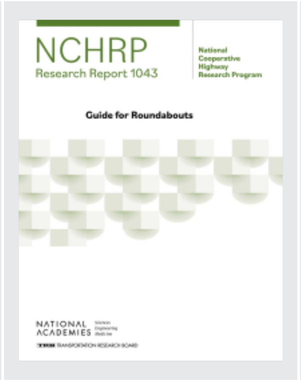

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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.

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The needs for highway research are many, and NCHRP can make significant contributions to solving highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement, rather than to substitute for or duplicate, other highway research programs.

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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.

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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).

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PART I Introduction to Roundabouts

PART II Planning and Stakeholder Considerations

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 Phase	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

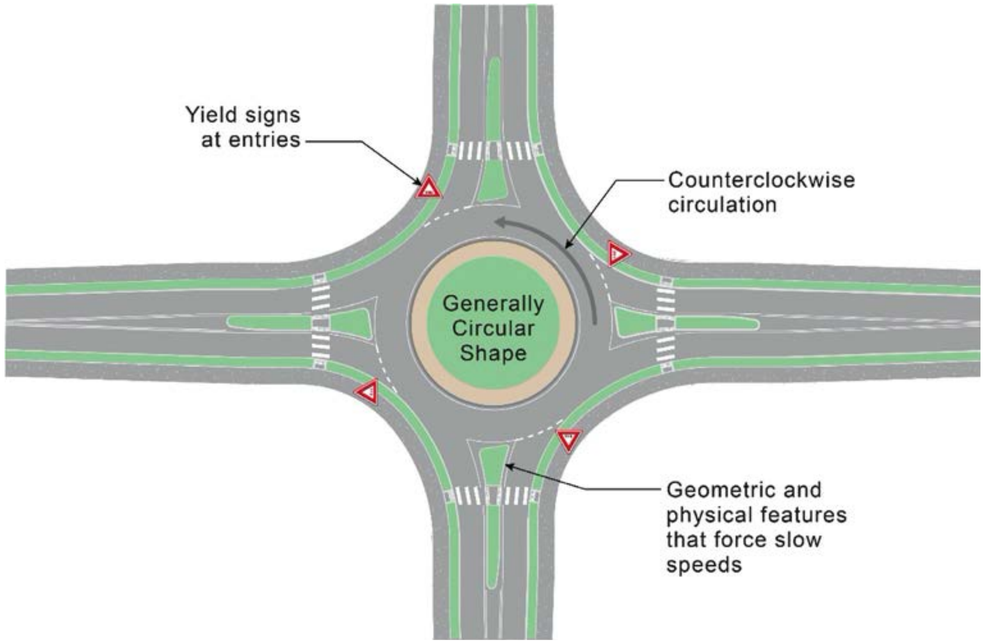
Contents

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*).

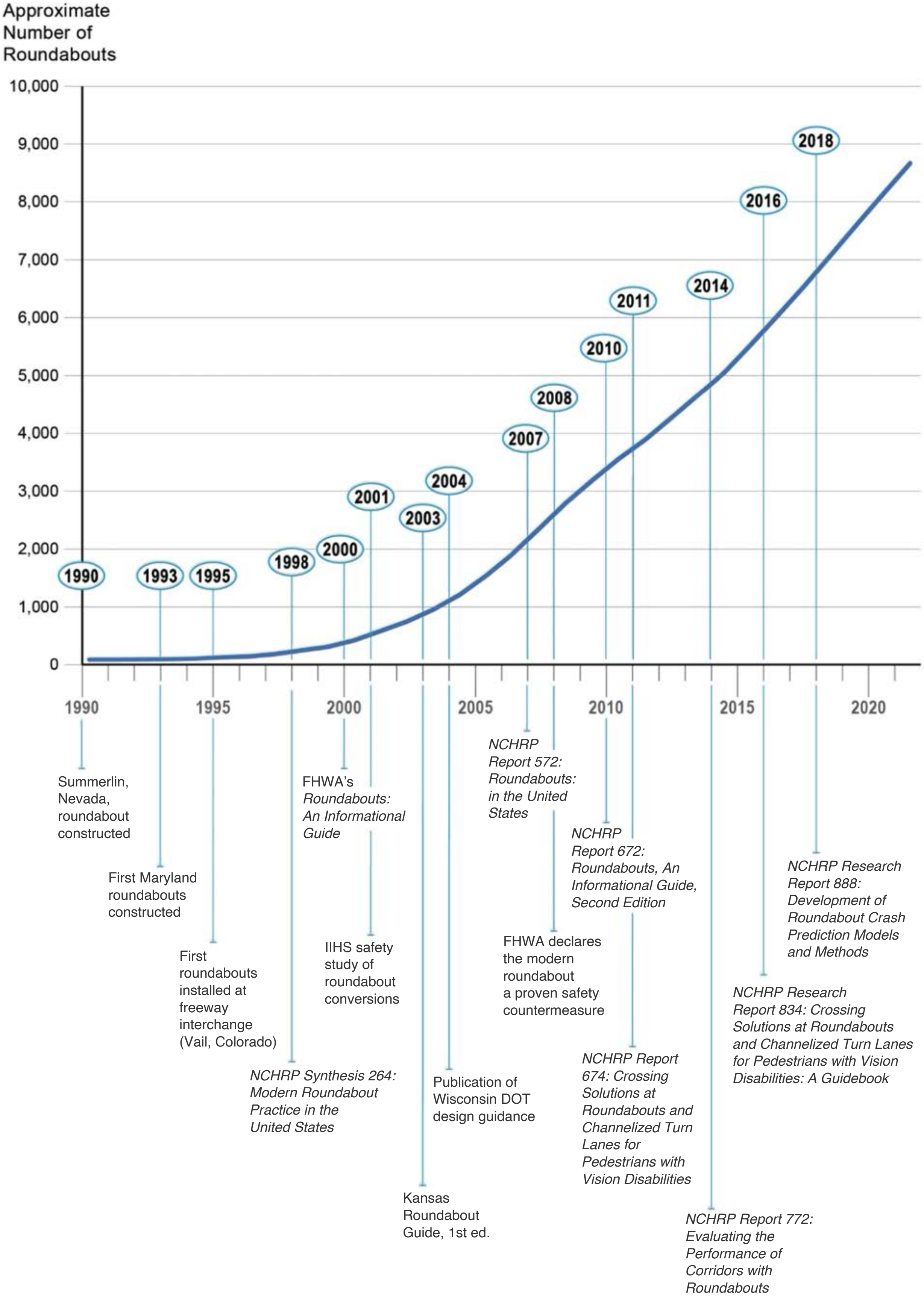
1.4 Policy and Practice Considerations

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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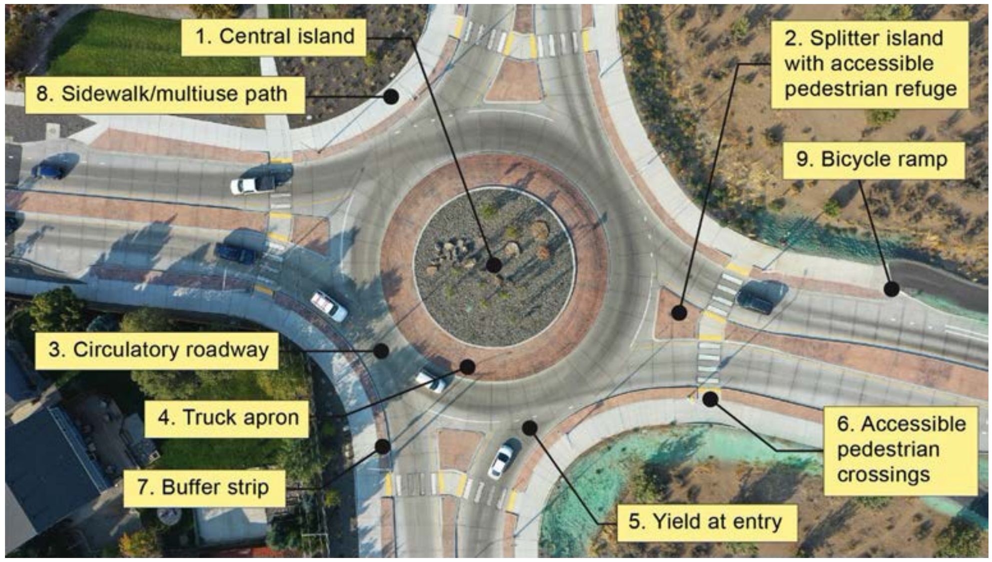
CHAPTER 2

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.

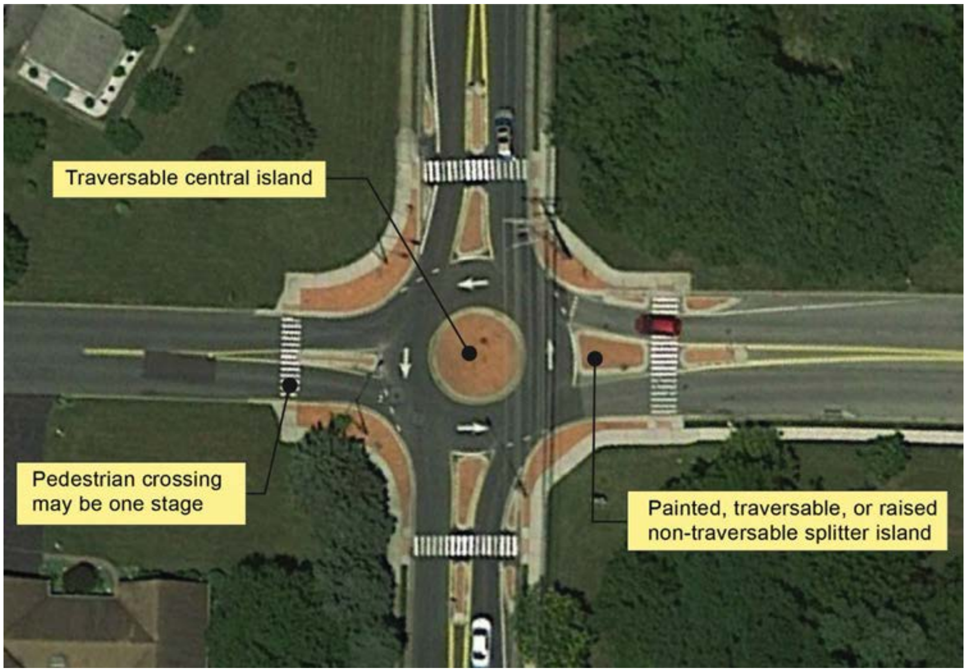
The design of a roundabout with traversable elements needs to align vehicles at entry to guide drivers to the intended path and minimize overrun of the central island to the extent possible. Exhibit 2.10 provides an example of such a roundabout. Note that the pedestrian crossings in this example are 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.

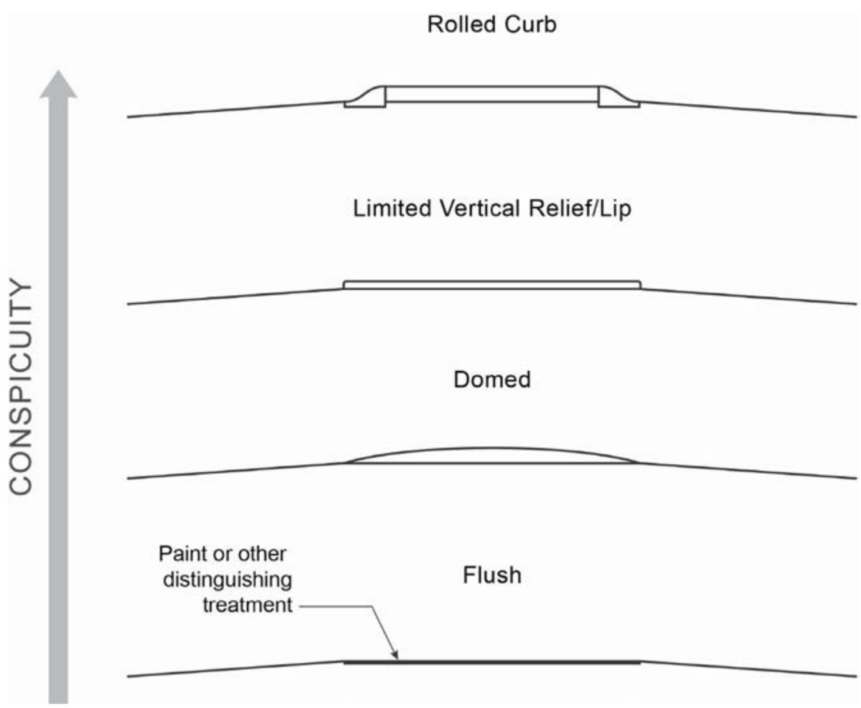


Exhibit 2.14. Example of painted splitter island at a roundabout with traversable features.

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.

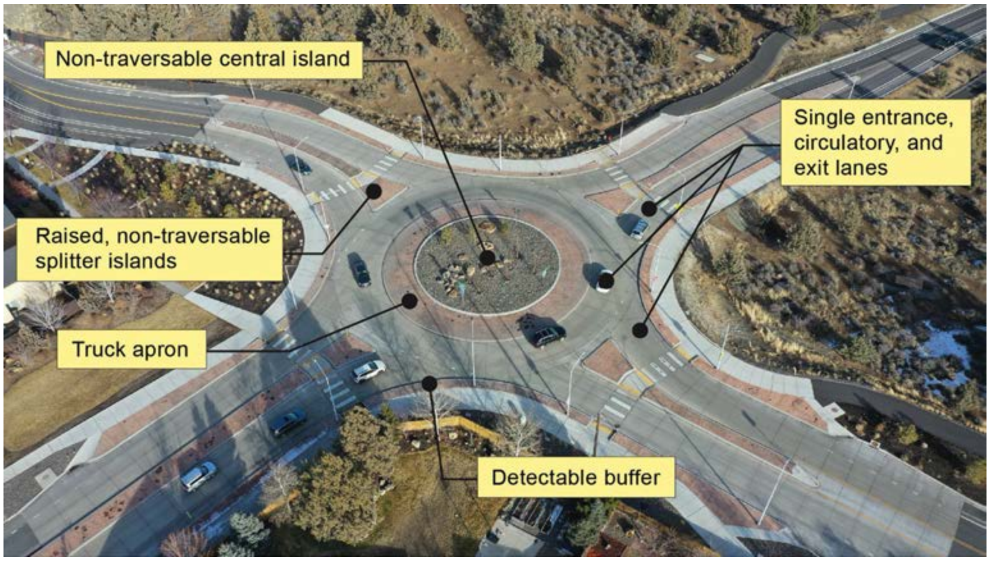
2.3.4 Multilane Roundabouts

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.

