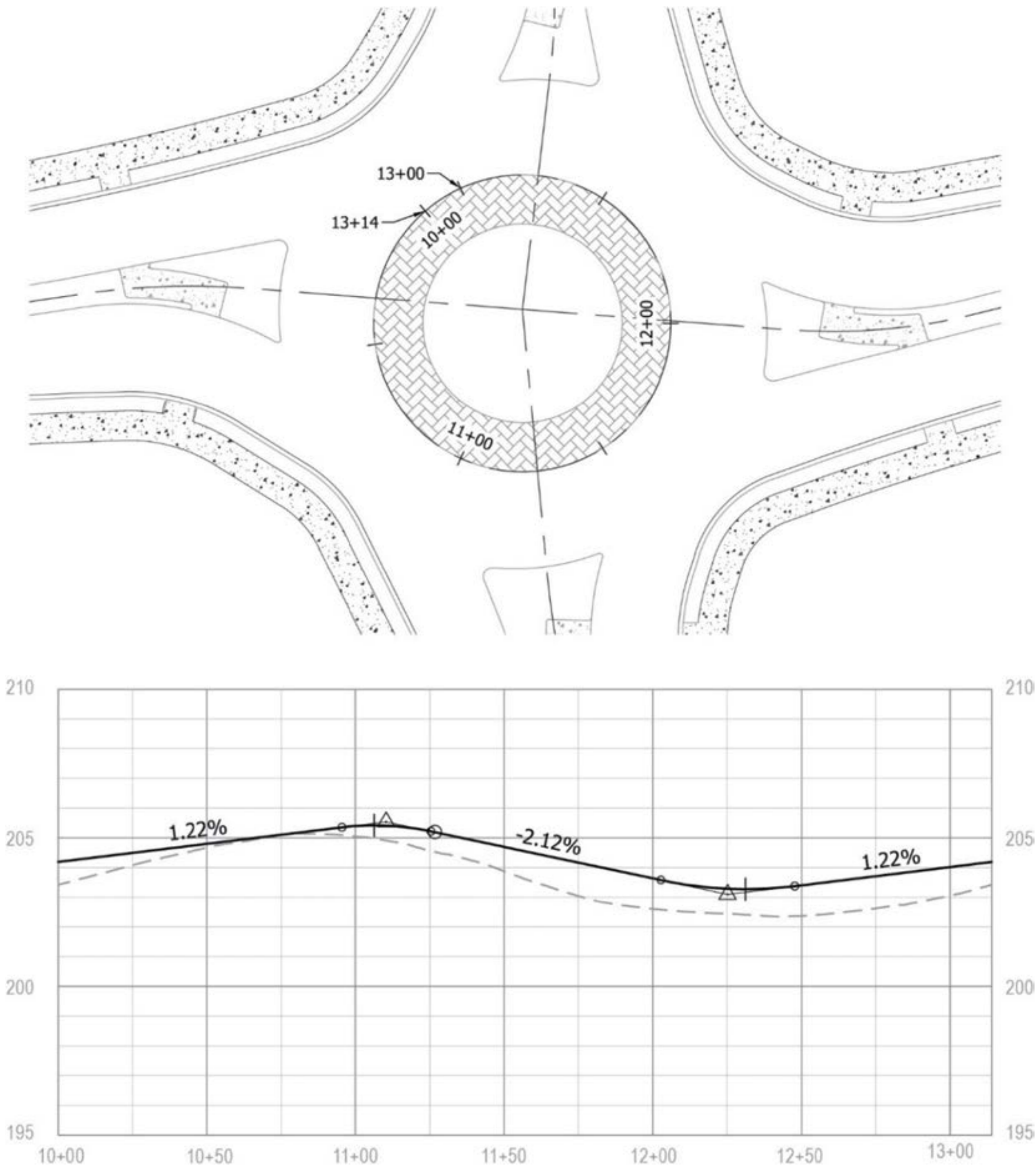


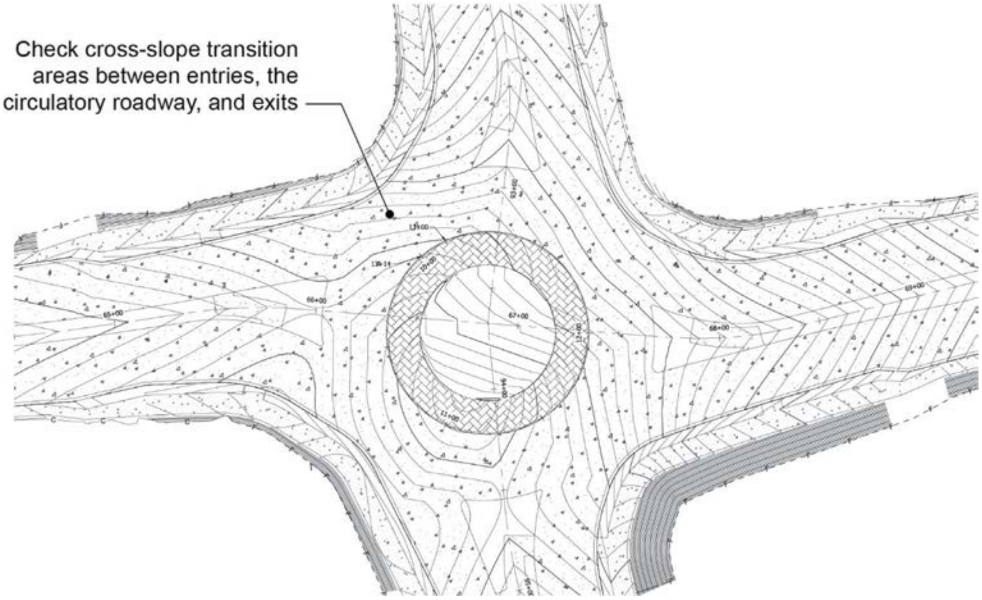
Exhibit 11.4. Example profile along outer edge of central island.



the approach roadways. Exhibit 11.5 provides an example of proposed grading as a result of this step. This example is for an outward sloping circulatory roadway; however, the tools and methods can apply to crowned roadways as well. Desired performance checks for this step include

- **Achieving minimum cross slope and longitudinal slopes for drainage purposes.** Practitioners will check cross slopes throughout, especially at locations where the horizontal curve deviates substantially from the centerlines (see Exhibit 11.5). Requirements may be jurisdictionally specific.
- **Establishing a curb return profile that creates the desired cross slopes.** If cross slopes are below or above the desired thresholds, the curb line elevations can be adjusted. Ultimately, the design cross slope may vary slightly between the entry, circulatory roadway, and exit. The goal is to avoid abrupt changes in cross slope and design drainage patterns so that water will shed in the desired direction.

Exhibit 11.5. Surface development with roadway profiles established.



- **Alternative approach: Proceed from the outside in.** Alternatively, practitioners can develop the outside edges of pavement and the splitter islands first, establishing alignments and setting the circle height on the basis of existing grades at the outside edges of the roundabout. This approach may be more desirable when implementing a retrofit into existing grades and curb lines. Furthermore, this approach may minimize property impacts and set the grades to build up the central island. This outside-in approach implies an iterative process of working from the outside in, followed by setting the inside grades on the central island and working them back out to set the final grades of the gutters and splitter islands. The cross slopes between the central island and the outside edge of the pavement, discussed in Section 11.4, become key variables.

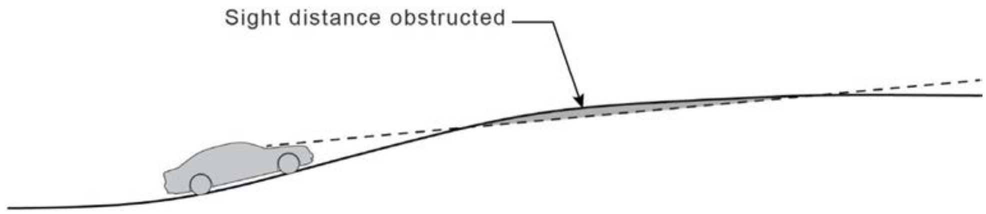
11.3 Roadways with Grades

Roundabouts can be effective and have been successfully implemented on roadways with approach grades. For any intersection located on a grade, including roundabouts, a few considerations apply:

- Motor vehicles making turning movements experience lateral forces affected by the speed of the vehicle and the localized grade and cross slope of the roadway where the vehicle is turning. Vehicle dynamics are especially important for trucks because of the potential for load shifting or for overturning when turning across negative superelevation (*2*).
- It is more difficult for entering drivers to slow or stop on an approach along a downgrade than on a flat approach or an upgrade. As a result, speed reduction and speed management are more critical on downgrades approaching the intersection.
- Crest vertical curves may limit available sight distance (Exhibit 11.6) to the pedestrian crossing or to the intersection entry. In such a circumstance, practitioners can reduce approach speeds through design or flatten the curve to allow adequate sight distance.
- Pedestrian crossings need to meet ADA requirements for longitudinal and lateral grades (refer to Section 11.5).

A primary focus for design is to reinforce slow speeds entering and through the roundabout. This helps to manage the speeds of vehicles, especially trucks, as they traverse through portions

Exhibit 11.6. Sight distance on crest vertical curve.



of negative superelevation. Research using simulation of truck dynamics over a range of conditions has found that speed management, cross section, and truck apron design are important design parameters for managing lateral forces on trucks (*2*). To promote low entry speeds, the designer may modify the location of the roundabout and adjust the horizontal alignment to manage vehicle speeds approaching and entering the roundabout. Practitioners can extend the splitter island upstream beyond the crest vertical curve and beginning outside curbs to help approaching drivers observe a change in the roadway typical section from the segment portion to the roundabout influence area. These techniques are discussed in Chapter 10: Horizontal Alignment and Design.

At the roundabout itself, the maximum negative superelevation for any movement and the speed transition into the negative superelevation are a focus of design evaluation to manage vehicle dynamics. The degree to which an approach grade may challenge specific users depends on the selected design vehicle and anticipated turning movements. The general practice in the United States has been to keep the grades and maximum negative superelevation through the roundabout to no more than negative 4 percent for affected turning movements (*3*, *4*). This may require adjusting the approach profiles to create the desired combination of grades and cross section within the roundabout.

Exhibit 11.7 and Exhibit 11.8 provide examples of vertical design approaches for a roundabout placed along a roadway with a steep grade—in this case, a 10 percent approach grade. Exhibit 11.7 demonstrates the option to carry a 3.5-percent grade through the roundabout along that alignment. This requires flattening the approach grade in advance of the roundabout entry and elevating the roundabout. Exhibit 11.8 demonstrates a second alternative—*benching* the roundabout—whereby the approach grades are increased and a vertical curve is placed to provide a roundabout that drains away from its central island. This configuration creates a more prominent platform for the roundabout; however, it also steepens the approach grade (potentially increasing speeds), requires more earthwork (i.e., roadway cuts), and may result in more environmental and right-of-way impacts. Designing for any location requires considering the trade-offs of each profile alternative and making choices appropriate for that site's location and context.

At the roundabout, the entry design and circulatory roadway require pavement warping or cross-slope transitions through each entry and exit and around the circulatory roadway. Roadway approaches, roundabout entries, and central island design need to establish sight distance associated with predicted approach and entry speeds.

Considerations when benching a roundabout include

- It is necessary that a benched design be configured to meet accessibility requirements at the crosswalk, as described in Section 11.5.
- Entry grade profiles need to strive to create a platform for yielding drivers to maintain a view of the circulatory roadway and avoid the sight distance obstruction shown in Exhibit 11.6. The longitudinal slope of the entry or exit grade also represents the cross slope of a pedestrian crossing.

Exhibit 11.7. Example of profile with modified downgrade profile through the roundabout.

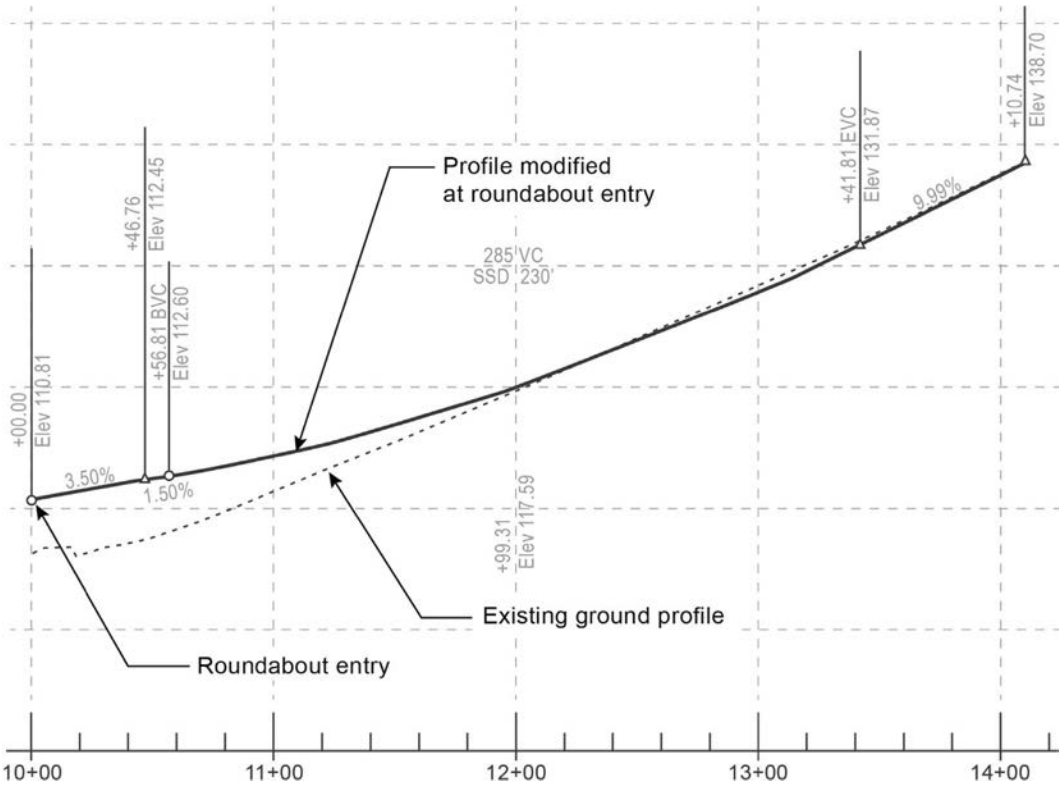
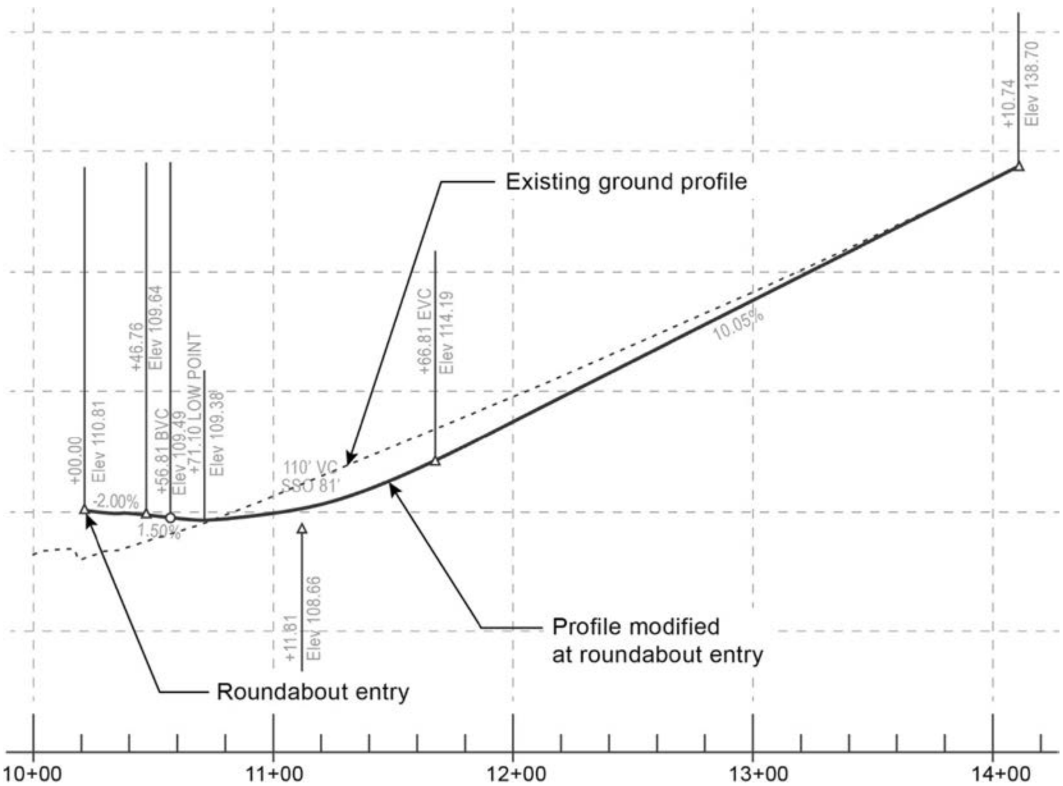


Exhibit 11.8. Example of benched profile with steeper approach grade to achieve a more desirable grade through the roundabout.



11.4 Transverse and Cross-Slope Design

The cross section influences roundabout profiles and surfaces. Together, the profile, cross section, and resulting surface influence roundabout performance in terms of drainage and meeting user needs. This section discusses cross-section design considerations for the circulatory roadway, central islands, and truck aprons.

Practitioners can consider the circulatory roadway vertical design once the central island has been located horizontally and vertically.

11.4.1 Outward Sloping Circulatory Roadway

The most common approach to grading the circulatory roadway is to slope it to the outside. This approach is particularly common for single-lane roundabouts because the overall drainage distance from the inside of the circulatory roadway to the outer curb is limited to a single-lane width.

When developing the circulatory roadway as part of the roundabout profile, it is often desirable to have a cross slope of 2 percent away from the central island to balance drainage needs with driver comfort. A 2 percent cross slope is a common crown section in roadway design but can vary by jurisdictional preference. Sloping outward from the central island is desirable for four main reasons:

- It promotes positive safety performance by raising the elevation of the central island and improving its visibility.
- It promotes lower circulating speeds by placing turning movements on a negative superelevation.
- It minimizes breaks in the cross slopes of the entrance and exit lanes.
- It helps drain surface water to the outside of the roundabout (*5*).

With this approach, the circulatory roadway is graded independently, and the outward slopes are typically at a grade of 1.5 to 3 percent. See Exhibit 11.9, *a* and *b*, for examples. This is most practical in flat terrain, as hilly terrain may require warping of the profile (see Section 11.4.3) and possibly an alternative vertical design. The location where the truck apron meets the circulatory roadway has potential ground clearance concerns for large vehicles and is discussed further in Section 11.6.

Other examples shown in Exhibit 11.9 show different combinations of inward and outward sloping truck aprons and circulatory roadway:

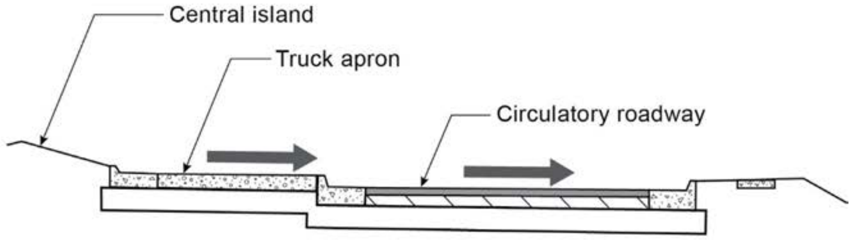
- The example in Exhibit 11.9*a* would provide the most conspicuous central island by making the central island a high point.
- The example shown in Exhibit 11.9*b* has flow lines running to the central island and may need drainage on the interior of the roundabout.
- The example shown in Exhibit 11.9*c* has flow lines running to the truck apron and would require a drainage feature at the apron (shown in Exhibit 11.10).
- The example in Exhibit 11.9*d* may need to capture stormwater runoff at the truck apron and on the interior of the roundabout.

Any of these combinations could be designed to meet vertical design needs.

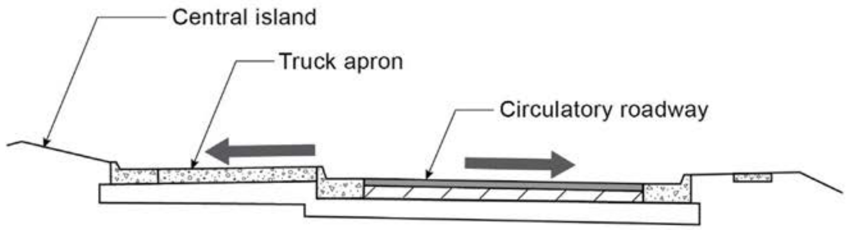
11.4.2 Crowned Circulatory Roadway

An alternative approach common with multilane roundabouts is to crown the circulatory roadway. Typically, the crowning will place two-thirds of the width sloping toward the central island and one-third sloping outward, though this may alternatively be reversed. Smooth crowning

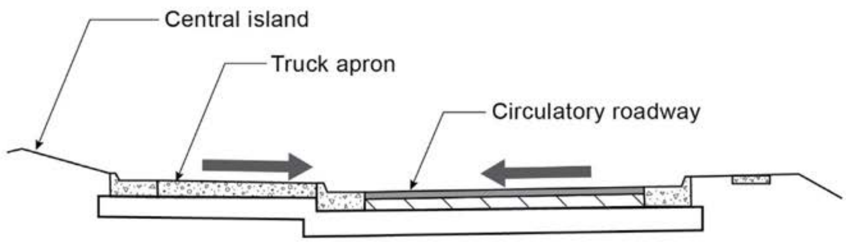
Exhibit 11.9. Variations of circulatory roadway cross sections.



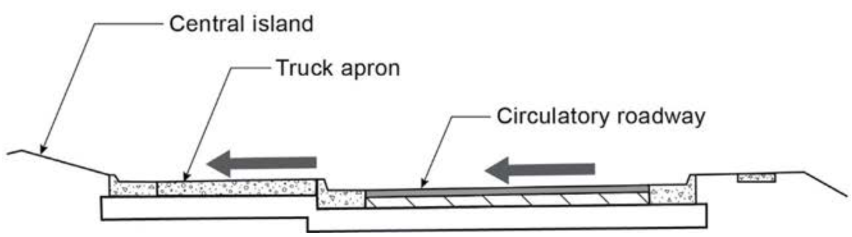
(a)



(b)



(c)



(d)

Exhibit 11.10. Example of circulatory roadway sloped inward to central island with sloped catch basin grate.

LOCATION: De Pere, Wisconsin. SOURCE: Wisconsin Department of Transportation.

may be easier to achieve using asphalt paving. Exhibit 11.11 shows an example of a crowned circulatory roadway.

Crowning the roadway may be beneficial for the following reasons:

- It may support truck movements through the intersection by reducing the slope on the rear wheels as they straddle the truck apron and adjacent lane (*5*).
- It creates shorter travel distances for snowmelt compared with an outward sloped roadway.

Crowning the roadway may also present some challenges:

- It may be more difficult to construct than an outward sloped roadway.
- It presents a need for inlets on the interior of the circulatory roadway and truck apron (see Exhibit 11.10).
- It provides positive superelevation for left-turning drivers, enabling slightly higher speeds compared with a negative superelevation (refer to Section 9.4.3).

11.4.3 Other Circulatory Roadway Grading Techniques

The outward sloping and crowned circulatory roadway approaches may be readily implementable on roadway approaches with modest grades; however, where relatively steep roadway approach grades converge, other options may be appropriate. In some locations where a retrofit is being considered, it may be desirable to use the existing ground elevation to reduce overall changes in profile. At the intersection of two major roadways, using the existing ground elevations may result in two crown lines crossing one another, with the circulating roadway *warping* between the crown lines to provide drainage. This same strategy is often applied in other intersection forms as well. However, it can affect driver comfort and lane discipline through the roundabout.

Exhibit 11.12 depicts a roundabout located and designed within existing vertical constraints and elevation lines. The picture makes clear that the curb lines of the truck apron on the right side of the image are substantially lower than those on the left side of the image, indicating that the design was matched to existing topographic constraints.

At some locations for roundabouts using these techniques, the cross slope from the truck apron to the splitter islands will pass through level (0 percent) at two points around the roundabout. At those points, the circulatory roadway would not resemble any of the examples in Exhibit 11.9, but the grade through the roundabout should be sufficient to drain stormwater. On the high side, water will drain to the truck apron and on the low side, water will drain to the outside.

11.4.4 Fully Traversable Central Islands

A fully traversable central island can be crowned or domed, or it can be sloped in one direction, as demonstrated in Exhibit 11.13. When the intersection profile is developed, the roundabout high point does not need to be placed in the center of the circle. If dictated by vertical clearance from OSOW checks, the central island can be sloped straight across from one side to the other if a high point is not achievable.

Exhibit 11.11. Typical cross section with crowned circulatory roadway.

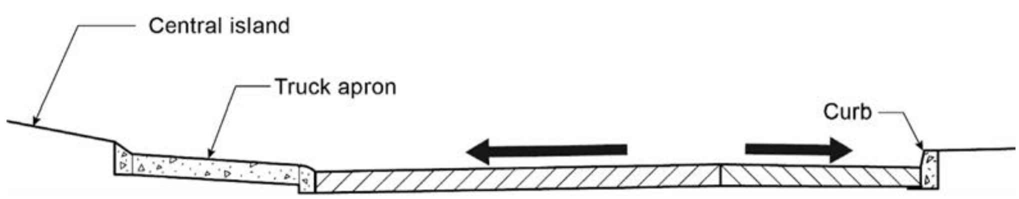
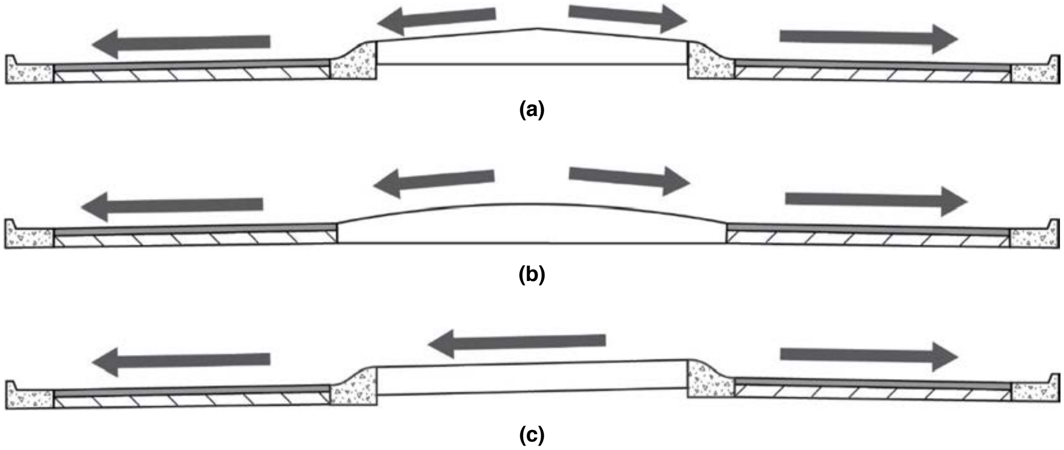


Exhibit 11.12. Example of roundabout fitting within constrained vertical environment.

LOCATION: Oberlin Road/Pullen Road/Groveland Avenue, Raleigh, North Carolina. SOURCE: Lee Rodegerdts.

Exhibit 11.13. Variations of fully traversable central islands for mini-roundabouts and compact roundabouts: (*a*) crowned, (*b*) domed, and (*c*) single slope.



Mini-roundabouts and compact roundabouts should have raised or domed central islands to promote conspicuity (refer to Section 2.3.2). In that case, it is desirable for visibility purposes that the central island be placed at the highest point of the intersection for visibility. Therefore, in most retrofit situations, mini-roundabouts and compact roundabouts may not necessarily require significant intersection re-grading. If raised, a fully traversable central island benefits from having a rolled curb (rather than a vertical curb) to support vehicle encroachment.

11.5 Pedestrian Design Influences

Accessible, ADA-compliant crosswalks are essential to serving pedestrians safely and effectively and are an integral part of the iterative vertical design process. Practitioners must follow the requirements and guidance in proposed PROWAG with regard to grades and cross slopes for the crossings (*6*, *7*). As previously mentioned, a construction tolerance of at most ± 0.5 percent is advisable. Locations with approach or departure grades that exceed PROWAG requirements could require that roadway approach and roundabout entries and exits be changed to meet

Exhibit 11.14. Example of aerial view of roundabout with raised crosswalks.

LOCATION: US 2 (Park Street)/Rangeley Road, Orono, Maine.
SOURCE: Jonathan French.

Exhibit 11.15. Example of ground-level view of raised crosswalks.

LOCATION: US 2 (Park Street)/Rangeley Road, Orono, Maine.
SOURCE: Jonathan French.

accessibility needs. This could increase the roundabout's footprint and require practitioners to reconfigure the vertical alignments of the roadway approach.

Raised crosswalks or speed humps force drivers to slow down; lower speeds have been linked to increased yielding behavior (*8*, *9*). A raised crosswalk can also guide pedestrians who are blind or have low vision to stay within the crosswalk if they can detect the crosswalk's side slopes as boundaries (*10*). The design of a raised crosswalk is a balance of a steep slope with a modest run (which may result in significant speed reductions) versus a gentler slope (which may have a more modest speed reduction but retain a higher capacity). Crosswalk design will also consider design vehicle maneuverability and needs (*10*). *NCHRP Research Report 834: Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities: A Guidebook* includes more information on raised crosswalk effectiveness, cost, and considerations (*10*). Exhibit 11.14 and Exhibit 11.15 depict a roundabout with raised crosswalks on entry and exit legs.

11.6 Trucks

Single-lane and multilane roundabouts with non-traversable portions of the central island typically include a truck apron at the outer edge of the central island to provide for truck encroachment. Where truck aprons are used, the slope of the apron should generally be no more than 2 percent, as greater slopes may increase the likelihood of loss-of-load incidents.

Truck aprons are commonly sloped toward the outside of the roundabout (Exhibit 11.9, *b* and *d*). However, some locations have also implemented roundabouts with truck aprons sloped inward toward the central island to minimize both water shedding across the roadway and load shifting in trucks. Agencies using this strategy reported that additional catch basins were provided along the outer edge of the central island (i.e., the inner edge of the circulatory roadway) to collect water and pipe it under the circulatory roadway to connect with the drainage system along the roundabout periphery.

The truck apron has to be elevated above the circulatory roadway to discourage passenger car use. Between the truck apron and the circulatory roadway, a curb is required to accommodate a change in elevation. Practitioners need to review the vertical design of the truck apron to confirm that there is sufficient clearance for trailers with low vertical clearance, some of which may have 6 in. to 8 in. (150 mm to 200 mm) between the roadway surface and the bottom of the trailer.

In areas where concrete curbing is used, a gutter pan incorporated into the truck apron design can create better delineation between the curb face and the roadway. Although a gutter pan is not necessary with an outward sloping circulatory roadway, its inclusion provides structure for the truck apron. Because it is preformed, the gutter pan creates a consistent height of curb visible above the roadway surface.

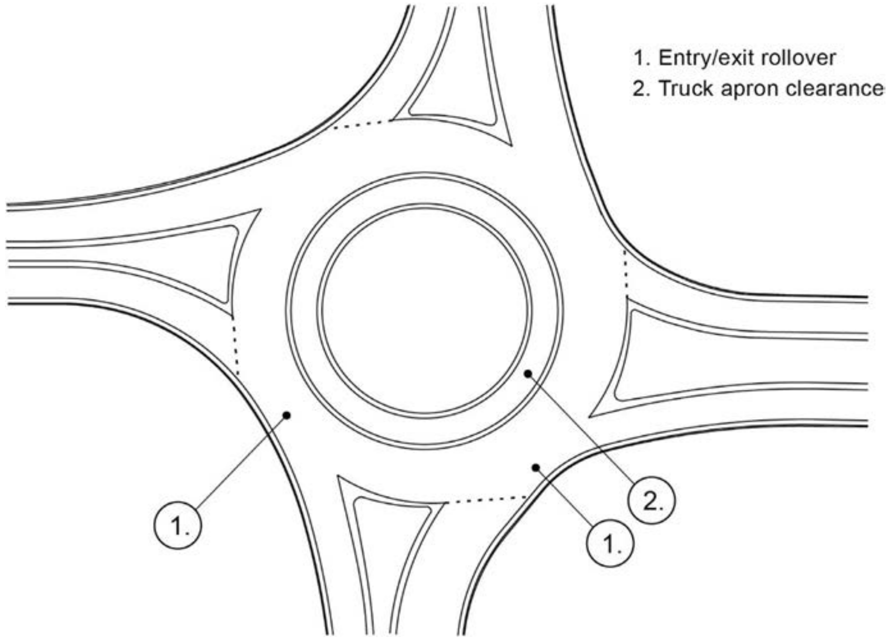
Depending on the design needs to support truck encroachment, an external truck apron may also be added to the exterior of the circulatory roadway. Exhibit 11.16 provides an example of an external truck apron.

For roundabouts that serve large vehicles with low vertical clearance, the profile must account for ground clearance. These vehicles typically have a ground clearance of 6 in. to 8 in. (150 mm to

Exhibit 11.16. Example of external truck apron.

LOCATION: Bryant Road/Greenway Cross, Madison, Wisconsin. SOURCE: Ourston.

Exhibit 11.17. Typical ground clearance concern locations.



SOURCE: Adapted from Wisconsin Department of Transportation (*11*).

200 mm), though it could be less. As part of profile and cross-section development, practitioners need to check these locations for adequate ground clearance (illustrated in Exhibit 11.17).

The locations and possible remedies presented in Exhibit 11.18 indicate some design treatments to accommodate large vehicles. Ultimately, the combination of grade, geometry, and sight distance can still be challenging.

Commercially available software packages include a feature to model the underside of a low-clearance truck to determine whether it would intersect the digital terrain model design surface of the roundabout and truck apron. This can be modeled and addressed by adjusting the grading surface or reducing the truck apron from 4 in. (100 mm) to 3 in. (75 mm). Alternatively, the vertical clearance

Exhibit 11.18. Ground clearance locations, issues, and possible remedies.

Location	Issue	Possible Remedies
1	Truck rollover incidents on entry and exit	• Flatten the circulatory roadway crown. • Avoid break-over grades over 3% within 200 ft (60 m) of the roundabout. • Limit the cross-slope rate of change, preferably between 0.02%/ft and 0.04%/ft (0.07%/m and 0.13%/m).
2	Trucks strike the truck apron (bottom out)	• Consider a maximum truck apron slope of 1%. • Locate the crest away from areas of concern. • Accommodate design vehicles within the circulatory roadway. • Keep the circulatory roadway profile as flat as possible while maintaining drainage requirements.

SOURCE: Adapted from Wisconsin Department of Transportation (*11*).

can be reviewed by drawing a chord across the apron in the position where the trailer would sweep across. In some cases, the warping of the profile along the circulatory roadway can create high spots that could cause trailers to drag or scrape along the truck apron.

11.7 References

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11. Chapter 11: Design, Section 26: Roundabouts. In *Facilities Development Manual*, Wisconsin Department of Transportation, Madison, 2004.

PART V

Final Design and Implementation

PROJECT DEVELOPMENT PROCESS

	Part I: Introduction to Roundabouts	Chapter 1: Introduction Chapter 2: Roundabout Characteristics and Applications
Planning	*Part II: Planning and Stakeholder Considerations*	Chapter 3: A Performance-Based Planning and Design Approach Chapter 4: User Considerations Chapter 5: Stakeholder Considerations Chapter 6: Intersection Control Evaluation
Identify and Evaluate Alternatives	*Part III: Roundabout Evaluation and Conceptual Design*	Chapter 7: Safety Performance Analysis Chapter 8: Operational Performance Analysis Chapter 9: Geometric Design Process and Performance Checks
Preliminary Design	*Part IV: Horizontal, Vertical, and Cross-Section Design*	Chapter 10: Horizontal Alignment and Design Chapter 11: Vertical Alignment and Cross-Section Design
Final Design Construction, Operations, and Maintenance	*Part V: Final Design and Implementation*	Chapter 12: Traffic Control Devices and Applications Chapter 13: Curb and Pavement Details Chapter 14: Illumination, Landscaping, and Artwork Chapter 15: Construction and Maintenance
Supplemental Appendix		Appendix: Design Performance Check Techniques

CHAPTER 12

Traffic Control Devices and Applications

Contents

This chapter discusses permanent traffic control devices at roundabouts. In the United States, traffic control devices are governed by the latest edition of the MUTCD (*1*). FHWA periodically issues interim approvals and updates to the MUTCD, and the latest version takes precedence over the content of this Guide.

Neither this Guide nor the MUTCD can present all possible combinations of traffic control devices applicable to a given roundabout. This chapter begins by presenting the principles of traffic control devices as they apply to roundabouts. The following sections discuss common traffic control devices used within and in the vicinity of roundabouts.

This chapter focuses on traffic control devices and applications, but practitioners can consider the content in this chapter concurrently with other chapters, specifically Chapter 8: Operational Performance Analysis and Chapter 10: Horizontal Alignment and Design. This chapter discusses permanent traffic control devices; refer to Chapter 15: Construction and Maintenance for information about temporary traffic control.

12.1 Principles of Traffic Control Devices

Traffic control devices—signs, pavement markings, signals, and beacons—work together to create a comprehensive system that regulates, warns, and guides road users through roundabouts. Practitioners can consider the following general principles for using traffic control devices:

- Per the MUTCD, traffic control devices should
  - Fulfill a need;
  - Command attention;
  - Convey a clear, simple meaning;
  - Command respect from road users; and
  - Give adequate time for proper response (*1*).
- Traffic control devices work as a system and need to be compatible with each other to present road users with consistent messaging.
- Traffic control devices complement a roundabout's geometric design. They clarify the rules of the road. **However, traffic control devices are not as effective on their own at providing desired performance as proper geometric design and may not fully correct the effects of faulty geometric design.**
- Traffic control devices are integral to the design process. During the conceptual and preliminary design stages, practitioners are advised to consider markings and, if needed, signal or beacon placement, especially for multilane roundabouts. Further details, such as sign size, width, and placement, typically come later in the design process, although it is helpful to plan horizontal and cross-section features and details (e.g., buffer strip widths for sign and signal or beacon placement) as needed.
- Traffic control devices need to be compatible with the context of the roundabout. For example, urban environments may need fewer signs than rural environments while having a greater need for bicyclist and pedestrian traffic control devices. Roundabouts with more legs or more lanes and roundabouts near freeway interchanges may need more robust guide signing.
- Traffic control devices for bicyclists and pedestrians are integral to roundabout design and are to be considered concurrently with those for motor vehicles.
- Practitioners need to consider traffic control devices in conjunction with the surrounding roadway system and land-use needs. Origins and destinations in the roadway system in the vicinity of the roundabout may dictate lane use and corresponding traffic control devices. Chapter 10: Horizontal Alignment and Design discusses this in more detail.

Traffic control devices at roundabouts can be grouped into four general areas, each with different goals:

- Transition area,
- Entry area,

- Circulating area, and
- Exit area.

The following sections detail many of the traffic control devices commonly used at roundabouts in each of these four general areas. Not all devices that may be used at roundabouts are covered. Practitioners are advised to consult the latest edition of the MUTCD and other documents for specific standards, guidance, options, and support for each device presented in these sections (and others not covered).

12.2 Transition Area

Traffic control devices in the transition area between the roadway segment and the roundabout support reducing speed, conveying changes in horizontal alignment, determining the intended exit from the roundabout, and getting into the correct lane to support the exiting decision. The type and configuration of signs and pavement markings depend on the roundabout's context, with more signs, more pavement markings, or both commonly needed in the following cases:

- Transitions from high-speed roadway approaches to the low-speed roundabout entry.
- Approaches where drivers need advance notice of destination information to make correct lane selections before entering the roundabout.
- Approaches where the roundabout is less visible from a distance because the central island is fully traversable.
- Approaches where the roundabout is offset to one side of the existing alignment and may be less visible as a result.
- Approaches where horizontal curvature, vertical curvature, or a combination of the two reduce the visibility of a roundabout from a distance.
- A roundabout where lighting is not used or lighting coverage is limited (see Chapter 14: Illumination, Landscaping, and Artwork). In these cases, signs and pavement markings provide primary visibility for the roundabout at night.

12.2.1 Advance Warning Signs and Markings

If advance warning of the roundabout is desired, practitioners have several options, including warning signs such as the following:

- **"Circular intersection" symbol sign (W2-6).** This sign warns road users they are approaching a roundabout. The "circular intersection" symbol sign is sometimes supplemented by a plaque with the legend "roundabout" (W16-17P), an advance street name plaque, flashing yellow beacons, flashing yellow LEDs embedded within the border of the sign, or a combination. Exhibit 12.1 shows an example. Some agencies use advisory speed plaques to supplement the "circular intersection" symbol sign.
- **"Yield ahead" sign (W3-2).** This sign is sometimes used to provide advance notice of the yield sign (R1-2) at the roundabout entrance. This sign is typically used where the roundabout and its yield signs are obscured by horizontal curvature, vertical curvature, or other visibility obstructions. The sign is sometimes used at isolated roundabouts or roundabouts on high-speed roadways. If used, the "yield ahead" sign most commonly supplements the "circular intersection" symbol sign.

Although not commonly used in practice, pavement word or symbol markings are sometimes used to supplement signing. Examples include the "yield ahead" triangle symbol marking or "yield ahead" word pavement markings.

Exhibit 12.1. Example of "circular intersection" symbol sign with supplemental street name plaque and flashing LED border.

LOCATION: Powell Butte Highway/Neff Road/Alfalfa Market Road, Deschutes County, Oregon. SOURCE: Lee Rodegerdts.

12.2.2 Advance Guide Signs

Guide signs provide drivers with proper navigational information. Guide signs can serve three purposes at roundabouts:

- **Advance information regarding intended destinations.** This enables roundabout users to prepare to make turning movements. This function is common to many intersection forms.
- **Confirmation signing regarding the appropriate exit.**
- **Supplemental warning that the user is approaching a roundabout.** The guide signs may take the place of similar warning signs.

Guide signs need to match the context of the location:

- Roundabouts at interchanges have the greatest need for guide signs to direct drivers between the crossroad and freeway ramps.
- Roundabouts on rural roadways with posted speeds of 40 mph or greater may benefit from guide signs to provide supplemental warning of the upcoming roundabout.
- Roundabouts where the primary route turns at the intersection may benefit from guide signs. Roundabouts located on state highways, for example, may have a more compelling need for guide signs than those on city streets.
- Roundabouts in urban areas may not need any guide signs aside from street name signs.

Several types of advance guide signs are available:

- **Diagrammatic exit destination signs.** Diagrammatic exit destination signs may be used on roundabout approaches to indicate destinations for each roundabout exit. The arrows representing the legs of the roundabout can be designed to represent the approximate angle of the exit legs. Diagrammatic signs can be especially useful where the geometry of the roundabout is non-typical, such as where more than four legs are present or where the legs are irregularly spaced. Diagrammatic signs are most common on state highways where numbered routes are shown. However, diagrammatic signs can be large when words (e.g., street names) are used instead of or in addition to route numbers to provide adequate legibility and separation of messages between legs. This makes such signs less desirable in many urban environments. Exhibit 12.2, Exhibit 12.3, Exhibit 12.4, and Exhibit 12.5 illustrate progressively larger diagrammatic sign assemblies.

Exhibit 12.2. Example of advance diagrammatic sign with route numbers.

LOCATION: STH 13/CR 2, Scott County, Minnesota. SOURCE: Lee Rodegerdts.

Exhibit 12.3. Example of advance diagrammatic sign with route numbers and destinations.

LOCATION: US 202–Route 4/Route 112, Gorham, Maine. SOURCE: Lee Rodegerdts.

Exhibit 12.4. Example of advance diagrammatic sign with street names.

LOCATION: Riverfront Drive/Broadway Street/Rockwater Boulevard, North Little Rock, Arkansas. SOURCE: Lee Rodegerdts.

Exhibit 12.5. Example of advance route assembly and advance text destination sign.

LOCATION: US 2/US 89, Browning, Montana. SOURCE: Lee Rodegerdts.

- **Text exit destination signs.** Exit destination signs with only text and arrows may be used on roundabout approaches to indicate destinations for each exit. Curved stem arrows can represent left-turn movements. Exhibit 12.4 illustrates an example.
- **Advance route number assemblies.** Advance route number assemblies can designate route destinations without text, and curved stem arrows may represent left-turn movements. Exhibit 12.5 illustrates an example.
- **Advance street name signs.** These guide signs are sometimes installed in advance of roundabouts to provide road users with the name of the next intersecting street. These are comparable to the "next signal" sign that is sometimes used in advance of signalized intersections.

12.2.3 Splitter Island Signs and Pavement Markings

Signs and pavement markings are commonly used to shift travel lanes, create space for the splitter island, and mark its leading edge. As noted in Chapter 10: Horizontal Alignment and Design, when an undivided roadway is divided to create space for a splitter island, pavement markings provide an initial shifting taper in advance of the splitter island. For the advance nose of non-traversable splitter islands, "keep right" signs (R4-7 or text variations R4-7a and R4-7b) with or without object markers, raised pavement markers on top of the splitter island curb, or a combination thereof are commonly used. Some agencies use internally illuminated bollards to highlight the end of the splitter island.

12.2.4 Lane Designations for Multilane Roundabouts

Lane designations—the combination of lane lines, lane-control signs, and lane-control pavement markings—are needed wherever drivers can use more than one lane. While lane designations are most obviously needed for multilane roundabouts with more than one circulating lane, they are also helpful at single-lane roundabouts where a right-turn-only lane is used on one or more approaches.

Lane designations that are consistent and compatible with the roundabout's geometric design and intended lane use are critical to achieving desired safety performance. Multilane roundabouts with exclusive left-turn lanes can lead to erratic maneuvers, conflicts, near-crashes, or property damage crashes, especially if not marked as such before entry (*2*, *3*). Research provides evidence that the safety performance of multilane roundabouts depends, in part, on effectively communicating lane-use assignments to drivers **before** they enter the roundabout (*2*). In turn, the lane-use assignments within the roundabout and on each exit must be compatible with entry lane-use assignments and the geometric configuration.

Lane-control signs and markings increase in importance with the complexity of the roundabout. These include the following conditions:

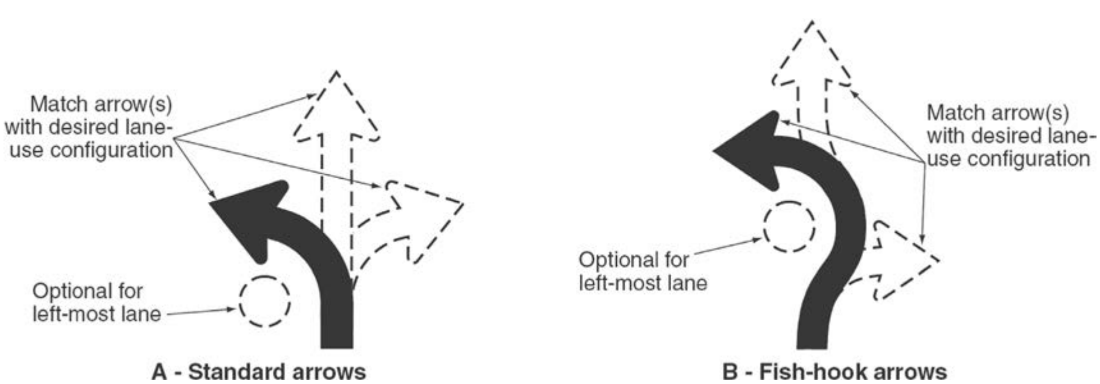
- The lane configuration is different from that specified by the default rules of the road, whereby left turns are allowed only from the leftmost lane, right turns are allowed only from the rightmost lane, and through movements are allowed from any lane.
- An approaching through lane becomes a left-turn-only lane or a right-turn-only lane.
- The lane configuration includes double left-turn movements, double right-turn movements, or both.
- The roadway system has destinations in the vicinity that would benefit from advance lane-use guidance for a given destination, such as establishing correct lane positioning for downstream freeway on-ramps.

On a typical two-lane entry, the left entry lane is for left turns and through movements, and the right entry lane is for right turns and through movements. Even in this common case, approach lane-use arrows are beneficial. Lane-use arrows become increasingly important for roundabout approaches with double left-turn or double right-turn lanes. Lane-use arrows can also improve lane utilization or provide consistent messaging to drivers across all roundabouts. Lane-use arrows are not typically necessary on single-lane roundabouts or a single-lane entry to a multilane roundabout; however, they are optional and have been used in some cases.

The MUTCD includes several options for arrow symbols on intersection lane-control signs and pavement markings, as shown in Exhibit 12.6. Both standard arrows and fishhook arrows are common, but agency requirements or preferences tend to dictate arrow selection. For roundabouts where a left-turn movement is intended, a left-turn arrow is used in advance of the roundabout. Field evidence has demonstrated that a lack of left-turn arrows for left-turn-only lanes can result in increased erratic maneuvers (*3*).

There is no clear research indicating that the fishhook arrow is superior to the standard arrow. Standard arrows are well established in practice and are easier to maintain because of their smaller size. In some states, the fishhook may be beneficial where left-turn arrows on a roundabout approach would otherwise be prohibited. Some agencies place a dot on the left side of the arrow in the inside lane. Exhibit 12.7 shows an example of this application. The style of arrow used for signs and pavement markings needs to be consistent.

Exhibit 12.6. Lane-use (*a*) standard and (*b*) fishhook arrow types used at roundabouts.



SOURCE: MUTCD (*1*).

Exhibit 12.7. Example of lane-control signs and markings with channelization island between lanes.

LOCATION: US 17–US 92/W Haven Road, DeLand, Florida.
SOURCE: Lee Rodegerdts.

Lane-control signs and pavement markings should allow time for drivers to select the appropriate lane for their maneuver before entering the roundabout. Some agencies locate the closest set of lane-control signs and markings approximately 50 ft to 100 ft (15 m to 30 m) in advance of the crosswalk. No lane-control signs or pavement marking arrows are recommended between the crosswalk and roundabout entry, where lane changes are typically discouraged or prohibited. Practitioners need to balance the MUTCD and the AASHTO decision sight distance criteria with local conditions to determine the most appropriate sign and marking placement and spacing. Oversize signs, overhead placement of signs, use of standard arrows to improve driver recognition, redundant sets of signs, or some combination may be needed in constrained environments to improve sign legibility that meets driver perception and reaction time needs. The MUTCD provides further guidance in this area (*1*).

In some cases, overhead lane-control signs may be beneficial at roundabouts. Exhibit 12.8 provides an example. Whereas roadside lane-control signs may get lost in background clutter and can be obscured by other vehicles, overhead lane-control signs are located directly above each

Exhibit 12.8. Example of overhead lane-control signs.

LOCATION: N Riverside Drive/Northern Cross Boulevard, Fort Worth, Texas.
SOURCE: Lee Rodegerdts.

lane for maximum visibility. Overhead signs are more expensive than ground-mounted signs because of the increased cost of sign supports and are to be factored into preliminary costs during ICE activities (see Chapter 6: Intersection Control Evaluation). As with ground-mounted signs, overhead lane-control signs are most effective if placed far enough in advance of the roundabout to allow drivers to select the proper lane before entering. Overhead lane-control signs may help with retrofitting an existing roundabout to improve lane use where existing ground-mounted signs and markings appear to be insufficient. Guide signs may also help convey lane use and destinations for each lane; however, guide signs cannot replace regulatory signs that legally define lane use.

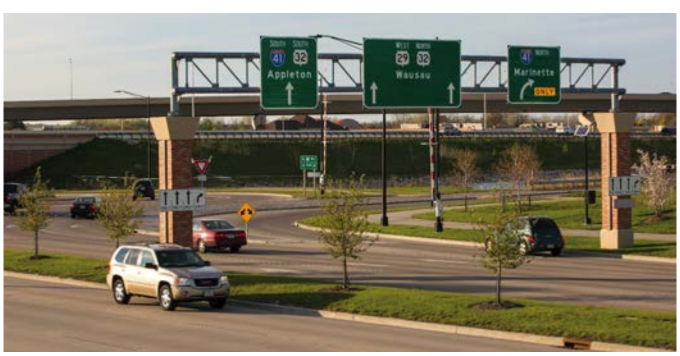
Overhead guide signs are another option for communicating destinations and lane-use requirements on the roundabout approach to supplement regulatory lane-control signs. Overhead signing has been implemented at various locations throughout North America and may be particularly beneficial on three-lane roundabouts. Overhead signing reduces the chances for trucks or other large vehicles to obscure the view of a roadside-mounted guide sign. Overhead signs are common at freeway interchanges where bridge structures provide natural mounting locations. Selecting roadside mounting versus overhead mounting of guide signs depends on the roundabout's environment, the complexity of the information being presented, and the approach geometry. Exhibit 12.9 shows an example of overhead guide signs providing lane-use information at a freeway interchange, supplementing side-mounted regulatory lane-control signs.

As noted in Chapter 4: User Considerations, some states have amended their vehicle codes to address specific roundabout uses, including driving next to trucks within a roundabout. To support this legal requirement specific to Oregon, the Oregon Department of Transportation's *Sign Policy and Guidelines* includes a regulatory sign, "Do Not Drive Beside Trucks," that is used at each entrance to a multilane roundabout (*4*).

Pavement markings showing route numbers, destinations, street names, or cardinal directions (i.e., north, south, east, or west) can help drivers select the appropriate entry lane on roundabout approaches. These markings typically supplement lane-use arrows, lane-control signs, and guide signs at roundabouts. At complex roundabouts with many legs, these markings can make it easier to adequately communicate appropriate lane use.

Route numbers may be shown using numerals and letters (e.g., I-275, US 97, or Hwy 22) or by using pavement markings that simulate Interstate, US, state, and other official highway route shield signs—but they need to be elongated for proper proportioning when viewed as a marking (refer to the MUTCD and FHWA's *Standard Highway Signs and Markings* for further detail) (*1*, *5*). Word

Exhibit 12.9. Overhead guide signs at a freeway interchange.



LOCATION: Shawano Avenue/I-41 Northbound Ramps, Green Bay, Wisconsin.
SOURCE: Lee Rodegerdts.

Exhibit 12.10. Example of route number guide marking.

LOCATION: E 10th Street/I-265 Westbound Ramps, Jeffersonville, Indiana.
SOURCE: Lee Rodegerdts.

pavement markings can also spell out destinations, street names, or cardinal directions using elongated letters or numerals. Exhibit 12.10 shows an example of route number guide markings.

At roundabouts with more than four legs, drivers can find it difficult to select the appropriate lane-use arrows—left, through, or right—to use on each approach. Practitioners are advised to use their engineering judgment to choose the appropriate lane-use arrows for each lane. Where there is a clear major route and three or more minor legs, the major route is likely best served if designated as a through movement to provide route continuity (e.g., using a through arrow to connect roadways with the same street name or route number). At some complex roundabouts with many legs, it can be desirable to use other traffic control devices to supplement lane-use arrows and designate the appropriate approach lanes. These can include pavement word and symbol markings as well as advance guide signs that indicate destinations for each lane.

12.3 Entry Area

The entry area is the area where conflicts with other modes begin. Traffic control devices in this area focus on drivers yielding to other users—bicyclists, pedestrians, and other vehicles within the roundabout—including stopping if necessary or required by state law. This section presents traffic control devices for the entry area.

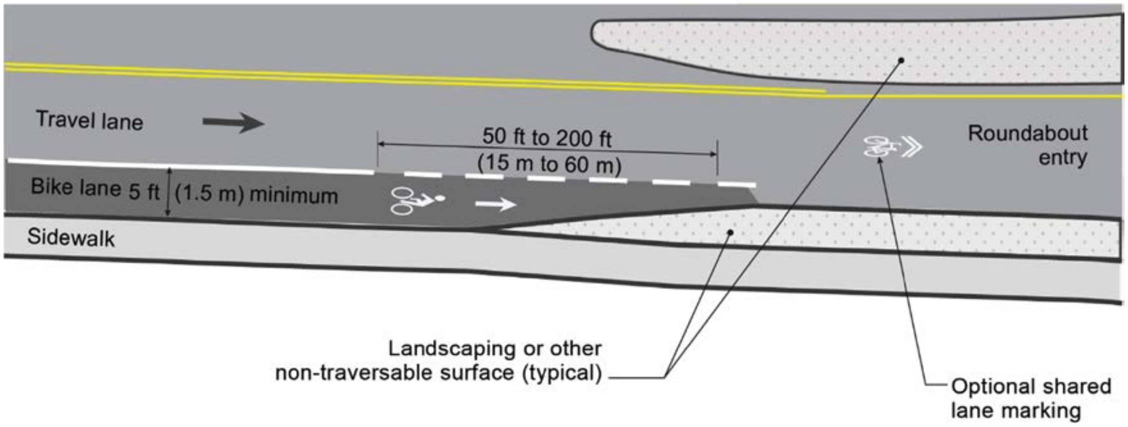
12.3.1 Signs and Pavement Markings for Bicyclists

As discussed in Chapter 10: Horizontal Alignment and Design, some roundabouts provide transitions from one type of bicycle facility approaching the roundabout to another type within the roundabout. On roundabout approaches where bicycles use on-street lanes or shoulders, the bicycle lane line or roadway edge line next to the shoulder is terminated as soon as the taper begins (commonly 8:1), at least 100 ft (30 m) in advance of the edge of the circulatory roadway and at least 50 ft (15 m) in advance of the crosswalk. The bicycle lane lines are to be dotted for the last 50 ft to 200 ft (15 m to 60 m), notifying cyclists in advance that they need to merge and providing enough room to achieve this maneuver and find an appropriate gap in traffic. A "Bike Lane Ends" sign sometimes marks the beginning of the taper. Exhibit 12.11 illustrates this concept.

Where bicycle lanes or shoulders are used on approach roadways and separated bike lanes or a shared-use path are not planned around the roundabout, the bicycle lanes are to end before the roundabout begins (see Exhibit 12.11).

When starting a bicycle lane on a roundabout exit, a dotted line is used to mark the start of the bicycle lane at the beginning of the taper. The solid bicycle lane line is to resume as soon as the normal bicycle lane width is available. Exhibit 12.12 illustrates this concept.

Exhibit 12.11. Markings for transition from on-street bicycle lane to shared lane at roundabout entry.



For approaches with separated bicycle facilities, signing and marking follows the examples provided in Chapter 10: Horizontal Alignment and Design. In some cases, it may be desirable to allow bicyclists to use the adjacent travel lane in addition to the separated facility. Exhibit 12.13 illustrates the transition from a buffered bicycle lane to a separated facility at the roundabout entry; similar markings can be provided at the roundabout exit. If the separated bicycle lane is raised at the roundabout, an additional speed hump marking showing the location of elevation increase at the transition is suggested.

12.3.2 Pedestrian and Bicycle Crossing Signs and Pavement Markings

"Pedestrian Crossing" signs (W11-2) are sometimes used at roundabout pedestrian crossings that are not controlled by regulatory devices (e.g., traffic control signals or pedestrian hybrid beacons). They are also sometimes paired with warning beacons, such as RRFBs. Where installed, these signs should not obstruct the view of the yield sign or signs at the roundabout entry.

At roundabouts, high-visibility crosswalk markings that are longitudinal to the flow of traffic (sometimes referred to as *zebra* or *continental* crosswalk markings) are advised for pedestrian-only crossings or crossings that bicyclists and pedestrians share. Details on the dimensions of

Exhibit 12.12. Markings for transition from shared lane to on-street bicycle lane at roundabout exit.

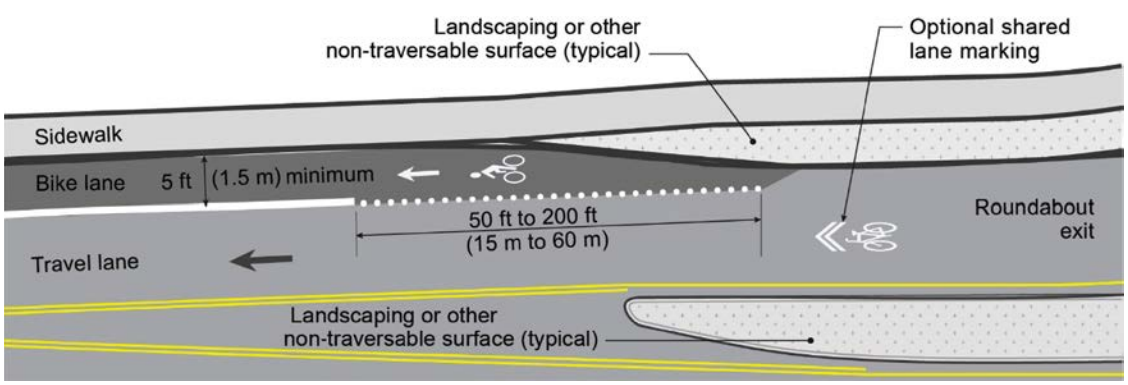
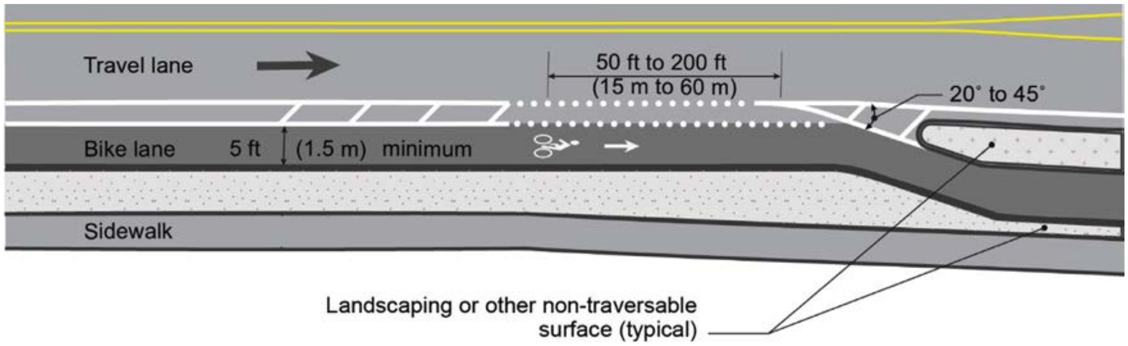


Exhibit 12.13. Markings for transition from buffered bicycle lane to separated bicycle facility at roundabout entry.



these markings can be found in the MUTCD. Longitudinal crosswalk markings have advantages over transverse crosswalk marking in roundabout applications:

- High-visibility longitudinal markings provide a higher degree of visibility, highlighting the location of the crossing away from the roundabout for drivers and crossing users. High-visibility crosswalks are detectable from about twice the distance upstream during daytime conditions as crosswalks with transverse marking elements only (*6*). Pedestrians with low vision especially benefit from the high-visibility markings because of their contrast with the underlying pavement surface.
- Drivers are less likely to confuse longitudinal crosswalk lines with the entrance line or the yield line.
- Although the initial cost is somewhat higher, longitudinal markings require less maintenance if properly spaced to avoid the wheelpaths of vehicles.

Aesthetic treatments at crosswalks can provide contrast with the surrounding roadway and are sometimes implemented for that reason, but the specific pedestrian crossing area should be smooth, with the markings providing the primary contrasting elements. Crossing surface inconsistencies (e.g., pavers or other features) can increase difficulty for people who use wheelchairs or have other special walking needs.

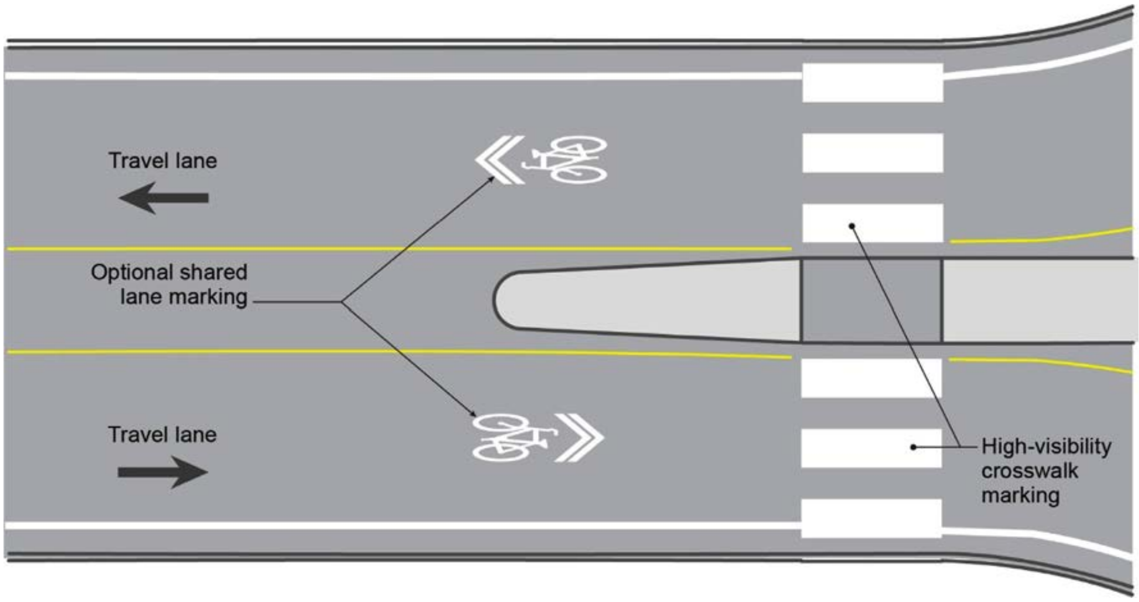
Exhibit 12.14 illustrates typical crosswalk markings for crosswalks at roadway level for a single-lane entry and exit. Where a raised crossing is used, the raised crossing should also be marked as illustrated in Exhibit 12.15.

Exhibit 12.16 illustrates separated bicycle and pedestrian crossing markings for raised crossings at a single-lane entry with a right-turn bypass lane.

12.3.3 Pedestrian and Bicycle Crossing Beacons and Signals

In some cases, additional treatments beyond signs and markings may be needed to provide pedestrian safety and accessibility, especially if the crossing is multilane. Research for *NCHRP Research Report 834: Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities: A Guidebook*, developed a method for estimating performance measures for a crossing that can inform geometric and traffic control device design decisions (*7*). Chapter 9: Geometric Design Process and Performance Checks and Appendix: Design Performance Check Techniques present suggested quantitative methods to support design decisions on the most appropriate application for a given crossing.

Exhibit 12.14. Typical markings for at-grade pedestrian crossing at single-lane entry and exit.



The proposed Public Rights-of-Way Accessibility Guidelines, as amended for shared-use paths, require pedestrian-activated signals with accessible pedestrian signals at multilane roundabout crossings and multilane channelized turn lanes (*8*, *9*). This is chiefly because of the multiple threat at multilane crossings, in which a driver's view of pedestrians in a crosswalk may be blocked by a yielding vehicle in another lane, and pedestrians crossing in front of a yielding vehicle may not see or hear a vehicle approaching in the next lane. As discussed in Chapter 10: Horizontal Alignment and Design, FHWA has recommended the proposed PROWAG as best practice (*10*).

The proposed Public Rights-of-Way Accessibility Guidelines also indicate that when pedestrian-activated signals are used on a splitter island, they are to be located and separated to avoid

Exhibit 12.15. Typical markings for raised pedestrian crossing.

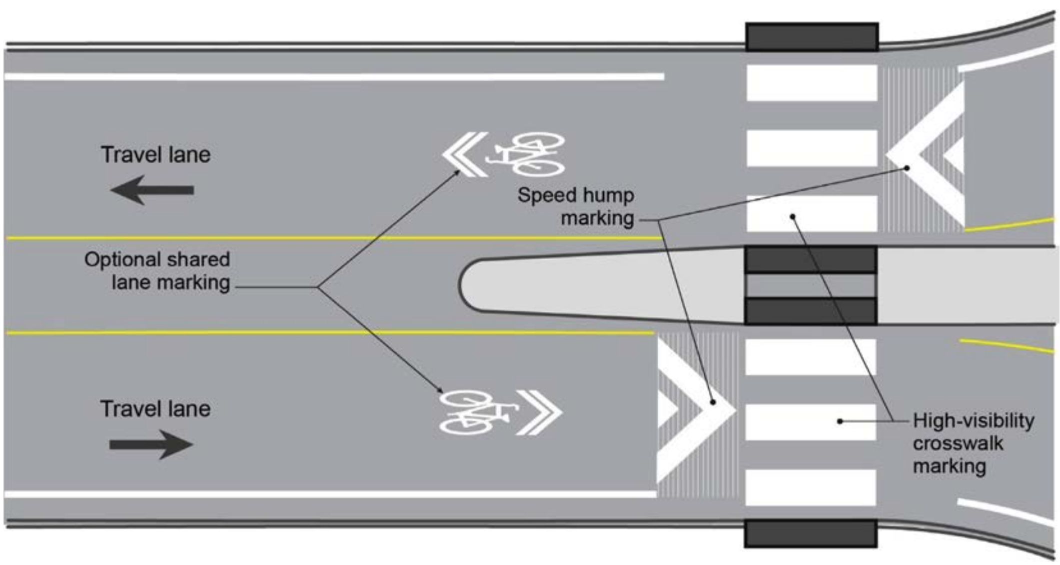
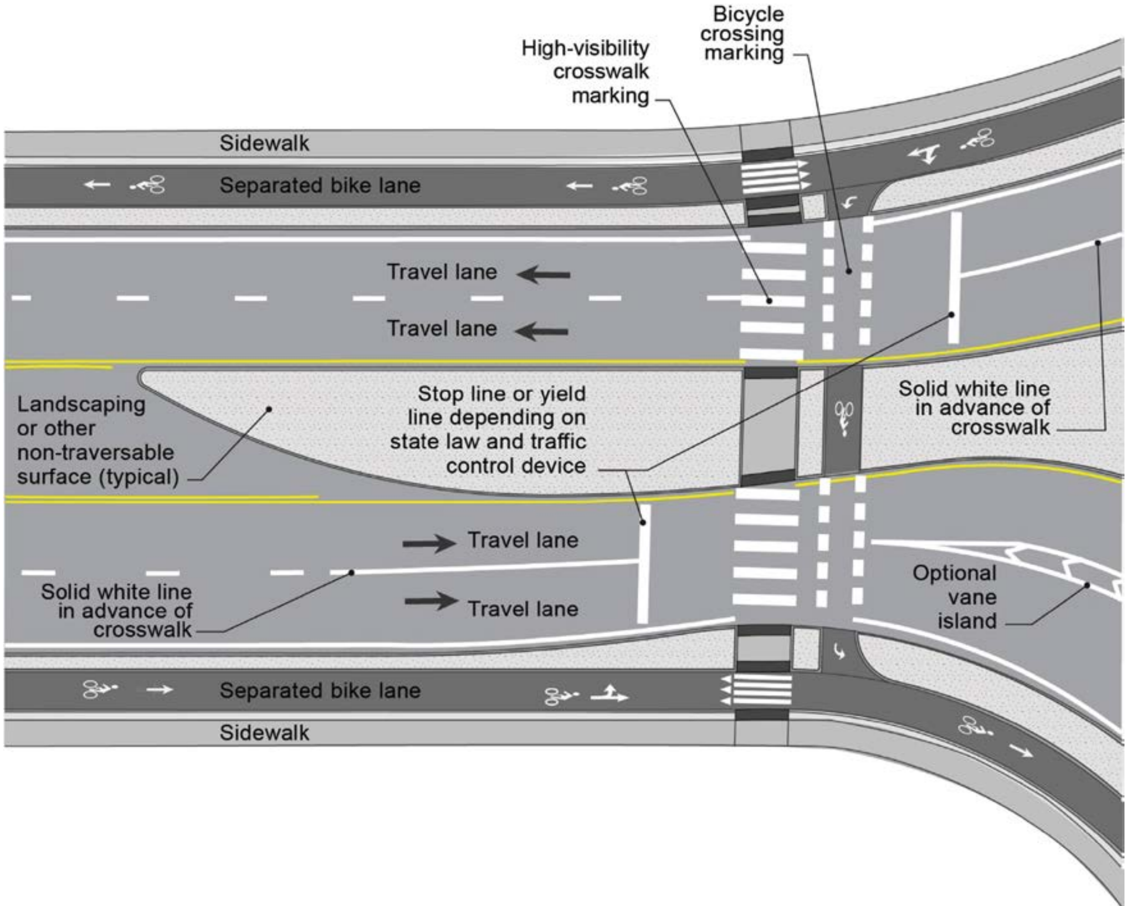


Exhibit 12.16. Typical markings for separated bicycle and pedestrian crossings.



communicating conflicting information about which pedestrian crossing has a walk indication displayed. Accessible pedestrian signals are optimally located on the downstream side of each crossing so that the pedestrian can better listen for oncoming vehicles. The MUTCD and associated interim approvals have standards, guidance, and options for applying these traffic control devices (*1, 11*).