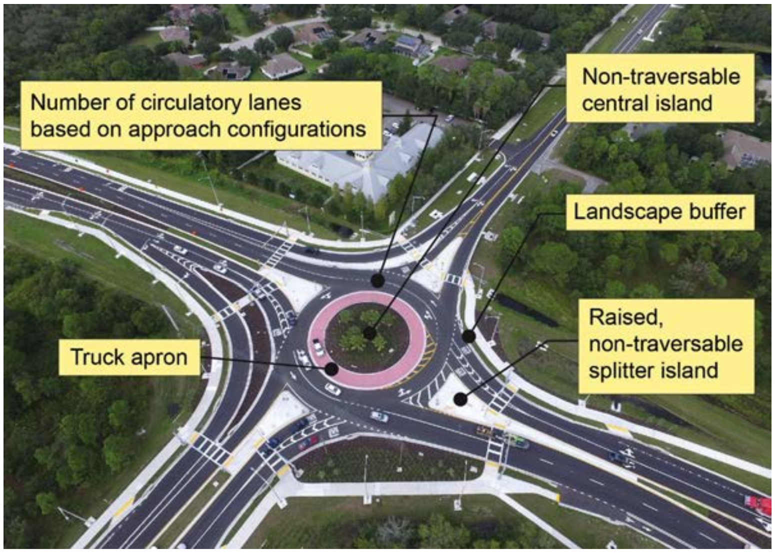
Exhibit 2.16. Example of single-lane roundabout with non-traversable central island and splitter islands.

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.

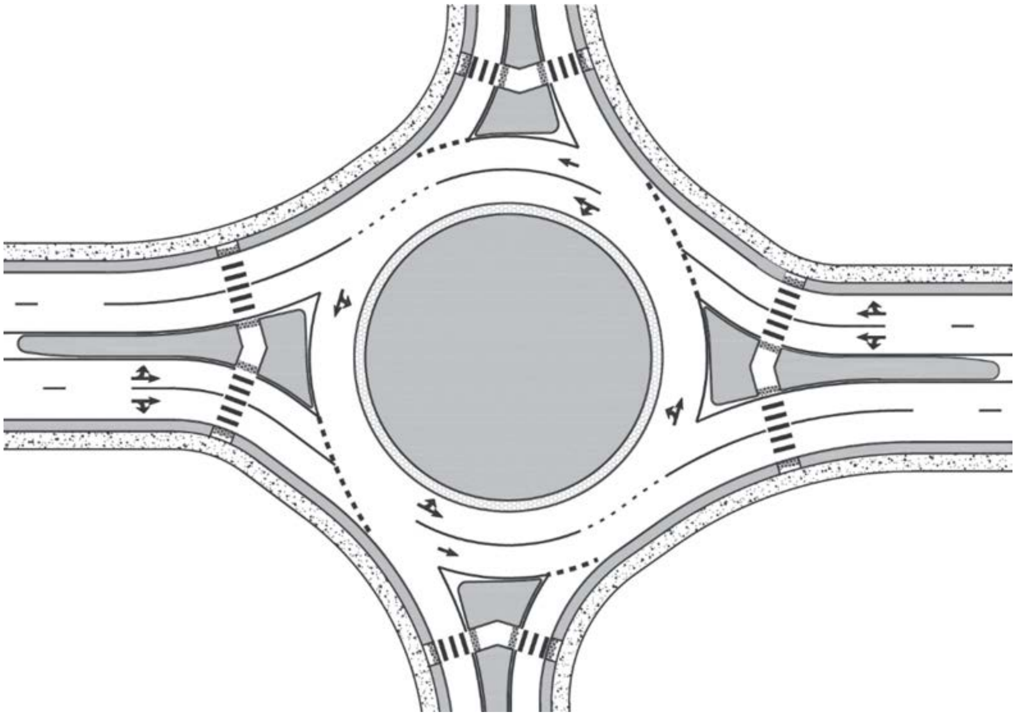
their larger ICD and wider entry and exit configurations that allow vehicles to navigate larger curve radii on their travel paths through the roundabout. Circulatory roadway widths may also vary, depending on the number of lanes and the design vehicle turning requirements. A constant width is not required 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.

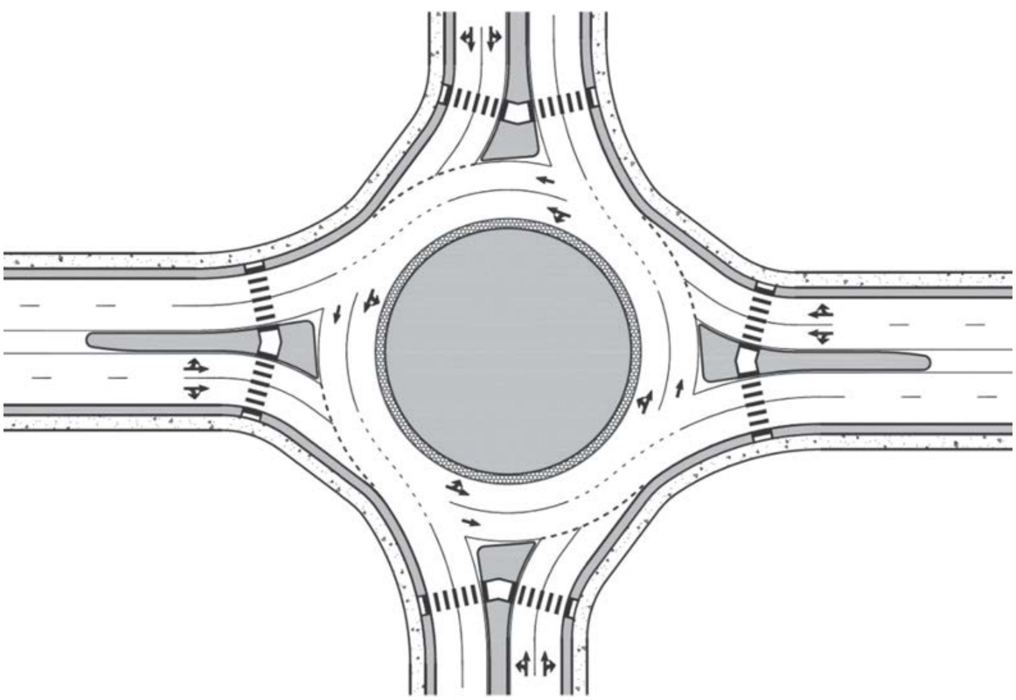
In some instances, the circulatory roadway width may have more lanes than the corresponding entrance that feeds that portion of the roundabout. For example, where dual turn lanes are provided with a two-lane upstream approach, a portion of the circulatory roadway will need two lanes. In these cases, 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.



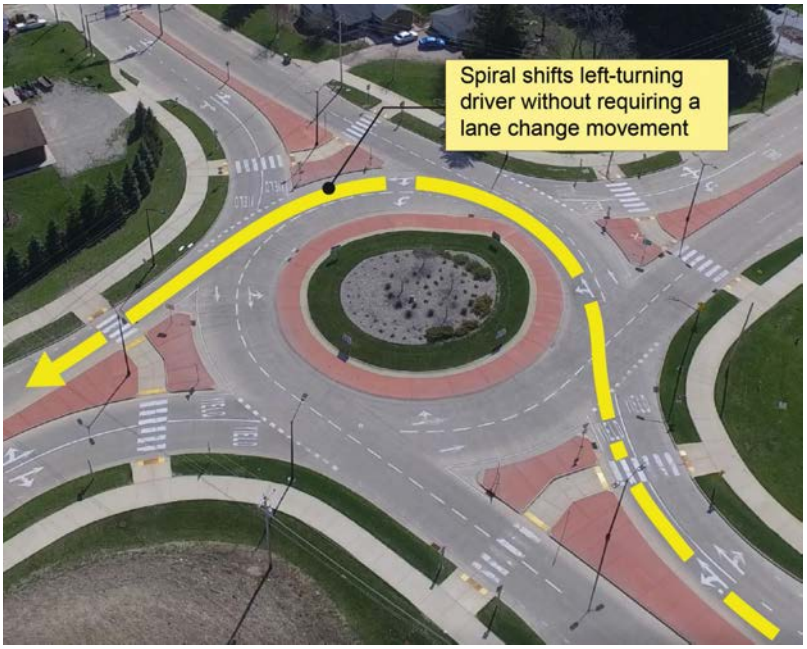
SOURCE: *NCHRP Report 672* (*1*).

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.

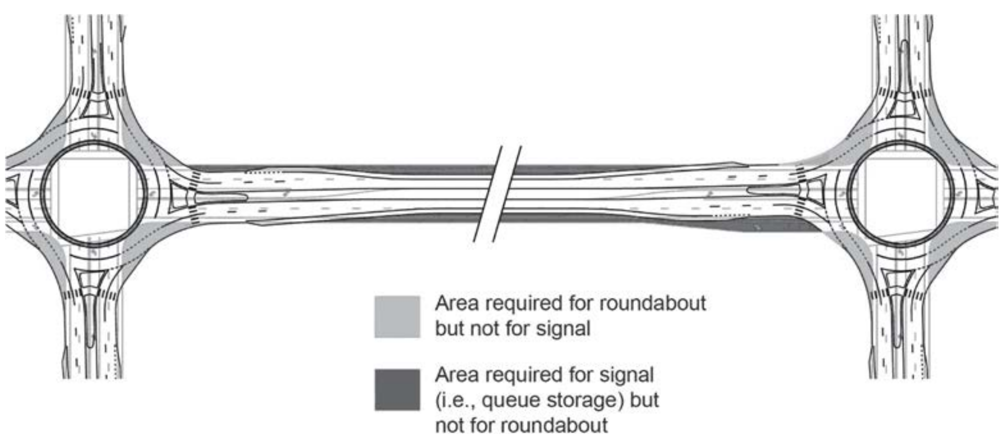
2.4.4 Access Management

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*).

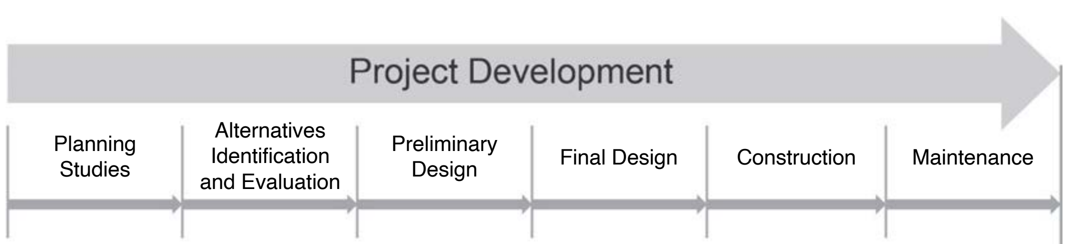
Performance goals and outcomes can influence a project even before project design begins. Early project scoping, alternatives identification, and evaluation efforts significantly influence subsequent design outcomes. As a project evolves from preliminary to final design, it becomes more difficult to 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.

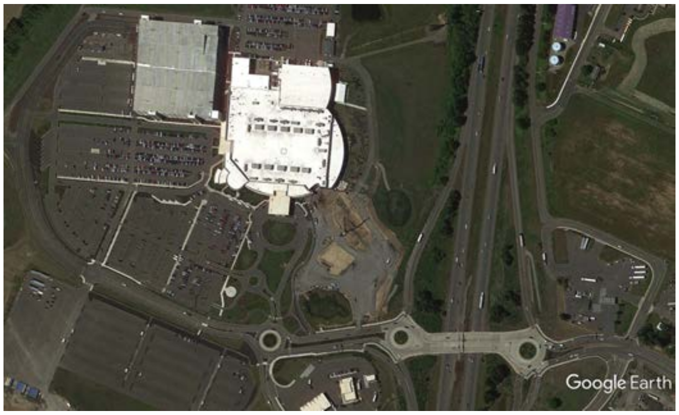
LOCATION: La Jolla Boulevard, San Diego, California. SOURCE: Map data ©2022 Google.

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

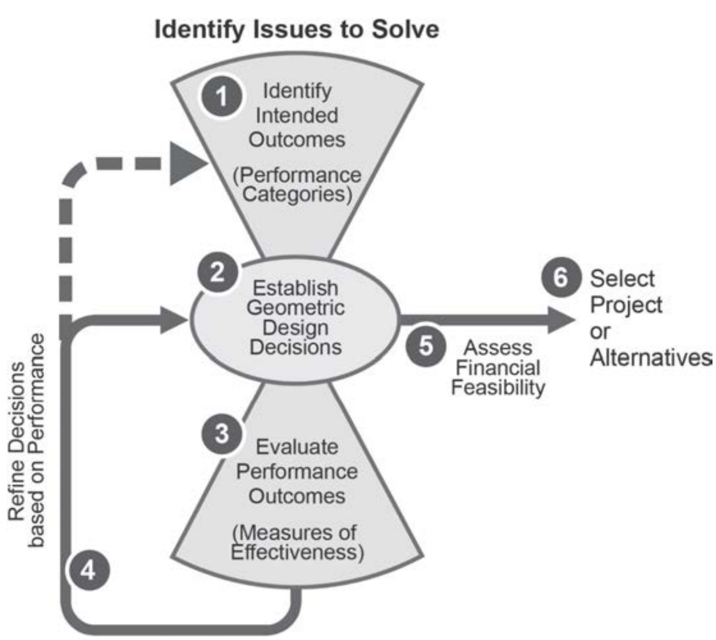
Many agencies have developed roundabout policies or ICE processes to guide designers and planners in making appropriate decisions when considering intersection traffic control. In some cases, these agencies have task forces that establish a policy for implementing roundabouts on their facilities. These 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

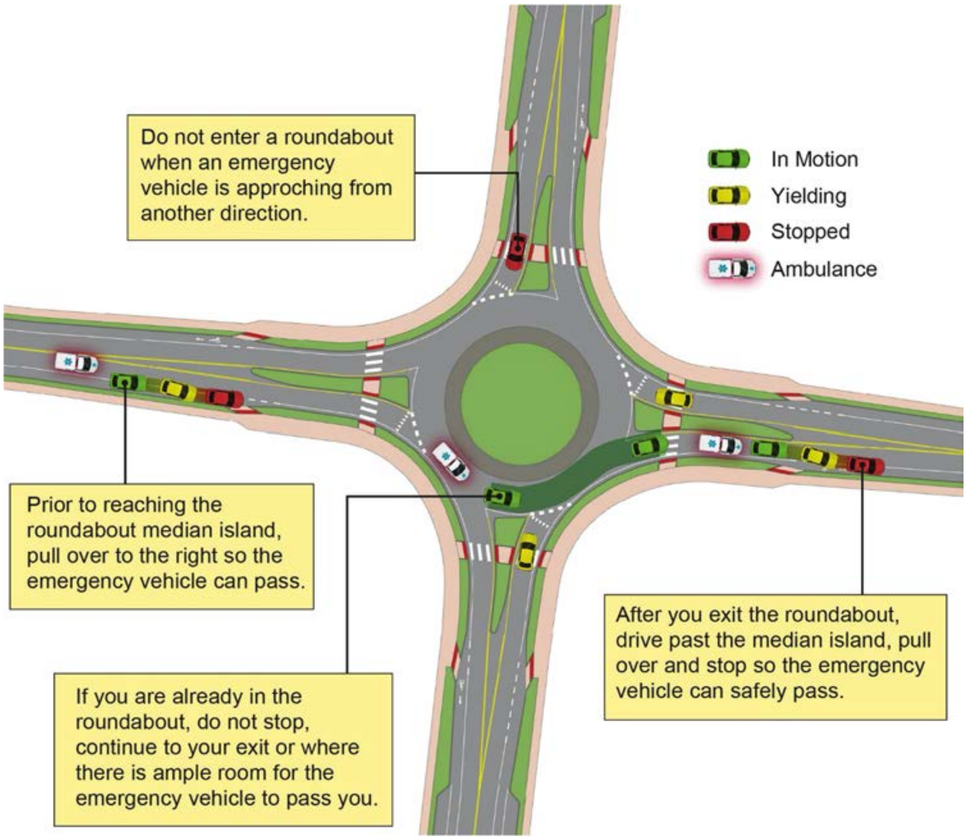
Exhibit 4.9. Examples of roundabout-specific rules of the road.