Common active traffic control devices at roundabout crossings include:

- **Rectangular rapid-flashing beacons.** As an active warning device, the RRFB rests in dark when not used and flashes for a predetermined time upon activation by the crossing user (*11*). These devices can be mounted along the roadside, overhead, or both. Exhibit 12.17 shows an example of roadside installation in Springfield, Oregon. RRFBs are not mentioned in the proposed PROWAG but may be suitable through the process of *equivalent facilitation* if they provide substantially equivalent or greater accessibility and usability than the minimum requirements provided within PROWAG (*8*, *9*).
- **Pedestrian hybrid beacons.** This device also rests in dark when not used and follows MUTCD guidelines for signal placement. A PHB was first implemented for research purposes in a temporary installation in Golden, Colorado (see Exhibit 12.18), as part of the research for *NCHRP Report 674: Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities* (*12*). The first permanent installation is in Oakland County, Michigan (see Exhibit 12.19). The proposed PROWAG indicates that PHBs with accessible pedestrian signals can be used at roundabouts (*8*, *9*).

Exhibit 12.17. Example of rectangular rapid-flashing beacon.

LOCATION: Pioneer Parkway E/Harlow Road/Hayden Bridge Way, Springfield, Oregon. SOURCE: Lee Rodegerdts.

Exhibit 12.18. Example of pedestrian hybrid beacon (temporary installation).

LOCATION: S Golden Road/Johnson Road, Golden, Colorado. SOURCE: Lee Rodegerdts.

Exhibit 12.19. Example of pedestrian hybrid beacon (permanent installation).

LOCATION: West Maple Road/Drake Road, Oakland County, Michigan. SOURCE: Lee Rodegerdts.

- **Traffic control signal.** This device displays a red–yellow–green indication to drivers and rests in green. Placement on the entry side has similar issues as a metering signal with respect to potential driver misinterpretation of the green indication as overriding the yield sign.

Exhibit 12.20 compares these three active traffic control devices and raised crossings. Further details for raised crossings can be found in Chapter 10: Horizontal Alignment and Design and *NCHRP Research Report 834* (*7*).

Practitioners are advised to consider the type, location, and design details of these treatments holistically during the planning and design process. For instance, if a PHB or traffic control signal is used on a roundabout exit, the crossing may need to be placed farther from the circulating roadway than if a raised crosswalk or RRFB is used. In addition, pushbuttons can be challenging for pedestrians to locate for effective use, particularly with separated bicycle facilities between roundabout approaches. In these locations, sufficient buffer space along the outside curb line must accommodate signs and pushbuttons along with design vehicle movements. The splitter island requires similar considerations. To meet pedestrian and driver expectations, the same crossing treatment is to be used on the entry and exit of a roundabout leg.

12.3.4 Lane Lines at Entry and Exit

Solid white lane lines are typically used at roundabout entries and exits to discourage lane changes. Solid lane lines provide the following benefits:

- Solid lane lines can discourage lane changes immediately before crosswalks to reduce the likelihood of multiple threat crashes between vehicles and pedestrians.
- Solid lane lines at entries may discourage late lane changes and reduce the potential for sideswipe crashes.
- Solid lane lines at entries and exits can discourage drivers from cutting across multiple lanes to attain a faster path through the roundabout. Using solid lane lines throughout the area of entry curvature provides this benefit. However, under lower-volume conditions, drivers frequently cross or straddle solid lane lines if they do not perceive a conflict.

On flared approaches, entry lane utilization may improve if the lane lines in the flared section extend back as far from the circulatory roadway as possible. For example, when flaring from one to two lanes, as soon as there is 20 ft (6 m) of paved entry width available, the lane line can begin, creating two 10-ft (3-m) approach lanes that will typically continue to widen as they approach the circulatory roadway.

White channelizing lines are recommended on the approach to and departure from right-turn bypass islands, where traffic passes on both sides of the islands. Some agencies have used channelizing lines to create painted islands between adjacent entry lanes, sometimes called *vane islands*. These islands, an example of which is shown in Exhibit 12.21, are intended to guide entering drivers to the appropriate lane within the circulatory roadway. These islands also provide an over-tracking area for larger vehicles. Evidence from research conducted for this Guide is mixed on whether truck drivers understand that trucks are intended to drive within the vane island (*14*). This may be because vane islands have a similar visual appearance to freeway gore striping, where driving in the gore is discouraged.

12.3.5 Entry Signs and Markings

The MUTCD requires a yield sign on the right side of each entry into the roundabout and recommends a second yield sign on the left side of the approach (mounted on the splitter island) for additional visibility and approaches with more than one lane. Practitioners need to locate yield signs on the left side to avoid obscuring the line of sight for some drivers (e.g., truck drivers).

Exhibit 12.20. Comparison of passive and active crossing traffic control device applications at roundabouts.

Attribute or Characterization	Raised Pedestrian Crossing	RRFB	PHB	Traffic Control Signal
• Active display to drivers	• Not applicable	• Two rectangular yellow indications that flash alternately in a prescribed pattern	• Flashing yellow ball, solid yellow ball, two simultaneous solid red balls, alternating flashing red balls	• Green ball, yellow ball, red ball
• Display to pedestrians	• Not applicable	• None	• Walk, flashing Don't Walk, and (in some cases) a pedestrian change interval countdown display	• Walk, flashing Don't Walk, and (in some cases) a pedestrian change interval countdown display
• Audible message to crossing users (if used)	• Not applicable	• Locator tone in rest; "yellow lights are flashing" when activated	• Locator tone in rest; "wait" when activated; percussive tone when Walk sign is displayed	• Locator tone in rest; "wait" when activated; percussive tone when Walk sign is displayed
• Advantages	• Provides geometric speed control • May be combined with active traffic control devices listed in this exhibit	• May provide sufficient accessibility for two-lane crossings under lower volume and speed conditions • Lower cost than PHB or traffic control signal	• Provides good accessibility because of red indication to drivers • Device rests in dark to prevent potential misinterpretation of green indication • Can be coordinated with other traffic control signals and PHBs	• Provides good accessibility because of red indication to drivers • Standard indication in common use, although not common at roundabouts in the United States • Alternating flashing red allows drivers to proceed after stopping if there is no conflicting pedestrian present • Device rests in green rather than dark • May also be used for metering applications (see Section 12.6) • Can be coordinated with other traffic control signals and PHBs
• Disadvantages	• May be more difficult to retrofit because of effects on drainage • May be more difficult to maintain in winter environments	• Does not provide sufficient accessibility for three-lane crossings • May not provide sufficient accessibility for two-lane crossings under higher vehicular volume and speed conditions • Driver education may be needed in some regions and areas	• Less common use than traffic control signal • Driver and crossing user compliance with device may not be as good as with a traffic control signal (e.g., *13*) • Higher cost than RRFB and raised crossing • Device rests in dark and may conflict with state laws requiring drivers to stop at a dark indication • Should not be used for metering applications (see Section 12.6) • Driver education may be needed in some regions and areas	• Higher cost than RRFB and raised crossing • Green indication to drivers may be misinterpreted as a green indication to enter the roundabout if located too close to the roundabout entry

Exhibit 12.21. Example of painted channelization lines between entry lanes.

LOCATION: US 17–US 92/W Haven Road, DeLand, Florida. SOURCE: Google Earth.

Despite having yield signs on both sides of a multilane entry, some roundabouts have exhibited crash patterns attributed to failure to yield on entry (*2*). To address this, some agencies have added supplemental word plaques below the yield signs on each side of the entry. These plaques have included language such as "To Both Lanes," "To Traffic in Circle," or other variations. The effectiveness of these supplemental plaques has not been assessed in isolation, as they have commonly been installed as part of a package of signing and pavement marking treatments.

At roundabouts with fully traversable central islands, signs cannot be placed within the central island. In these situations, the MUTCD provides a Roundabout Circulation (R6-5P) plaque, as shown in Exhibit 12.22. This sign is placed below each yield sign on each roundabout approach to define the direction of circulation within the roundabout.

The MUTCD prohibits the "No Left Turn" (R3-2) sign, the "No U-Turn" (R3-4) sign, and the combination "No U-Turn/No Left Turn" (R3-18) sign at roundabout entries. These signs conflict with roundabout operations as a single intersection where left-turn and U-turn movements circulate the central island within the intersection. These signs may be necessary at larger rotaries or traffic circles that could be interpreted as a ring of T-intersections.

Exhibit 12.22. Example of roundabout circulation plaque under yield sign.

LOCATION: W Crescent Rim Drive/W Eastover Terrace, Boise, Idaho.
SOURCE: Lee Rodegerdts.

A roundabout directional arrow sign, an example of which is shown in Exhibit 12.23, indicates the direction of travel within the circulatory roadway at roundabouts with non-traversable central islands. The black-on-white chevron design provides a regulatory message, legally establishing the direction of circulation at roundabouts. These signs are placed on the central island opposite the roundabout entrances to direct traffic counterclockwise around the central island. On multi-lane approaches, high-speed approaches, approaches with limited visibility, or in other circumstances in which increased sign visibility is desirable, larger versions of the sign or multiple copies of the same sign are sometimes used.

Although "One Way" signs (R6-1R) have been used instead of or in addition to the roundabout directional arrow signs, these are more commonly used for one-way roadways connecting to the roundabout, such as freeway entrance and exit ramps. "One Way" signs may also be useful at rotaries and other circular intersections where the circulatory roadway of the roundabout is legally defined as a separate one-way roadway rather than being part of a single intersection.

Most roundabouts have been installed with a dotted circulatory roadway edge-line extension across the entry lane or lanes. These edge lines act as *entrance lines*, marking the boundary between entering and circulating vehicles. These entrance lines have been commonly installed with widths greater than a typical wide line: 12 in. to 24 in. (300 mm to 600 mm) is common. Many agencies have also used a marking pattern unique to this application, with patterns of 2-ft to 3-ft (0.6-m to 0.9-m) lines with 2-ft to 3-ft (0.6-m to 0.9-m) gaps being common.

Yield lines are sometimes used in addition to entrance lines to further indicate the point behind which vehicles are required to yield in response to the yield signs at roundabouts. As described in the MUTCD, yield lines consist of a row of solid white isosceles triangles pointing toward approaching vehicles. Like other applications of yield lines and stop lines, the yield lines should normally be placed at right angles to the entry roadway. Exhibit 12.24 illustrates an example.

Debate continues about best practices for entrance markings. The MUTCD defines different purposes for edge-line extensions and yield lines, but in practice edge-line extensions often function as yield lines when paired with the required yield signs. There is little documented evidence that the supplemental yield line improves yielding behavior enough to justify the increased

Exhibit 12.23. Example of roundabout directional arrow sign.

LOCATION: NW 13th Street/W Fletcher Avenue, Lincoln, Nebraska.
SOURCE: Lee Rodegerdts.

Exhibit 12.24. Example of yield line at single-lane roundabout entry.

LOCATION: US 2/US 89, Browning, Montana. SOURCE: Lee Rodegerdts.

installation and maintenance costs. Some agencies have instead used a yield word pavement marking at a roundabout entrance to supplement the yield sign and edge-line extension.

If yield lines or yield word markings are used at multilane roundabouts, they should be staggered on a lane-by-lane basis to help drivers waiting at the yield line in the outer lane(s) see in front of vehicles waiting in the inner lane(s), as illustrated in Exhibit 12.25.

12.3.6 Full Signalization of Entry-Circulating Junction Points

Rotaries and other large, multilane circular intersections may benefit from full signalization at each entry-circulating point if there is adequate storage space in the circulatory roadway. In these cases, the circular intersection operates as a ring of coordinated signalized intersections with queue storage between them. The resulting combination of coordinated signalized intersections has operational, safety, and accessibility characteristics that can be different from roundabouts as defined in US practice. A detailed discussion of full signalization is outside the scope of

Exhibit 12.25. Example of yield word marking at multilane roundabout entry.

LOCATION: W Mason Street/I-41 Southbound Ramps, Green Bay, Wisconsin.
SOURCE: Lee Rodegerdts.

this document, but references from countries where this is more common (particularly the United Kingdom) are available to provide insight into possible practices, for example, *Signal Controlled Roundabouts* (*15*).

12.4 Circulating Area

Traffic control devices for drivers in the circulating area focus on maintaining the correct lane while circulating. They are most critical for multilane roundabouts where maintaining lane position is desired.

12.4.1 Markings Adjacent to the Central Island

In general, roundabout central islands do not need supplemental markings. Some agencies use a solid yellow line to delineate the edge of the central island. This practice is not specifically required by the MUTCD, which allows edge lines to be excluded on the basis of engineering judgment (e.g., if the traveled way is delineated by a curb). Given that most central islands have truck aprons or are fully traversable and intended for regular use by large vehicles, a yellow edge line next to the truck apron is routinely traversed by trucks and becomes more difficult to maintain over time.

Some agencies have used yellow edge lines to spiral traffic away from the central island toward a specific circulating lane. Research has found that yellow edge lines are ineffective at channelizing vehicles, with drivers commonly following the circular truck apron curb line rather than the yellow markings. This has resulted in documented late lane changes near the exits that can lead to increased vehicle conflicts and property damage crashes (*2, 3*). An extended raised central island truck apron is suggested instead of yellow striping for the purposes of spiraling circulating lanes; this is discussed further in Chapter 10: Horizontal Alignment and Design.

12.4.2 Circulating Lane Lines and Lane-Use Arrows

Lane lines within the circulatory roadway provide guidance, and many countries around the world use them. The practice recommended in the United States is to include lane lines within the circulatory roadway, so drivers are guided to the intended exit without needing to change lanes. As discussed in Chapter 10: Horizontal Alignment and Design, this practice requires the horizontal geometry of the roundabout to be compatible with the intended lane use. This is distinct from the practice used in some countries where concentric lane lines within the circulatory roadway require drivers in the interior circulating lane(s) to change lanes to exit. The MUTCD prohibits continuous concentric lane lines within the circulatory roadway of the roundabout because of the exit-circulating conflicts the concentric lane lines introduce.

The type of lane line within the circulatory roadway varies considerably in practice, often following agency preference. Exhibit 12.26 shows an example of a combination of solid lines and dotted lines.

The dilemma with circulatory roadway lane line marking patterns stems from the following observations:

- From the perspective of circulating traffic, a continuous solid line would best discourage lane changing within the circulatory roadway. This would appropriately support the principle of allowing a driver to choose the appropriate lane on the approach and not change lanes to get to the desired exit.

Exhibit 12.26. Example of circulatory roadway lane line pattern using solid–dotted combination.

LOCATION: 40th Street/East Yukon Street, Tampa, Florida. SOURCE: Google Earth.

- From the perspective of traffic entering a roundabout in any lane but the rightmost entry lane, a solid lane line across the roundabout entrance on the circulatory roadway may discourage drivers in the left entry lane from crossing the lane line to enter the left circulating lane. The dotted line facilitates this entry movement.
- From the perspective of truck drivers, a continuous solid line suggests they will not need to cross the line to circulate, but this is only true if the roundabout was designed with a true stay-in-lane configuration. Most multilane roundabouts with solid lane lines built in the United States have been implicitly designed for trucks to straddle lanes within the circulatory roadway. However, research conducted for this Guide indicates truck drivers were unable to distinguish the design intent for trucks (i.e., straddling lanes versus staying in lane).

If a solid line transitions to a dotted line, some circulating drivers might think they are allowed to change lanes at the dotted line before exiting the roundabout, contributing to exit-circulating crashes. Exhibit 12.27 illustrates an alternative marking pattern that some agencies within the United States have used. This strategy uses a consistent pattern of stripes and gaps throughout the circulatory roadway and exits. The rationale for this pattern is that it may be less likely to concentrate lane changes at the vulnerable entry-exit conflict area, and it is a line marking pattern that has been successfully employed in other countries, as shown in *Design of Road Markings at Roundabouts* (*16*).

Research to identify a preferred circulatory marking pattern is inconclusive. All documented modifications of existing roundabouts where a consistent broken or dotted line type was retrofitted also have other signing and pavement marking changes as part of a package of modifications, making it impossible to isolate circulatory roadway markings as a factor (*13*). Practitioners need to confirm that any selected marking pattern complies with the MUTCD and seek request for experimentation from FHWA for non-compliant marking patterns.

Research on property damage crash patterns at multilane roundabouts included a combination of sites with uniform dotted patterns and sites with a combination of dotted and solid lane lines (*2*). The biggest factors influencing lane changes within the roundabout did not appear to be caused by the lane marking pattern but rather by the base geometry, as well as factors such as approach signing and markings (ability to get drivers in the correct lane before entry), lane

Exhibit 12.27. Example of consistent circulatory roadway lane line pattern.

LOCATION: Shawano Street/South Taylor Street, Green Bay, Wisconsin.
SOURCE: Google Earth.

utilization, and network origin–destination patterns. In some cases, the uniform broken or dotted line type was shifted laterally to make the inside lane narrower and the outside lane wider. This may have improved crash performance because of better alignment with entry lanes and a smoother alignment into the exits.

Some agencies have used double solid lines that change to dotted lines, where entering traffic must cross the lane line. In some cases, the double solid lines have been supplemented with raised pavement markers or other traversable devices as needed for the passage of large trucks unable to stay in-lane (e.g., OSOW trucks). Exhibit 12.28 shows an example of this type of installation. **In all cases, any proposed variations from what is provided in the MUTCD may require approval of experimentation from FHWA (*1*).**

It is most common in the United States to use standard lane-use arrows within the circulatory roadway. Arrow placement varies, with some roundabouts having the arrows closer to the exit (at the beginning of the segment in front of the splitter island) and some having them closer to the entry. Research suggests that there may be advantages to placing the arrows in the circulating lane closer to the entry side (*2*):

- A through arrow in the outside circulating lane next to the entry is at the point where a circulating driver may be deciding whether to attempt to continue circulating from the outside lane (an improper left turn). The through arrow may emphasize the need to exit.
- Circulating arrows next to the entry may reinforce the correct direction of circulation for entering drivers.
- Arrows in each circulating lane may inform entering drivers that there are two circulating lanes and that both lanes may exit. This may improve driver yielding to other drivers in both circulating lanes.

Exhibit 12.28. Example of circulatory roadway double solid lane line pattern.

LOCATION: N Tamiami Trail/Fruitville Road, Sarasota, Florida. SOURCE: Ken Sides.

In some cases where splitter islands are wider, two sets of circulating arrows—one set close to the exit side and a second set close to the entry side—may be beneficial.

12.4.3 Signs and Pavement Markings in Circulatory Roadway for Bicyclists

Bicycle lanes are not advised within the circulatory roadway. Continuing a bicycle lane along the circulatory roadway can create two different conflicts:

- A conflict between through bicyclists and exiting drivers, increasing the potential for *right-hook* crashes with exiting drivers who cut off circulating bicyclists.
- A conflict with entering drivers who fail to yield to circulating bicyclists.

For many roundabouts, no specific signs or markings for bicyclists are needed. Some agencies have used sharrow markings to encourage bicyclists to ride in the middle of the circulatory roadway and communicate to drivers that people biking are expected to circulate with traffic. These markings are sometimes accompanied by “Bikes May Use Full Lane” or “Do Not Pass Bikes” signs.

12.5 Exit Area

As with the entry area, traffic control devices for drivers in the exit area focus on yielding to other users—bicyclists and pedestrians—as discussed in Section 12.3. The exit area also provides guidance and confirmation to drivers that they have selected the correct exit. At single-lane roundabouts, the destination decision can be made in the exit area. At multilane roundabouts, the destination decision must be made in the transition area before entry, discussed in Section 12.2.

Several types of confirmation guide signs may be applicable at roundabouts:

- **Exit guide signs and directional assemblies.** These signs designate the destinations, street names, or route designations of each exit from the roundabout and are commonly placed on the splitter island. Examples are shown in Exhibit 12.29 and Exhibit 12.30.
- **Route confirmation assemblies.** For roundabouts involving the intersection of one or more numbered routes, confirmation guide signs can be used on the right side of the exiting roadway beyond the crosswalk.

Exhibit 12.29. Example of street name exit guide sign and directional assembly.

LOCATION: W Tapp Road/I-69 Southbound Ramps, Bloomington, Indiana.
SOURCE: Lee Rodegerdts.

Exhibit 12.30. Example of combination route number and destination exit guide sign.

LOCATION: SR 16/CR 89, Madison, California. SOURCE: Lee Rodegerdts.

12.6 Entry Metering Signals

During peak periods, the flow from one entry can dominate downstream entries to the point that insufficient gaps are available, causing excessive delays and queues at the downstream entry. In these cases, entrance metering can provide significant operational benefits during peak periods. In some applications, entry metering signals may be a more economical solution than geometric improvements and may improve the overall safety performance of the roundabout because of the reduced number of lanes. This could include locations where the traffic condition requiring metering is of short duration and the geometric improvements would require adding lanes. In some cases, it may be advantageous to meter more than one entry during the same peak period or to change which entries are metered by time of day.

A basic metering system consists of two components:

- **Queue detector.** This can be placed on the downstream entry exhibiting excessive delays and queues. When a long queue is detected, the signal controller activates the metering signal.

- **Metering signal.** This is provided on the dominant approach, preferably set far enough back from the entry to minimize confusion with the yield sign but not so far as to require excessive red time to clear the queue in front of the metering signal. Experience in the United States is too limited to specify a standard minimum or maximum distance, but metering applications to date have been 100 ft to 200 ft (30 m to 60 m) in advance of the roundabout entry. If the metering signal cannot be set back sufficiently, some countries (e.g., Australia) use a special changeable message sign that shows a yield sign but can be changed to read "Stop on Red Signal."

  An example of a simple metering system is shown in Exhibit 12.31.

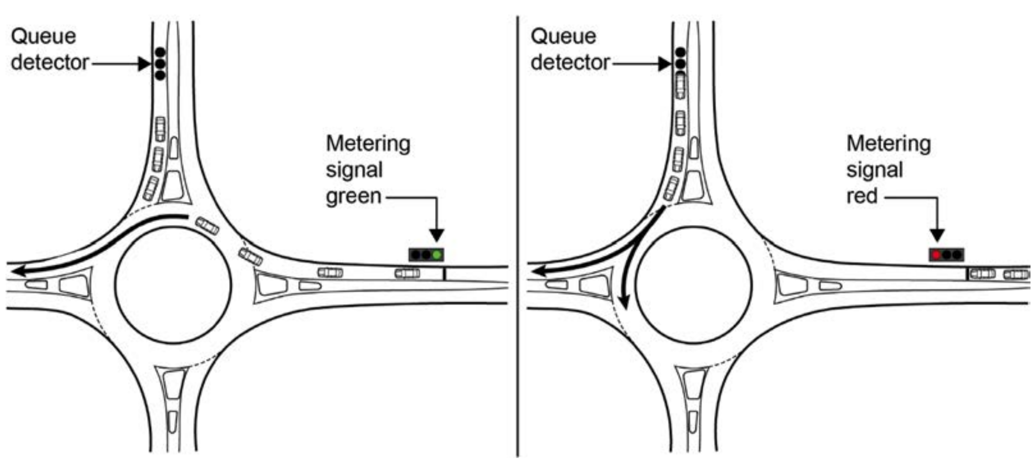
Four installations in the United States with permanent roundabout metering, one temporary installation, and one using freeway ramp metering on a roundabout approach yielded the following observations:

- Roundabout meters have successfully created gaps in circulating traffic so that vehicles can enter the roundabout from approaches other than the high-volume approach.
- Roundabout meters are operated only when queues on one or more legs create an operational or safety issue (sometimes both).
- Roundabout meter installations have most often been used where one of the legs is a freeway exit ramp and queues from the roundabout extend back onto the freeway. The roundabout metering signals have successfully limited the encroachment of the exit ramp queues onto the freeway.
- The distance between the signal and the roundabout entry varies between locations. Data and experience are insufficient to judge a minimum separation distance for use in guidelines.

Metering may also be possible by controlling the timing of an upstream signalized intersection to limit flows toward the roundabout. Practitioners need to evaluate expected queue lengths on the roundabout exits between the signalized intersection used for metering and the circulatory roadway for the most appropriate operation. Metering by upstream signalized intersections is generally not as effective as direct entrance metering because of vehicles turning into the roadway at or downstream of the signalized intersection.

If used at a roundabout, PHBs (discussed in more detail in Section 12.3.3) are best reserved for pedestrian crossing applications and not used for entry metering, although they may have a secondary entry metering effect. The activation of PHBs by queue detection in metering applications without the presence of pedestrians may dilute the effectiveness of the devices for crossing users.

Exhibit 12.31. Metering signal operation.



12.7 At-Grade Rail Crossings

At-grade rail crossings present a challenge near any intersection; this is not unique to roundabouts. Having an intersection near an at-grade rail crossing is sometimes unavoidable, and a roundabout may be the preferred intersection form (e.g., for safety reasons) even with the at-grade rail crossing present. This section discusses techniques to manage the interaction between a roundabout and an at-grade rail crossing. Considering these issues early during ICE stages is highly advised to help with decision making.

For any intersections near at-grade rail crossings, including roundabouts, two concerns are common:

- Queuing at the intersection may extend back to and through the at-grade rail crossing. The queue may be caused by conflicting traffic in front of the subject entry, pedestrian activity, parking activity that blocks the intersection, or other factors. Rail operators usually raise this concern.
- Queuing at the at-grade rail crossing during train passage may extend to the intersection and disrupt intersection operations. The relevant road authority usually raises this concern.

Unlike signalized intersections, roundabouts or other unsignalized intersections do not have an option for clearing the queue on an approach before a train arrives. Without the ability to flush or clear the queue on a roundabout approach, traffic can be occupying a grade crossing when a train arrives. However, queues at unsignalized intersections can often be shorter than at signalized intersections because of lower roadway volumes, thus reducing the likelihood of traffic occupying the grade crossing in the first place.

Where roundabouts include or are near a highway–rail grade crossing, practitioners have to carefully consider whether vehicles will queue across the tracks and, if so, how the queues can be cleared in advance of an oncoming train. The MUTCD requires conducting an engineering study for any roundabout near a highway–rail grade crossing to determine whether queuing could impact the rail crossing and develop provisions to clear the highway traffic from the highway–rail grade crossing before the train's arrival (*1*). The FHWA and Federal Railroad Administration *Highway-Rail Crossing Handbook,* 3rd edition, discusses the use of a diagnostic team to assess the rail crossing and suggests that traffic control signals or queue-cutter signals may be needed (*17*).

A limited range of experiences in the United States precludes definitive guidance in this important topic area. Each at-grade rail crossing at or near a roundabout often has unique conditions. Railroad-operated gates, road authority–operated highway traffic signals, or some combination thereof may be appropriate. In some cases, no special treatments between the at-grade rail crossing and roundabout are needed; an example is provided in Exhibit 12.32. The following sections discuss factors to consider and some of the common cases experienced to date.

12.7.1 Factors to Consider

Many factors can influence traffic operations, safety, and traffic control near a roundabout when there is an at-grade rail crossing in its vicinity. Key influencing factors include:

- Rail operators are often concerned about the likelihood of queuing extending into the rail crossing. The potential for a queue extending from a roundabout to a rail crossing is highly dependent on local conditions, with the level of treatment needed scalable to those conditions. Treatments may range from doing nothing more than existing conditions to a variety of active treatments. Many factors can influence the likelihood of queuing:
  - **Traffic volumes and the proximity of the crossing to the intersection.** These two factors are interrelated. A grade crossing located on a major leg of the roundabout with higher

Exhibit 12.32. Example of at-grade rail crossing near roundabout.

LOCATION: D Street/I-5 Southbound Ramps/Marine Drive, Blaine, Washington.
SOURCE: Lee Rodegerdts.

vehicle volumes may have a peak period queue from the roundabout that extends 0.25 miles (0.4 km) or more. Conversely, if a grade crossing is located on a leg of a roundabout with lower overall vehicular volumes, a queue will not likely extend to the rail crossing, even if the rail crossing is within 100 ft (30 m) of the roundabout.

  - **The control of the crossing itself.** Rail crossings that are currently passively controlled (i.e., controlled by stop or yield signs) are often on low-volume roadways. In some cases, these passively controlled crossings are supplemented with a "Do Not Stop on Tracks" sign. Queuing in these cases may change little with the installation of a roundabout. Crossings requiring active control (i.e., signals or signals and gates) can be paired with more active treatments of a nearby roundabout or other intersection. These treatment approaches are discussed in Section 12.7.2.
  - **The nature of train traffic at the rail crossing.** Rail crossings along railroad mainlines or light rail lines with higher train speeds and frequencies have a higher likelihood of interaction with queues than, for example, industrial sidings that operate infrequently and at low train speeds. The associated traffic control at the crossing can be scaled accordingly.
- An agency concern regarding grade crossings near roundabouts is the queue from the rail crossing extending back into the roundabout and blocking the roundabout. Many factors can influence the queue length that results from a train at a grade crossing:
  - **Length of the train.** Some freight trains can exceed 10,000 ft (3,048 m) in length, and such lengths are likely to become more commonplace.
  - **Speed of the train.** Communities that have established lower train speeds create longer queues at grade crossings. High-speed trains create the need for long advance warning times.
  - **Frequency of train arrivals.** Where crossings serve light rail or other transit vehicles, frequent train arrivals may perpetuate queues.
  - **Conflicting highway traffic volume.** Where conflicting highway traffic is highly peaked or serves comparatively high volumes (e.g., related to special events or freeway off-ramps), queues may be highly variable.
- The complications of an at-grade rail crossing in or near a roundabout lessen when roundabout traffic volumes are low, train frequency is low, or both.
- Double-rail lines have a higher potential for a queuing condition over the tracks when traffic is clearing after a first train with a second train arriving shortly after.
- Railroad signals and gates operate differently than highway signals during power outages. Railroad gates drop with a loss of power; highway signals flash or go dark.

12.7.2 General Treatment Approaches

A variety of generalized treatment approaches can address queuing when a grade crossing is in or near a roundabout and the queuing is deemed to warrant treatment.

- **Railroad gate arms.** Most at-grade rail crossings at or near roundabouts in the United States have railroad gate arms at the rail crossing. Some roundabouts have used railroad gate arms on other approaches to essentially close the roundabout to traffic when a train is nearing or present at the crossing. Closing the roundabout to all traffic during train passage is more practical for shorter light rail crossings. This technique is less common for at-grade crossings involving heavy rail, as railroad gate arms are typically owned and operated by the railroad but would be located outside the railroad right-of-way.
- **Traffic control signals or beacons.** Some existing roundabouts have used some form of traffic control signal or beacon to create a stop condition when a train approaches a grade crossing on the roundabout entries that do not cross the tracks. By stopping the traffic on the approaches not crossing the tracks, vehicles on the approach crossing the tracks can enter the roundabout and clear the crossing. The MUTCD would determine the form and function of these signals, which would be operated by the road authority. This approach is similar in concept to using traffic control signals for roundabout metering, as described in Section 12.6.
- **Intersection configuration changes.** A right-turn bypass lane for the approach crossing the tracks can reduce the queuing potential over the railroad tracks.
- **Signs at the grade crossing.** The MUTCD provides a regulatory sign, “Do Not Stop on Tracks” (R8-8), which may be sufficient for some grade crossings at roundabouts. This is especially true for crossings with a low frequency of train use and low roadway volumes.

As noted previously, the context of the roundabout installation affects what, if any, treatments are needed at the grade crossing. In some cases, a roundabout replacing another intersection form or control will either maintain or reduce the queuing on the subject leg with the grade crossing. An example is a proposed roundabout replacing an existing two-way stop-controlled intersection where the leg with the grade crossing is stop controlled. If the distance for queuing between the proposed roundabout and rail crossing is the same as between the existing stop-controlled intersection and rail crossing, and if the roadway volumes are the same in both cases, queuing from the roundabout to the grade crossing is likely to be the same or shorter. This is because yield control is generally more efficient than stop control. For this example, the existing passive or active traffic control systems at the grade crossing itself may be sufficient without additional treatments. An engineering study can confirm the recommended approach for the specific site conditions.

The following sections discuss issues associated with two generalized cases found in the United States. Other guidance is provided in state-level documents, such as that from the Georgia Department of Transportation (*18*).

12.7.3 Rail Crossing on One or More Legs

When rails cross only one roundabout leg, the simplest and most common treatment is to provide gates only on the leg where the rails cross. These gates would commonly be in the railroad right-of-way and operated by the railroad. An example of this application in Richland, Washington, is shown in Exhibit 12.33.

In another example, additional flashing red beacons were installed on the legs of the roundabout not crossing the railroad. This application in Reedley, California, is shown in Exhibit 12.34.

12.7.4 Rail Crossing through Central Island

Where rails pass through the roundabout’s central island, either diagonally or along the median of one of the intersecting roadways, the simplest and most common treatment is to provide gates

Exhibit 12.33. Aerial perspective of at-grade rail crossing on one leg.

NOTE: Railroad gates located only at the at-grade rail crossing. No gates are provided across the sidewalk at the at-grade railroad crossing. LOCATION: W Clearwater Avenue/E Badger Road/Ridgeline Drive/Leslie Road, Richland, Washington. SOURCE: Google Earth.

Exhibit 12.34. Example of aerial perspective of railroad crossing near roundabout.

NOTE: Railroad gates are located only at the at-grade railroad crossing. Supplemental horizontal flashing red beacons are located on the roundabout leg in the lower right corner of the image. LOCATION: N Reed Avenue/W North Avenue, Reedley, California. SOURCE: Google Earth.

only on the circulatory roadway where the rails cross. These gates are commonly in the railroad right-of-way and operated by the railroad. An example of this application in Daingerfield, Texas, is shown in Exhibit 12.35 (aerial perspective) and Exhibit 12.36 (ground-level view of one of the at-grade crossings).

A similar case occurs where rails pass along the median of one of the intersecting roadways and then through the central island. An example of this occurs in a light rail application in Salt Lake City, Utah, as shown in Exhibit 12.37 and Exhibit 12.38.

12.8 Pavement Marking Materials

The types of pavement marking materials used at roundabouts vary widely across the United States. These types typically mirror the applications used elsewhere on the roadway system, often reflecting agency preference for installation and maintenance. Materials range from paint to more

Exhibit 12.35. Example of railroad diagonally through roundabout.

NOTE: Gates are located only at the at-grade railroad crossing. LOCATION: Webb Street/Myrtle Street/Jefferson Street/Coffey Street, Daingerfield, Texas. SOURCE: Google Earth.

Exhibit 12.36. Example of gate arm and signal on circulatory roadway.

LOCATION: Webb Street/Myrtle Street/Jefferson Street/Coffey Street, Daingerfield, Texas. SOURCE: Lee Rodegerdts.

Exhibit 12.37. Example of rail crossing along median through central island.

NOTE: Railroad gates are located at the at-grade light rail crossing and on each of the two entries parallel to the light rail tracks. LOCATION: E South Campus Drive/Campus Center Drive, Salt Lake City, Utah. SOURCE: Google Earth.

Exhibit 12.38. Example of rail crossing along median through central island.

LOCATION: E South Campus Drive/Campus Center Drive, Salt Lake City, Utah.
SOURCE: Lee Rodegerdts.

durable materials, such as thermoplastic. Pavement markings are sometimes inlaid to improve durability. Sometimes, pavement markings are supplemented or replaced by raised or depressed pavement markers. Further discussion on this topic can be found in other documents, such as the FHWA *Synthesis of Pavement Marking Research* (*19*).

12.9 Other Devices

Other devices, including traffic control devices governed by the MUTCD, have been used in some cases to address specific site conditions. These devices include

- Flexible, internally illuminated bollards;
- Transverse rumble strips placed in advance of the roundabout;
- Warning beacons supplementing approach warning signs;
- Speed reduction markings placed transversely across travel lanes; and
- Vehicle-activated speed warning signs commonly triggered by speeds exceeding an acceptable threshold.

12.10 References

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CHAPTER 13

Curb and Pavement Details

Contents

This chapter provides guidance on design, surface, and material details that bridge a roundabout's design from the horizontal and vertical layouts described in Chapter 10: Horizontal Alignment and Design and Chapter 11: Vertical Alignment and Cross-Section Design to the construction process described in Chapter 15: Construction and Maintenance. This chapter discusses

- Pavement and surface treatments,
- Curb types, and
- Median and splitter island features that facilitate maintenance.

This chapter is not an exhaustive discussion of all relevant design details. Many geometric design considerations related to these topics are fundamental to all intersection types, including those presented in Chapters 10 and 11.

13.1 Roadway Pavement Type

Pavement type and surface material treatment preference vary by agency and are based on climate and established local practice. Two material types are common for the top surface of approach, departure, and circulatory roadways at roundabouts: asphalt concrete (AC) and portland cement concrete (PCC). Whether to use AC or PCC depends on local preferences and the pavement type on the approach roadways. Some trade-offs for each are described in Exhibit 13.1.

Project context often dictates the choice between AC and PCC. For example, a complex staging and traffic management scenario may be more readily executed using PCC. Conversely, AC may be beneficial for a multilane roundabout with complex lane configurations that need a spiral marking pattern.

Exhibit 13.1. Considerations for pavement type at roundabouts.

	Asphalt Concrete	Portland Cement Concrete
Maintenance	• Mill and overlay of the existing roundabout are easier with traffic present. • Easier to surface repair.	• Joint repair is not possible with traffic present, so more detailed traffic control plans are necessary for maintenance.
Pavement marking	• Best contrast with any type of marking material.	• Requires using contrast tape, which is more costly to maintain.
Staging	• May be able to take advantage of temporary pavement as a base below the leveling course. • No joint lines to address. • Temporary pavement and other surfaces may be covered if the top asphalt layer is placed all at once in a later stage. • If joint lines are not perpendicular, longitudinal cracking will occur over time. • Adding curb in later stages requires a sawcut and backfilling with specified compaction.	• Joint lines provide a clean break for stages. • Temporary AC adjacent to PCC can be easily removed without a sawcut. • Staging requires stage cuts at joint lines, which may be more difficult with traffic present. • Overall construction time may be longer because of curing time.
Durability	• Shorter design life. • More prone to rutting, which affects drainage characteristics. • Requires substantial base material and depth and surface mix design for optimal durability and skid resistance. • Rehabilitation is feasible, cost-effective, and practical.	• Longer design life; more likely to retain initial drainage characteristics. • Near the end of the design life, complete reconstruction is required—pavement rehabilitation is not possible.
Color contrast	• If splitter islands are AC, there will be minimal contrast as color lightens over time. • Provides good contrast with pavement markings and with PCC truck aprons. • Colored AC is possible but less common than colored PCC.	• Mixes can be colored to provide contrast and textured for aesthetics. • More difficult to establish contrast with pavement markings and truck apron. • Requires using contrast tape (more costly to maintain).
Other	• AC placement will be more rounded through cross-slope transitions, which may help oversized vehicles and lowboy trailers traverse through the roundabout. • Easier to construct a smooth crown line.	• Skid resistance declines more rapidly. • Joint lines may resemble lane lines in the multilane design.
Expandability or staged design expansion	• Adjustability of grades is easier, and drainage is less impacted.	• The PCC joint pattern may not be compatible with an expanded layout. • Dowels may be required for expansion areas.

SOURCE: Adapted from American Concrete Pavement Association *(1)*.

13.2 Truck Apron Material

Agencies use a range of aesthetic treatments, including simple broomed PCC, stamped/patterned PCC (broomed finish), and various types of paver materials—there is no preferred texture for the truck apron. However, it is beneficial for the truck apron to be a different color and texture from the circulatory roadway and non-traversable surfaces (e.g., sidewalks) to improve its visibility to drivers and distinguish it from other elements. There are multiple ways to accomplish this, three of which are discussed below.

- **PCC and AC.** Some agencies use PCC for truck aprons (for durability) and AC for the circulatory roadway. This way, the truck apron is less prone to rutting. The visual distinction also helps communicate the difference in the intended uses.
- **PCC only.** For roundabouts constructed entirely of PCC, mixtures can be colored to provide visual distinction. The apron may also be textured or patterned. With this approach, an agency preferably will not select a color that may be mistaken for one that the MUTCD designates for a specific use (*2*). For example, red and green coloring denotes travel lanes for transit and bicycle use. Therefore, some agencies have adopted designated colors for associated roundabout design elements.
- **AC and pavers.** Some agencies use pavers (or other stone material) in the truck apron (see Exhibit 13.2 and Exhibit 13.3), with the uneven driving surface dissuading drivers from

Exhibit 13.2. Example of raised truck apron using pavers.

LOCATION: US 5/Route 9, Brattleboro, Vermont. SOURCE: Lee Rodegerdts.

Exhibit 13.3. Example of flush truck apron using pavers.

LOCATION: Broad Street/Coburn Avenue/Chuck Druding Drive, Nashua, New Hampshire. SOURCE: Lee Rodegerdts.

Exhibit 13.4. Example of placing truck apron curb.

LOCATION: Route 9–Route 126/I-95 Northbound Ramps/Service Plaza Drive, West Gardiner, Maine. SOURCE: Jonathan French.

traversing the area. Pavers can be an effective design element that provides an aesthetic quality, but they require more time, money, and expertise—paver installation is labor intensive and can result in water ponding or erosion if pavers are improperly installed.

Exhibit 13.4 and Exhibit 13.5 demonstrate the means and methods for constructing a PCC truck apron. In this example, the truck apron curb was located and constructed before the remainder of the truck apron. Steel reinforcing in the truck apron adds durability for anticipated design vehicle loads.

The shape of the truck apron curb more effectively discourages passenger cars from using the apron than the material it is made from. The curb helps reinforce the use of the circulatory roadway while allowing the intended vehicles to track upon the truck apron; this practice permits the use of smooth truck aprons that are easier to construct and maintain. Section 13.4 further discusses curb types.

Pedestrians should not access the roundabout's central island. Truck apron material and color alone are not appropriate ways to reinforce this because these differences are not adequate for people who are blind or have low vision. Instead, landscaping and buffer strips or

Exhibit 13.5. Example of steel reinforcing being placed for truck apron.

LOCATION: Route 9–Route 126/I-95 Northbound Ramps/Service Plaza Drive, West Gardiner, Maine. SOURCE: Jonathan French.

other detectable edges between the sidewalk and circulatory roadway, discussed in Chapter 10: Horizontal Alignment and Design, more effectively discourage pedestrians of all abilities from accessing the central island.

13.3 Pavement Jointing

If PCC is used for the circulatory roadway of a multilane roundabout, expansion joint design and location are key considerations. Practitioners must carefully develop a jointing plan to avoid joint lines being mistaken for lane lines.

In general, the best joint patterns are those that are concentric and radial to the circulatory roadway within the roundabout.

- On single-lane roundabouts, jointing must not split the circulatory roadway into equal parts, as this can give the illusion of a two-lane roundabout. This can be particularly problematic at night and in wet conditions when vehicles may drive along the joints. This introduces the potential for side-by-side movements. Alternatively, the jointing may split the roadway into larger and smaller segments that are unlikely to be confused for distinct travel lanes (see Exhibit 13.6).
- On multilane roundabouts, circumferential joints within the circulatory roadway need to follow pavement markings to the extent practical (see Exhibit 13.7).

Cracking in PCC has been a problem at some roundabouts, particularly around the outside of the circulatory roadway near outside curbs or splitter islands. Practitioners can solve this issue by isolating the circulatory roadway portion with an expansion joint and constructing special monolithic sections in key areas on the approaches and around splitter islands. When the joints are laid out independently of each other, the joint spacing adjacent to the truck apron and the outside of the circulatory roadway can be more uniform, rather than closer together near the truck apron and farther apart on the outside of the circulatory roadway.

Practitioners need to prepare a jointing plan and associated detail sheets as part of the final design plan set and submit them to the review authority. Exhibit 13.6 provides an example concrete jointing plan and the resulting roundabout that illustrates the radial pattern. Exhibit 13.7 shows an example of jointing alignment with pavement markings.

Exhibit 13.6. Example jointing plan for a single-lane roundabout.

LOCATION: US 75/K-31/K-268, Osage County, Kansas. SOURCE: Kansas Department of Transportation.

Exhibit 13.7. Example of pavement markings aligned with concrete jointing at a single-lane roundabout.

LOCATION: Rice Road/I-70 Eastbound Ramps/Cyprus Drive, Topeka, Kansas.
SOURCE: Lee Rodegerdts.

A jointing plan is needed so the joint layout will be constructed properly; the plan is the key by which the joints will be correctly located. The American Concrete Pavement Association (ACPA) identifies a six-step process for developing a jointing plan (*1*):

1. Draw all pavement edge and back-of-curb lines in plan view. Draw locations of all manholes, drainage inlets, and valve covers so that joints can intersect them.
2. Draw all lane lines on approach legs and in the circulatory roadway. Confirm that joint spacing does not exceed the maximum recommended width of 15 ft (4.5 m).
3. In the circulatory roadway, add transverse joints radiating out from the center of the circle. Extend these joints through the back of the curb and gutter.
4. On the approaches, add transverse joints at all locations where a width change occurs in the pavement (at bullnose of splitter islands; beginning and ending of curves, tapers, tangents, curb returns; etc.). Extend these joints through the back of the curb and gutter.
5. Add transverse joints beyond and between those added in Step 4. Space joints evenly between other joints, making sure to not violate maximum joint spacing.
6. Adjust for in-pavement objects and fixtures and to eliminate L-shapes, small triangular slabs, and so on.

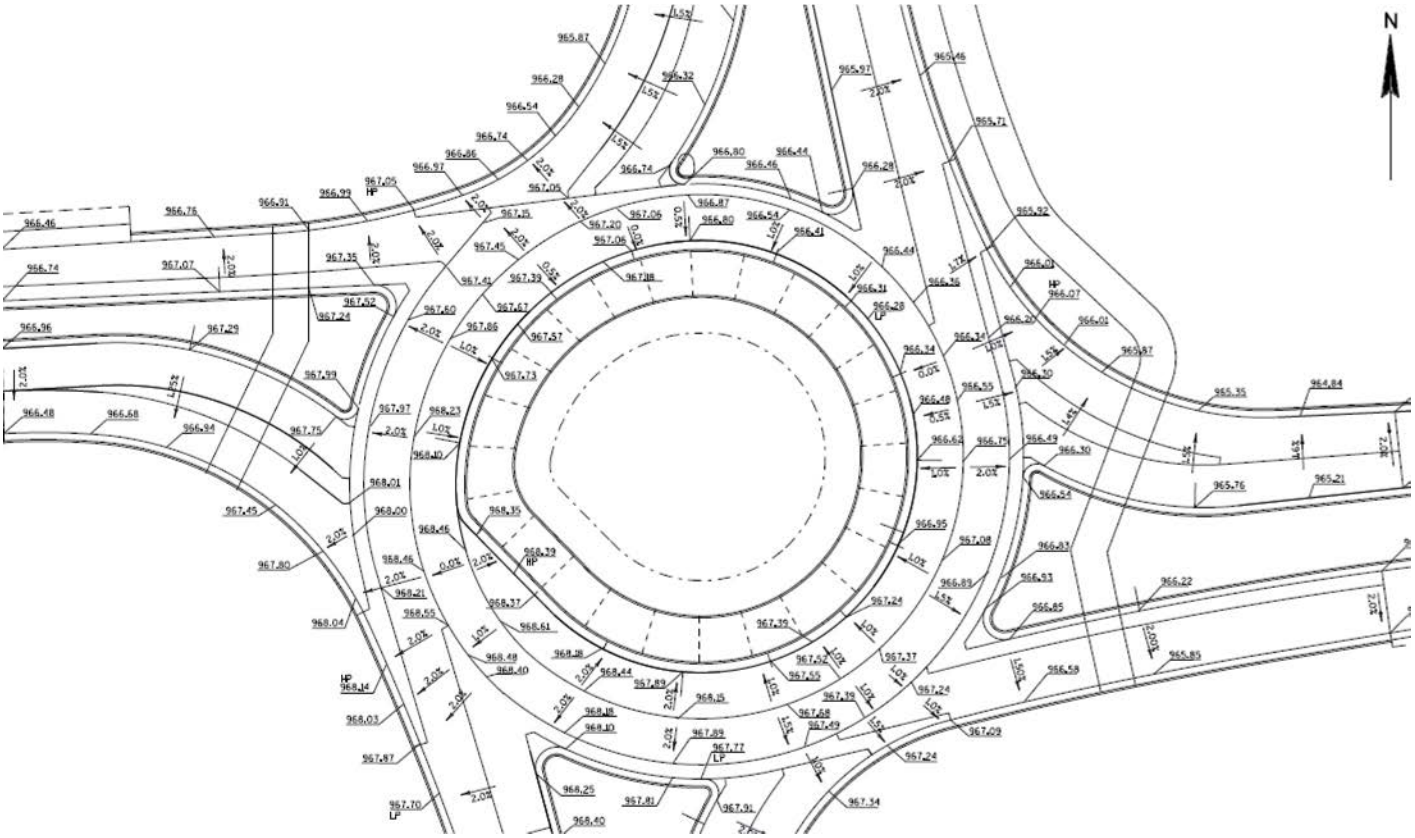
The ACPA recommends considering the following when preparing a jointing plan for a roundabout (*1*):

- Match existing joints and cracks wherever possible.
- Place joints to meet in-pavement structures.
- Set maximum joint spacing as follows:
  - 24 times concrete thickness (on unstabilized base)
  - 21 times concrete thickness (on stabilized base)
  - Maximum of 15 ft (4.5 m) for streets and highways
- Understand that practical adjustments can be made to joint locations.

Similarly, the ACPA recommends avoiding the following (*1*):

- Slabs less than 1 ft (300 mm) wide
- Slabs greater than 15 ft (4.5 m) wide
- Angles less than 60 degrees created by dog-legging joints through curve radius points (approximately 90 degrees is best)

Exhibit 13.8. Example of multilane roundabout jointing plan.



LOCATION: Radio Road/Paulson Road, Saint Croix County, Wisconsin. SOURCE: Wisconsin Department of Transportation.

- Creating interior corners (L-shaped slabs)
- Creating odd shapes (keep slabs square or pie-shaped)

As noted in Section 10.8, a roundabout may be built as a single-lane roundabout with plans for expansion in the future based on projected traffic volumes. However, because concrete jointing can be mistaken for striping, the jointing plans established for the opening-year roundabout should be reasonably compatible with plans for the ultimate roundabout configuration.

Exhibit 13.8 illustrates an example of a jointing plan for a multilane roundabout with a spiral design. Exhibit 13.9 shows how the painted lane lines are aligned with the longitudinal jointing.

13.4 Curb Type

Two general curb (or curb and gutter) types are used at roundabouts. One group of curb types is traversable and accommodates vehicles driving onto and over them if necessary. Other curb types are non-traversable, typically with more vertical rise, and are expressly designed to discourage any driver from mounting or driving over them. Exhibit 13.10 shows a wide array of concrete curb types, demonstrating that curbs and local design standards dictate the details but that various designs can support the traversable or non-traversable intent. Variations using granite curbs are possible.

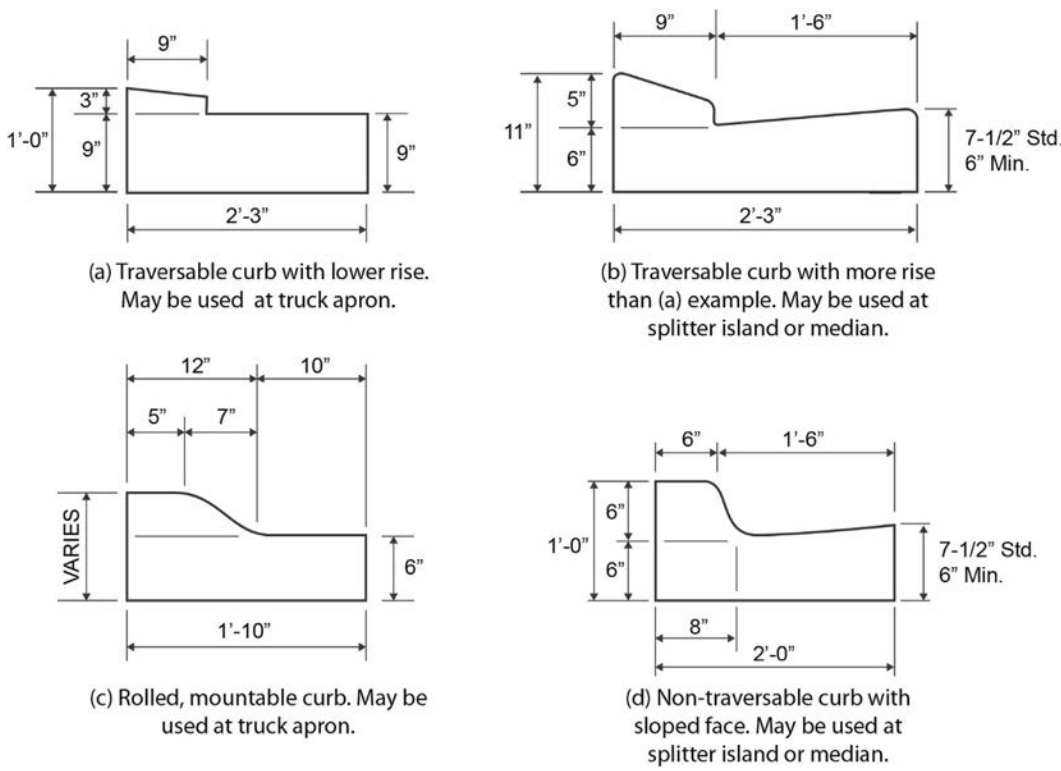
- **Traversable curbs.** These are sometimes called *rolled* or *mountable* curbs. These are most common for the leading edges of truck aprons but are sometimes used throughout a roundabout

Exhibit 13.9. Example of multilane roundabout jointing along pavement markings.

LOCATION: Mason Street / I-41 Southbound Ramps, Green Bay, Wisconsin.
SOURCE: Lee Rodegerdts.

in higher-speed environments. In the higher-speed context, mountable curbs may be used at splitter islands or medians with a taller height and different profile from those at truck aprons. Traversable curbs generally have a low vertical component of 1 in. to 2 in. (25 mm to 50 mm), a low overall rise of 3 in. to 4 in. (75 mm to 100 mm), and a broad slope in a vertical-to-horizontal ratio of 1:4. Curb types can vary, but general practice favors keeping the vertical component and the overall rise lower to minimize the adverse effects on truck dynamics or damage to truck tires while still discouraging passenger car use. There is considerable variation from agency to agency. Exhibit 13.10 provides a few examples of curb type variations.

Exhibit 13.10. Concrete curb type variations.



(a) Traversable curb with lower rise. May be used at truck apron.

(b) Traversable curb with more rise than (a) example. May be used at splitter island or median.

(c) Rolled, mountable curb. May be used at truck apron.

(d) Non-traversable curb with sloped face. May be used at splitter island or median.

NOTE: Variations using granite curbs are possible but not shown. SOURCE: Adapted from Florida Department of Transportation and Washington State Department of Transportation details (*4, 5*).

- **Non-traversable curbs.** These are sometimes called *vertical* or *slope-faced* curbs. They are most common in the vicinity of pedestrian crossings but are sometimes used throughout a roundabout in lower-speed environments (except for the front edge of truck aprons). Non-traversable portions of central islands can also be separated from truck aprons with vertical curbs. Agency preferences vary widely, but these are often 6-in. (150 mm) vertical curbs that provide protection and detectable edging for pedestrians, typical of what is provided in most urban areas. These curb types may also have a sloped face but remain unmountable (see Exhibit 13.10, *d*).

Curb strikes are one of the leading causes of motorcyclist fatalities, which are overrepresented at roundabouts compared with other intersection forms (*3*). Mountable curb types around the perimeter and along the inside of the truck apron may improve recovery for these vehicle types. Curb types need to be consistent with the intersection plan to accommodate oversize or overweight vehicles.

13.5 Splitter Islands with Sloped Noses

As discussed in Chapter 10: Horizontal Alignment and Design, channelization of splitter islands includes the fundamental principles of offsetting and matching the radius to the intended driver-funneling effect (*6*). For roundabouts in locations with snowfall that needs to be cleared, plowable end treatments (depicted in Exhibit 13.11 and Exhibit 13.12) can allow snowplows to push

Exhibit 13.11. Example of plowable end treatment at splitter island.

LOCATION: CR 17/52nd Avenue S, West Fargo, North Dakota.
SOURCE: Lee Rodegerdts.

Exhibit 13.12. Example of plowable end treatment at bypass island.

LOCATION: US 50/California State Route 89, El Dorado County, California.
SOURCE: Michael Alston.

snow up to and on the splitter island. Some agencies also use sloped edges at pedestrian ramps and pedestrian routes through splitter islands to reduce damage from plowing operations. This is a viable treatment where winter weather is a serious consideration.

13.6 References

1. *Research & Technology Update No. 6.03: Concrete Roundabouts*. American Concrete Pavement Association, Washington, DC, 2005.
2. *Manual on Uniform Traffic Control Devices for Streets and Highways*, 2009 ed., Including Revision 1, Dated May 2012; Revision 2, Dated May 2012; and Revision 3, Dated August 2022. FHWA, US Department of Transportation, 2022. http://mutcd.fhwa.dot.gov/.
3. Steyn, H. J., A. Griffin, and L. Rodegerdts. *A Review of Fatal and Severe Injury Crashes at Roundabouts*. Vol. IV of VII, *Accelerating Roundabout Implementation in the United States.* Publication FHWA-SA-15-072. FHWA, US Department of Transportation, 2015.
4. *FY 2022–23 Standard Plans: Curb and Gutter*. Index 520-001. Florida Department of Transportation, Tallahassee, 2021. https://www.fdot.gov/design/standardplans/current/default.shtm. (Accessed June 9, 2022.)
5. *Roundabout Cement Concrete Curbs: Standard Plan F-10.18-02.* Washington State Department of Transportation, Olympia, 2020. https://wsdot.wa.gov/engineering-standards/all-manuals-and-standards/standard-plans. (Accessed June 9, 2022.)
6. *A Policy on Geometric Design of Highways and Streets*, 7th ed. AASHTO, Washington, DC, 2018.

CHAPTER 14

Illumination, Landscaping, and Artwork

Contents

This chapter discusses illumination, landscaping, and artwork at roundabouts. Illumination information encompasses general considerations, lighting levels, and illumination equipment type and location, including suggested lighting levels for various applications, transition lighting recommendations, and equipment and pole location suggestions. This chapter also addresses horizontal and vertical illuminance needs and uses illumination terms and concepts defined and described in the Illuminating Engineering Society's (IES) *Recommended Practice for Design and Maintenance of Roadway and Parking Facility Lighting*, ANSI/IES RP-8-18 (*1*).

Landscaping information includes general objectives and guidance for landscaping within the central island, in medians and approaches, and associated with sidewalks and path buffers. Additional guidance and considerations for artwork and other objects at the roundabout are also included.

14.1 General Illumination Considerations

As with any intersection lighting, roundabout lighting makes the roundabout visible from a distance and makes vehicular and non-motorized traffic more visible in conflict areas. Motor vehicles have headlights and taillights to improve their visibility at night. However, pedestrians and bicyclists may not have lights or be as visible, and unexpected objects (e.g., a boulder that has fallen into the roadway) or animals may be in the travel lanes. The view a driver needs for stopping sight distance within the circulatory roadway is often beyond the range covered by typical fixed headlight configurations, unless the headlights can steer to the left to match the vehicle trajectory. As a result, the IES recommends providing roundabout lighting (*1*).

Delineation—retroreflective signs, pavement markings, pavement markers, and other devices—can also help a driver understand the changing conditions from the roadway segment to the roundabout. Delineation can mimic the presence of curbing and the splitter island to provide positive guidance to and through the roundabout. In some cases, delineation without supplemental lighting may be desired, especially if providing lighting is impractical. However, delineation does not provide supplemental lighting to illuminate conflict areas with other drivers or with bicyclists or pedestrians, nor does it help identify unexpected objects or wildlife in the roadway.

14.1.1 Lighting Policies

Requiring or recommending roundabout lighting is a policy-level decision. In general, agencies that have published their own roundabout design or lighting standards have specified that lighting is required (*2, 3, 4*). Agency practices vary widely with respect to providing lighting for any type of isolated rural intersections (*5*).

As an example of a specific lighting policy for roundabouts, the Pennsylvania Department of Transportation (PennDOT) requires roundabout lighting if the roundabout meets one or more of the following factors based on the design year (*6*):

- The roundabout is part of an interchange that has full or partial lighting.
- Any of the intersecting roads have an AADT exceeding 1,500 vehicles per day.
- Nighttime pedestrian activity exceeds 10 pedestrians per hour during the highest average annual nighttime hour.
- One or more of the roundabout legs has or is expected to have lighting.
- The roundabout is in an urban or urban core environment.

PennDOT requires approving an exception to the lighting policy if one or more of the above warranting factors is not met. If lighting is not provided, retroreflective signs and pavement markings to identify fixed-object hazards are required. This includes delineating the central island, the splitter island noses, and the beginning of any curb sections.

Internationally, roundabout lighting recommendations are mixed. One study found that of 22 European countries, 12 Asian countries, 2 African countries, and 9 countries in the Americas outside the United States, 16 percent of the surveyed countries attempt to light all roundabouts (*7*). The researchers also examined crash data from Minnesota and concluded that partial illumination achieves significant benefits compared with leaving the roundabout unlit. The researchers concluded with a “qualified yes” that it may be feasible to use a reduced illumination roundabout as a safety treatment for either uncontrolled or stop-controlled rural intersections (*7*). The French lighting guide reports that two-thirds of all roundabouts in rural areas are not illuminated and that nighttime injury crashes are divided equally between illuminated and unlit roundabouts. The French guide also notes that almost all nighttime crashes involve the loss of control of single vehicles and result in property-damage-only crashes, many of which may not be reported. As a result, the crash history is not as readily quantifiable (*8*).

14.1.2 Dark Sky Principles

The International Dark-Sky Association and IES have jointly published five principles for responsible outdoor lighting (*9*):

1. **Useful.** All light should have a clear purpose.
2. **Targeted.** Light should be directed only to where it is needed.
3. **Low light levels.** Light should be no brighter than necessary.
4. **Controlled.** Light should be used only when it is useful.
5. **Color.** Warmer-color lights should be used where possible.

These principles can be applied through a variety of means:

- Lighting only the parts of the roundabout that require it. This includes the key conflict areas where drivers with headlights may encounter bicyclists and pedestrians or where headlights are less effective because of horizontal curvature.
- Using only the minimum necessary lighting level. The following sections provide lighting-level recommendations consistent with IES principles and are more flexible to meet site-specific needs.
- Selecting lighting fixtures that provide the most targeted coverage and use lighting sources that are warmer where possible.
- Using and maintaining photocells so lighting is on only when needed.
- Balancing landscaping uplighting with dark sky principles.

14.2 Lighting Levels

AASHTO and IES provide lighting-level guidance, with IES guidance offering more detail (*10, 1*). IES RP-8-18 presents three classifications of intersection lighting:

- **Full intersection lighting** is used for intersections on one or more streets with continuous lighting.
- **Partial intersection lighting** is used for areas within interchanges and for isolated intersections where no continuous lighting is provided on the intersecting streets.
- **Intersection delineation lighting** is used to identify the location of an intersection.

Lighting-level metrics for roundabouts include a combination of horizontal and vertical illuminance. In general terms, horizontal illuminance is a measure of how much light is projected onto a horizontal plane, and vertical illuminance is a measure of how much light is projected onto a vertical plane. Horizontal illuminance is, therefore, used to evaluate the lighting levels for the roadway surface, and vertical illuminance is used to evaluate how much light is projected onto pedestrians in crosswalks. More detail, including recommended grid patterns for evaluations, can be found in IES RP-8-18 (*1*).

The following sections were adapted from IES RP-8-18 for PennDOT and are suggested for general use in the United States (*11*). These suggested lighting levels vary on the basis of whether the roundabout is isolated or within a system of continuous lighting, and they consider the roundabout pavement material, AADT levels, and nighttime pedestrian activity.

14.2.1 Roundabouts on Streets with Continuous Lighting

If two or more of the intersecting roadways have continuous lighting, the following practice is suggested:

- If the roundabout is paved with asphalt concrete (excluding any truck aprons, if provided), Exhibit 14.1 can help determine the appropriate horizontal illuminance level for the roundabout.

Exhibit 14.1. Pavement illuminance criteria for roundabouts with asphalt concrete paving.

Major Street AADT (veh/day)	Minor Street AADT (veh/day)	Pedestrian Activity Level During Highest Average Annual Nighttime Hour			Uniformity Ratio E_{avg}/E_{min}
		>100 p/hr	10–100 p/hr	<10 p/hr	
>3,500	>3,500	3.2 fc (34 lx)	2.4 fc (26 lx)	1.7 fc (18 lx)	3.0
>3,500	1,500–3,500	2.7 fc (29 lx)	2.0 fc (22 lx)	1.4 fc (15 lx)	3.0
>3,500	<1,500	2.4 fc (26 lx)	1.9 fc (20 lx)	1.2 fc (13 lx)	3.0
1,500–3,500	1,500–3,500	2.2 fc (24 lx)	1.7 fc (18 lx)	1.1 fc (12 lx)	4.0
1,500–3,500	<1,500	2.0 fc (21 lx)	1.5 fc (16 lx)	0.9 fc (10 lx)	4.0
<1,500	<1,500	1.7 fc (18 lx)	1.3 fc (14 lx)	0.7 fc (8 lx)	6.0

NOTE: AADT = average annual daily traffic; fc = foot-candle; lx = lux; p/hr = pedestrians per hour; veh/day = vehicles per day.
SOURCE: Adapted from IES RP-8-18, Table 12-4, Section 12.1.2, and Section 12.1.3 (*1*), as presented in PennDOT Lighting Policy for Roundabouts (*11*).

- If the roundabout is paved with PCC, Exhibit 14.2 can help determine the appropriate horizontal illuminance level for the roundabout.

If an approach has a higher lighting level than IES recommends for that type of facility, the roundabout illuminance level should be equal to the sum of the intersecting roadways.

14.2.2 Isolated Roundabouts (No Continuous Lighting on Any Approach)

If none of the intersecting roadways have continuous lighting, practitioners can use Exhibit 14.3 to determine the appropriate roundabout illuminance level.

The number of luminaires needed for an isolated roundabout depends in part on the target uniformity ratio. For roundabouts on a major street with 3,500 vehicles per day or greater, the uniformity ratio of 3.0 may require luminaires in each quadrant (four for a typical four-leg roundabout). Conversely, it may be possible to use fewer luminaires to adequately light a roundabout on a major street with less than 1,500 vehicles per day depending on the size of the roundabout

Exhibit 14.2. Pavement illuminance criteria for roundabouts with portland cement concrete paving.

Major Street AADT (veh/day)	Minor Street AADT (veh/day)	Pedestrian Activity Level During Highest Average Annual Nighttime Hour			Uniformity Ratio E_{avg}/E_{min}
		>100 p/hr	10–100 p/hr	<10 p/hr	
>3,500	>3,500	2.2 fc (24 lx)	1.7 fc (18 lx)	1.1 fc (12 lx)	3.0
>3,500	1,500–3,500	1.9 fc (20 lx)	1.4 fc (15 lx)	0.9 fc (10 lx)	3.0
>3,500	<1,500	1.5 fc (16 lx)	1.3 fc (14 lx)	0.8 fc (9 lx)	3.0
1,500–3,500	1,500–3,500	1.5 fc (16 lx)	1.1 fc (12 lx)	0.7 fc (8 lx)	4.0
1,500–3,500	<1,500	1.3 fc (14 lx)	1.0 fc (11 lx)	0.7 fc (7 lx)	4.0
<1,500	<1,500	1.1 fc (12 lx)	0.9 fc (10 lx)	0.6 fc (6 lx)	6.0

NOTE: AADT = average annual daily traffic; fc = foot-candle; lx = lux; p/hr = pedestrians per hour; veh/day = vehicles per day.
SOURCE: Adapted from IES RP-8-18, Table 12-4, Section 12.1.2, and Section 12.1.3 (*1*), and illuminance criteria for R1 roadways as published in IES RP-8-00 (*12*), as presented in PennDOT Lighting Policy for Roundabouts (*11*).