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.

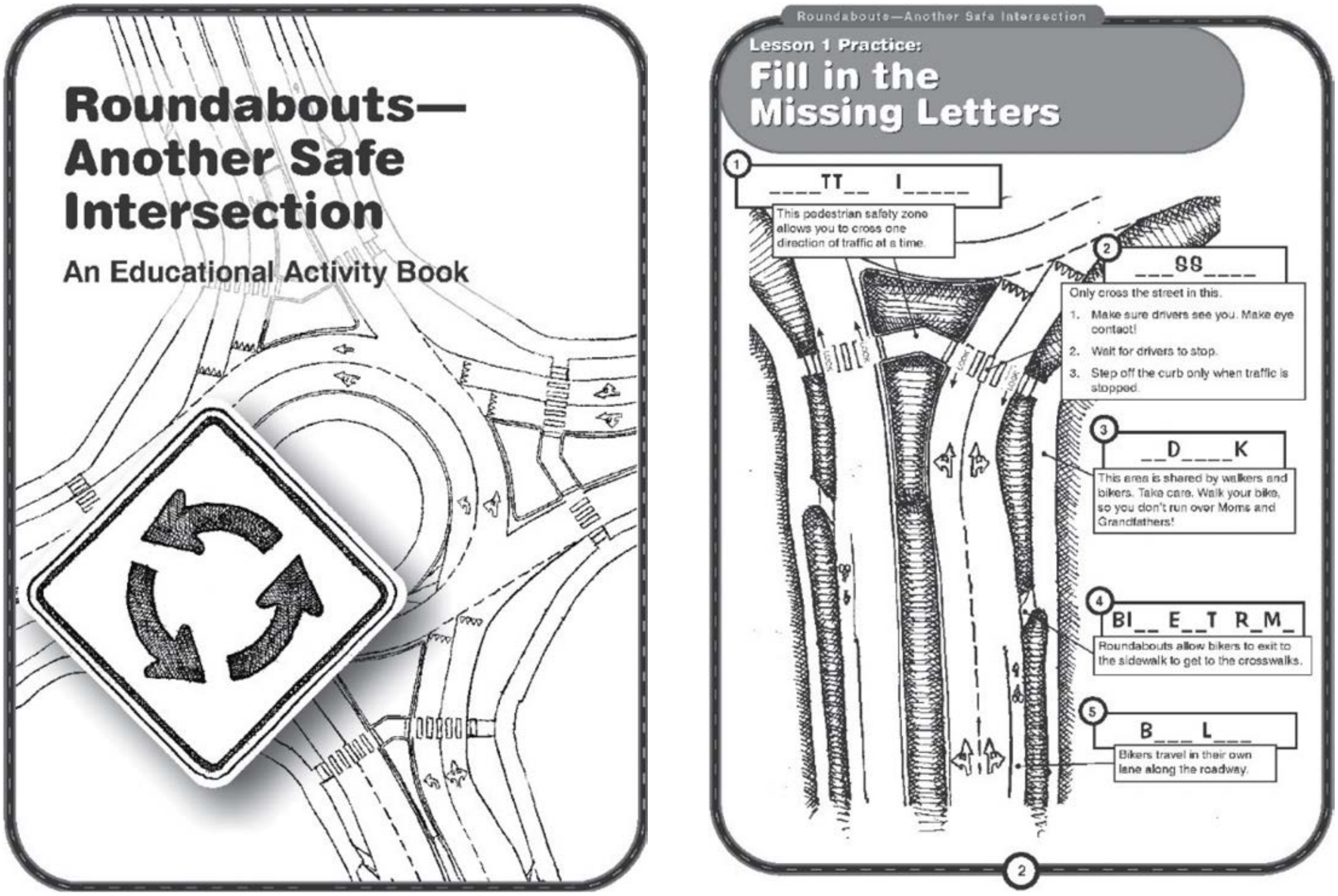
Exhibit 5.2 illustrates a children's activity book developed by the City of Bend, Oregon, to help educate school-aged children about navigating a roundabout (*1*).

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.



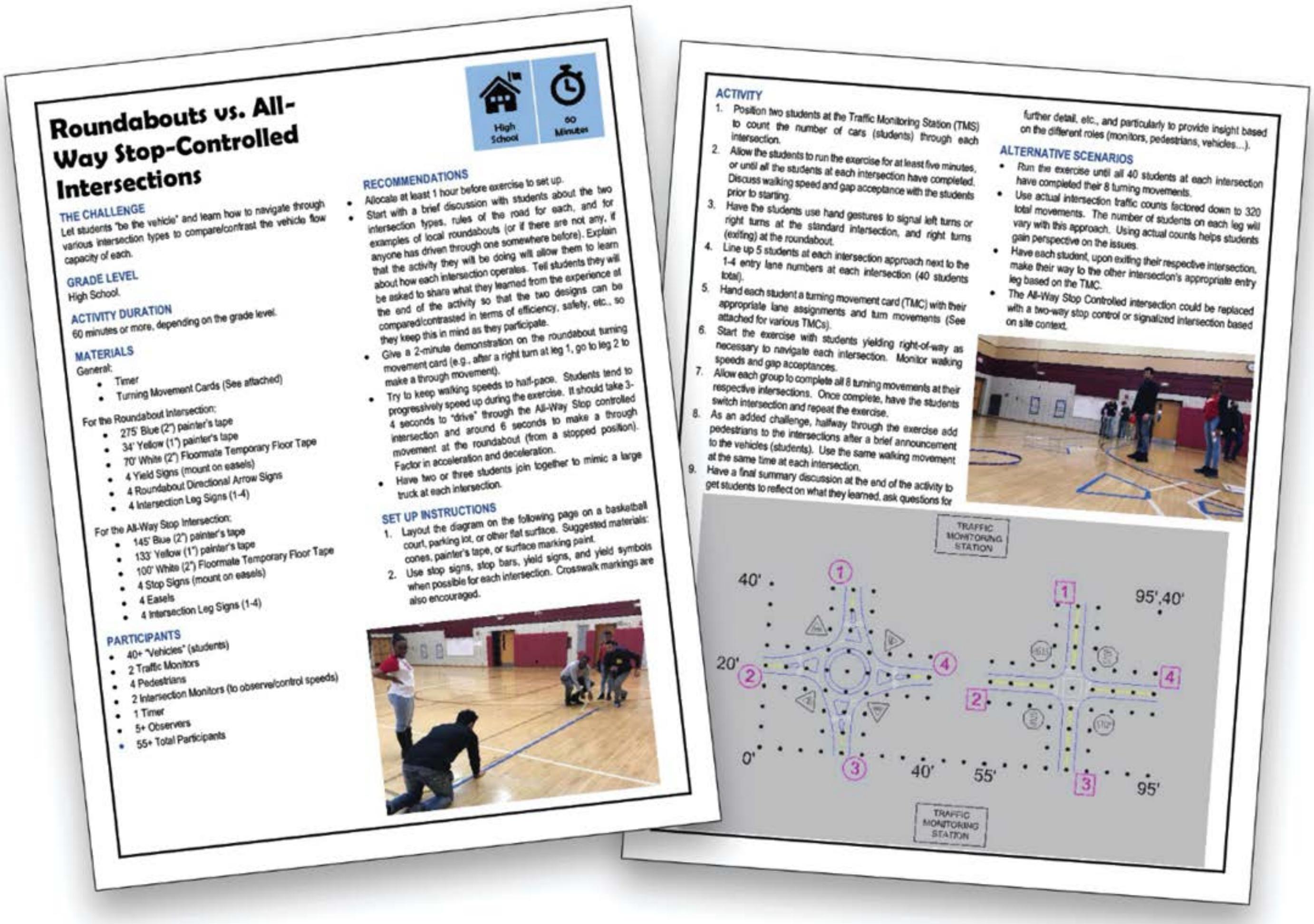
SOURCE: City of Bend, Oregon (*1*).

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.



Roundabouts vs. All-Way Stop-Controlled Intersections

High School | 60 Minutes

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.

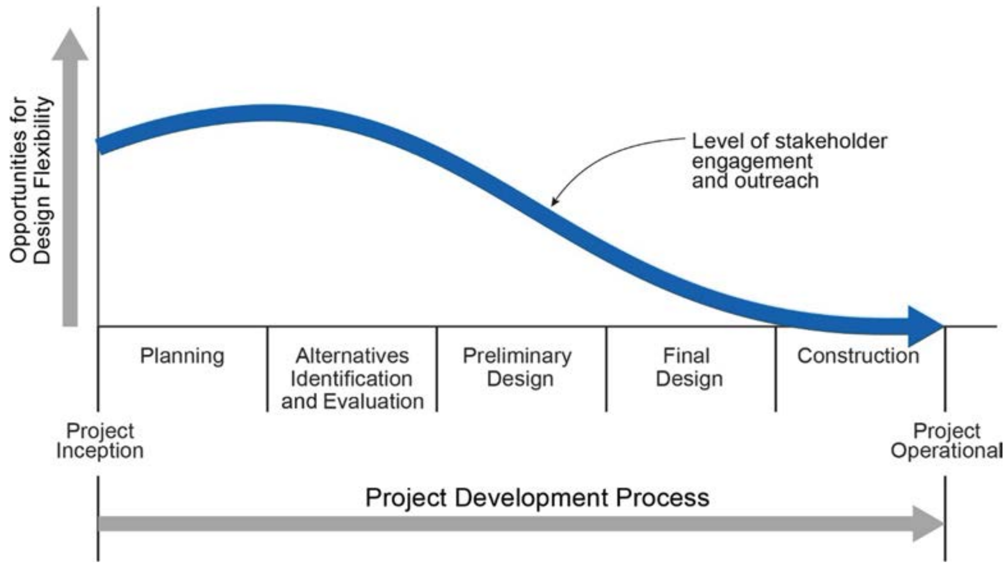
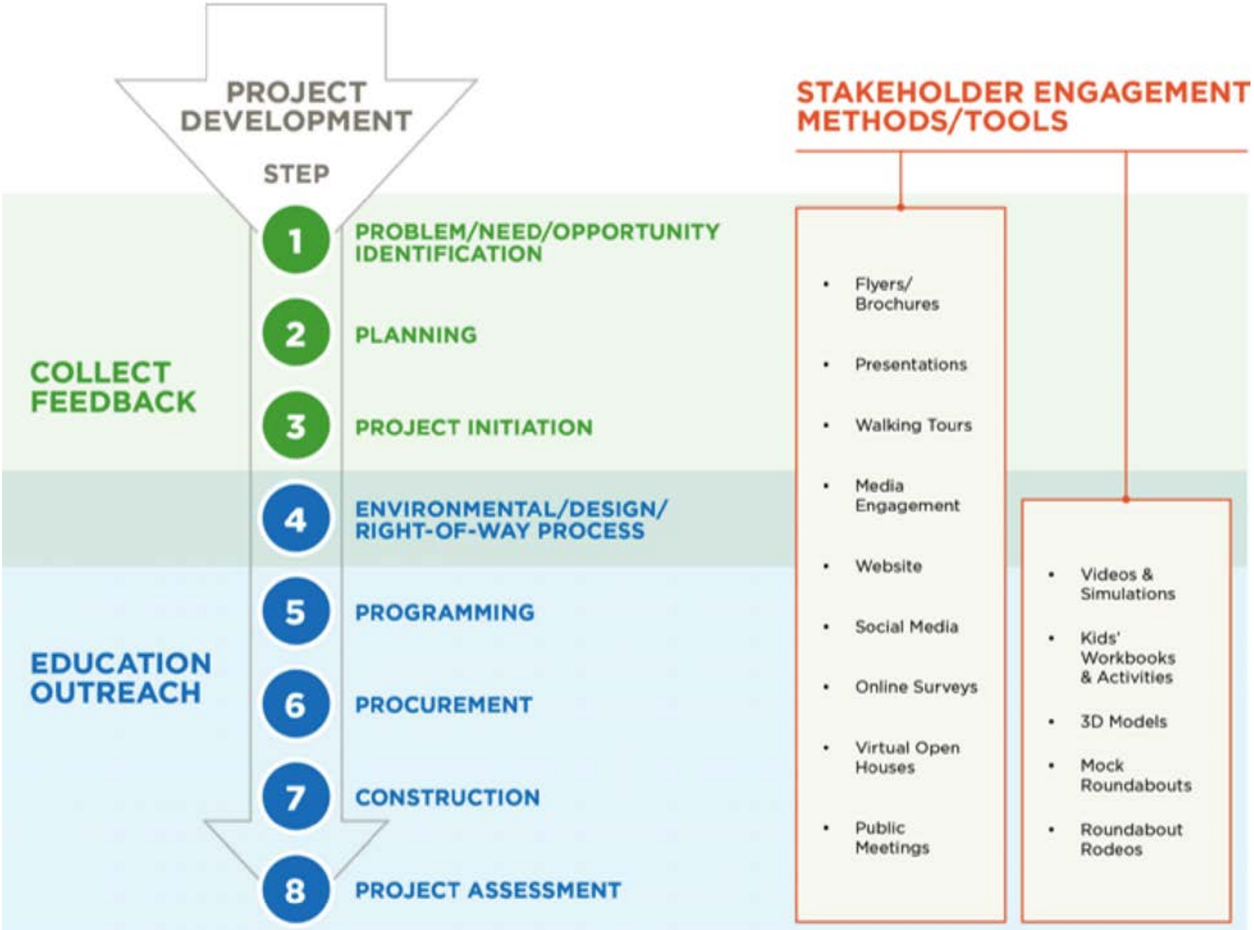


Exhibit 5.6. Example of information sharing with stakeholders.