Exhibit 14.3. Pavement illuminance criteria for isolated roundabouts.

Major Street AADT (veh/day)	Road Surface		Uniformity Ratio E_{avg}/E_{min}
	Portland Cement Concrete	Asphalt Concrete	
>3,500	0.6 fc (6 lx)	0.8 fc (9 lx)	3.0
1,500–3,500	0.4 fc (4 lx)	0.6 fc (6 lx)	4.0
<1,500	0.3 fc (3 lx)	0.4 fc (4 lx)	6.0

NOTE: AADT = average annual daily traffic; fc = foot-candle; lx = lux; veh/day = vehicles per day. SOURCE: Adapted from IES RP-8-18, Table 12-2 and Section 12.1.2 (*1*), as presented in PennDOT Lighting Policy for Roundabouts (*11*).

and the mounting height, lumen level, and distribution type of the selected luminaires. A case-specific design will be necessary to determine the applicable lighting configuration.

14.2.3 Crosswalk Lighting

In addition to roundabout horizontal illuminance, practitioners need to evaluate vertical illuminance at each crosswalk. This consists of evaluating points above the crosswalk (commonly 5 ft [1.5 m]) and achieving a vertical illuminance that matches the design horizontal illuminance. Crosswalk vertical illuminance is to be measured as viewed by drivers approaching each crosswalk (i.e., toward the roundabout on entry, away from the roundabout on exit). Other references on crosswalk lighting include the FHWA *Street Lighting for Pedestrian Safety* and the FHWA *Informational Report on Lighting Design for Midblock Crosswalks* (*13*, *14*).

14.2.4 Transition Lighting

When a roadway transitions to no lighting from an illuminance level that exceeds the values in Exhibit 14.3, roundabouts need transition lighting as appropriate for the pavement type to allow time for driver eyes to adjust to the change in lighting level. This may happen, for example, if the roundabout was designed to fit into an existing or future continuous lighting system on one or more legs, even if the subject leg is not part of a continuous lighting system. AASHTO and IES provide inflexible values on the length of transition lighting needed: 400 ft (121 m) for AASHTO and 262 ft (80 m) for IES (*1*, *10*).

A flexible transition lighting method based on human factor principles allows for lighting that is sensitive to the roundabout design, its context, and other factors. Useful parallels in IES RP-8-18 can be found for tunnels. IES provides a transition adaptation curve showing the percentage of threshold luminance declining exponentially as a function of time in seconds, reflecting the human eye's adaptation from light areas to darkness.

Lighting levels at or below those in Exhibit 14.3 for isolated roundabouts do not require transition lighting. If transition lighting is not provided on a given leg, the start of curbing within the median or outside edges of the approaching roadway needs to be highlighted. This includes using retroreflective signs, pavement markings, pavement markers on top of curbs, or other techniques to mark the leading edge of the splitter island as well as the start of any curbing on the outside edge of the approach roadway.

For lighting levels above those in Exhibit 14.3 for isolated roundabouts, Exhibit 14.4 presents the extent of necessary transition lighting. The exhibit identifies a series of zones that step away from the roundabout. Depending on the lighting level of the roundabout itself, the number of transition zones needed may range from zero to three. The first zone, Zone 1, represents 70 percent of the main intersection illuminance level; the illuminance level in each subsequent zone decreases

Exhibit 14.4. Transition zones based on roundabout illuminance levels.

Roundabout Illuminance	Transition Lighting Needed?	Transition Zone Illuminance		
		Zone 1 (70%)	Zone 2 (40%)	Zone 3 (16%)
3.2 fc (34 lx)	Yes	2.2 fc (24 lx)	1.3 fc (14 lx)	0.5 fc (5 lx)
2.7 fc (29 lx)	Yes	1.9 fc (20 lx)	1.1 fc (12 lx)	0.5 fc (5 lx)
2.4 fc (26 lx)	Yes	1.7 fc (18 lx)	0.9 fc (10 lx)	0.4 fc (4 lx)
2.2 fc (24 lx)	Yes	1.6 fc (17 lx)	0.9 fc (10 lx)	0.4 fc (4 lx)
2.0 fc (22 lx)	Yes	1.4 fc (15 lx)	0.8 fc (9 lx)	None
2.0 fc (21 lx)	Yes	1.4 fc (15 lx)	0.7 fc (8 lx)	None
1.9 fc (20 lx)	Yes	1.3 fc (14 lx)	0.7 fc (8 lx)	None
1.7 fc (18 lx)	Yes	1.2 fc (13 lx)	0.7 fc (7 lx)	None
1.5 fc (16 lx)	Yes	1.0 fc (11 lx)	0.6 fc (6 lx)	None
1.4 fc (15 lx)	Yes	1.0 fc (11 lx)	0.6 fc (6 lx)	None
1.3 fc (14 lx)	Yes	0.9 fc (10 lx)	0.6 fc (6 lx)	None
1.2 fc (13 lx)	Yes	0.8 fc (9 lx)	None	None
1.1 fc (12 lx)	Yes	0.7 fc (8 lx)	None	None
1.0 fc (11 lx)	Yes	0.7 fc (8 lx)	None	None
0.9 fc (10 lx)	Yes	0.7 fc (7 lx)	None	None
0.8 fc (9 lx) or less	No	None	None	None

NOTE: fc = foot-candle; lx = lux. SOURCE: Adapted from PennDOT Lighting Policy for Roundabouts (*11*).

with increased distance from the roundabout. Values in the exhibit may be interpolated as needed or rounded up to the next highest value.

The length of each zone is a function of the roundabout's exiting speed and the posted speed of the leg downstream from the roundabout. As exiting speed and posted speed increase, each zone length also increases. Exhibit 14.5 provides design values for the length of each zone based on the design exit speed from the roundabout (and the posted speed downstream of the roundabout). Values in between the values in the exhibit may either be interpolated or rounded up to the next higher value. All zones are to be measured along the centerline of the roadway.

Exhibit 14.6 summarizes the results of these recommendations for transition lighting. The need for transition lighting is primarily dictated by the roundabout lighting level (shown in the exhibit as Zone 0) and the amount of time it takes for the human eye to adapt from a bright condition to a dark condition. If transition lighting is needed, the extent of necessary transition is a function of the roundabout lighting level, the exit speed, and the posted speed downstream of the roundabout.

14.3 Illumination Equipment Type and Location

A photometric analysis is required to determine the appropriate lighting fixture and pole location. Practitioners should consider the number of fixed objects in the public right-of-way adjacent to a roundabout when identifying optimal locations for lighting poles; fewer poles with higher-intensity light fixtures minimize the number of fixed objects. The type of area should also

Exhibit 14.5. Transition zone lengths based on roundabout exit speed and downstream speed limit.

Transition Zone Length (ft)			
Downstream Posted Speed	Zone 1 (70%)	Zone 2 (40%)	Zone 3 (16%)
Exit Speed = 20 mph (30 km/h)			
30 mph (50 km/h)	30 ft (9 m)	90 ft (27 m)	140 ft (43 m)
35 mph (55 km/h)	30 ft (9 m)	100 ft (30 m)	160 ft (49 m)
40 mph (65 km/h)	30 ft (9 m)	100 ft (30 m)	180 ft (55 m)
45 mph (70 km/h)	30 ft (9 m)	100 ft (30 m)	190 ft (58 m)
50 mph (80 km/h)	30 ft (9 m)	100 ft (30 m)	190 ft (58 m)
55+ mph (90+ km/h)	30 ft (9 m)	100 ft (30 m)	190 ft (58 m)
Exit Speed = 25 mph (40 km/h)			
30 mph (50 km/h)	40 ft (12 m)	90 ft (27 m)	140 ft (43 m)
35 mph (55 km/h)	40 ft (12 m)	90 ft (27 m)	140 ft (43 m)
40 mph (65 km/h)	40 ft (12 m)	120 ft (37 m)	180 ft (55 m)
45 mph (70 km/h)	40 ft (12 m)	120 ft (37 m)	200 ft (61 m)
50 mph (80 km/h)	40 ft (12 m)	120 ft (37 m)	220 ft (67 m)
55+ mph (90+ km/h)	40 ft (12 m)	120 ft (37 m)	220 ft (67 m)
Exit Speed = 30 mph (50 km/h)			
30 mph (50 km/h)	50 ft (15 m)	90 ft (27 m)	140 ft (43 m)
35 mph (55 km/h)	50 ft (15 m)	110 ft (34 m)	160 ft (49 m)
40 mph (65 km/h)	50 ft (15 m)	120 ft (37 m)	180 ft (55 m)
45 mph (70 km/h)	50 ft (15 m)	140 ft (43 m)	200 ft (61 m)
50 mph (80 km/h)	50 ft (15 m)	140 ft (43 m)	230 ft (70 m)
55+ mph (90+ km/h)	50 ft (15 m)	140 ft (43 m)	250 ft (76 m)

NOTE: Zone 1 begins 50 ft (15 m) from the edge of the circulatory roadway or 20 ft (6 m) beyond the farthest edge of the crosswalk, whichever is longer. SOURCE: Adapted from PennDOT Lighting Policy for Roundabouts (*11*); metric values rounded to nearest 5 km/h and 1 m.

be considered when determining the equipment type and location. In an urban area with a high level of pedestrian activity, it may be more appropriate to install illumination at lower mounting heights. In these cases, the illumination at lower mounting heights may need to be supplemented with taller, cobra-style assemblies to provide adequate lighting.

A wide variety of illumination equipment types have been used at roundabouts and typically reflect the local practices of the road authority or power company providing the illumination. Three common types of fixtures are used:

- Cobra style,
- Pedestal, and
- High mast.

Of these, cobra-style fixtures commonly use a lighting distribution to focus the lighting in a specific area below the lighting fixture. Other fixtures tend to have an omnidirectional distribution to light areas in all directions of the fixture.

Exhibit 14.6. Summary of transition lighting recommendations.

Roundabout Illuminance	Transition Lighting Needed Beyond the Roundabout (Zone 0)?	Length of Transition Lighting				
		Roundabout (Zone 0) (100% Illuminance)	Zone 1 (70%)	Zone 2 (40%)	Zone 3 (16%)	Total
>2.0 fc (>22 lx)	Yes	50 ft (15 m), or 20 ft (6 m) beyond farthest edge of crosswalk	30 ft to 50 ft (9 m to 15 m)	90 ft to 140 ft (27 m to 43 m)	140 ft to 250 ft (43 m to 76 m)	310 ft to 490 ft (94 m to 149 m)
>1.2 fc to 2.0 fc (>13 lx to 22 lx)	Yes	50 ft (15 m), or 20 ft (6 m) beyond farthest edge of crosswalk	30 ft to 50 ft (9 m to 15 m)	90 ft to 140 ft (27 m to 43 m)	None	170 ft to 240 ft (52 m to 73 m)
>0.8 fc to 1.2 fc (>9 lx to 13 lx)	Yes	50 ft (15 m), or 20 ft (6 m) beyond farthest edge of crosswalk	30 ft to 50 ft (9 m to 15 m)	None	None	80 ft to 100 ft (24 m to 30 m)
≤0.8 fc (≤9 lx)	No	50 ft (15 m), or 20 ft (6 m) beyond farthest edge of crosswalk	None	None	None	50 ft (15 m)

NOTE: Zone 0 includes the circulatory roadway and extends 50 ft (15 m) from the edge of the circulatory roadway, or 20 ft (6 m) beyond farthest edge of crosswalk, whichever is longer. fc = foot-candle; lx = lux. SOURCE: Adapted from PennDOT Lighting Policy for Roundabouts (*11*); metric values rounded to nearest 1 m.

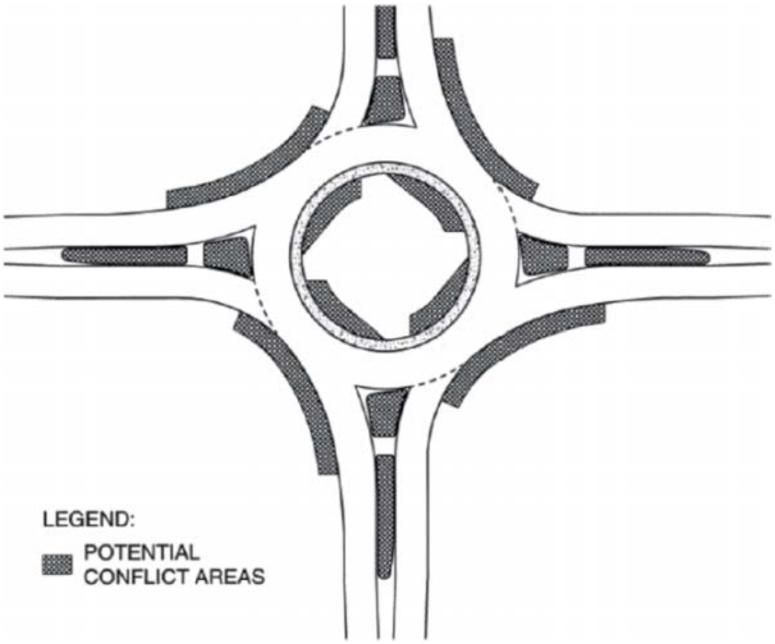
The ability to provide adequate visibility at a roundabout depends largely on the illumination pole locations. Roundabout lighting can be achieved by installing lighting within the central island or around the perimeter of the intersection. IES recommends placing lighting around the perimeter of the roundabout and at locations on the approach side of the crosswalks (*1*). Perimeter illumination provides the most optimal visibility within the key conflict areas and allows vehicles approaching the roundabout to see circulating vehicles. In addition, the vertical lighting level in the crosswalks cannot be achieved without approach lighting. Therefore, roundabouts with central island illumination may require additional approach lighting or may be combined with perimeter illumination to achieve vertical lighting levels. Further discussion and illustrations can be found in IES RP-8-18 (*1*).

Some agencies provide guidance on critical conflict areas where errant vehicles may be more likely to hit poles. For example, Exhibit 14.7 provides guidance from the Kansas Department of Transportation (KDOT). KDOT recommends placing light poles as far back from the curb face as practical; in rural areas where pedestrian activity is low, KDOT requires breakaway pole bases for poles located in these critical areas (*15*).

14.4 Landscaping

At all intersection types, landscaping can improve aesthetics, decrease impervious surfaces, indicate a change of context, and promote context sensitivity. All intersections have landscaping opportunities along their outer edges and median islands. At roundabouts, however, the central island provides a unique additional location for landscaping that most other intersections do not have.

Exhibit 14.7. Critical conflict areas affecting pole placement.



SOURCE: *Kansas Roundabout Guide*, 2nd ed. (*15*).

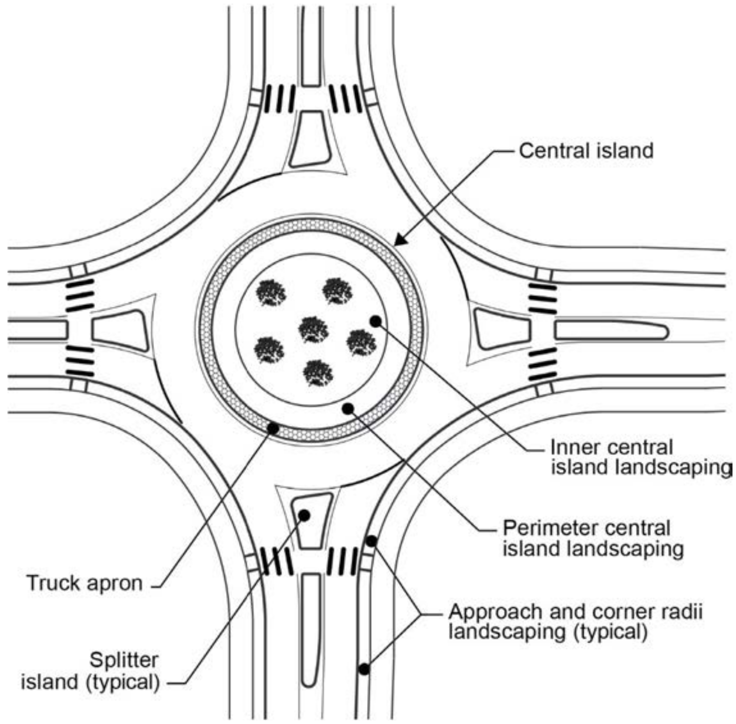
Discussions about the type and quantity of landscaping or other material to incorporate into a roundabout design, maintenance considerations, and the available planting zones best occur early in planning and design. Choosing between soft landscaping and hardscaping may affect funding and maintenance agreements, and discussions about the type or extent of possible treatments are appropriate during ICE activities. Intersection sight distance requirements affect landscaping details, and landscaping plans must coordinate with design performance checks. As described in Chapter 9: Geometric Design Process and Performance Checks, sight distance requirements at the roundabout dictate the size and types of landscaping materials appropriate for each of these areas. Sight distance needs are also dictated by vehicle speeds and project context. The following sections describe landscaping considerations specific to roundabouts and locations in the roundabout, as illustrated in Exhibit 14.8.

14.4.1 Landscaping Objectives

A landscaping plan consistent with the project context and type can help provide several benefits without sacrificing other design outcomes. Fundamentally, landscaping at a roundabout has several objectives:

- **Support intersection visibility on approach and maintain adequate sight distance.** Landscaping should allow drivers to observe the signing and shape of the roundabout as they approach, and it should provide adequate visibility for making decisions within the roundabout. While sight distance is often thought to be influenced only by static features, landscape and vegetation growth and maintenance can also temporarily affect sight distance.
- **Prevent excessive sight distance.** Excessive intersection sight distance can lead to higher vehicle speeds that increase crash risk and severity for all road users. Landscaping features indicate to approaching drivers that they cannot pass straight through the intersection. International evidence suggests it is advantageous to provide no more than the minimum required intersection sight distance on each approach (*16*). Practitioners should also note that mounding the central island can reduce headlights shining across the circle to opposing directions of travel.

Exhibit 14.8. Landscaping zones at a roundabout.



- **Help pedestrians who are blind or have low vision locate sidewalks and crosswalks.** The buffer strip beside a sidewalk or walking path is an essential wayfinding component for pedestrians who are blind or have low vision. Traversable walking surfaces versus non-traversable surfaces, such as soft landscaping or hardscaping, are effective components that support wayfinding (*17*).

If achieved, these landscaping objectives provide considerable benefit over a roundabout without such landscaping.

14.4.2 Central Island Landscaping

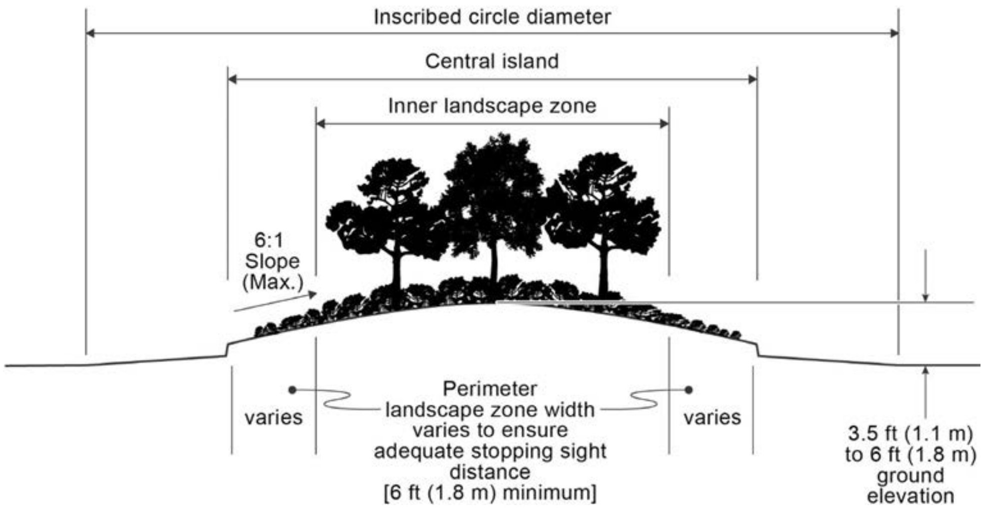
Within non-traversable central islands, landscaping can

- Improve intersection conspicuity,
- Promote lower speeds,
- Break the headlight glare of oncoming vehicles, and
- Focus driver attention to the left at the entry to look for conflicting vehicles.

Typically, different types of landscaping are selected for the inner and outer portions of the central island, as described in the following and depicted in Exhibit 14.9. They can be classified into the *inner landscape zone* and the *perimeter landscape zone*.

Within the inner landscape zone, landscaping can be strategically located and managed to limit the amount of excess intersection sight distance, help encourage slow speeds, and provide a *terminal vista* for supporting approach visibility and stopping sight distance. The perimeter portion of the central island can be landscaped with low-level shrubs, grass, or groundcover, which can help maintain stopping sight distance requirements for vehicles within the circulatory roadway as well as improve intersection sight distance for vehicles entering the roundabout. The planting zone width around the perimeter of the central island will vary depending on the size of the

Exhibit 14.9. Landscaping profile for non-traversable central island.



SOURCE: Adapted from Wisconsin Department of Transportation (*18*).

roundabout and the required sight triangles, as described in Chapter 9: Geometric Design Process and Performance Checks. Exhibit 14.10 illustrates an example of central island landscaping.

A roundabout with a larger diameter provides more opportunity for prominent placemaking or landscaping that can serve as a gateway feature. However, an agency may not be able to provide ongoing maintenance because of cost or other resource limitations. Practitioners need to consider maintenance when developing the landscape plan to inform the types and quantity of landscaping that might be needed. This includes needs for irrigation, drought tolerance, and frequency of required maintenance. As trees grow, they can affect sight distance triangles if not properly maintained. In northern climates, practitioners need to consider the salt tolerance of any plant material along with snow storage and removal practices. In addition, landscaping requiring watering may increase the likelihood of wet and potentially slippery pavement.

A domed or mounded central island can provide the same conspicuity and terminal vista benefits as landscaping but should not exceed a horizontal-to-vertical ratio of 6:1 (adapted from

Exhibit 14.10. Example of central island landscaping.

LOCATION: NE Lombard Street/Airport Way Frontage Road/PDX Economy Parking Lots, Portland, Oregon. SOURCE: Lee Rodegerdts.

the guidance for transverse slopes in the AASHTO *Roadside Design Guide*) (*19*). Exhibit 14.9 provides elevations and sloping for a mounded central island. Mounding can deflect errant drivers to the right and reduce the likelihood of a head-on collision while absorbing some of the energy of entry. However, a mounded central island without landscaping does not adequately deter drivers from occasionally driving onto or over the central island.

Illuminating features on the central island can also provide positive visual evidence of the roundabout. Lighting aimed at plantings and signs provides the necessary contrast for non-traversable areas of the roundabout. Eco-luminance is a concept that integrates lighting with vegetation by using lower mounting heights and reflected light from plants and retroreflective elements. The potential benefits of this approach include illuminating a roundabout using less energy and with improved aesthetics and positive contrast for all users (*20*).

For roundabouts with traversable central islands, central island landscaping is not an option. Exhibit 14.11 illustrates a retrofitted mini-roundabout that retained median landscaping even though the fully traversable central island does not provide landscaping opportunities.

14.4.3 Median and Approach Landscaping

Landscaping on a roundabout's approaches can enhance safety by making the intersection a focal point (i.e., enhancing its visibility) and narrowing the visual field for approaching drivers. This creates a funneling effect that induces drivers to slow down on approach.

Landscaping at splitter islands is subject to different considerations than landscaping on the central island. Landscaping at splitter islands must avoid obstructing stopping sight distance to the crosswalk, yield signs, and the roundabout entrance, particularly if reverse curvature is present on an approach. However, median and splitter island landscaping can be used to help remove excess sight distance. As discussed in Chapter 9: Geometric Design Process and Performance Checks, splitter islands are within intersection sight distance triangles between entering and conflicting vehicles, and they frequently serve as part of bicyclist and pedestrian crossings. Exhibit 14.12 and Exhibit 14.13 provide examples where the vegetation in the splitter island is beginning to undesirably encroach on stopping sight distance and intersection sight distance, respectively.

Exhibit 14.14 provides an example of low-lying vegetation in the splitter island with no risk of obstructing sight distance. The size of the splitter islands and the location of the roundabout

Exhibit 14.11. Example of roundabout with traversable central island and exterior landscaping.

LOCATION: Brunswick Forest Parkway/Low Country Boulevard, Leland, North Carolina. SOURCE: Kittelson & Associates, Inc.

Exhibit 14.12. Example of undesirable blockage of stopping sight distance on roundabout approaches.

SOURCE: Larimer County, Colorado.

Exhibit 14.13. Example of undesirable blockage of intersection sight distance at roundabout entry.

LOCATION: La Jolla Boulevard/Midway Street, San Diego, California.
SOURCE: Mark Lenters.

Exhibit 14.14. Example of low vegetation in splitter island.

LOCATION: Old Meridian Street/N Pennsylvania Street, Carmel, Indiana.
SOURCE: Lee Rodegerdts.

Exhibit 14.15. Example of low-lying vegetation providing a detectable buffer.

LOCATION: Monterey Avenue/Causey Avenue, Clackamas, Oregon.
SOURCE: Lee Rodegerdts.

are determining factors when assessing whether to provide landscaping within the splitter islands. Generally, low-growing landscaping is recommended within sight triangles on either side of the pedestrian crossing and between the crossing and the circulatory roadway.

14.4.4 Sidewalk or Path Buffers

Section 10.4 presented key design considerations for pedestrians traversing a roundabout, including the need for a detectable edge treatment that buffers sidewalks wherever crossings are not intended. Low shrubs, grass, and other tactile material distinct from normal walking surfaces, such as river rock or stone, are likely detectable underfoot and make for suitable buffers. Along with the benefits discussed in Chapter 10: Horizontal Alignment and Design, a sidewalk buffer also further indicates to pedestrians that a walking path to the central island is not available. Exhibit 14.15 provides examples of suitable sidewalk buffers at roundabouts. Chapter 9: Geometric Design Process and Performance Checks and Appendix: Design Performance Check Techniques describe a wayfinding assessment for providing accessible walking paths and crossings.

A primary technique to encourage pedestrians to remain on the perimeter of the roundabout is an ADA-compliant pedestrian access route, including detectable buffers between the sidewalk and circulatory roadway curb. Exhibits 14.15 and 14.16 provide examples. Per proposed Public Rights-of-Way Accessibility Guidelines, the detectable buffer must be at least 2 ft (600 mm) wide (wider is better) or have a continuous vertical feature, like a fence, that a person can detect by hand, cane, or foot (*21*). If the same material is used for both the truck apron and the sidewalk, practitioners are encouraged to include a separate, distinguishing factor to differentiate the two, such as a color or stamped texture.

14.5 Art and Other Fixed Objects

In addition to landscaping, some agencies use the roundabout's central island as an opportunity to display local art or other gateway features. Communities often desire public art or other large aesthetic objects within the central island, including statues, fountains, monuments, and other gateway features for community enhancement. In some areas, a roundabout design can help define a community, township, or region by displaying a piece of art that represents local

Exhibit 14.16. Example of embedded river rock being placed in the buffer.

SOURCE: Fred Wismer.

heritage. Art can also aid placemaking, giving each roundabout in a community a distinct look. While the choice of art can sometimes spark debate due to differences in aesthetic tastes, it can also bring critically needed support to the project. Examples of artwork and other objects on the central island are shown in Exhibit 14.17 through Exhibit 14.22.

Including art and other fixed objects at roundabouts depends largely on the context of the roundabout. Any central island art or other objects need to be of a size and scale to be readily appreciated and observable from the outer perimeter of the intersection. The central island is not to include any inviting elements, such as benches or plaques, that might encourage a person to walk onto the central island for closer inspection. In addition, the central island features cannot

Exhibit 14.17. Example of central island art.

LOCATION: 14th Street/Galveston Avenue, Bend, Oregon. SOURCE: Lee Rodegerdts.

Exhibit 14.18. Example of central island art.

LOCATION: Gannett Avenue/Rittenhouse Street, Des Moines, Iowa.
SOURCE: Lee Rodegerdts.

Exhibit 14.19. Example of central island art.

LOCATION: Monterey Avenue/Stevens Road, Clackamas, Oregon.
SOURCE: Lee Rodegerdts.

Exhibit 14.20. Example of central island art.

NOTE: Boulders should be constructed of frangible materials.
LOCATION: Carlsbad Boulevard/State Street, Carlsbad, California.
SOURCE: Lee Rodegerdts.

Exhibit 14.21. Example of central island art.

LOCATION: Portage Road/Aspen Boulevard/Birch Street, Pemberton, British Columbia, Canada. SOURCE: Lee Rodegerdts.

affect the drivers circulating the roundabout. For example, fountains on the central island of a roundabout may be feasible, but maintenance, the potential for leaks, and the range of spray under windy conditions must be considered.

Fixed objects present a potential hazard to vehicles that depart from the roadway, and they become more critical as approach speeds increase. **If fixed objects are placed on the central island, they need to be designed and located to minimize crash risk and severity.** This is especially important in environments with higher approach speeds, where fixed objects may improve visibility from a distance but introduce the risk of a crash with the fixed object. Roundabouts may have different levels of entry channelization depending on site context and intersection geometry. For example, if speed control relies on the central island (rather than entry curvature and splitter island channelization), the likelihood of errant vehicles striking the central island may be greater. If used, fixed objects are to be placed within the inner landscape zone at a location where the roundabout's geometry deflects approaching vehicles away from the object, as discussed in Section 14.4. To the extent possible, frangible materials are to be used in the perimeter landscape zone.

Exhibit 14.22. Example of central island art.

LOCATION: Rehoboth Avenue/Grove Street/Columbia Avenue, Rehoboth Beach, Delaware. SOURCE: Lee Rodegerdts.

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CHAPTER 15

Construction and Maintenance

Contents

This chapter focuses on issues related to constructing and maintaining roundabouts. As with any roadway or intersection construction project, construction can affect adjacent properties and roadway travelers. Continuous and meaningful stakeholder engagement and outreach from design through construction can reduce disruption and promote goodwill and project support.

15.1 Introduction

Roundabouts have been successfully implemented throughout the United States, and many tribal, state, county, and city agencies are becoming efficient at preparing roundabout construction plans. However, not all engineers, contractors, and inspectors have extensive experience with some of the distinctive aspects of preparing roundabout construction documents or constructing the roundabout. Early design and pre-construction coordination between all parties occurs with any intersection or roadway project, but it is beneficial to emphasize design and construction attributes particular to roundabouts.

Each project location is unique, and there is no single best approach to staging construction while maintaining traveler access. Roundabout concept design and ICE benefit from considering constructability and staging needs early in the planning and design process. If practitioners address specific site implementation needs at each planning and design stage, fewer issues will likely arise during construction.

The project type (i.e., new construction versus reconstruction) greatly influences construction staging and sequencing needs. In constrained locations where maintaining traffic during construction is critical, the roundabout design or construction materials, techniques, and durations could be influential. Practitioners establish work zone traffic control for each unique construction staging and phasing, with the basic objective to provide efficient and effective travel opportunities for each user.

Like construction staging, facility maintenance and serviceability need to be part of early roundabout planning and ICE. The types of materials and features provided at an intersection directly affect long-term serviceability and future rehabilitation needs. Maintenance costs need to be included with project life-cycle costs to guide intersection and traffic control selection. In addition to the extent of maintenance any intersection needs, landscaping and other aesthetic features may require special consideration or maintenance partnerships and agreements between cooperating agencies.

15.2 Stakeholder Engagement and Construction

Public engagement and outreach need to begin during the planning phase and carry through final design and project construction. As with other intersection projects, stakeholder and public engagement during project development can guide construction sequencing and staging needs. As projects move from final plan preparation to construction bidding, the construction engineering and contracting team needs to review and understand the stakeholder input received during planning and design. There may be roundabout-specific subjects or needs, such as changes to access or issues associated with a footprint larger than the current intersection. This type of information could be shared in contract bid request packages and at pre-bid information meetings. Upon initiating construction activities, general outreach commonly transitions to the property owner or other affected users.

Stakeholder engagement during design and pre-construction provides the opportunity to consider the benefits and trade-offs of full intersection closures compared with partial closures. Full closures, when possible, may reduce the number of construction days compared with partial closures that maintain traffic during construction. In some cases, there are no options for full closures during construction (e.g., no alternative routes or inability to address emergency response needs). However, agencies and communities may see the benefits of a shorter full closure over a longer, but potentially more disruptive, construction staging and sequencing plan. Community engagement creates the opportunity to discuss and provide input on project construction sequencing plans.

When a traffic pattern is set to change after roundabout implementation, practitioners need to inform stakeholders, property owners, and the public of what to expect. This could include broad information about general traffic pattern changes throughout the construction project as well as project phasing–specific information, such as changes to travel patterns, temporary closures, and temporary alternative access plans. If a roundabout is one of the first in an area, it can be beneficial to educate users about roundabout navigation and reinforce messages beyond the construction information. Practitioners need to customize public involvement techniques to specific community needs. Chapter 5: Stakeholder Considerations provides more information and techniques.

The following suggestions can help alleviate initial driver confusion:

- Conduct meetings with affected property owners and the public before initiating construction.
- Prepare news releases, handouts, or other media detailing what property owners and motorists can expect before, during, and after construction.
- Install temporary fixed signs, changeable message signs, or both before, during, and immediately after construction to communicate traffic pattern changes.
- Use travelers' advisory radio before and during construction to disseminate information on how to drive, etc.
- Use websites or other online social media to broadcast construction progress and use of the roundabout.
- Meet with neighborhood, business, institution, or advocacy groups as applicable for the construction location and influence area.

15.3 Construction Plans

Construction plans, specifications, estimates, permits, and other documentation are established by supporting agencies. These documents present horizontal, vertical, and cross-section design complemented by details and other sheets outlining demolition, drainage, utilities, landscaping, and traffic control. The design and construction methods are evolving, and new approaches to promoting strong connections between computer-aided design and construction activities are conducive to roundabout design and implementation.

Building information modeling (BIM) is a process supported by various tools and technologies to expand on traditional plan, profile, and cross-section design information and provide three-dimensional digital representations of the proposed design. This direct transfer of digital information from designers to contractors can improve construction efficiency and reduce errors and change orders. The increased computing power provided by three-dimensional modeling is especially helpful for roundabout design and construction. For example, the ability to develop and share models with the contractor promotes efficient and effective communication of the complex vertical and cross-section design often present at a roundabout. In addition to BIM information, roundabout final design plan sheets may include

- Staging plan with detour routes (as appropriate),
- Staking plan with curve data (coordinates, radius, elevations),
- Paving plan and jointing plan (concrete pavement),
- Utility plan,
- Lighting plan,
- Signing plan,
- Pavement marking plan, and
- Landscaping plan.