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.

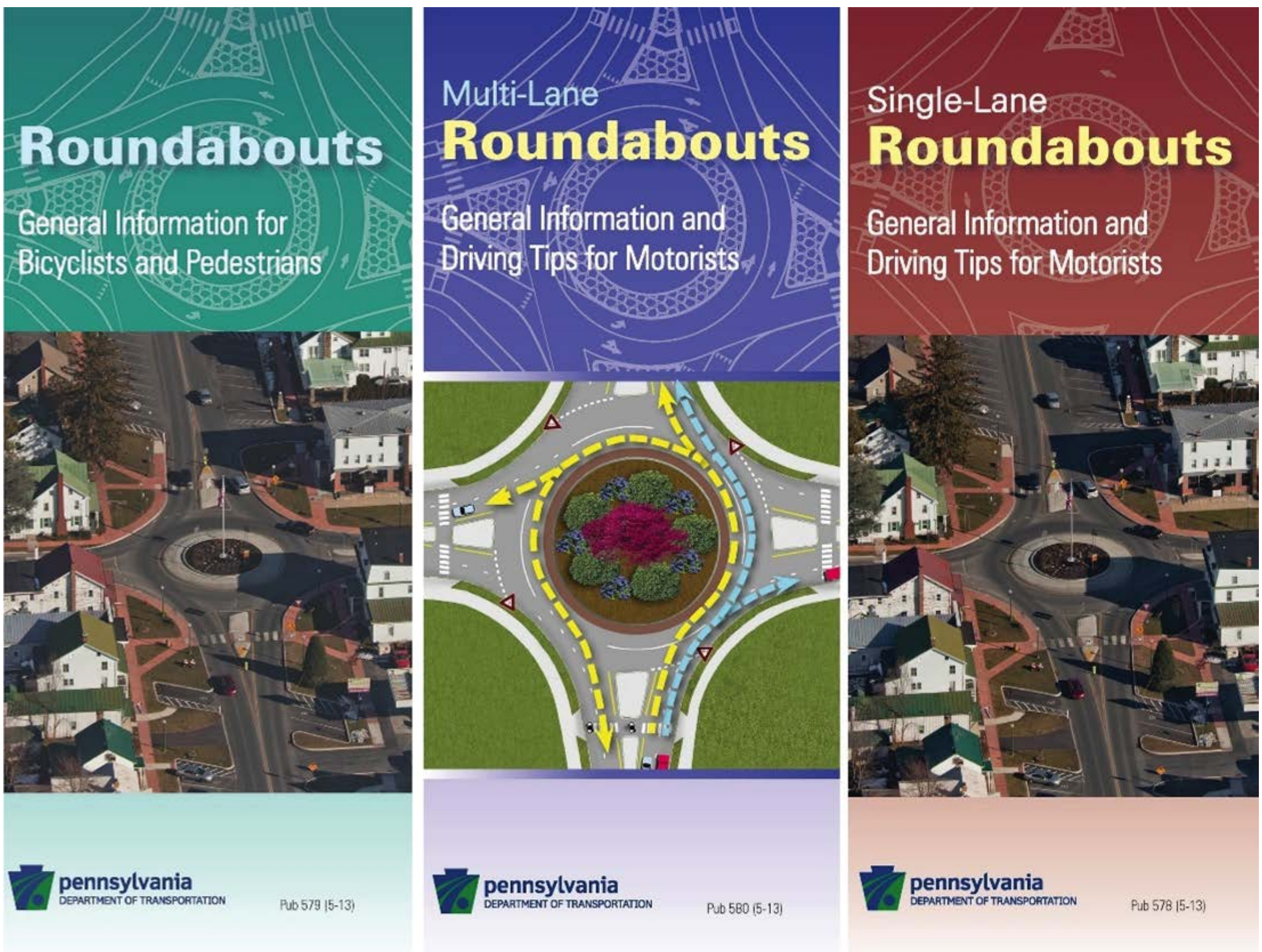
- **Media engagement** may include newspaper articles to provide information on upcoming projects or announcements about in-person training or public meetings.
- **Children's workbooks** can explain how to navigate a roundabout and bring awareness to roundabouts in the community or near schools.
- **3-D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

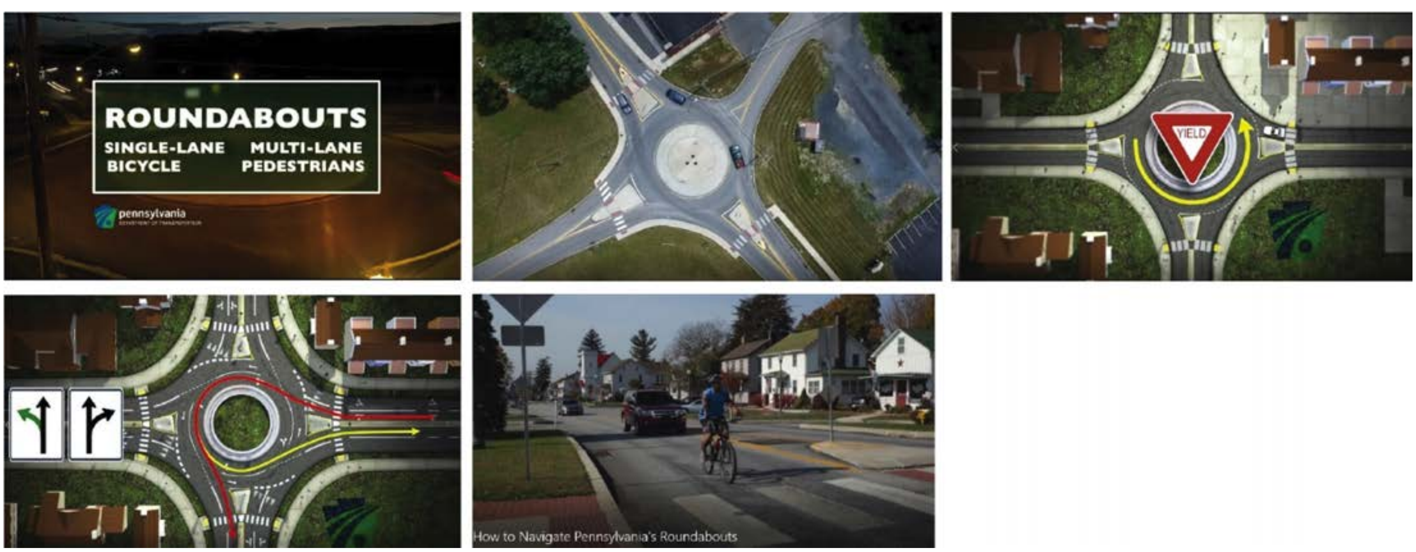
Exhibit 5.8 shows frame captures from an informational video that gave general information about how to navigate a roundabout. The video includes information about single-lane and multilane roundabouts and shows simulation videos with instructions for users (*7*).

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:

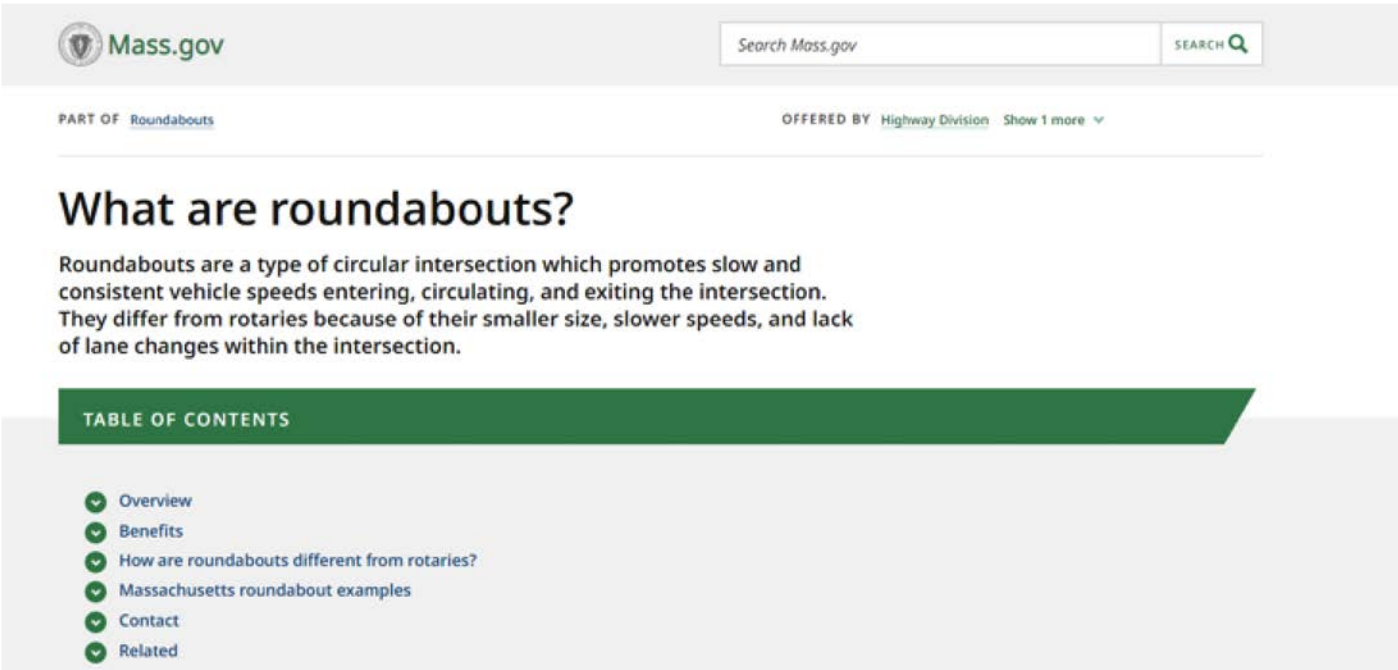
- **Mock roundabouts** with scaled plots can be used with scaled toy vehicles to demonstrate roundabout operations and navigation.
- **Roundabout rodeos** create closed-course driving exercises on full-size roundabout setups, allowing stakeholders to walk, bike, and drive through roundabouts.
- **Walking 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.

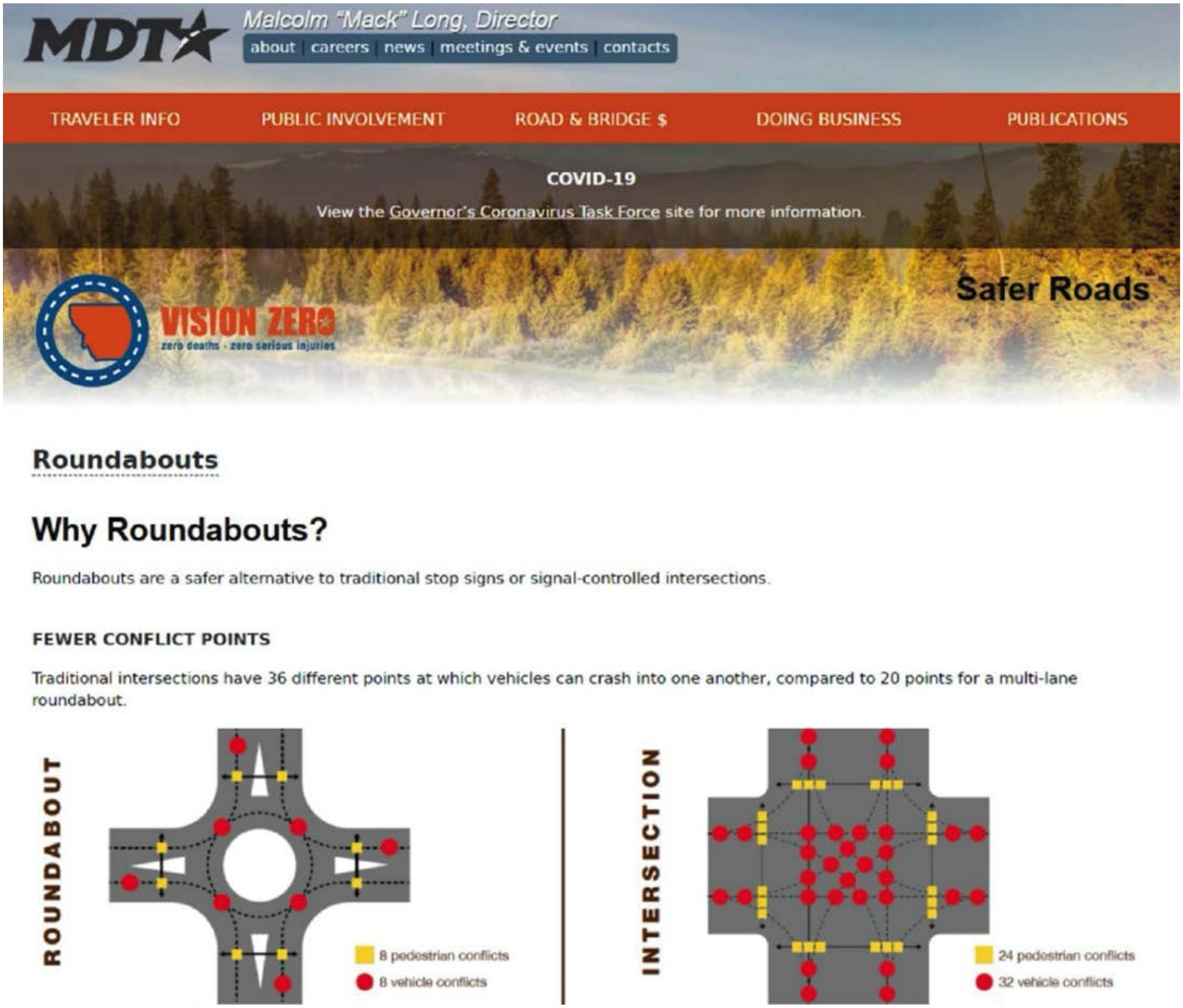
For some projects, it may be useful to conduct specific roundabout training for police and fire departments. This allows them to ask questions they may not want to ask in a public setting and to review with their staff how to stage at a roundabout when responding to a collision, how to direct traffic 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