15.4 Construction Coordination

Roundabout construction requires coordination among the engineer, contractor, inspector, utility providers, project owner, and supporting agencies. The following sections provide examples of possible roundabout-specific coordination that may occur during construction.

15.4.1 Contractor and Designer Coordination

The design team needs to address proposed design changes to adapt to project conditions. Roundabout safety and operational performance can be affected by geometric design, signing, and pavement markings. Changes can influence vehicle speeds, vehicle alignments, non-motorized user quality of service, and how trucks are served. For example,

- Multilane roundabout operations require precisely placing pavement markings according to the plan. If the markings stray from the design, the roundabout may not operate as expected, as the entering and receiving lanes need to line up appropriately.
- If provided, spiral markings need to support drivable and flowing alignments that assist driver navigation and promote lane discipline.
- Where PCC is used, the jointing plans must reflect the pavement marking of lane lines and edge continuity lines. Joint lines that contradict lane lines can be mistaken for lane lines, and changes to joint patterns proposed during construction need to be carefully reviewed.
- Contractors are to follow the design details and dimensions for each aspect of the roundabout design, particularly the truck apron. A truck apron too flush to the circulatory roadway could reduce its ability to control vehicular speeds, while too much curb reveal could discourage truck drivers from using the apron and make the apron an impact risk for other vehicles.

15.4.2 Utility Coordination

Utility coordination for roundabouts is the same as that of other intersections. During intersection reconstruction, however, a roundabout approach alignment may deviate from the existing roadway horizontal alignment, vertical alignment, or both. The roundabout may have a larger footprint than the existing intersection, and the power supply for illumination, conduit for future potential beacons, or drainage facilities may require special attention. Lighting may need to be installed before or during roundabout placement to maintain safe traffic management during construction. Utility vaults and access portals within the roundabout may require special consideration for maintenance vehicle parking or safe crew access to the central island. This parking could be outside the roundabout or provided as a specific parking space within the central island.

15.5 Construction Staging

Roundabout construction staging varies by site and project conditions. In general, constructing a roundabout requires the same considerations as other intersection forms. However, because of their unique configuration and associated operations, roundabout planning and design may sometimes be more influenced by construction staging and traffic sequencing needs compared with other intersection forms. Depending on user demands, construction staging considerations could influence the roundabout's size or location. Pavement material selection could also affect construction staging and may influence initial roundabout planning and design.

During construction, the roundabout's vertical design and ability to serve large vehicles could influence how staging might occur. This could lead to temporary roadways through the central island or other practical considerations regarding truck vertical clearance between truck aprons and intermediate paving courses. Splitter islands and non-traversable central island elements may need to be completed during later stages to support each user's needs during each construction stage. In general, roundabouts are often constructed under the following scenarios and traffic conditions:

- No traffic,
- Some traffic diverted, and
- Full traffic.

As with any intersection that must be constructed while maintaining traffic, a common goal is to minimize staging and construct substantial portions of the roundabout during each construction stage. Longer construction stages can improve construction quality and efficiency, reduce user confusion, reduce overall construction duration, and save construction costs. Generally, diverting or detouring as much traffic from the intersection as possible is the most desirable option. However, in many circumstances, full or partial detours are not feasible.

15.5.1 Construction Under No Traffic

Constructing a roundabout without traffic passing through the work zone can significantly reduce the construction duration and cost while also reducing crash risks for the construction personnel. This is possible under two common scenarios:

- The roundabout is on a new roadway.
- All traffic can be diverted away from the roundabout, even for a short time.

In some cases, traffic can be diverted for only a portion of the construction time to build the central island and circulatory roadway. With that substantial work completed, traffic can be maintained while constructing the splitter islands and other areas outside the central island.

Minimizing detour changes during construction helps reduce public confusion. It is easier to communicate one or two different detours to the driving public through the course of a project and establish some consistency than to frequently change routes. Before traffic is detoured, peripheral items (e.g., signing, illumination, and landscaping) outside the traveled way or items with minimal effect on traffic can be completed to reduce road closure durations before the first detour is in place.

15.5.2 Construction with Some Traffic Diverted

Construction under partial traffic commonly includes closing the minor roadway approaches and maintaining all major street movements. The major street alignments generally occur on the existing roadway or temporary roadways during staging. This technique is to eliminate intersection conflicts while still allowing some traffic to use the intersection.

Practitioners might consider reasonable alternative routes for each mode—motor vehicle, truck (if different from passenger cars), bicyclist, and pedestrian. Splitting detours by mode may be feasible and desirable, recognizing that out-of-direction travel is less feasible for pedestrians and bicyclists and that trucks may be restricted to certain routes.

Exhibit 15.1 provides an example of constructing a single-lane roundabout under partial traffic (*1*). The staging plan maintained traffic flow on the major roadway using temporary roadways. Most of the roundabout construction occurred during Stage II, with the minor approaches closed. Stage III completed the west approach and Stage IV addressed the relatively small remaining portions on the south approach.

15.5.3 Construction Under Full Traffic

Detouring as many approaches as possible reduces the intersection traffic volume and the number of turning movements available. However, when a roundabout is under full traffic, some intersection movements must be maintained with a level of traffic control commensurate with the volume. Practitioners need to integrate pedestrian and bicycle traffic needs into the early staging plan effort.

In many cases, the intersection can operate as a roundabout during construction after initial work is completed outside the roundabout limits. Other work can often include utility relocation,

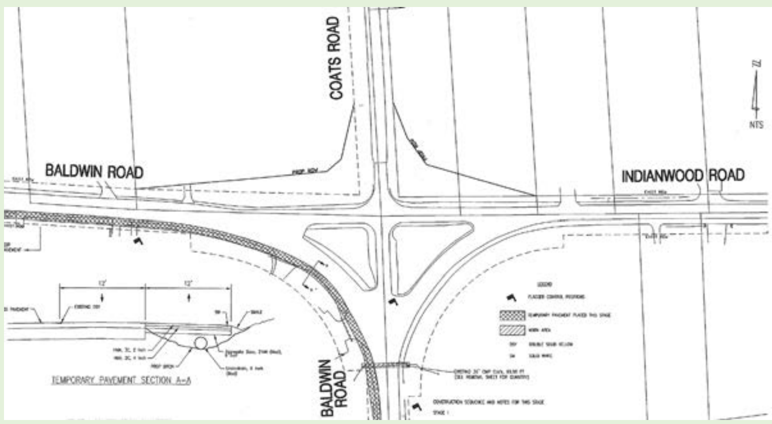
Exhibit 15.1. Example construction with some traffic diverted.

Example Construction Staging: Baldwin Road/Coats Road/Indianwood Road

Baldwin Road is the major roadway, which includes the west and south approaches. Construction was completed in four stages. The shaded portions of the plans represent the permanent pavement under construction, temporary pavement being placed for construction staging, or temporary pavement under traffic.

Stage I: Temporary Roadway Construction

- Construct a 12-ft (3.6-m) temporary roadway adjacent to the existing Baldwin Road for the east and south approaches.
- Construct a replacement culvert over the south approach.
- Maintain two-way traffic on the east, west, and north approaches.
- Maintain traffic on the south approach with partial lane closure controlled by flagging.



Stage II: Primary Roundabout Construction

- Close Coats Road and Indianwood Road to traffic.
- Shift traffic to temporary roadway on the east and west approaches to maintain two-way traffic on Baldwin Road.
- Close the southeast business driveway and restrict the northwest business driveway to right-in/right-out only.
- Construct all roundabout elements on the east and north approaches.
- Construct partial roundabout elements on the west and south approaches.
- Construct temporary pavement at the west and south approaches.

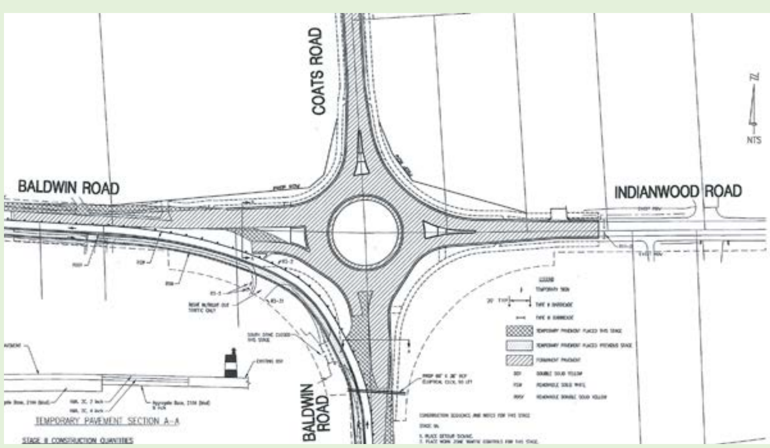
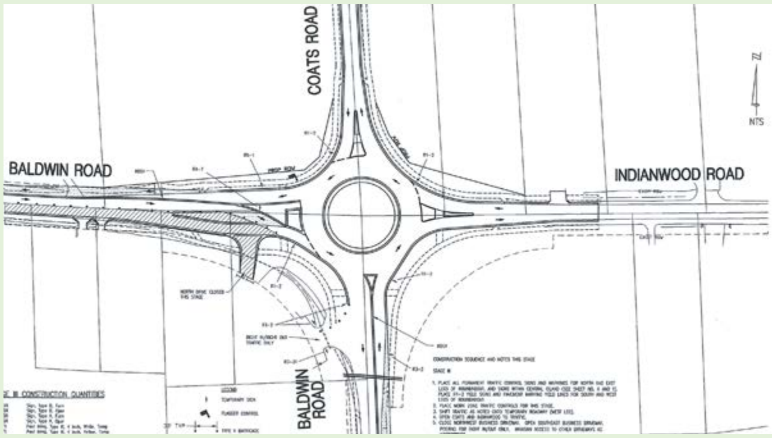


Exhibit 15.1. (Continued).

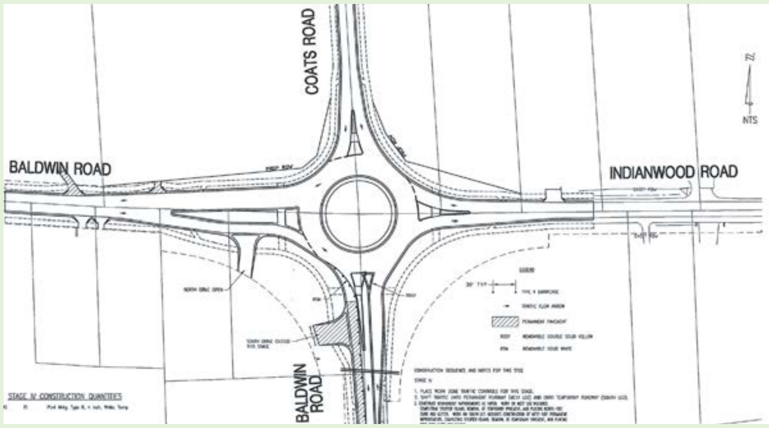
Stage III: West Approach Construction

- Complete the roundabout elements on the west approach.
- Remove temporary pavement on the south and west approaches.
- Shift traffic to temporary roadways on the west approach to maintain two-way traffic on Baldwin Road.
- Close the northwest business driveway and open the southeast business driveway to right-in/right-out only movements.
- Install permanent signing on the north and east approaches and on the central island.
- Install signing and markings on the south and west approaches.
- Open Coats Road and Indianwood Road to traffic on permanent roadways.
- Begin operating the east, north, and south approaches as a roundabout with two-way traffic.



Stage IV: South Approach Construction

- Shift traffic to the permanent roadway on the west approach.
- Shift traffic to the temporary roadway on the south approach.
- Complete the south approach, including the splitter island, and complete the permanent roadway on the west side of the approach and remove temporary pavement.
- Complete the west approach, including the splitter island, and remove temporary pavement.
- Install the remaining permanent signing and striping on all approaches.



SOURCE: *NCHRP Report 672* (*1*).

permanent signing (covered until the roundabout configuration matches the signing), lighting, and some pavement markings. These items, if installed before the central and splitter islands are constructed, expedite completion and introduce roundabout safety performance benefits during construction.

At some previously congested locations, traffic flow may improve during construction because of the roundabout's yield control. Roundabout operation during construction has the benefit of helping drivers establish driving habits that are a similar pattern to the final roundabout configuration. However, during construction, barrels and cones around a central island may limit lane widths during construction and lead to side-by-side vehicle conflicts in multilane configurations. Side-by-side travel during construction is only allowed if there is adequate space to prevent vehicle-to-vehicle conflicts.

Other staging considerations include

- Night or weekend work reduces the impact on peak-period traffic.
- Flagging can be used on the approaches and exits to allow the contractors to work.
- Temporary signals can be used on the approaches under certain stages.
- Temporary roadway construction may be necessary during certain stages.
- Temporary traffic patterns that counter normal roundabout operation (i.e., vehicles circulating clockwise instead of counterclockwise) are undesirable.
- For multilane roundabouts along multilane roadways, side-by-side vehicle travel during various stages of construction (including tractor trailer vehicles) must occur only if adequate space is available to avoid vehicle-to-vehicle conflicts during side-by-side travel. In some situations, it may be beneficial or even required to temporarily reduce to one lane of travel.

Exhibit 15.2 and Exhibit 15.3 provide examples of temporary traffic signals and temporary pavement through a roundabout using PCC. Temporary pavement has been placed where the ultimate splitter island will be located. This allows traffic to use the newly constructed pavement as temporary lanes. The raised curbing of the central island and splitter islands was constructed during a later stage.

One possible sequence for staging construction under full traffic is as follows:

1. Install signing and lighting (roundabout signing should initially be covered).
2. Construct outside widening.
3. Reconstruct or resurface approaches.

Exhibit 15.2. Example construction with temporary signals and pavement.

SOURCE: Ourston.

Exhibit 15.3. Example construction with temporary signals and pavement.

SOURCE: Ourston.

4. Construct splitter islands and delineate the central island. At this point, the signs could potentially be uncovered, and the intersection could operate as a roundabout. A splitter island under construction is shown in Exhibit 15.4.
5. Finish construction of the central island.
6. Prepare the final grade and apply the final paving course for the circulating roadway and entry/exits. Grading of the circulatory roadway is shown in Exhibit 15.5.

A practical, cost-effective alternative to consider for construction staging is to create a large paved area of the intersection by delaying the construction of the splitter islands and central island until the final stage of construction.

The existing intersection can be milled and leveled to the near-finished pavement elevation of base asphalt. When the widening and resurfacing of the intersection are complete, lanes can be moved around as needed to finalize the pavement grade changes. Once the whole intersection area is leveled to near-final grades at base asphalt, the splitter islands can be added to the base

Exhibit 15.4. Constructing the splitter island.

LOCATION: SW Terwilliger Boulevard/SW Palater Road, Portland, Oregon.
SOURCE: Lee Rodegerdts.

Exhibit 15.5. Constructing the central island and circulatory roadway.

LOCATION: SW Terwilliger Boulevard/SW Palater Road, Portland, Oregon.
SOURCE: Lee Rodegerdts.

asphalt as monolithic slabs. The truck apron can also be applied to base asphalt and dowelled in place. The central island is cut out of the paved surface and mounded after curbs are placed. This creates a flexible traffic management scheme with minimal disruption to existing traffic, and it often shortens the overall construction duration.

15.6 Work Zone Traffic Control

During roundabout construction, the intended travel paths need to be clearly identified. This may be accomplished through pavement markings, signing, delineation, channelizing devices, and guidance from police or construction personnel. Pedestrian wayfinding and accessible routes for people with disabilities are to be included during construction planning and integrated into project construction staging. Channelizing devices should give motorists, bicyclists, and pedestrians a clear indication of the required travel path. Overall, MUTCD requirements regarding work zone traffic control are to form the basis for work zone applications (*2*).

Exhibit 15.6 illustrates the use of cones and barrels to delineate the roundabout approaches and circulatory roadway while the splitter island and central island are constructed.

Exhibit 15.6. Temporary traffic control during construction.

LOCATION: Grand Avenue/Broadway/N 1st Street/I-70 Business Loop, Grand Junction, Colorado. SOURCE: Kaitlin Clark, Colorado Department of Transportation.

Exhibit 15.7. Temporary traffic signal during early roundabout construction.

LOCATION: DeLand, Florida. SOURCE: Florida Department of Transportation.

It is common to use flaggers or temporary traffic signals during construction. Exhibit 15.7 presents a temporary signal used during the early stages of roundabout construction.

15.6.1 Pavement Markings

Pavement markings in work zones need to have the same layout and dimensions as those used for the final installation. Because of the potential confusion in a work area and change in traffic patterns, additional pavement markings may be used to clearly show the intended direction of travel. In some cases, when pavement markings cannot be placed, temporary channelizing devices (e.g., cones, tubular markers, drums) should be used to establish the travel path.

15.6.2 Signing

Work zone signing includes user needs in the work area, pre-construction signing advising the public of the planned construction, and regulatory and warning signs addressing traffic needs outside the work area. The permanent roundabout signing needs to be installed where practicable during the first construction stage so it is available when the roundabout is operable. Permanent signing that cannot be installed initially needs to be placed on temporary supports in the proposed location until permanent installation can be completed.

15.6.3 Illumination

Illumination, discussed in Chapter 14: Illumination, Landscaping, and Artwork, is needed in the work area. Lighting needs to be provided specifically in construction areas so pedestrians and bicyclists are visible to motorized users. Exhibit 15.8 depicts temporary lighting on a roundabout approach under construction.

15.7 Maintenance

Facility maintenance includes landscaping, illumination, pavement marking, pavement replacement, and curb replacement. A maintenance operation plan is always necessary and may include tasks such as trimming shrubs; removing snow; or completing routine refurbishing of

Exhibit 15.8. Temporary lighting on roundabout approach.

LOCATION: DeLand, Florida. SOURCE: Florida Department of Transportation.

pavement, signing, and markings. Practitioners need to consider maintenance and potential maintenance agreements for funding early in the planning and design process. Practitioners also need to consider maintenance in life-cycle cost evaluations and ICE activities.

As with any transportation project, a realistic maintenance program is to be considered when designing a roundabout's landscape features. While it is generally necessary for local governments to assume maintenance responsibilities for landscaping, formal maintenance agreements with local civic groups, neighborhood associations, and garden clubs are also possible when complex planting arrangements are planned. Early enthusiasm and consistent activities by volunteer groups may wane, but creating access to areas near active traffic creates risks for all users. Safety plans and equipment are, therefore, important elements of any (public or private) landscaping maintenance plan. If a willing maintenance party is not identified, simple plant materials or hardscape items that require little or no maintenance are preferred.

In addition, maintenance vehicles should be able to properly access the central island and splitter islands if needed. Potential stoppage or pullout areas for maintenance vehicles can be located so that visibility and access for vehicles and pedestrians are preserved. Exhibit 15.9 provides an example of a pullout area for maintenance vehicles.

Exhibit 15.9. Example of maintenance vehicle pullout area in central island.

LOCATION: NW Shevlin Park Road/Newport Avenue/College Way, Bend, Oregon. SOURCE: Lee Rodegerdts.

15.7.1 Landscaping Maintenance

Landscaping maintenance needs can vary by extent and frequency depending on the type of climate and extent of plantings. Proper drainage for any watering system should be provided and should minimize the water runoff onto the circulatory roadway. Watering systems with a mist-type spray should be avoided, as water spray onto windshields could create safety concerns.

Access to landscaped areas is fundamental, and project planning, ICE, and preliminary design need to consider equipment parking and worker access. Maintenance in high-traffic volume locations could require flaggers or short-duration lane closures to allow workers or equipment to access focus areas. In some conditions, parking pullouts may need to be located on the roadway approaches or the central island (see Exhibit 15.9).

Plants and trees within the roundabout cannot interfere with the sight distance approaching and within the roundabout. Therefore, practitioners need to consider the expected growth of specific plant and tree species in a landscape plan and prioritize lower-maintenance species. In addition, grass, trees, and shrubs are to be regularly trimmed or pruned to prevent obstruction of the sight triangles and maintain the intersection's aesthetics.

15.7.2 Pavement Maintenance and Rehabilitation

Pavement maintenance and rehabilitation are generally completed under traffic using the techniques described for work zone traffic control. The American Traffic Safety Services Association and FHWA's *Temporary Traffic Control for Building and Maintaining Single and Multi-lane Roundabouts* provides an example of a flagging operation for conducting maintenance work on one quadrant of an existing roundabout (*3*). It also describes how work might be completed under full traffic with four flaggers (one at each approach) to guide traffic flow. In addition, it may be necessary to include another flagger on the central island to direct traffic through the roundabout.

15.7.3 Curb and Sidewalk

Curb and sidewalk rehabilitation may be associated with vehicle strikes and truck encroachment. Replacing or repairing the curb and sidewalk would be completed under traffic and follow techniques for construction staging during rehabilitation activities. Unlike conventional intersections, curbs at splitter islands, central islands, truck aprons, and other potential encroachment or strike areas are susceptible to more degradation than at other intersection forms. Adding steel reinforcement to PCC curbs and sidewalk areas susceptible to vehicle encroachment could reduce future maintenance needs.

15.7.4 Utilities in the Roundabout Area

Constructing a roundabout at an existing intersection or rehabilitating an existing circular intersection may result in utilities located on the roundabout central island. These issues and needs need to be identified early in roundabout planning and design to minimize difficulty after the roundabout has been implemented.

Beyond the central island, it is desirable to avoid locating utilities and their access within the circulatory roadway. If possible, practitioners will locate utilities in the legs of the roundabout to allow for future maintenance and access at an isolated leg versus affecting the entire roundabout.

15.8 Snow Plowing and Storage

Roundabouts often operate in winter climates that include snow and ice. Practitioners need to consider winter maintenance along with roundabout safety and operational performance benefits on a life-cycle cost basis. It is not necessary to reject a roundabout on the basis of winter maintenance needs alone.

Exhibit 15.10. Example of snow-plowed roundabout.

LOCATION: Chena Hot Springs Road/Steese Highway Northbound Ramps, Fairbanks, Alaska.
SOURCE: Gary Katsion.

Each agency in a cold climate has its own technique and routine for plowing snow. For the first roundabout in a jurisdiction, it may be helpful to develop a plowing sequence plan until the plow operators become familiar with plowing the roundabouts.

Many jurisdictions have standard widths for snowplows within their fleet. In areas where snow removal is anticipated to be a regular occurrence, the roundabout dimensions may be tailored to accommodate the width of the plow blade and the turning radii of anticipated maintenance vehicles. Maintenance crews must be able to identify and locate the splitter island and truck apron locations. Special curb types that support plowing operations and splitter island plowable end treatments may be integrated into the roundabout design. Exhibit 15.10 shows an example of a roundabout at an interchange ramp terminal intersection plowed for snow.

Exhibit 15.11 shows a roundabout with a traversable central island that has been plowed along the circulatory roadway but not within the central island where trucks traverse. Exhibit 15.12

Exhibit 15.11. Example of plowed roundabout with traversable central island.

LOCATION: W Bemis Road/Moon Road, Washtenaw County, Michigan.
SOURCE: Washtenaw County Road Commission.

Exhibit 15.12. Example of plowed roundabout in heavy snow conditions.

LOCATION: SW Bond Street/SW Wilson Street, Bend, Oregon.
SOURCE: Kittelson & Associates, Inc.

presents a roundabout in heavy snow conditions. The roadways had been plowed, but additional snowfall covered the approach roadways and circulatory roadway.

One plowing method is to start on the innermost section of the circulatory roadway, often on the truck apron, and keep circulating while spiraling outward, with each revolution pushing the snow outward from the circulatory roadway. This same operator or a second plow operator may clear the entries and exits once the circulatory roadway is clear. The crown of the circulatory roadway, if present, will also help dictate the roundabout's plowing sequence.

Snow storage is sometimes part of snow management. Snow storage should not create a sight obstruction for drivers approaching or circulating the roundabout, nor should it impact bicyclist and pedestrian access through a roundabout. Knocking down the height of the snow piles or removing snow from the islands may be necessary after prolonged periods of snowfall.

Exhibit 15.13 illustrates snow accumulated on the channelized island of a dedicated right-turn lane. Snow storage areas should not limit sight distance on the roundabout approaches or circulatory roadway. Snow storage can result in thaw and freeze cycles that allow ice buildup on the circulatory roadway. In some cases, drainage inlets in the non-traversable central island or along the truck apron can reduce ice buildup. Practitioners are advised that snow plowed from

Exhibit 15.13. Example of snow accumulation on a channelized island.

LOCATION: Chena Hot Springs Road/Steese Highway Northbound Ramps, Fairbanks, Alaska.
SOURCE: Gary Katsion.

the roadway may contain road salts and other automobile waste that could impact vegetation if placed in sensitive landscaped areas.

15.9 References

1. Rodegerdts, L., J. Bansen, C. Tiesler, J. Knudsen, E. Myers, M. Johnson, M. Moule, B. Persaud, C. Lyon, S. Hallmark, H. Isebrands, R. B. Crown, B. Guichet, and A. O'Brien. *NCHRP Report 672: Roundabouts: An Informational Guide*, 2nd ed. Transportation Research Board of the National Academies, Washington, DC, 2010. http://dx.doi.org/10.17226/22914.
2. *Manual on Uniform Traffic Control Devices for Streets and Highways*, 2009 ed., Including Revision 1, Dated May 2012; Revision 2, Dated May 2012; and Revision 3, Dated August 2022. FHWA, US Department of Transportation, 2022. http://mutcd.fhwa.dot.gov/.
3. *Temporary Traffic Control for Building and Maintaining Single and Multi-lane Roundabouts*. Grant Agreement DTFH61-06-G-00004. American Traffic Safety Services Association, Fredericksburg, Va., and FHWA, US Department of Transportation, 2012.

APPENDIX

Design Performance Check Techniques

Contents

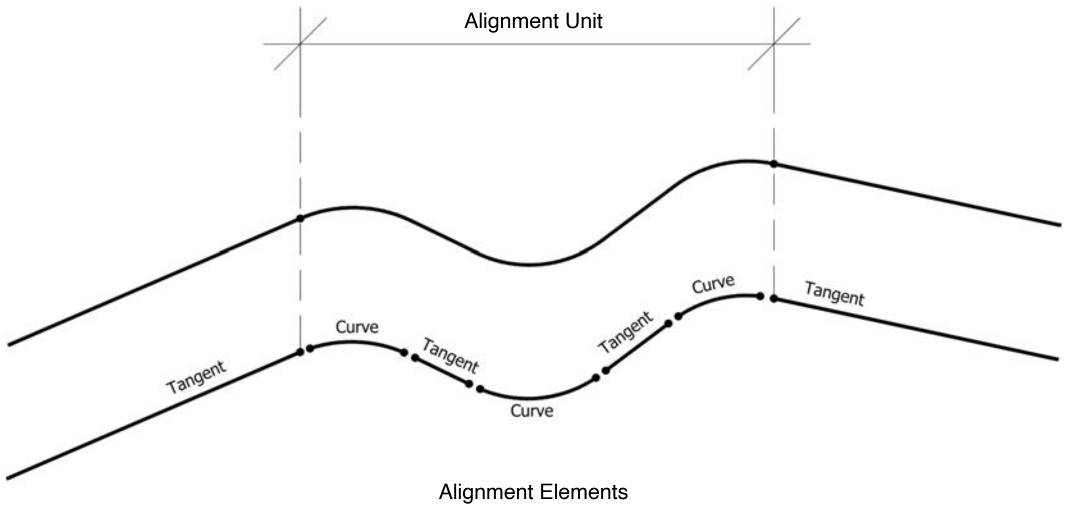
This appendix details a variety of design performance check techniques that can facilitate the check process discussed in Chapter 9: Geometric Design Process and Performance Checks. The techniques in this appendix are representative but not exhaustive of all possible techniques. Practitioners must sometimes modify performance check techniques to meet a specific configuration; any modifications need to be compatible with the design principles in Chapter 9.

A.1 Geometric Speed Check Techniques

This section presents a variety of geometric speed check techniques, including both hand-drawn and CAD-based methods. Each method varies in detail but can produce results that are consistent with the principles presented in Chapter 9: Geometric Design Process and Performance Checks.

The geometric speed check method is an easy, efficient, and effective way to check speeds for hand-sketched concepts or red-lined revision markups of early CAD-based designs. CAD-based methods offer increased precision in computing estimated speeds. The geometric speed model is based on a generalized vehicle dimension and assumed driver behavior. Both geometric speed techniques use the same model assumptions; because of these assumptions, computed speeds should be assessed only to the nearest 1 mph or 1 km/h.

Exhibit A.1. Alignment elements.



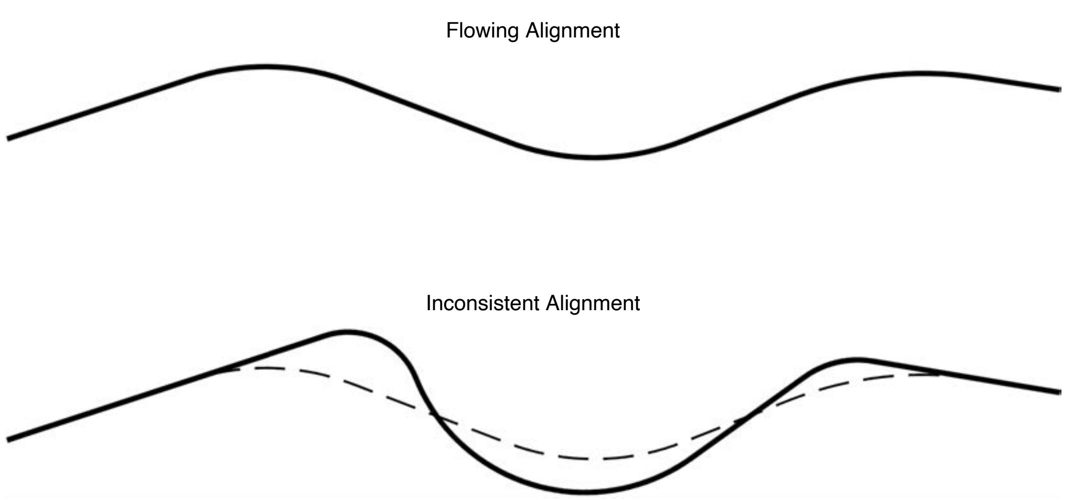
The geometric speed check method combines individual alignment elements: tangents, curves, and spirals. Each curve has an associated speed based on its radii and assumed side friction and superelevation. Drivers navigate a curvilinear horizontal alignment by viewing the roadway ahead and adjusting their speed and position based on the combination of alignment elements, in effect considering an alignment as a unit rather than as its individual components. Drivers naturally follow a spiral path between curves and tangents, which can be captured using hand-drawn and CAD-based techniques.

Exhibit A.1 depicts the concept of alignment elements and an alignment unit.

Exhibit A.2 represents two curvilinear paths: one alignment that can be characterized as a *flowing alignment* and another that can be characterized as an *inconsistent alignment*. The flowing alignment path represents a smooth curvilinear alignment resulting in similar speeds, associated lateral forces, and similar driver comfort between alignment elements. The inconsistent alignment represents a driving path that may be possible to drive but that is not likely to be the fastest or smoothest alignment possible within the given geometry.

Regardless of the method, practitioners need to review each developed fastest path alignment objectively to assess if it represents the model's intent. The desired fastest path alignment

Exhibit A.2. Flowing and inconsistent alignment.



is the smoothest, flattest path possible for a single vehicle in the absence of other traffic and ignoring all lane markings.

A.1.1 Hand-Sketch Method

A possible method for conducting a geometric speed check using hand-sketch techniques includes the following steps:

1. Draw the roundabout or plot a CAD drawing at a scale that allows the roundabout and its approaches to fit onto a common size of paper (typically 11 in. × 17 in./A3 or smaller). For most roundabouts, a scale of 1 in. = 50 ft or 1:500 is most useful.
2. Place a vellum or other trace paper over the roundabout concept and secure it with tape. Place a registration mark on the trace paper.
3. Scale appropriate offsets from curbs and stripes as appropriate using the recommendations in Chapter 9: Geometric Design Process and Performance Checks. Sometimes, it is helpful to place a few small pencil dots along the possible path.
4. Start 125 ft to 200 ft (40 m to 60 m) upstream from the roundabout entrance based on a location on the approach not affected by the roundabout entry. Lightly sketch an entry path.
5. Similarly, work backward from a point approximately 125 ft to 200 ft (40 m to 60 m) downstream of the roundabout exit and lightly sketch upstream toward the circulatory roadway.
6. Using an offset of 5 ft (1.5 m) from the central island, sketch a light line upstream and downstream from the circulatory roadway, aiming toward the entry alignment and the exit alignment. This forms the initial circulating alignment.
7. Lightly sketch the entry alignment toward the circulating alignment and from the circulating alignment toward the entry until the paths meet. Include tangents or gradual transitions between reversing curves.
8. Lightly sketch the exit alignment upstream toward the circulating alignment and from the circulating alignment toward the exit alignment until the paths meet. Include tangents or gradual transitions between reversing curves.
9. Lightly pass over the fastest path alignment to darken the pencil sketch, smoothing the drawn path as needed to create a balanced and flowing alignment. It is common to erase small portions of the sketched path and resketch portions to improve the fastest path.
10. Measure the radius using a template. Look up the speed to the nearest 1 mph or 1 km/h corresponding to the measured radius using the speed–radius graphs (see Section A.1.3) based on positive or negative superelevation for the location of the curve being measured. Record the speeds and compare them to the target performance.
11. Conduct the evaluations for other through and turning movements.
12. If the estimated speeds are adequate for all movements, continue refining the roundabout. If speeds on some movements are too fast, make geometric changes as needed to reduce speeds and repeat the assessment.

A.1.2 CAD-Based Methods

Several states provide guidance for CAD-based methods. Many of these methods apply spline curves that generate smooth spiral curves like those obtained using freehand methods. Strategically placed points along the spline curve result in a path dictated by the roundabout's geometric elements. Best-fit circular curves are then used to measure the controlling curves along the spiral path to identify R_1 through R_5 radii for each approach.

The general approach for each CAD-based method is to create construction lines offset from curbs and edge lines that represent the center of the passenger car. It is common to consider the approaching and departing evaluation distance to be 165 ft (50 m), but the distance may be shorter or longer depending on the roundabout's approach and departure geometry. Practitioners must consider each roundabout movement individually and employ the CAD-based method to best reflect the geometric speed exercise's intent to create a smooth and consistent pathway reflecting likely driver behavior.