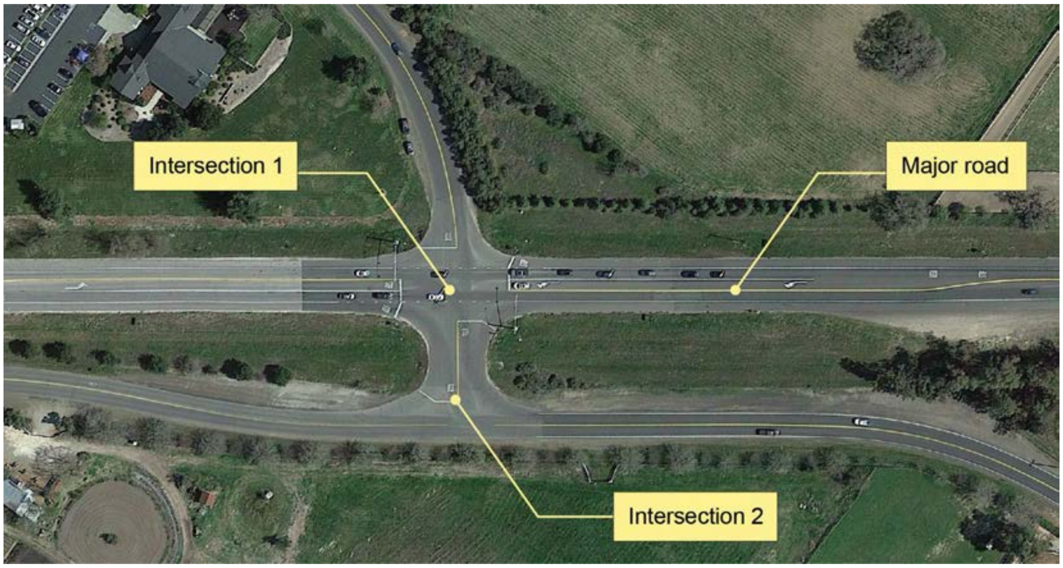
The Step 1 assessment identifies the following typical measures to test alternatives in relation to intended project outcomes:

- 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

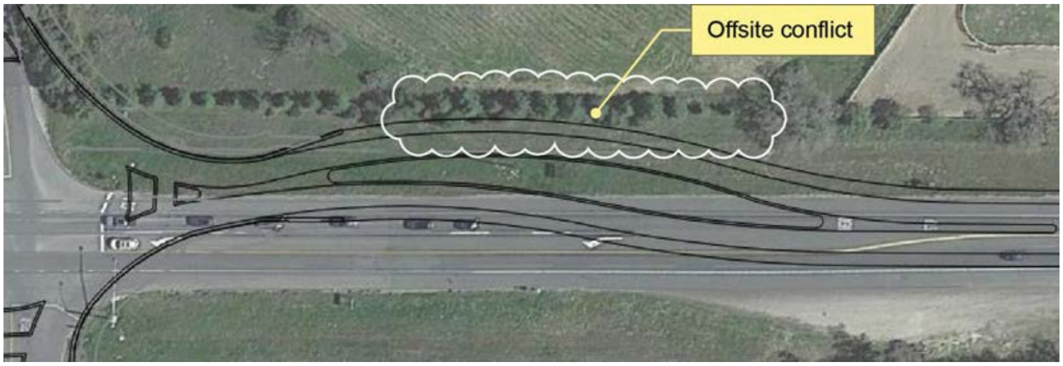
The Step 2 assessment evaluates Alternative 2a in more detail as the project is advanced to the next step of project development and more engineering and environmental data are available. During Step 2, off-site conflicts are discovered in the northeast corner of the intersection as the preliminary concept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

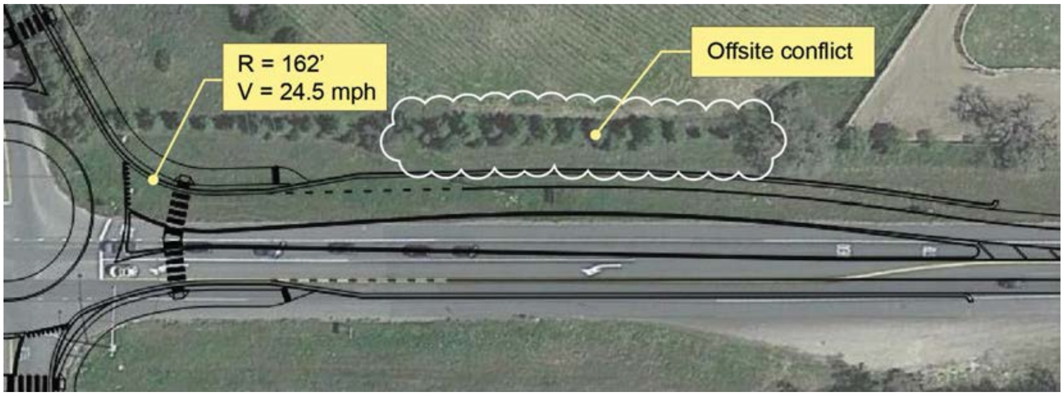
Exhibit 6.3. ICE example—conceptual sketch for Alternative 2a, roundabouts at intersections 1 and 2.

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)

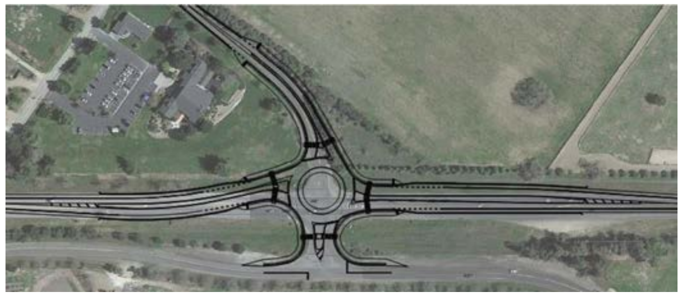


(b)

(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:

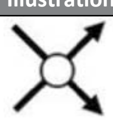
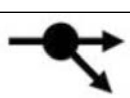
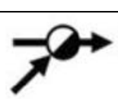
- Separating conflicts by assigning priority or by timing vehicle travel using separated signal phases. Conflicts may arise from legal and illegal maneuvers, even if a conflict is separated in time or priority by a traffic signal or regulatory sign. Traffic control devices can significantly reduce the 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

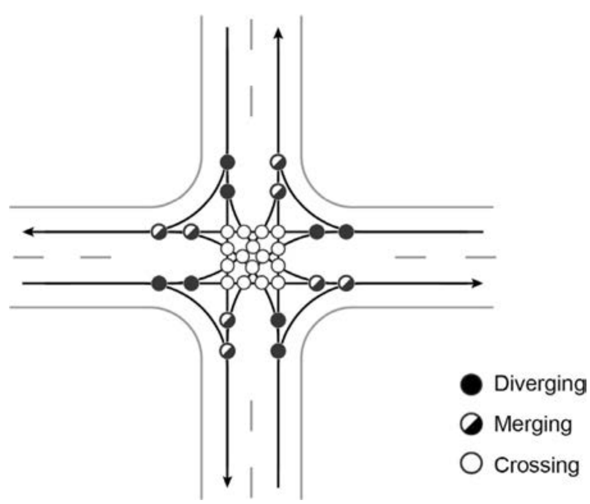
A four-leg stop-controlled or signalized intersection with four legs and a single lane on each approach has been traditionally described as having 32 conflict points for motor vehicles: 16 crossing, 8 merging, and 8 diverging. Exhibit 7.2 shows this configuration.

- 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:

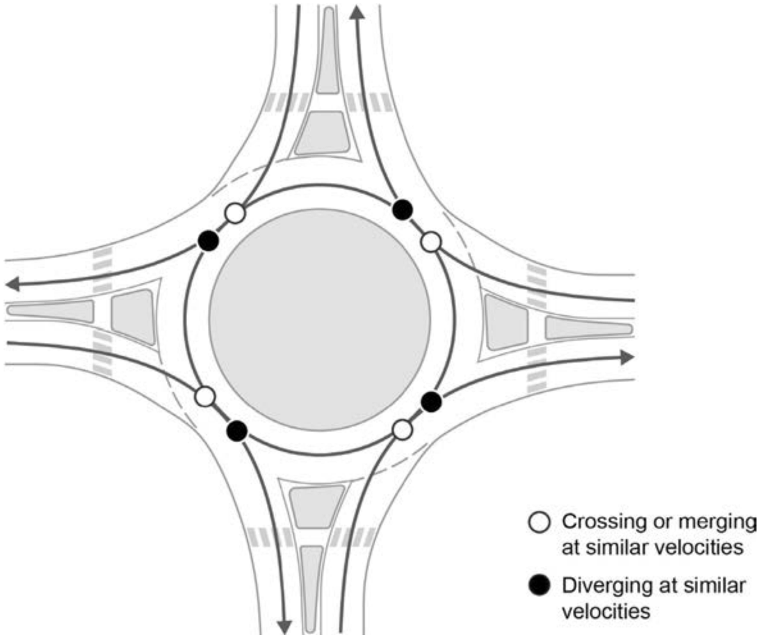
- The 16 crossing conflicts and 8 merging conflicts for motor vehicles reduce to **4 crossing or merging conflicts** with similar velocities. The **geometry of the roundabout** primarily manages these conflicts. First, the central island eliminates the more severe crossing conflicts for left-turning 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*).

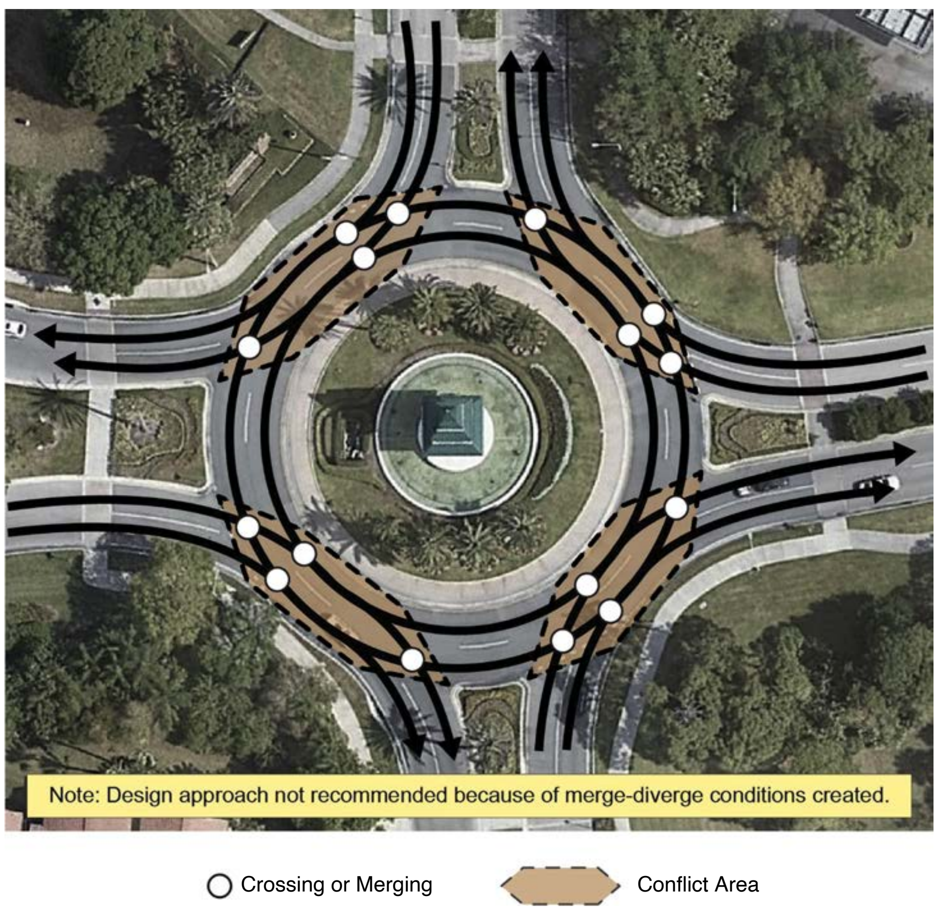
Lower relative velocities result in less severe crashes. Empirical data from multiple studies in the United States and worldwide confirm real-world experience with this reduction in severity—up to an 87 percent reduction in injury crashes compared with two-way stop-control intersections and 78 percent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

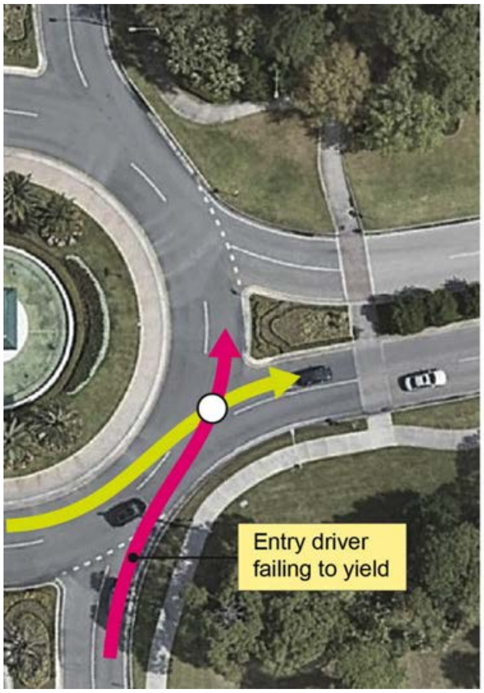
A multilane roundabout's geometric configuration is believed to directly impact conflict potential. Exhibit 7.5 through Exhibit 7.6 illustrate this relationship using a series of multilane roundabout concepts, each designed to serve two through lanes on each leg. The additional conflicts are generally 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.

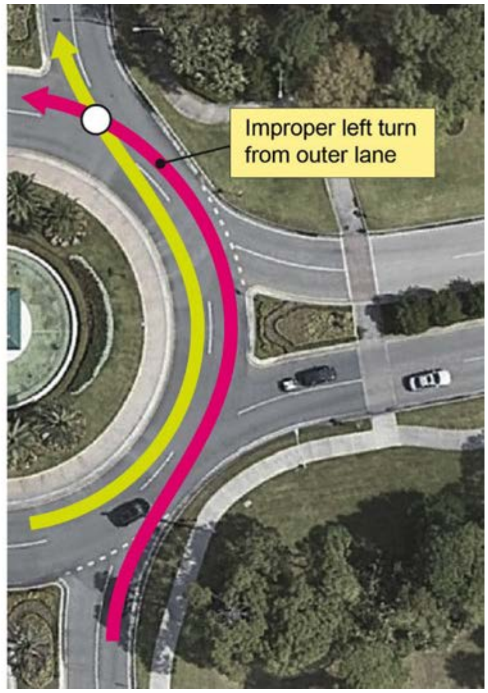


SOURCE: Google Earth.

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



(a)



(b)

SOURCE: Google Earth.