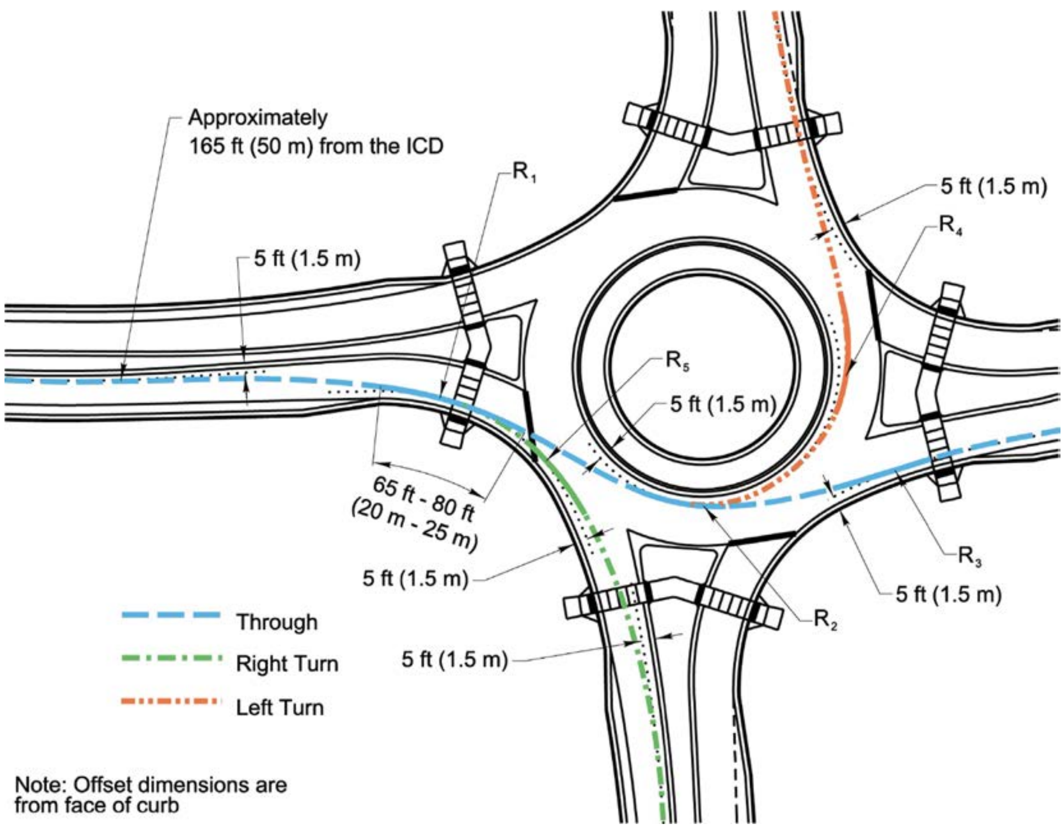
Exhibit A.3 illustrates how to construct the fastest vehicle paths at a single-lane roundabout.

Exhibit A.4a and Exhibit A.4b illustrate how to construct the fastest vehicle paths at a multilane roundabout. Each path should be reviewed to assess if the CAD-drawn path reflects likely driver behavior. The CAD-drawn path may not always represent the probable actual path. Exhibit A.4b shows the potential difference between the "probable actual path" and the "CAD-drawn path." The actual exiting speeds between these two paths might not result in substantive predicted speed performance differences.

There may be differences in CAD commands depending on the platform. However, the process and intent are the same between methods and software applications. CAD-based geometric speed checks usually include the following steps.

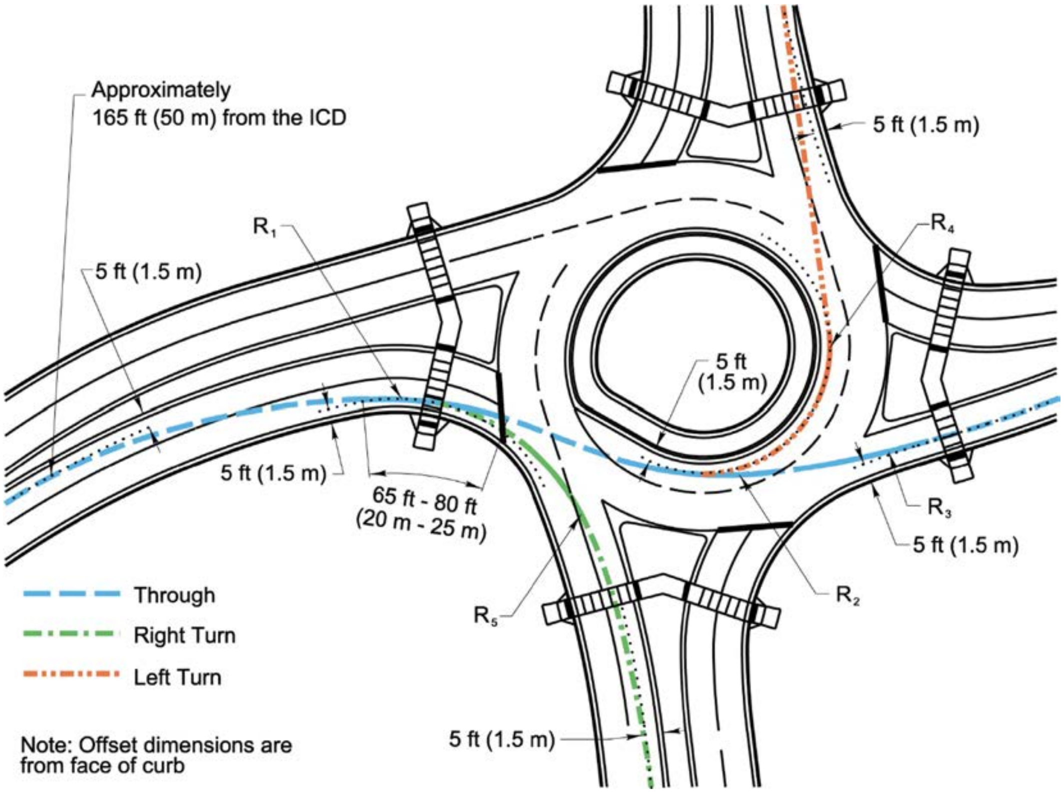
1. Copy curb offsets from the face of the curb or painted lines using values associated with the cross-section feature. See Chapter 9: Geometric Design Process and Performance Checks for additional information about the offset dimensions.
2. Establish the upstream limit line and downstream limit line for each roadway approach and departure. This is commonly 165 ft (50 m). The actual value depends on the roundabout's approach and departure geometry and may be closer to or farther from the roundabout to best represent a smooth and consistent path.

Exhibit A.3. Fastest vehicle paths for a single-lane roundabout.



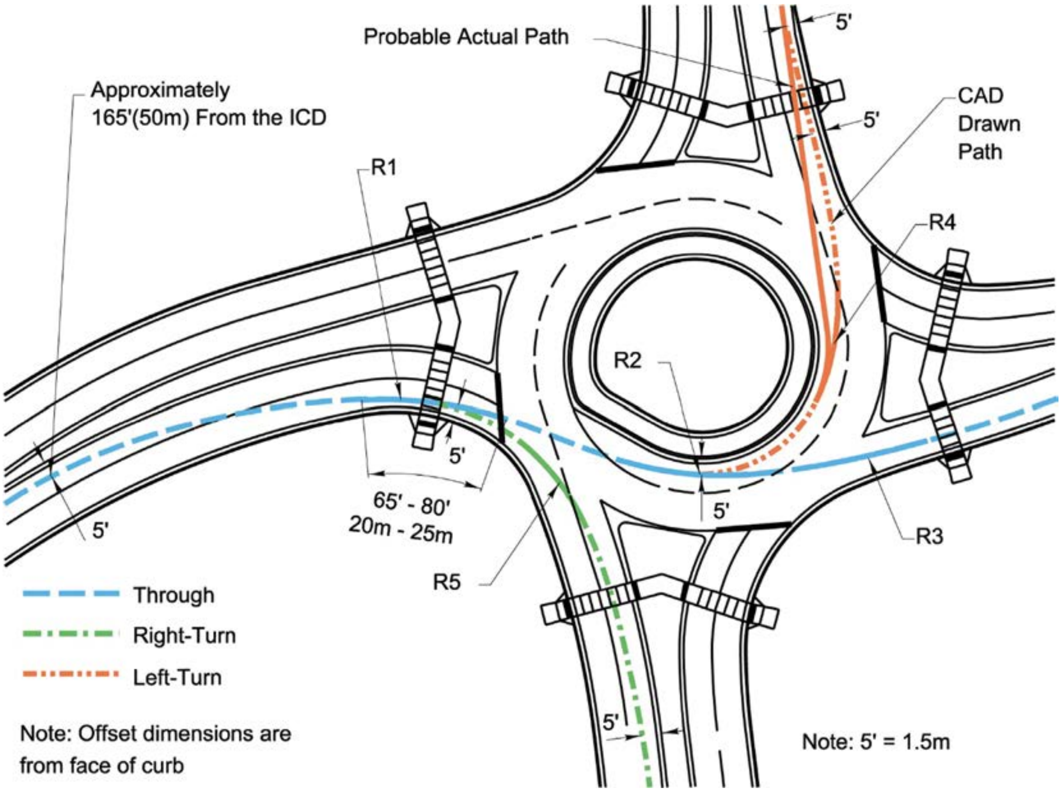
SOURCE: Adapted from Georgia Department of Transportation (*1*).

Exhibit A.4a. Fastest vehicle paths for a multilane roundabout.



SOURCE: Adapted from Georgia Department of Transportation (*1*).

Exhibit A.4b. Fastest vehicle path through a multilane roundabout with CAD-drawn path.



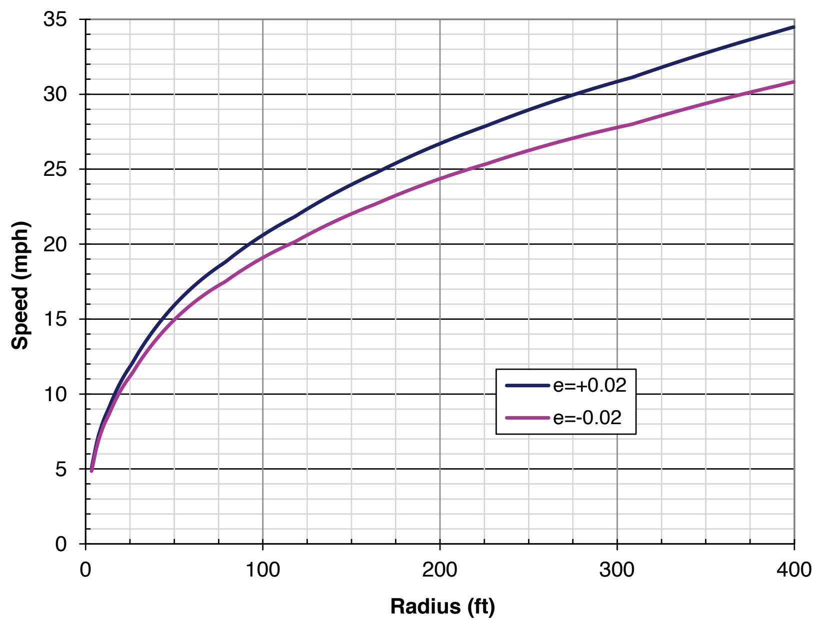
SOURCE: Adapted from Georgia Department of Transportation (*1*).

3. Draw the spline curve between the upstream movement and the offsets. This is typically accomplished by snapping three points that occur outside the upstream limit line, on the upstream limit line, and on the curb offset line.
   a. In some configurations, the left or right curb line could be the control depending on the logical vehicle driving path.
   b. In some configurations, often at exits, the logical vehicle driving path is outside the offset line, and the fastest path may not be affected by the curb offset line.
   c. In some right turns, the fastest paths could be offsets from the right (inside) of the turning radii or from the left (outside) of the turning radii that are controlled by the splitter island, truck apron, and exiting splitter island.
4. Review and revise the spline lines to be sure they are outside required offsets or located as needed to represent a fastest path. The beginning or end of the spline may need to be pulled farther away from the roundabout (up or downstream) to create a realistic fastest path.
5. Measure the radius values. Arc lengths for any circular curve should extend from 65 ft to 80 ft (20 m to 25 m). If they are shorter than that, the path should be modified to achieve these lengths. Achieving these lengths may require adjusting the spline lines to be sure the fastest path reflects driver behavior.
6. Conduct the evaluations for other through and turning movements.
7. If the estimated speeds are adequate for all movements, continue refining the roundabout. If speeds on some movements are too fast, make geometric changes as needed to reduce speeds and repeat the assessment.

A.1.3 Speed–Radius Graphs

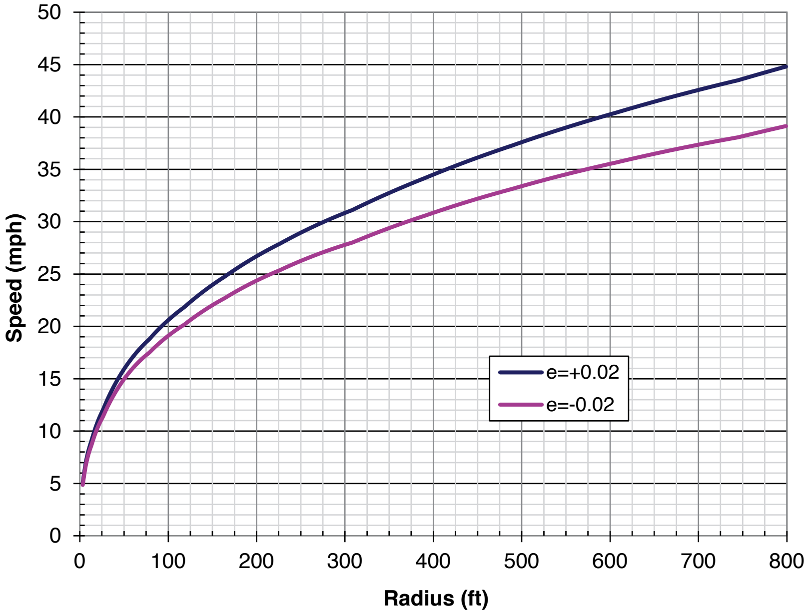
Chapter 9: Geometric Design Process and Performance Checks explains the speed–radius graphs used for estimating speeds when conducting geometric speed checks. Exhibit A.5 through Exhibit A.8 provide larger versions of the graphs in Chapter 9 to allow for easier use when conducting checks.

Exhibit A.5. Speed–radius relationship, US customary up to 400 ft.



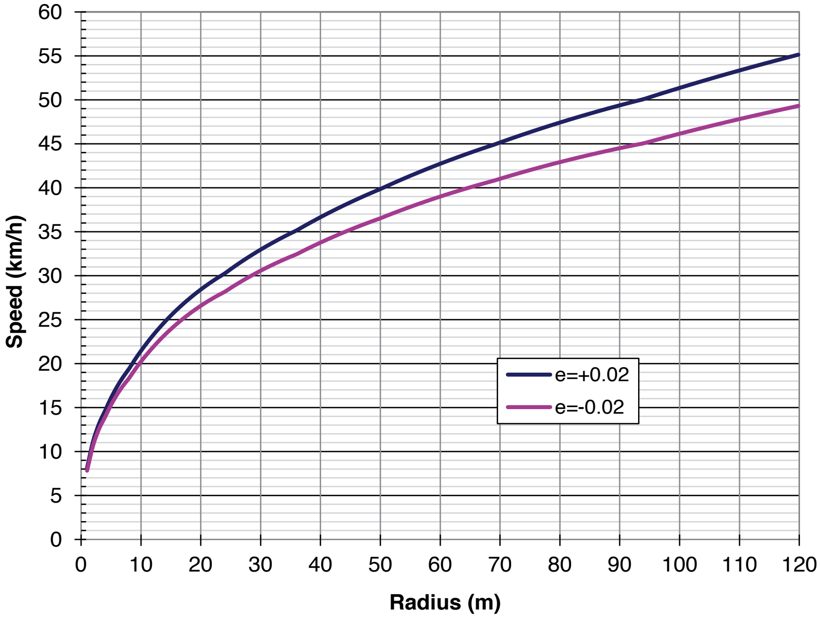
SOURCE: Based on AASHTO *Green Book*, Equation 3-7 and side friction factors assumed for design (AASHTO Figure 3-4) (*2*).

Exhibit A.6. Speed–radius relationship, US customary up to 800 ft.



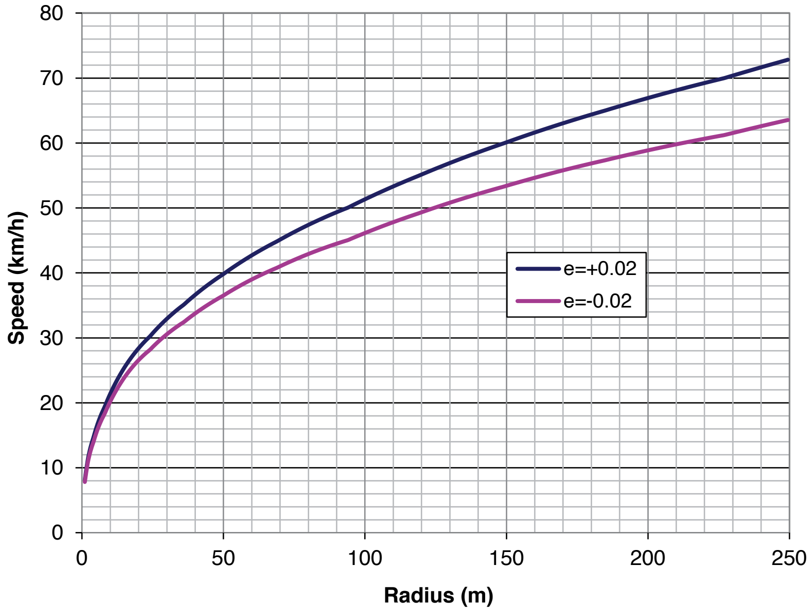
SOURCE: Based on AASHTO *Green Book*, Equation 3-7, and side friction factors assumed for design (AASHTO Figure 3-4) (*2*).

Exhibit A.7. Speed–radius relationship, metric up to 120 m.



SOURCE: Based on AASHTO *Green Book*, Equation 3-7, and side friction factors assumed for design (AASHTO Figure 3-4) (*2*).

Exhibit A.8. Speed–radius relationship, metric up to 250 m.



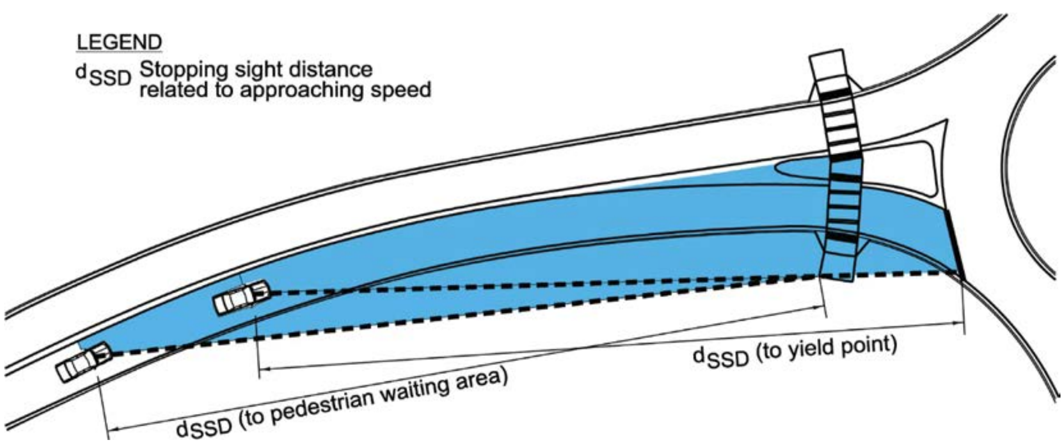
SOURCE: Based on AASHTO *Green Book*, Equation 3-7, and side friction factors assumed for design (AASHTO Figure 3-4) (*2*).

A.2 Sight Distance and Visibility

Chapter 9: Geometric Design Process and Performance Checks discusses stopping and intersection sight distance. Practitioners will use geometric speed check values to establish stopping and intersection sight distance. A possible method for conducting stopping sight distance evaluations, illustrated in Exhibit A.9 through Exhibit A.13, includes the following steps:

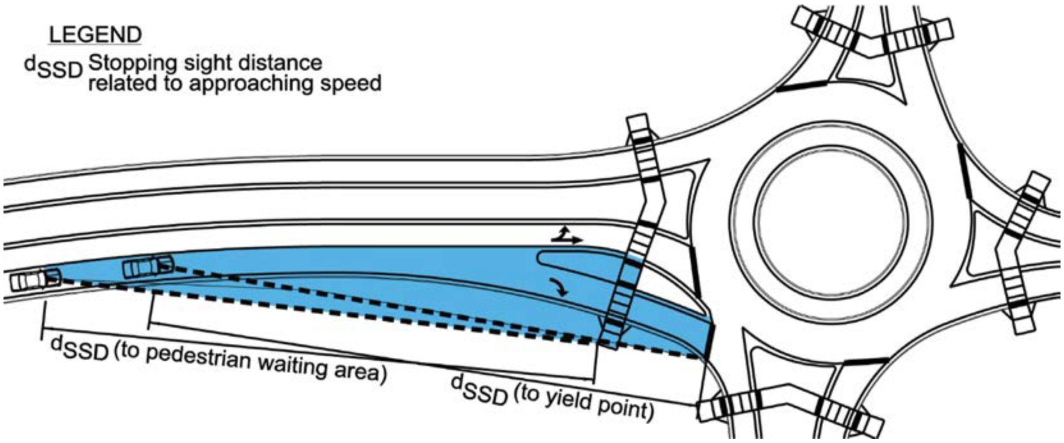
1. Assess the stopping sight distance on the approach by considering the approach speed and establishing the appropriate sight distance corresponding to that speed.
2. Measure the distance along the roadway approach path to the pedestrian waiting area or to the entrance line as appropriate. From the vehicle positioned at the distance along the traveled

Exhibit A.9. Stopping sight distance to the pedestrian crossing and entrance line on the approach.



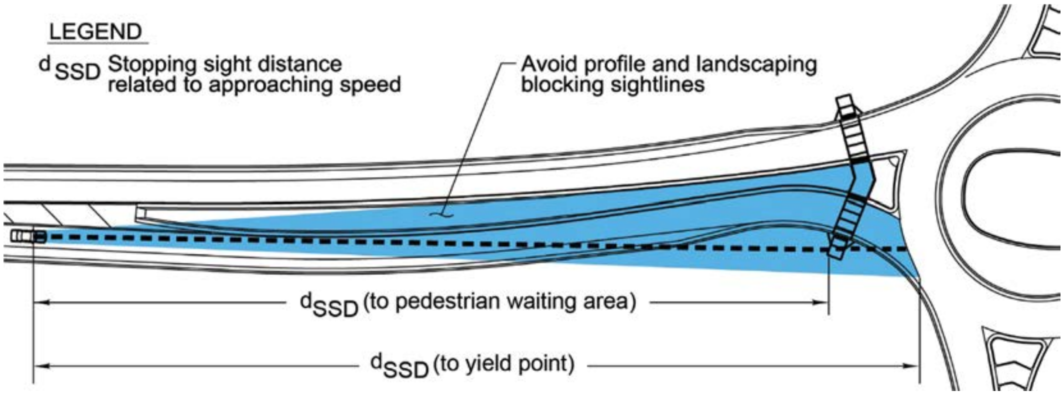
SOURCE: Adapted from Georgia Department of Transportation (*1*).

Exhibit A.10. Stopping sight distance for a right-turn bypass lane.



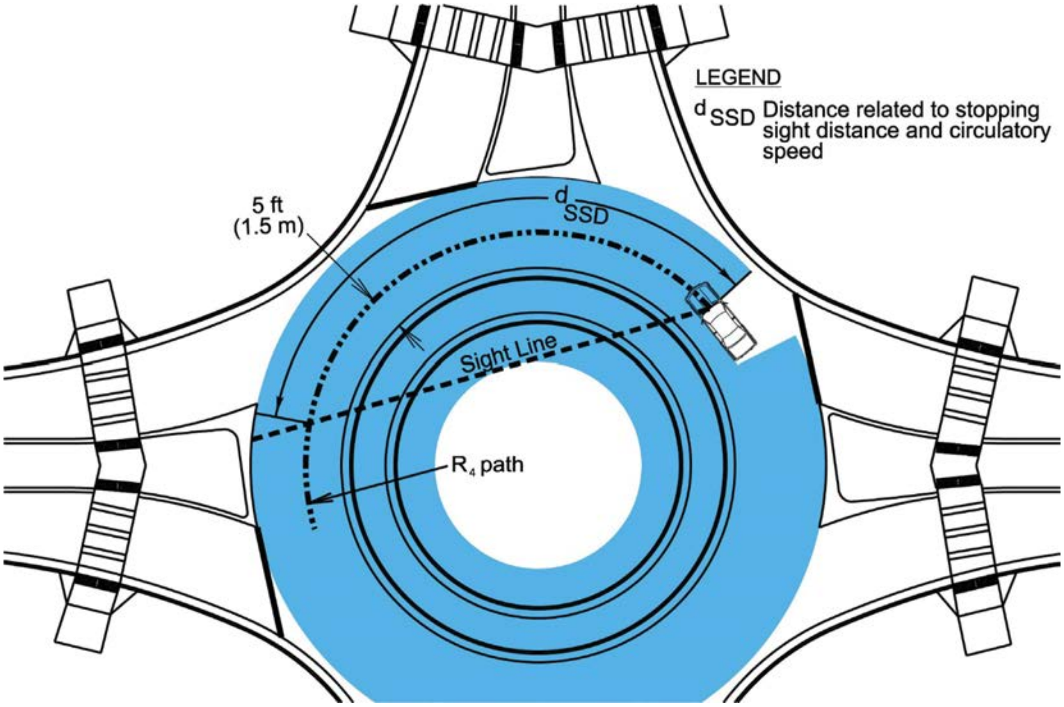
SOURCE: Adapted from Georgia Department of Transportation (*1*).

Exhibit A.11. Stopping sight distance for approach curvature.



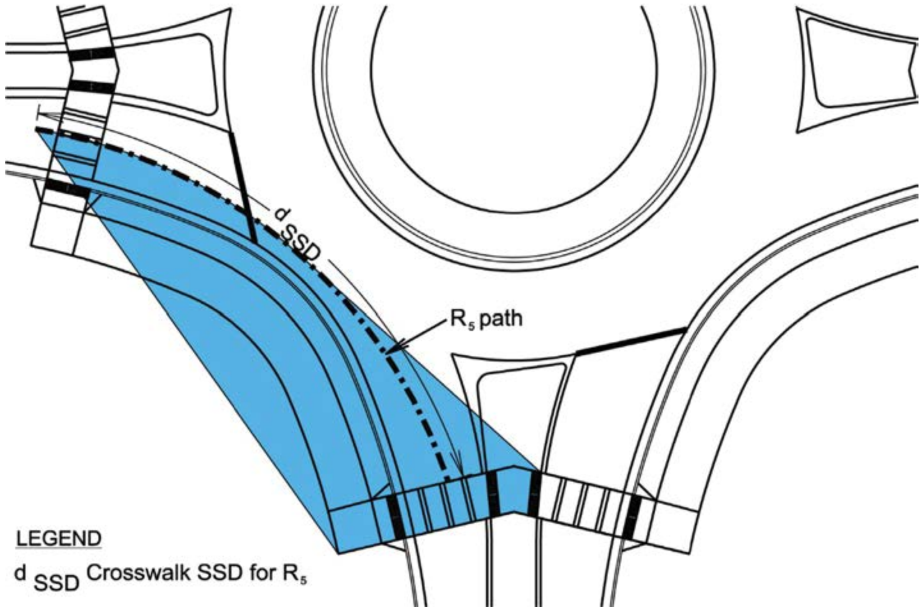
SOURCE: Adapted from Georgia Department of Transportation (*1*).

Exhibit A.12. Stopping sight distance on a circulatory roadway.



SOURCE: Adapted from Georgia Department of Transportation (*1*).

Exhibit A.13. Sight distance to a crosswalk on exit.



SOURCE: Adapted from Georgia Department of Transportation (*1*).

approach, the sightline to the waiting area can be established. For roundabouts with a separated right-turn lane, the stopping sight distance should be provided to the pedestrian waiting area and entrance line.

3. Measure the distance along the roadway approach path to the entrance line. From the vehicle positioned at the distance along the traveled approach, establish the sightline to the entrance line.
4. Verify that there are no sight distance obstructions within the inscribed sightline.
5. Assess the stopping sight distance along the circulatory roadway using the computed R_4 speed. Measure the distance along the circulatory roadway with an offset of 5 ft (1.5 m) from the central island curb. Then, establish a sightline to a forward position on the circulating path. Note that this sightline can be projected as if the driver circulated the entire roundabout to provide stopping distance at the central island. For noncircular roundabouts, practitioners can use the various geometric speed check speeds and establish sightlines similarly.
6. Assess the stopping sight distance to the pedestrian waiting area on the exit by locating the vehicle at the entrance line and establishing the sightline to the pedestrian waiting area. Even if a crosswalk is not provided, it is prudent not to preclude a future crossing, so the sight distance to the exit should be established.
7. Verify that there are no sight distance obstructions within the inscribed sightline on the central island.

Exhibit A.14 illustrates a possible intersection sight distance method that includes the following steps:

1. Consider a vehicle waiting at the entry and the two potential conflicts on the circulatory roadway and the immediate upstream entry.
2. Consider sight distance in advance of the entry: The length of the approach leg of the sight triangle and of the conflicting branch for the immediate upstream entry, b_1, should be limited to 50 ft (15 m). The length of the conflicting branch on the circulatory roadway, b_2, is calculated as previously described. If the combination of sight distance along the approach leg and the immediate upstream entry leg of the sight triangle exceeds these recommendations, it may be advisable to add landscaping that restricts sight distance to the minimum requirements.

3. Use Equation A.1 through Equation A.4 to compute the intersection sight distance for the two branches, b_1 and b_2. Exhibit A.14 shows the lengths of the two conflicting branches.

US Customary	Metric
Equation A.1 $$b_1 = 1.47V_{ent}t_g$$	Equation A.3 $$b_1 = 0.278V_{ent}t_g$$
Equation A.2 $$b_2 = 1.47V_{circ}t_g$$	Equation A.4 $$b_2 = 0.278V_{circ}t_g$$
where	where
b_1 = length of entering branch of sight triangle, ft	b_1 = length of entering branch of sight triangle, m
b_2 = length of circulating branch of sight triangle, ft	b_2 = length of circulating branch of sight triangle, m
V_{ent} = speed of vehicles from upstream entry for the conflicting through movement, assumed to be average of V_1 and V_2, mph	V_{ent} = speed of vehicles from upstream entry for the conflicting through movement, assumed to be average of V_1 and V_2, km/h
V_{circ} = speed of circulating vehicles, assumed to be V_4, mph	V_{circ} = speed of circulating vehicles, assumed to be V_4, km/h
t_g = design headway, s, assumed to be 5.0 s	t_g = design headway, s, assumed to be 5.0 s

Exhibit A.15 shows the computed length of the conflicting leg of an intersection sight triangle using an assumed value of design headway, t_g, of 5.0 s. This design headway is based on the amount of time required for a vehicle to safely enter the conflicting stream. This is an assumed value based on judgment and experience, originally developed using observational data for critical headways from *NCHRP Report 572* and more recent observational data from FHWA research (*3*, *4*). Some agencies use smaller values for design headway or other alternatives for locations with restricted sight distance.

Exhibit A.14. Intersection sight distance.

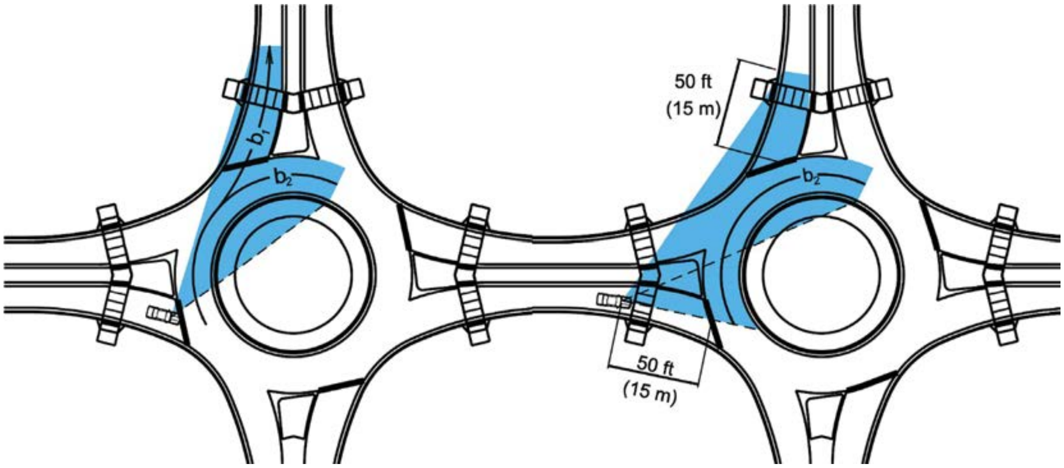
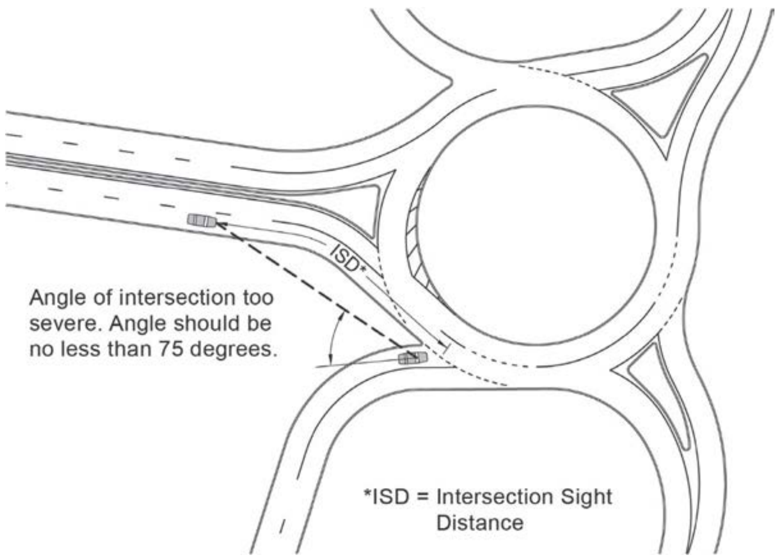


Exhibit A.15. Computed length of a conflicting leg of an intersection sight triangle.

Conflicting Approach Speed (mph)	Computed Distance (ft)	Conflicting Approach Speed (km/h)	Computed Distance (m)
10	73.4	20	27.8
15	110.1	25	34.8
20	146.8	30	41.7
25	183.5	35	48.7
30	220.2	40	55.6

NOTE: Computed distances are based on a critical headway of 5.0 s.

Exhibit A.16. Example design with a severe angle of visibility to the left.



SOURCE: Adapted from Tian et al. and *NCHRP Report 672* (*5, 6*).

View angles use the intersection sight distance values from this section. A possible method for conducting view angle evaluations includes the following steps:

1. Determine the vehicle location at the yield line. For multilane entries, each lane should be checked. View angles must also be checked for right-turn bypass lanes.
2. Establish the sightline assuming there is a vehicle at the yield line and a vehicle upstream at the location needed for intersection sight distance (distance b_1).
3. Measure the angle between the alignment of the vehicle at the yield line and the alignment of the sightline.

Exhibit A.16 depicts an approach with an intersection angle less than 75 degrees.

A.3 Vehicle Path Alignment

Chapter 9: Geometric Design Process and Performance Checks discusses vehicle path alignment evaluations, which are specific to multilane roundabouts. The natural vehicle paths are the paths approaching vehicles will take through the roundabout geometry, guided by their speed and orientation in the presence of other vehicles. The key consideration in evaluating vehicle path alignment is that drivers cannot change the direction or speed of their vehicle instantaneously.

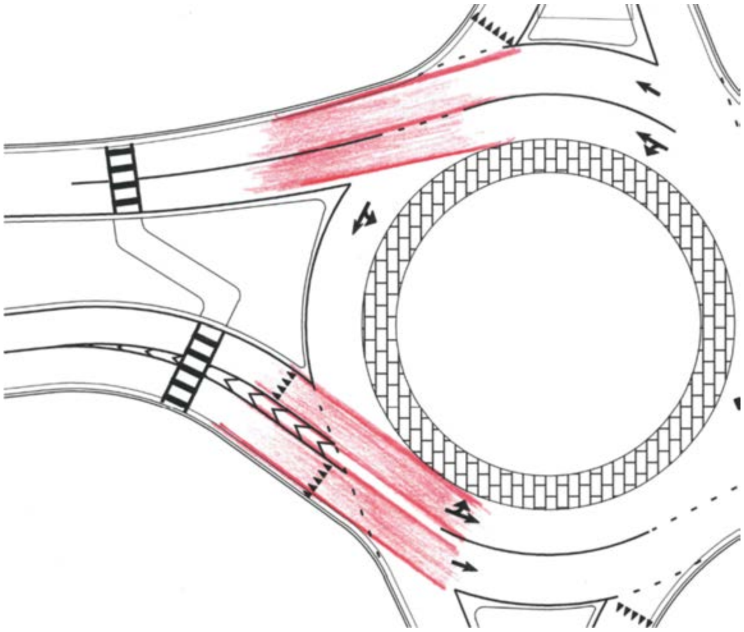
A possible method for vehicle path alignment evaluations includes the following steps:

1. Ensure that the roundabout entry directs vehicles to their intended lanes in the circulatory roadway.
2. Assess if the roundabout approach and entry channelization (e.g., splitter islands or traffic islands for right-turn lanes) allow transitions (tangents) between reverse curves (i.e., no back-to-back reverse curves).
3. Verify that consecutive vehicle path curves have a relatively similar radius that supports consistent speeds.
4. Assess if the vehicles circulating the roundabout are being directed to their intended exit lanes.
5. Verify that there is a tangent between the circulating lanes and the exit curve.
6. Assess if the exit curve provides speeds that are comparable to or larger than the circulating curve.
7. Inspect roundabouts (especially noncircular forms) for circulating speeds that are faster than exit speeds and require drivers to decelerate. However, if entry speeds are kept low, the added speed associated with a noncircular configuration may be 2 mph to 3 mph (3 km/h to 5 km/h) and have few adverse effects.

Exhibit A.17 shows a hand sketch of paths to assess vehicle alignment at a roundabout entry and exit. It also shows how to assess how effectively the geometry guides entering vehicles to their correct circulating lanes and how vehicles exiting the circulatory roadway are guided to their exit lanes.

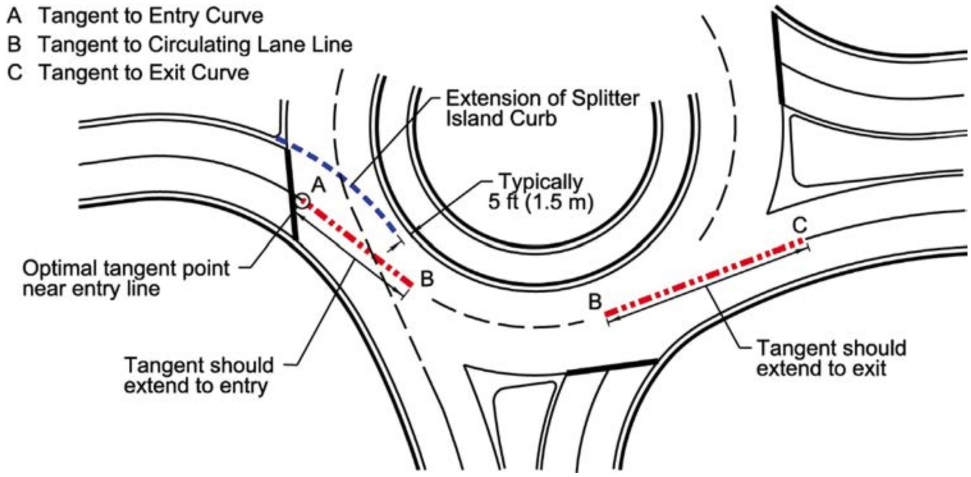
Exhibit A.18 presents a CAD-based example of assessing entry and exit configurations. The entry includes a tangent portion that guides the driver in the right lane along that bearing to the right circulating lane. This tangent also helps guide the left lane to the left circulating lane. It is common to include 2 ft to 5 ft (0.6 m to 1.5 m) of tangent on the left side of the left lane, with a

Exhibit A.17. Vehicle path alignment entering and exiting the roundabout.



SOURCE: Kittelson & Associates, Inc.

Exhibit A.18. Vehicle path alignment using CAD.



SOURCE: Adapted from Georgia Department of Transportation (*1*).

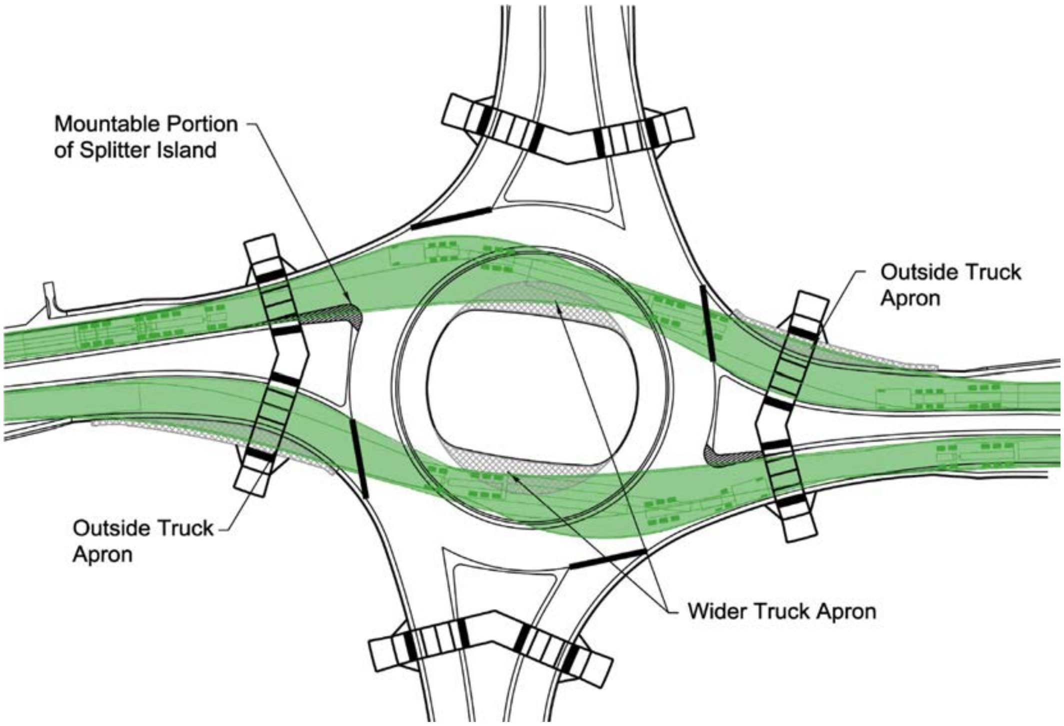
forward bearing that is tangential to the left edge of the left circulating lane. The exhibit also shows a tangent from the circulating lanes to the exit. This tangent provides a transition between reverse curves and guides the driver to the exit, where their path follows the exit curvature. Lines A–B and B–C need to be in the range of 40 ft to 60 ft (12 m to 18 m).

A.4 Design Vehicle

Chapter 9: Geometric Design Process and Performance Checks discusses design vehicle performance and checks. Software is commonly used to conduct design vehicle checks. However, some agencies continue to use truck templates to support early concept design development. A possible method for conducting a design vehicle evaluation includes the following steps:

1. Establish and document the design vehicle, which is the primary design check for trucks. Ensure that the design vehicle can travel through the roundabout between curbs, with some movements possibly using a truck apron for trailer off-tracking.
2. Establish and document what larger vehicle must be *accommodated*. This is based on serving a less frequent but larger control vehicle (or *check vehicle*). The check vehicle is an anticipated but infrequent user of the roundabout that simply needs to "get through." The check vehicle may require design features, such as additional truck aprons along the exterior, hardened surfaces beyond the curb, passageways through splitter islands or the central island, removable signs, or other treatments. A check vehicle may be required to allow a truck driver to drive their cab onto the truck apron to complete some movements.
3. For multilane roundabouts, establish and document if design vehicles may straddle lanes (use the entire curb-to-curb width for entering, circulating, and exiting plus the truck apron as needed) or be required to stay in-lane.
4. Conduct design vehicle performance checks:
   a. For the design vehicle, AASHTO recommends providing 1 ft to 2 ft (0.3 m to 0.6 m) of shy distance between the vehicle path (the traveled way) and the curb (*2*). Buses are to be accommodated within the circulatory roadway without tracking over the truck apron.
   b. Swept paths should be prepared for each turning movement. Frequently, right-turn movements are critical for truck movements, particularly at single-lane roundabouts.
   c. A smooth vehicle path should reflect a driver's realistic travel path. The cab of a tractor trailer design vehicle is typically assumed to stay within the travel lanes and not mount curbs, with truck aprons supporting off-tracking of only the trailer.

Exhibit A.19. Through movement swept path of an OSOW vehicle.



SOURCE: Adapted from Georgia Department of Transportation (*1*).

d. When conducting the design vehicle check, avoid using crawl speed and going wheel-lock to wheel-lock, as these are unrealistic operational assumptions. Understand and show the difference between the tire locations relative to the curb and the truck envelope itself, which may extend above and beyond the curb.

Exhibit A.19 presents the typical swept paths for an oversize/overweight (OSOW) vehicle making a through movement.

A.5 Bicycle and Pedestrian Design Flags

This section considers the design flag procedure in *NCHRP Research Report 948: Guide for Pedestrian and Bicyclist Safety at Alternative and Other Intersections and Interchanges* (*7*). Of the 20 design flags (Exhibit A.20 through Exhibit A.22) identified in *NCHRP Research Report 948* and summarized in Chapter 9: Geometric Design Process and Performance Checks, many can apply to roundabouts. Each flag can have a comfort aspect, a safety performance aspect, or both. A design review can proceed through the set of design flags and identify if any comfort or safety flags are present. These flags can provide a metric for comparing alternatives in the ICE activities, and they can also support preliminary design, including identifying potential design modifications to reduce or eliminate the flag.

A possible method for applying the design flags includes the following steps:

1. Review a design for each of the flags and identify if there are any comfort-related or safety-related flags. Practitioners should evaluate these flags for each of the bicyclist or pedestrian movements through the intersection, depending on the nature of the design flag.
2. If possible, modify the design to address any identified flags, or identify the modification that would be necessary for the concept to advance for further design refinement.

Exhibit A.20. Summary of design flags for pedestrian and bicycle intersection assessment, part 1 of 3.

Design Flag	Comfort Flag	Safety Flag	Notes
Motor vehicle right turns	na	na	The typical roundabout design of setting bicycle and pedestrian crossings at least one vehicle length away from the circulatory roadway addresses this flag. This flag is more common at other intersection forms.
Uncomfortable/tight walking environment	Pedestrian facilities less than 5 ft (1.5 m) of effective width.	Pedestrian facilities that do not meet ADA requirements, which creates significant out-of-direction travel and exposure for people who are blind or have low vision.	na
Nonintuitive motor vehicle movements	na	na	The typical roundabout design of setting bicycle and pedestrian crossings at least one vehicle length away from the circulatory roadway addresses this flag. This flag is more common at other alternative intersection forms.
Crossing yield or uncontrolled vehicle paths	Pedestrian crossings that result in high pedestrian delay.	Pedestrian crossings that do not satisfy pedestrian crossing assessment for people who are blind or have low vision.	na
Indirect paths	Pedestrian crossings that are farther than one to two vehicle lengths from the circulatory roadway if unsignalized or farther than 80 ft (25 m) from the circulatory roadway if staggered and signalized.	Pedestrian crossings that are omitted from a leg of a roundabout, forcing other routing around the roundabout or to adjacent intersections.	na
Executing unusual movements	na	na	The typical roundabout design of setting bicycle and pedestrian crossings at least one vehicle length away from the circulatory roadway addresses this flag. This flag is more common at other alternative intersection forms.
Multilane crossings	Pedestrian crossings with splitter islands that are too narrow for refuge can confuse pedestrians who are blind or have low vision, who may mistake a narrow island for a place where they can stop.	Multilane pedestrian crossings that do not have supplemental vertical deflection or active traffic control devices (signals, pedestrian hybrid beacons, or rectangular rapid-flashing beacons).	Multilane crossings at roundabouts are shorter than multilane crossings at other intersection forms, but multilane crossings are typically signalized at other intersection forms.
Long red times	na	Can occur if pedestrian crossings are signalized and coordinated with a long background cycle length.	This does not generally apply to roundabouts, except possibly when signalized crossings are implemented. This flag is more common at signalized intersections of various forms.

NOTE: na = not applicable. SOURCE: Adapted from *NCHRP Research Report 948* (*7*).

Exhibit A.21. Summary of design flags for pedestrian and bicycle intersection assessment, part 2 of 3.

Design Flag	Comfort Flag	Safety Flag	Notes
Undefined crossing at intersections	na	na	Pedestrian crossings are typically marked at roundabouts.
Motor vehicle left turns	na	na	The typical roundabout design of setting bicycle and pedestrian crossings at least one vehicle length away from the circulatory roadway addresses this flag. This is more common at other intersection forms.
Driveways and side streets at or near intersection	Driveways and side streets within or in proximity to the roundabout may adversely affect wayfinding for pedestrians with vision disabilities.	Driveways may introduce conflicts with both pedestrians and bicyclists.	At roundabouts with high vehicular volumes or where ambient noise is high, it may not be possible for pedestrians who are blind or have low vision to hear vehicles entering from a driveway or side street. Geometric speed control may be needed to ensure yielding by vehicles entering from a driveway or side street close to a circulatory roadway.
Sight distance and auditory distance for gap acceptance movements	na	Inadequate sight distance between drivers and pedestrians. Inadequate auditory distance, especially in noisy environments, for pedestrians who are blind or have low vision to make gap or yield judgments.	In noisy environments, it may be difficult to hear vehicles well enough to make safe gap or yield judgments at even single-lane roundabouts.
Grade change	na	Inadequate sight distance between drivers and bicyclists or between drivers and pedestrians.	These are most often caused by grade breaks or vertical curves adjacent to intersections.
Riding or walking in mixed traffic	Roundabouts with a shared bicycle-pedestrian facility around the perimeter.	Multilane roundabouts without any type of bicycle facility that is separated from motor vehicles around the perimeter.	This is typically more of an issue with on-street bicycle facilities on high-speed or high-volume roads. Separated bicycle and pedestrian facilities are more comfortable for people riding and walking. Pedestrians, especially those who are elderly or who have disabilities, may be unable to hear or see bicycles or to quickly move out of the path of bicyclists who assume that pedestrians will move out of their way.
Bicycle clearance times	na	na	This does not apply to roundabouts and is more common with larger signalized intersections.

NOTE: na = not applicable. SOURCE: Adapted from *NCHRP Research Report 948* (*7*).

Exhibit A.22. Summary of design flags for pedestrian and bicycle intersection assessment, part 3 of 3.

Design Flag	Comfort Flag	Safety Flag	Notes
Lane change across motor vehicle travel lane(s)	na	Left-turning bicyclists at multilane roundabouts without a separated bicycle or shared bicycle-pedestrian facility around the perimeter; nonyielding, right-turn bypass lanes, where through bicyclists using the travel lanes must cross bypass lane to continue.	na
Channelized lanes	na	na	The typical roundabout design does not have bicyclists traveling next to motor vehicles in long channelized lanes. This is more common at other intersection forms.
Turning motorists crossing bicycle path	na	na	The typical roundabout design of setting bicycle and pedestrian crossings at least one vehicle length away from the circulatory roadway addresses this flag. This is more common at other intersection forms.
Riding between travel lanes, lane additions, or lane merges	Right-turn bypass lanes where a parallel acceleration lane or deceleration lane is next to a bicycle lane.	na	na
Off-tracking trucks in multilane curves	na	na	The typical roundabout design of not using bicycle lanes at entry or exit or in the circulatory roadway addresses this flag. This is more common at other intersection forms.

NOTE: na = not applicable. SOURCE: Adapted from *NCHRP Research Report 948* (*7*).

3. If a concept continues to have flags (which it might, depending on the alternative), the flags can be tallied to determine the total number of comfort-related flags and safety-related flags. *NCHRP Research Report 948* provides examples of forms for this process.
4. If desired, use a qualitative rating or ranking to compare alternatives based on the number of comfort-related or safety-related design flags, recognizing that these design flags are only part of the overall evaluation process. If a concept has safety-related design flags that cannot be addressed through design modifications, the concept could be flawed enough to eliminate from subsequent evaluations. If a concept has comfort-related design flags, the quantity and nature of these flags may help differentiate alternatives.

A.6 Pedestrian Crossing Assessment

This section summarizes the key assessment models for crossing delay and expected level of risk as presented in *NCHRP Research Report 834: Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities: A Guidebook* and its successor project, NCHRP Project 03-78c, "Training and Technology Transfer for Accessibility Guidelines for Roundabouts and Channelized Turn Lanes," which amended the assessment procedure in *NCHRP Research Report 834* (*8*, *10*, *11*). Further detail can be found in those documents, including sample checklists and worksheets. Crossing sight distance has been integrated into the sight distance procedure presented in Chapter 9: Geometric Design Process and Performance Checks.

A.6.1 Possible Method

A possible method for conducting a pedestrian crossing assessment may include the following steps:

1. Assess vehicle path speeds using one of the techniques described in Section A.1.
2. Assess sight distance using one of the techniques described in Section A.2.
3. Assess pedestrian delay and crossing risk using the models presented in this section, supported by *NCHRP Research Report 834* as amended by NCHRP Project 03-78c (*10*).
4. Assess the sufficiency of these calculated performance measures to determine an appropriate crossing treatment, if any. Section A.6.2 illustrates a possible application.

The worksheets and models in Exhibit A.23 and Exhibit A.24 were developed for NCHRP Project 03-78c in US Customary units only. Appropriate conversions need to be used for inputs and outputs.

A.6.2 Possible Application

This section presents an example of a possible application based on unpublished work prepared for the Montana Department of Transportation and the Pennsylvania Department of Transportation (*10*, *11*). **This example of a possible application should not be misconstrued as a standard, as it requires deciding what constitutes an acceptable level of risk, which is beyond the scope of this document and the Transportation Research Board.**

Exhibit A.25 shows results from this possible application. The three models used for this possible application are as follows:

- **Intervention model.** This model predicts *high risk* at two-lane exits for fastest path speeds exceeding 25 mph. The research defines an intervention as an event when a pedestrian who is blind or has low vision makes a crossing decision that would have resulted in a certified orientation and mobility specialist stopping the person from crossing, such as stepping in front of an oncoming vehicle that the person who is blind or has low vision did not detect. This is based on an assumed maximum acceptable crossing risk of 4 percent, which is comparable to most single-lane roundabouts studied under *NCHRP Research Report 834*. Using this threshold, two-lane entries show acceptable risk up to 40 mph based on the NCHRP Project 03-78c models and, therefore, do not suggest the need to evaluate a risk-based treatment for entries unless ambient noise level is high. The intervention model results in the region denoted high risk in Exhibit A.25.
- **Delay model.** This model predicts *high delay* at a combination of high speeds (results in low yielding) and high volumes (results in low gap availability). The maximum acceptable pedestrian delay was set at 30 seconds, based on the *Highway Capacity Manual* observation (HCM Exhibit 20-3) that for delays exceeding 30 seconds per pedestrian, the delay approaches a tolerance level with the risk-taking behavior likely (*12*). Everything above the trend line in Exhibit A.25 is considered high delay.
- **Yielding model.** This model predicts yielding as a function of speed and other variables. The *high yield* (more than 50 percent) is shown in Exhibit A.25. In low-speed environments, low yielding is typically only a concern in combination with high volume, which results in high delay. As a result, the yielding model results are shown for reference only and are not used in the guidance development.

Exhibit A.23. Pedestrian crossing assessment, part 1 of 2.

Crossing Assessment Worksheet			Quadrant A for CTL or		Quadrant B for CTL or		Quadrant C for CTL or		Quadrant D for CTL or	
Task	Default Values	Units	Crossing A-B Entry	Crossing A-B Exit	Crossing B-C Entry	Crossing B-C Exit	Crossing C-D Entry	Crossing C-D Exit	Crossing D-A Entry	Crossing D-A Exit
Step 1. Gather Site Data and Other Inputs										
Step 2. Predict Vehicle Speed at Crosswalk										
Speed at crosswalk, $V_{critical}$	(none)	[mph]								
Step 3. Calculate Crossing Sight Distance										
Crosswalk length, L_n	(none)	[ft]								
Design ped walking speed, S_p	3.5	[ft/s]								
Ped start-up time and end clearance time, t_s	2	[s]								
Critical headway, $t_{n,c} = \frac{L_n}{S_p} + t_s$	(none)	[s]								
Crossing sight distance, $d_n = 1.47\ V_n t_{n,c}$	(none)	[ft]								
Step 4. Checking Sight Distance Provisions										
Performance Check 1: Is Adequate Sight Distance Available?										
Step 5. Predict Crossing Opportunities (Gaps and Yields)										
Volume, N_{veh}	(none)	[veh]								
Crossing type	1L, 2L, CTL	[]								
Probability of encountering usable gap, $P_g = e^{\frac{-t_{n,c} * N_{veh}}{3600}}$	(none)	[]								
Single-lane crossing/CTL crossing										
Indicator variable for exit, I_{ex}	1 = exit, 0 = entry/CTL	[]								
Indicator variable for entry, I_{en}	1 = entry, 0=exit/CTL	[]								
Indicator variable for high compliance region, I_{HC}	1=high, 0=low	[]								
Prob. of yields, single-lane roundabout/CTL, $P_Y = (0.6888 - 0.07688 * I_{ex} + 0.62954 * I_{en} + 0.37418 * I_{HC})e^{-0.03465 * V}$	(none)	[]								
Two-lane crossing										
Indicator variable for RRFB, I_{RRFB}	1=yes, 0=no	[]								
Indicator variable for exit, I_{ex}	1=exit, 0=entry	[]								

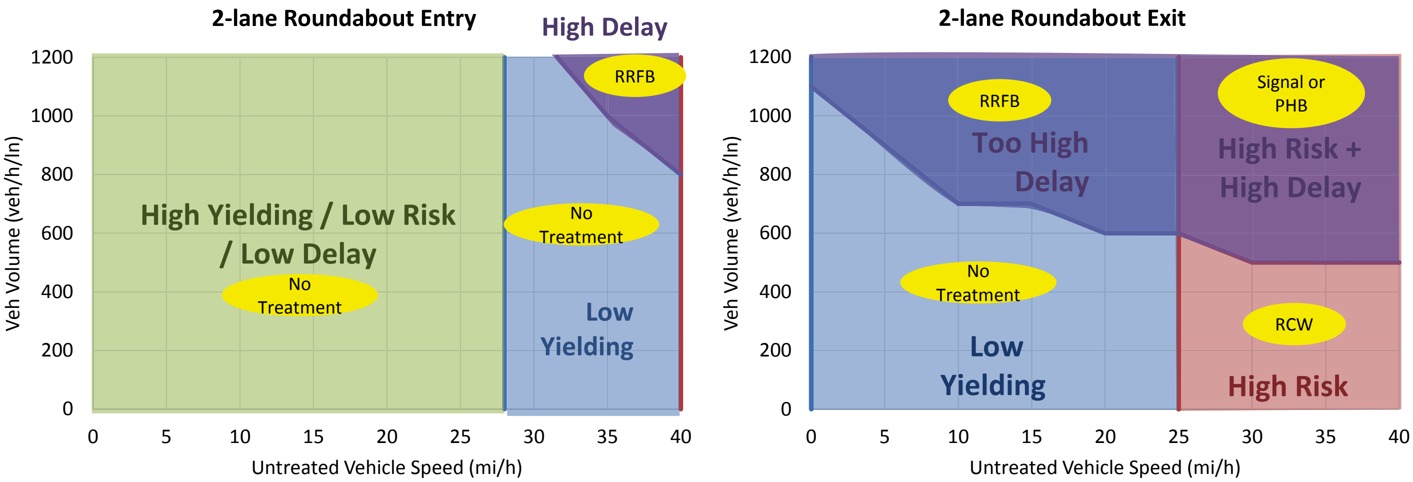
SOURCE: NCHRP Project 03-78c (*9*).

Exhibit A.24. Pedestrian crossing assessment, part 2 of 2.

Crossing Assessment Worksheet			Quadrant A for CTL or		Quadrant B for CTL or		Quadrant C for CTL or		Quadrant D for CTL or	
Task	Default Values	Units	Crossing A-B Entry	Crossing A-B Exit	Crossing B-C Entry	Crossing B-C Exit	Crossing C-D Entry	Crossing C-D Exit	Crossing D-A Entry	Crossing D-A Exit
Indicator variable for high compliance region, I_{HC}	1=high, 0=low	[]								
Prob. of yields, two-lane roundabout, $P_Y = (0.7259 + 0.2105 * I_{RRFB} - 0.2574 * I_{ex} + 0.3244 * I_{HC})e^{-0.0129*V}$	(none)	[]								
Probability of yields, P_Y (select row based on 1L/2L/CTL)	(none)	[]								
Probability of yield crossing opportunities, $P_{YC} = P_Y * (1 - P_G)$	(none)	[]								
Step 6. Estimate Utilization of Gaps and Yields										
Probability of using a gap, P_{UG} (default for roundabouts = 65%)	Rbt = 0.65, CTL = 0.60	[]								
Probability of using a yield, P_{UY} (default for roundabouts = 70%)	Rbt = 0.70, CTL = 0.35	[]								
Step 7. Estimate Blind Pedestrian Delay										
Probability of crossing, $P_C = P_{YC} * P_{UY} + P_G * P_{UG}$	(none)	[]								
Delay, single-lane crossing, $d_p = 9.37 - 9.78 * ln(P_C)$	(none)	[s/veh]								
Delay, two-lane crossing, $d_p = 6.14 - 8.53 * ln(P_C)$	(none)	[s/veh]								
Delay, CTL, $d_p = 10.75 - 9.95 * ln(P_C)$	(none)	[s/veh]								
Delay, d_p (select row based on 1L/2L/CTL)	(none)	[s/veh]								
Step 8. Determine Delay-Based Pedestrian LOS										
Performance Check 2: Is the Pedestrian LOS within the guidelines for your agency?										
Step 9. Estimate Crossing Risk										
Indicator variable for entry/exit, I_{ex}	1=exit, 0=entry/CTL	[]								
Indicator variable for noise, I_N	1=noisy, 0=low noise	[]								
Indicator variable for number of lanes, I_{1L}	1=1L or CTL, 0=2L	[]								
Probability of intervention, $P_I = (0.011895 + 0.008443 * I_{ex} + 0.021915 * I_N - 0.007186 * I_{1L})e^{0.027697*V}$	(none)	[]								
Step 10. Check Crossing Risk										
Performance Check 3: Is probability of an intervention within range allowable by your agency?										
Step 11. Visibility of Traffic Control Devices										
Step 12. Complete Crosswalk Assessment										

SOURCE: NCHRP Project 03-78c (*9*).

Exhibit A.25. Example of a possible assessment of treatments by risk, delay, and yielding for two-lane roundabouts in low-noise environments.



SOURCE: Montana Department of Transportation and Pennsylvania Department of Transportation (*10, 11*). RRFB = rectangular rapid-flashing beacon; PHB = pedestrian hybrid beacon; RCW = raised crosswalk.

For each of the different regions, the treatment selection is as follows:

- **High Risk + High Delay.** This condition suggests using a traffic control signal or a pedestrian hybrid beacon (PHB).
- **High Risk + Low Delay.** This condition suggests using at least a raised crosswalk (RCW) and may require more advanced treatments, like a traffic control signal or a PHB. A rectangular rapid-flashing beacon (RRFB) is not suggested because vehicle speeds are too high.
- **Low Risk + High Delay.** This condition suggests at least an RRFB and may require more advanced treatments, like a traffic control signal or a PHB. An RCW is not suggested because vehicle volumes are too high.
- **Low Risk + Low Delay.** This condition suggests no additional treatments are needed, but additional treatments could certainly be considered.

This exhibit is based on assumed thresholds for acceptable performance and is an example of possible guidance. This should not be misconstrued as a recommended standard or guidance in this Guide or by the Transportation Research Board.

Exhibit A.25 suggests that under certain vehicle speed and vehicle volume conditions, it may be possible to provide equivalent accessibility using treatments other than active regulatory devices, such as a traffic control signal or a PHB. As noted in Chapter 12, to meet pedestrian and driver expectations, the same crossing treatment should be used on the entry and exit of a roundabout leg.

A.7 Pedestrian Wayfinding Assessment

Exhibit A.26 provides a checklist for pedestrian wayfinding performance. The checklist has been adapted from Appendix C of the NCHRP Project 03-78c Final Report, which amends *NCHRP Research Report 834* (*9*, *8*). The checklist references *NCHRP Research Report 834* for design details, many of which have been superseded by content in this Guide. The checklist also references US DOT regulations related to the ADA (42 USC 12131-12134) and the *Manual on Uniform Traffic Control Devices* (MUTCD) as well as proposed Public Right-of-Way Accessibility Guidelines (PROWAG) (*13–15*).

Exhibit A.26. Pedestrian wayfinding checklist.

Question	Sources for Information
Determining the Crossing Location	
Do sidewalks lead to the crosswalks?	Chapter 10; *NCHRP Research Report 834* (*8*).
Is continuous, cane-detectable edge treatment or landscaping provided between the sidewalk and the curb?	Chapter 10; *NCHRP Research Report 834* (*8*). Required by proposed PROWAG at roundabouts (*15*).
Are there detectable warning surfaces at the bottom of curb ramps or on the sidewalk at each end of raised crosswalks?	Chapter 10; *NCHRP Research Report 834* (*8*). Required by US DOT ADA regulations (*13*) and proposed PROWAG (*15*).
If other ramps or driveways are nearby, are they adequately delineated and separated from the pedestrian crossing ramps?	Chapter 10; *NCHRP Research Report 834* (*8*).
Are traffic control devices, including push buttons for signals and beacons, accessible?	Chapter 12; *NCHRP Research Report 834* (*8*); MUTCD (*14*). Required by proposed PROWAG (*15*).
Aligning to Cross and Establishing a Correct Heading	
Is the curb ramp width the same as the crosswalk width?	Chapter 10; *NCHRP Research Report 834* (*8*).
Is the curb ramp slope aligned with the crossing?	Chapter 10; *NCHRP Research Report 834* (*8*).
Are ramp edges aligned with the crossing?	Chapter 10; *NCHRP Research Report 834* (*8*).
Is the detectable warning aligned with the slope of the curb ramp?	Chapter 10; *NCHRP Research Report 834* (*8*).
If push buttons for traffic control devices are provided, are they accessible and in the correct location?	Chapter 12; *NCHRP Research Report 834* (*8*); MUTCD (*14*).
Is there a sufficiently level landing for turning at either the top of perpendicular curb ramps or the bottom of parallel ramps?	Required by US DOT ADA regulations (*13*) and proposed PROWAG (*15*).
Maintaining a Correct Heading while Crossing and Staying Within the Crosswalk	
Is the crossing configured at the shortest distance practical?	Chapter 10; *NCHRP Research Report 834* (*8*).
Is the crossing aligned perpendicular to the curb and splitter edges?	Chapter 10; *NCHRP Research Report 834* (*8*).
Are markings clearly visible?	Chapter 12; *NCHRP Research Report 834* (*8*); MUTCD (*14*).
Crossing from Channelization Islands and Splitter Islands	
Are islands wide enough to provide safe refuge?	Chapter 10; *NCHRP Research Report 834* (*8*).
Are there detectable warning surfaces at the bottom of curb ramps or on the sidewalk at each end of raised crosswalks (unless the islands are less than 6 ft, or 1.8 m, in width)?	Chapter 10; *NCHRP Research Report 834* (*8*). Required by US DOT ADA regulations (*13*) and proposed PROWAG (*15*).
Are paths through islands clearly defined by grade difference or landscaping?	Chapter 10; *NCHRP Research Report 834* (*8*).
If push buttons for traffic control devices on the island are provided, are they accessible and in the recommended location?	Chapter 12; *NCHRP Research Report 834* (*8*); MUTCD (*14*).

SOURCE: Adapted from Kittelson & Associates, Inc., and Accessible Design for the Blind, Appendix C (*9*).

A possible method for conducting a pedestrian wayfinding assessment may include the following steps:

1. Evaluate each of the wayfinding questions for each quadrant of the roundabout. Examples of wayfinding assessments are in *NCHRP Research Report 834*.
2. Review a design using each of the wayfinding questions and identify any design gaps. These should be evaluated for each quadrant or leg of the roundabout.
3. If possible, modify the design to address any identified gaps, or identify the modification necessary for the concept to advance for further design refinement.
4. If desired, use a qualitative rating or ranking to compare alternatives based on how well the concept addresses wayfinding. These ratings or rankings may help differentiate alternatives.

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Abbreviations and Acronyms

AADT	annual average daily traffic
AC	asphalt concrete
ACPA	American Concrete Pavement Association
ADAAG	*ADA Accessibility Guidelines*
AWSC	all-way stop-controlled
BIM	building information modeling
CAD	computer-assisted drafting
Cap-X	Capacity Analysis for Planning of Junctions
CAV	connected and automated vehicle
CFR	US Code of Federal Regulations
CMF	crash modification factor
DC	Washington, DC
DOT	department of transportation
DWS	detectable warning surface
DDI	diverging diamond interchange
The Guide	*Guide for Roundabouts*
HCM	*Highway Capacity Manual*
HMA	hot-mix asphalt
ICD	inscribed circle diameter
ICE	intersection control evaluation
IES	Illuminating Engineering Society
IIHS	Insurance Institute for Highway Safety
K	ratio of peak hour to daily traffic
KDOT	Kansas Department of Transportation
LOS	level of service
LTS	level of traffic stress
MUTCD	*Manual on Uniform Traffic Control Devices for Streets and Highways*
NACTO	National Association of City Transportation Officials
OSOW	oversize or overweight
PCC	portland cement concrete
PDO	property damage only
PennDOT	Pennsylvania Department of Transportation
PHB	pedestrian hybrid beacon
PROWAG	Public Right-of-Way Accessibility Guidelines
RCW	raised crosswalk
RRFB	rectangular rapid-flashing beacon
SPF	safety performance function
SPICE	Safety Performance for Intersection Control Evaluation

SU	single unit
TDI	tactile directional indicator
TWD	tactile warning delineator
TWSC	two-way stop control
TWSI	tactile walking surface indicator
V2V	vehicle-to-vehicle
Veh/hr	vehicles per hour
WB	wheelbase

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
GHSA	Governors Highway Safety Association
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S. DOT	United States Department of Transportation

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