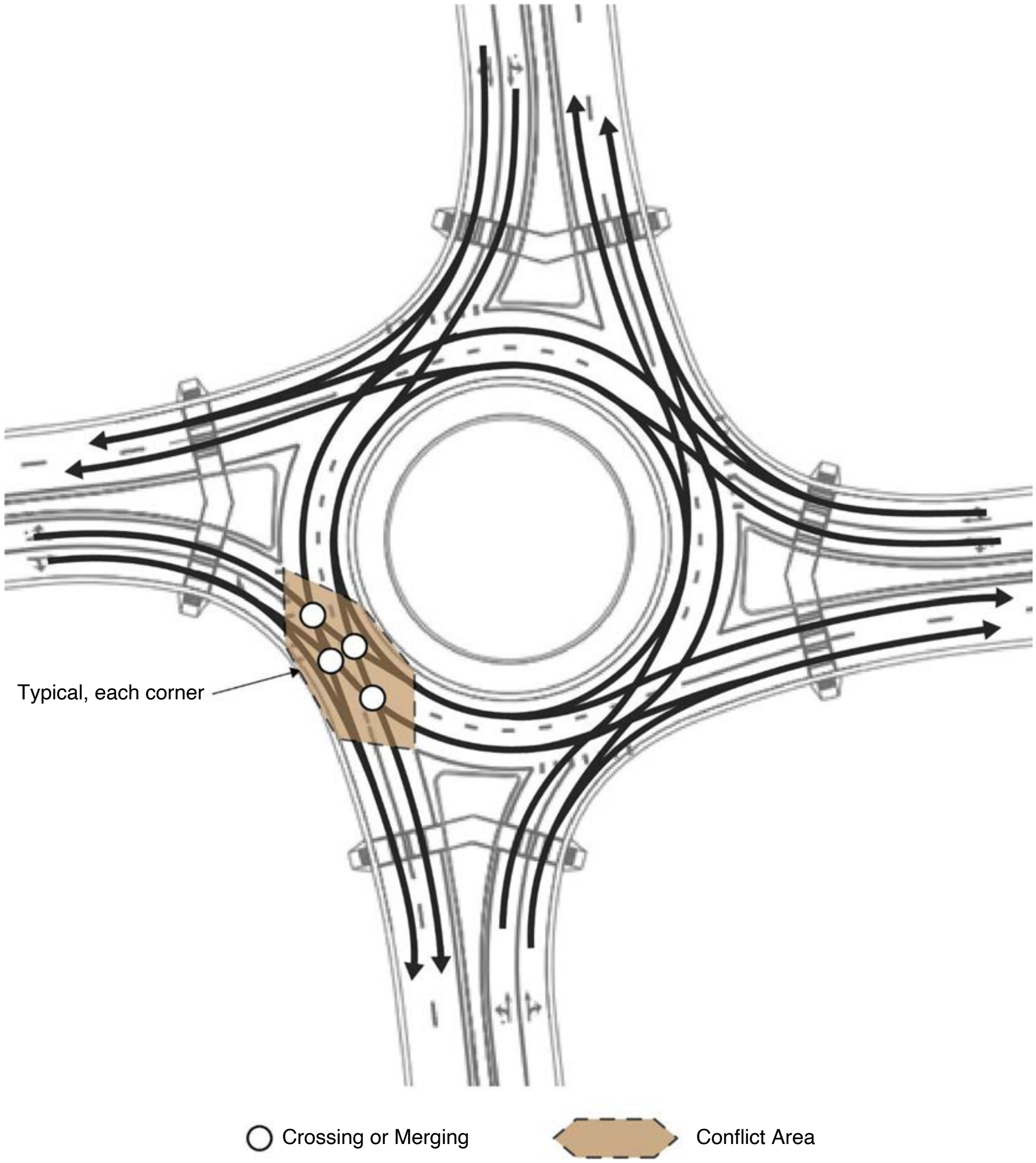
Exhibit 7.5 shows a multilane roundabout design that is not recommended because of the merge–diverge conditions it creates in the circulatory roadway. Chapter 10: Horizontal Alignment and Design discusses how practitioners can address such conditions. In the United States and internationally, this design 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.

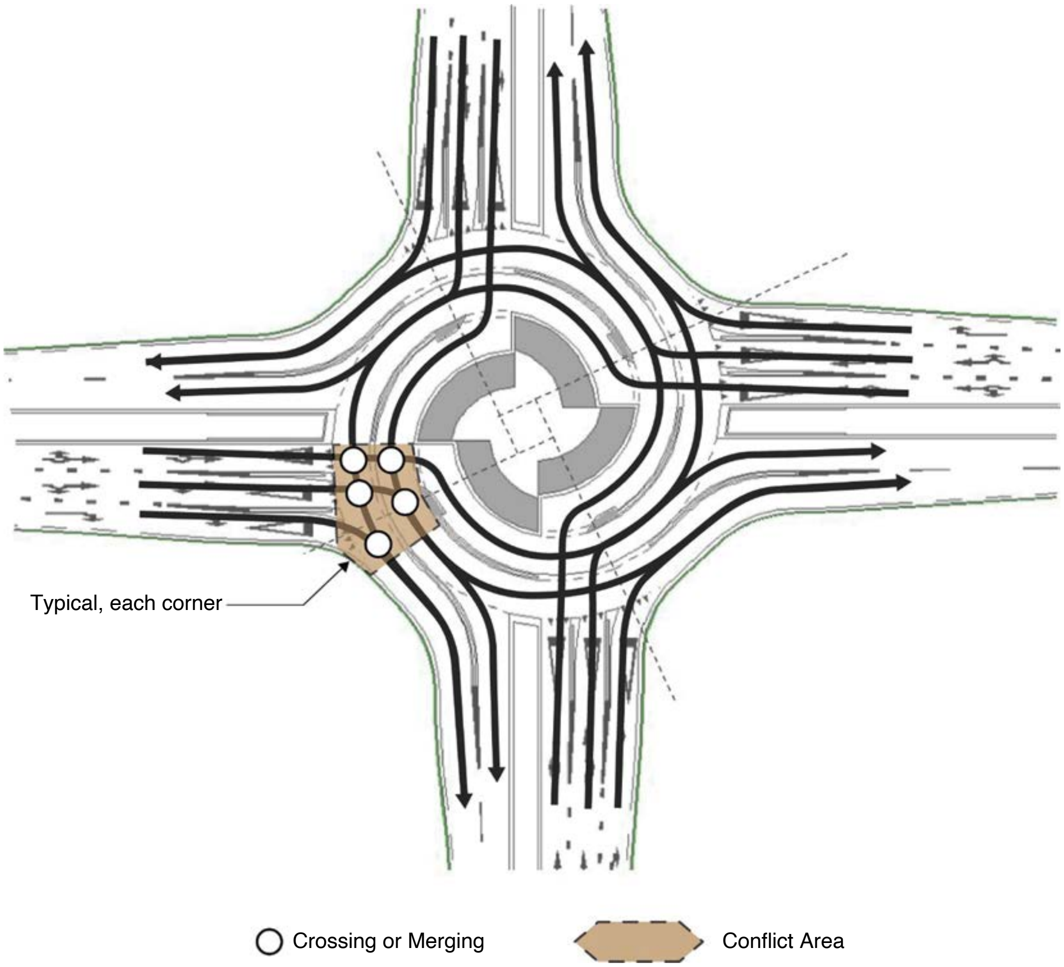


SOURCE: Adapted from Georgia Department of Transportation (*9*).

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.

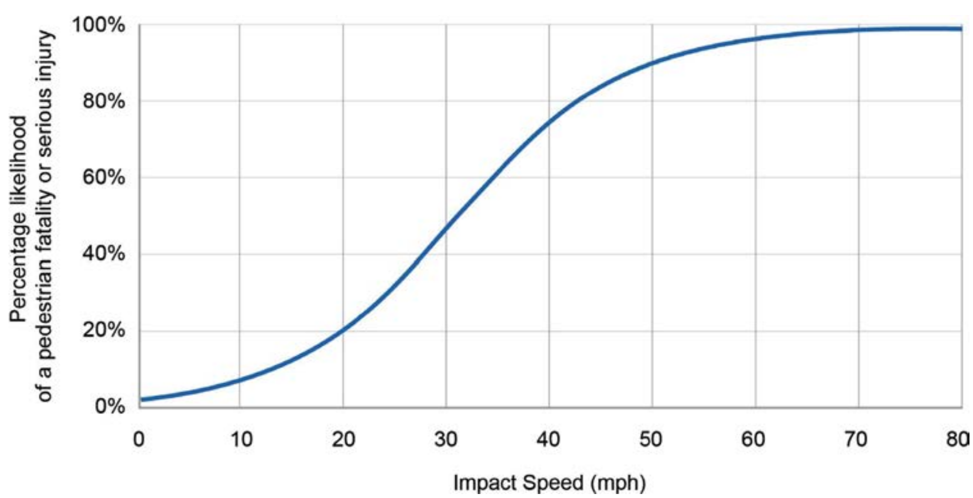
7.2.4 Pedestrians

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.

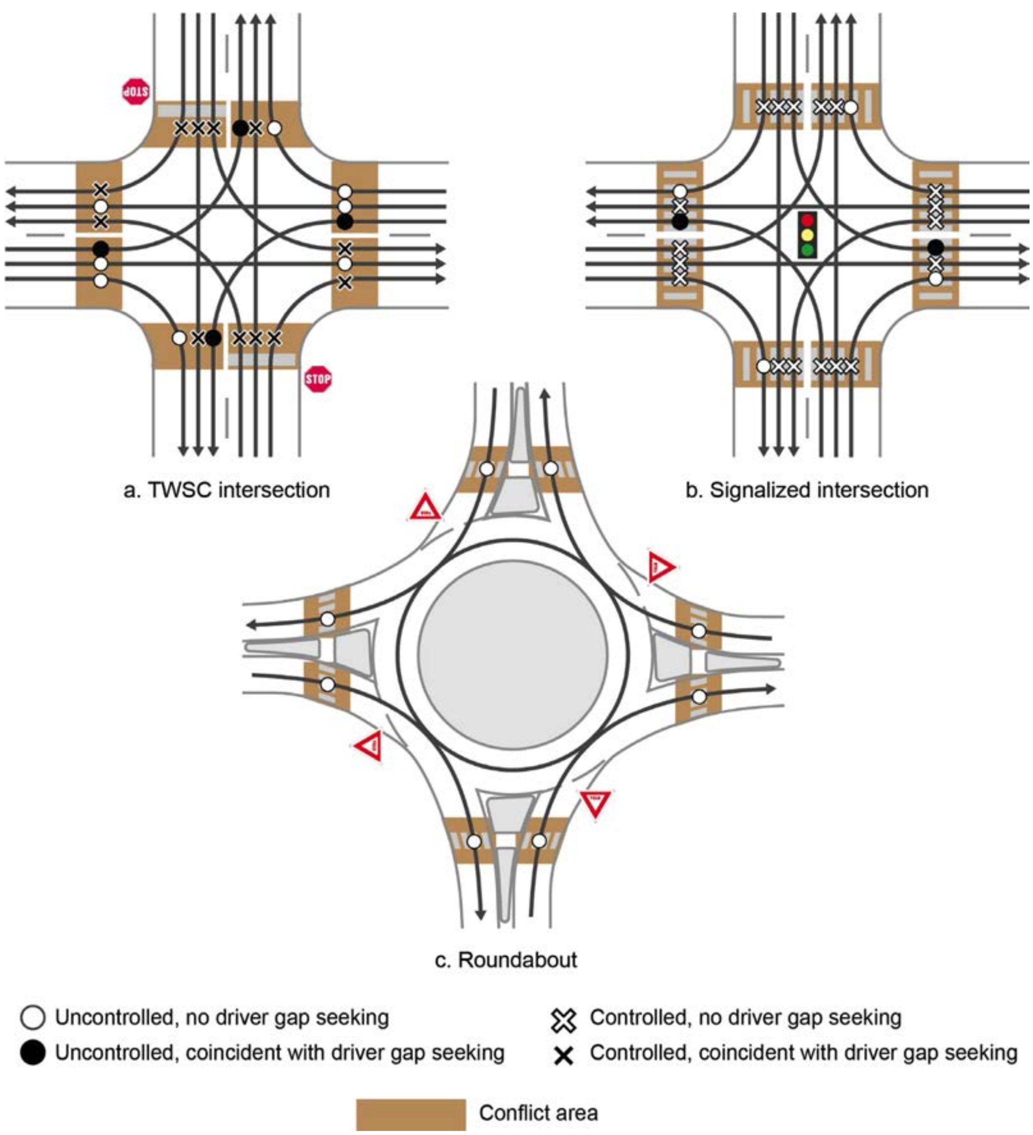


Exhibit 7.11. Vehicle–pedestrian conflict points by intersection type.

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: All	Crash Type: Injury	Source
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.

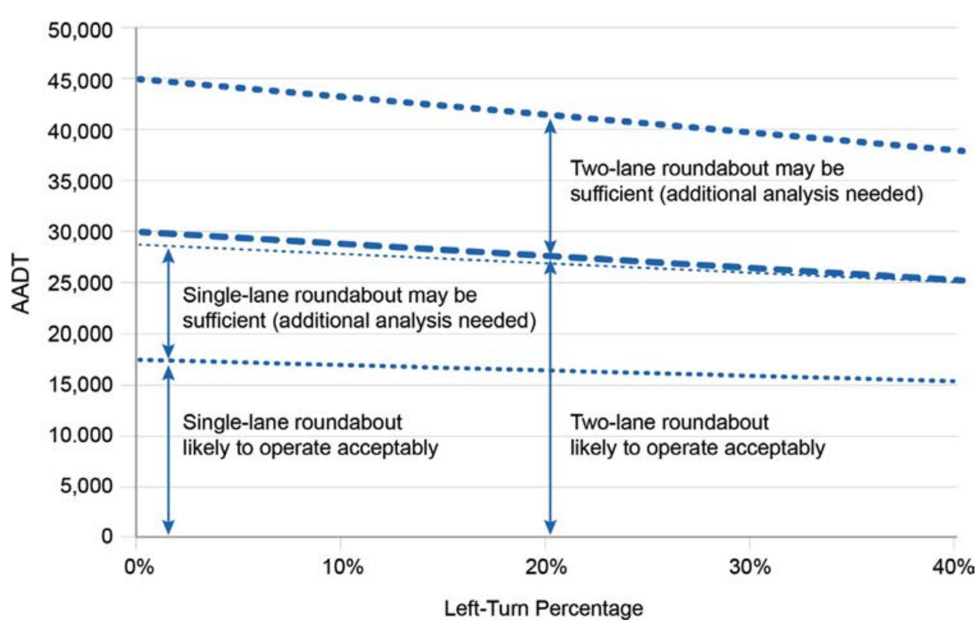
Sketch-level planning often requires an initial screening of alternatives when daily volumes (e.g., AADT) are known but more detailed information may not be available. Exhibit 8.2 presents ranges of daily traffic volumes to identify scenarios under which single-lane and two-lane roundabouts may perform 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

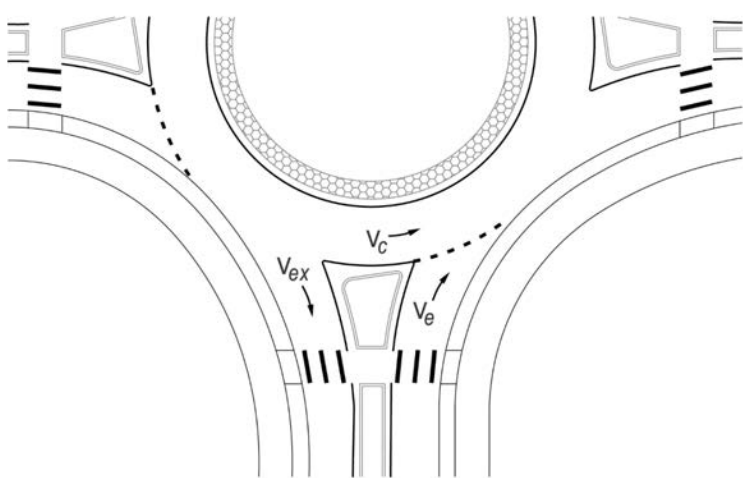
Where existing or projected turning movement data are available at the planning level, practitioners can improve their estimate of the required lane configurations. Even if future projections of turning movements are not available, estimating future turning movements using existing turning movements 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.

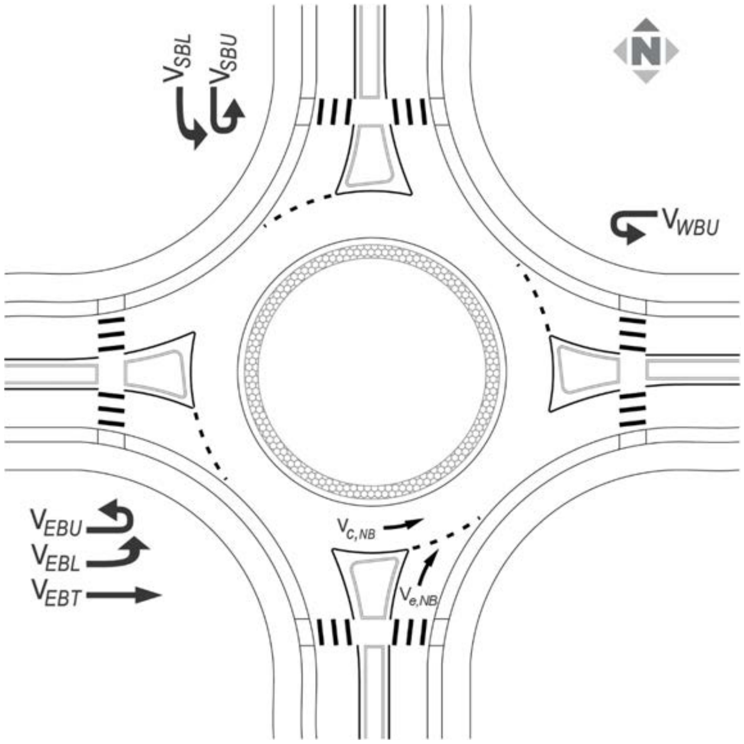
The conflicting flow rate opposing a given entry is defined as the flow circulating immediately upstream of where the entry flow joins the circulatory roadway. Exhibit 8.4 shows the turning movements that constitute the conflicting traffic volume at the northbound entry, such that $v_{c,NB} = v_{EBT}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

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.

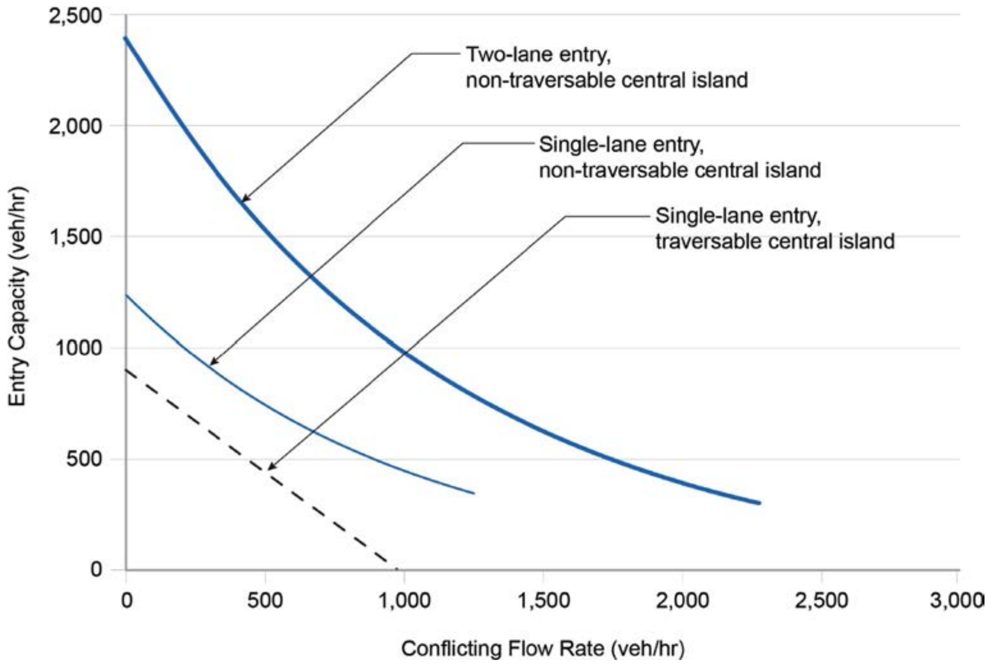
Exhibit 8.6 presents a simplified table that uses the sum of entering and conflicting flows as a planning guide on the type of roundabout and number of lanes that may be needed. The table can be augmented or superseded by Exhibit 8.5 or the detailed analysis discussed in sections 8.7 through 8.10.

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.



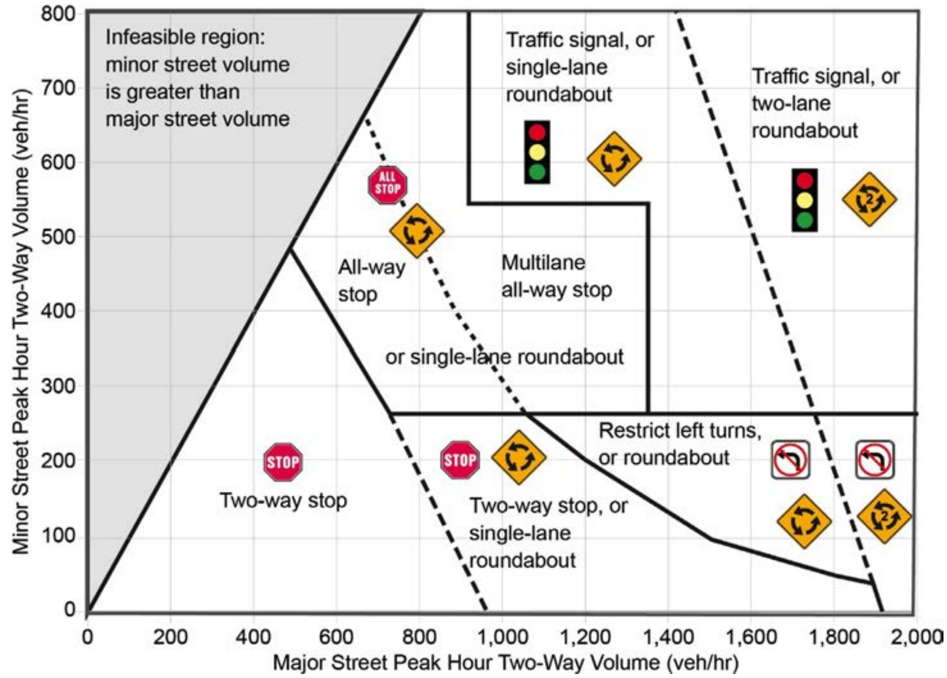
NOTE: Practical capacity is assumed to be 90 percent of maximum capacity. Conclusions not valid at planning level for conflicting flow rates above 1,250 veh/hr for a single-lane circulatory roadway and 2,300 veh/hr for a two-lane circulatory roadway. Values beyond these practical limits may be possible, 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

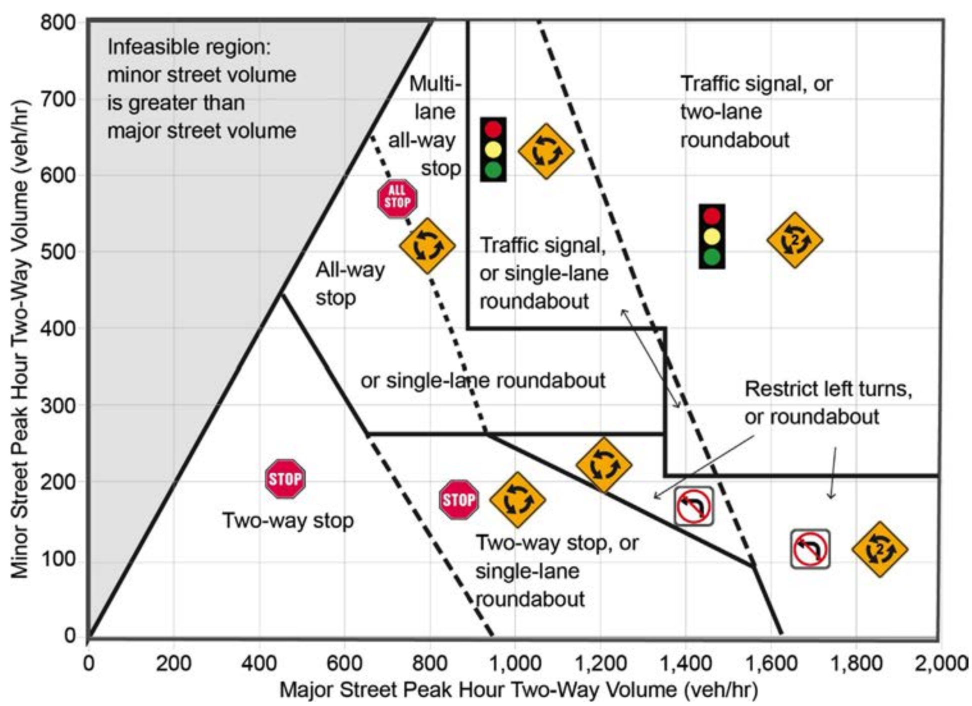
NOTE: Derived from Exhibit 8.5.

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*).

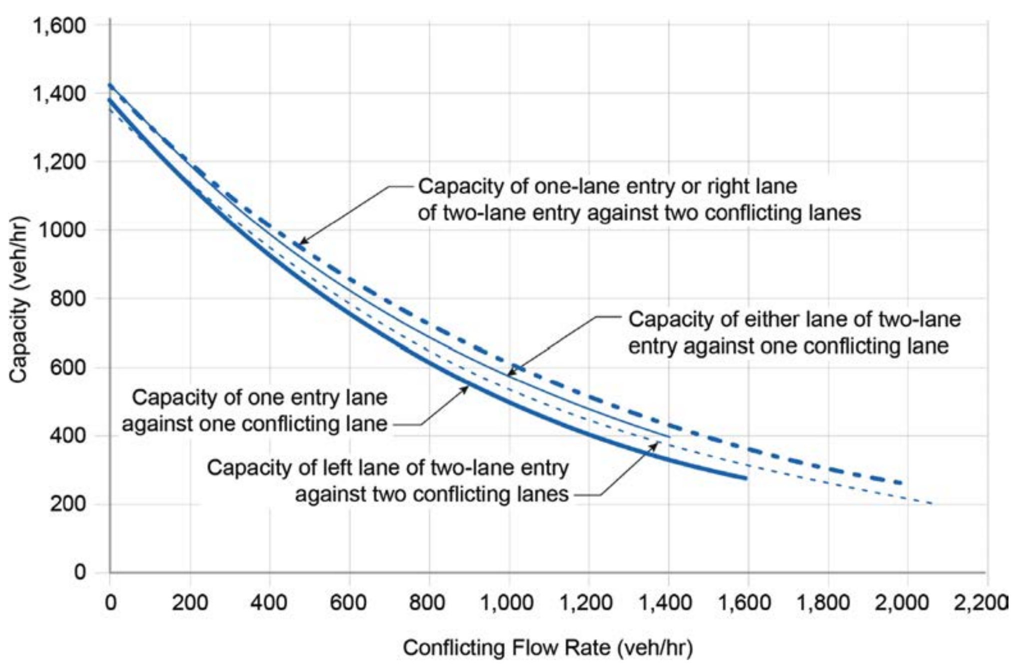
8.7 *Highway Capacity Manual* Analysis Techniques

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

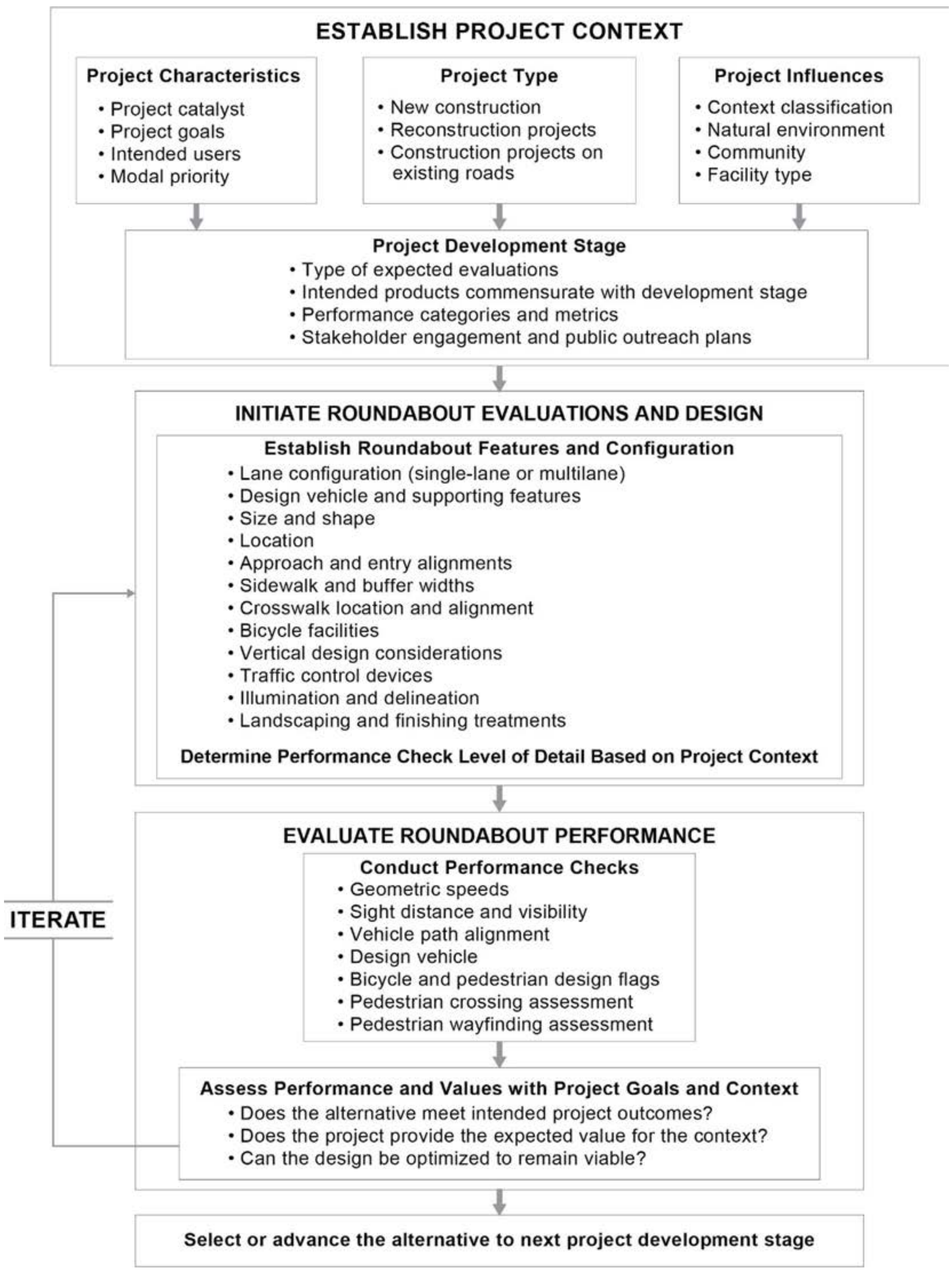
Roundabout design is a process of assessing anticipated users and then determining an appropriate balance of safety and operational performance, user quality of service, and ways to serve identified design vehicles. This process requires balancing several competing objectives while working within site-specific 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

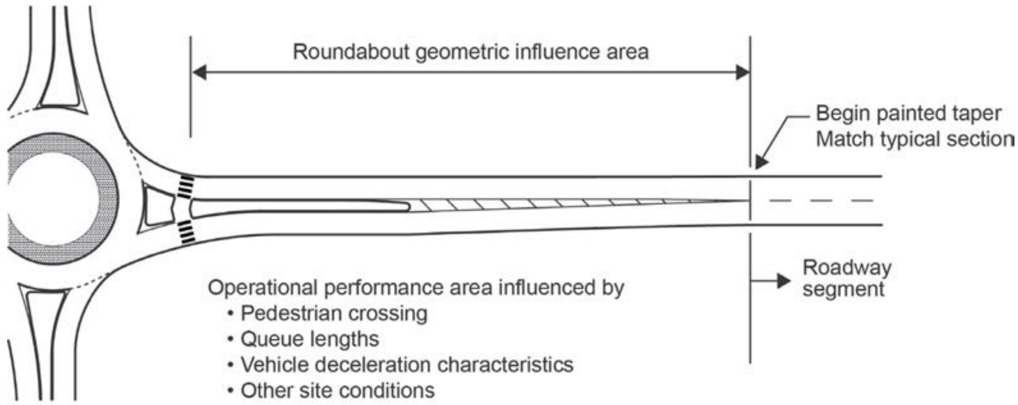
Vehicular speed is foundational to roundabout safety performance and is a product of roundabout geometry, resulting in what is termed *geometric speeds*. Achieving appropriate geometric speeds entering and traveling through the roundabout is a critical design objective, as speed affects safety performance 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.

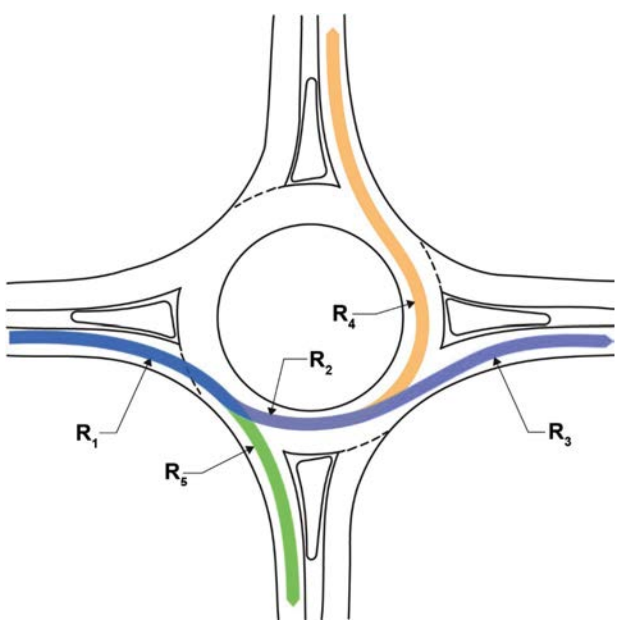
The R_1 through R_5 radii measured in this procedure represent the vehicle centerline in its path through the roundabout. A vehicle is assumed to be 6 ft (1.8 m) wide and maintain a minimum clearance of 2 ft (0.6 m) from its outer wheelpath to a perceived conflict, such as a roadway centerline or concrete 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.

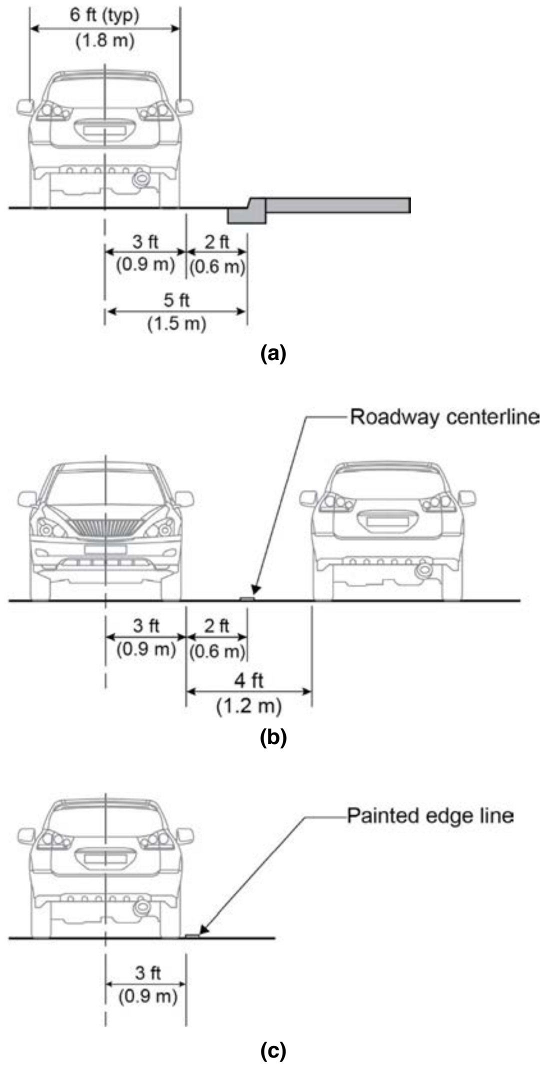
This assumes that drivers stay away from raised fixed objects and opposing traffic. For evaluation purposes, the curb face should be considered the constraint even if it is part of a curb and gutter.

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.



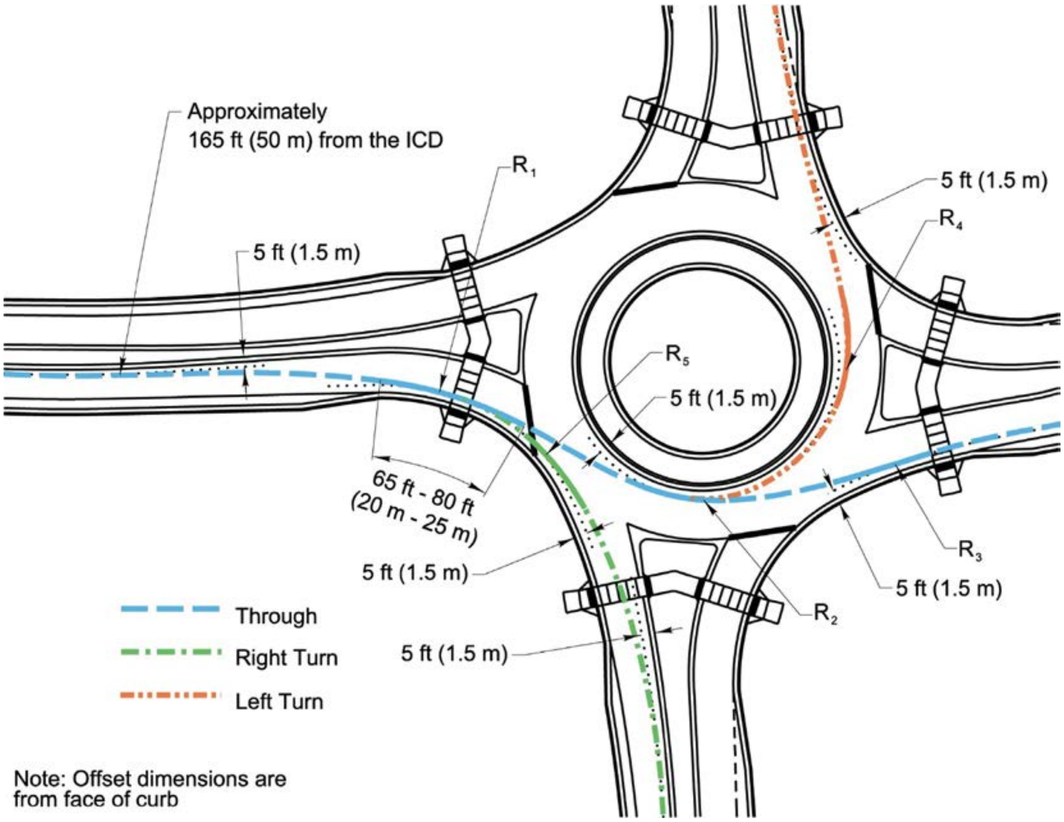
Limited relief vertical curb lips, rolled curbs, and other curb and gutter forms that are less concerning for a driver could lead to actual driving paths that infringe on the assumed buffer of 2 ft (0.6 m) to the curb face.

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.

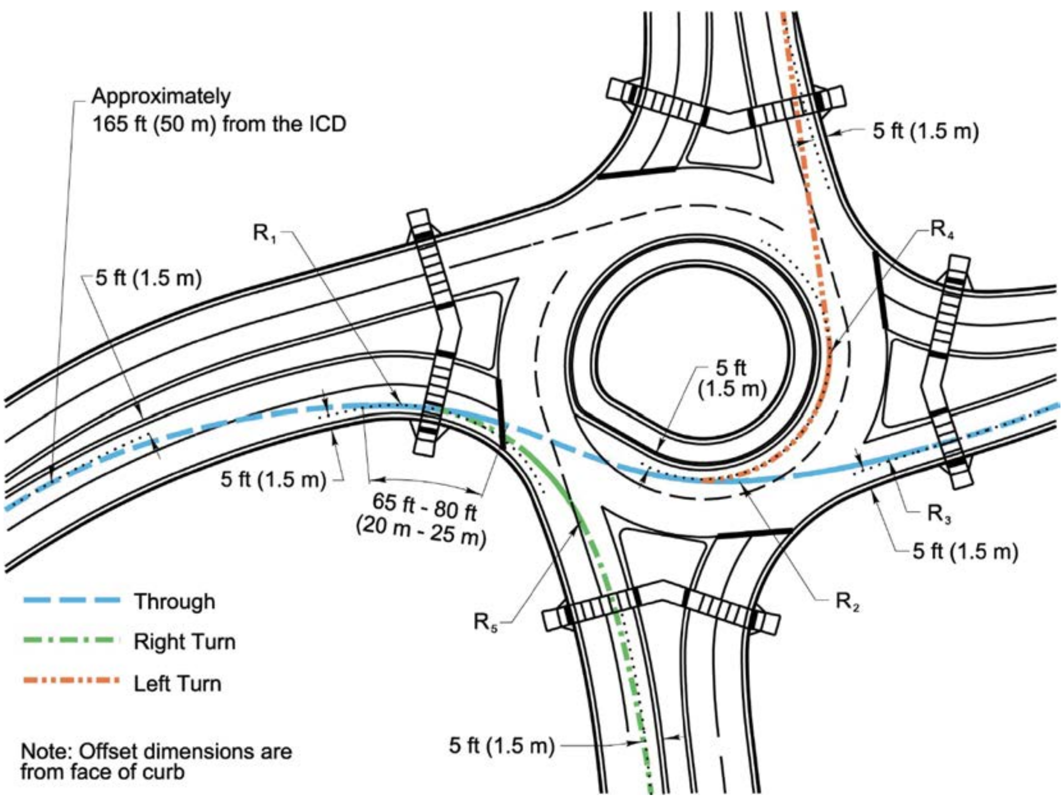
Exhibit 9.7 and Exhibit 9.8 illustrate the general construction of the fastest vehicle paths at a single-lane and a multilane roundabout, respectively. The fastest path needs to be drawn and

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).

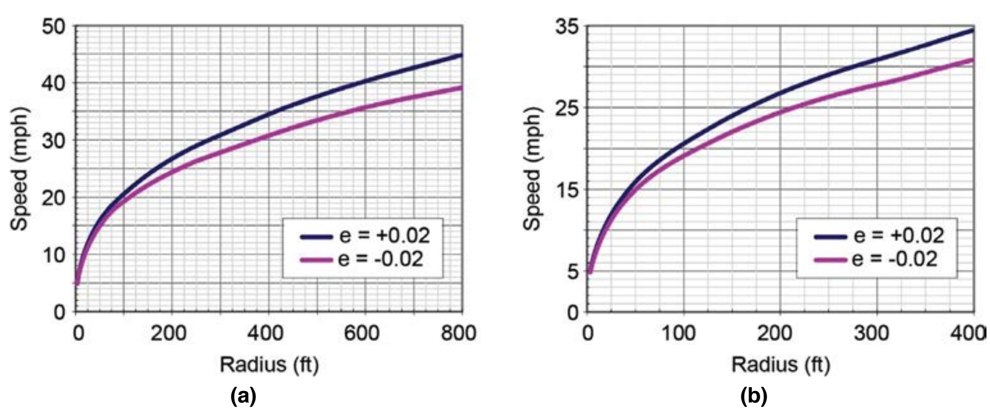
For roundabout planning and design in a low-speed environment, the most common superelevation values are +0.02 and –0.02, corresponding to cross slopes of 2 percent pointing down in the direction of the curve and against the direction of the curve, respectively. Equation 9.3 and Equation 9.4 provide 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.

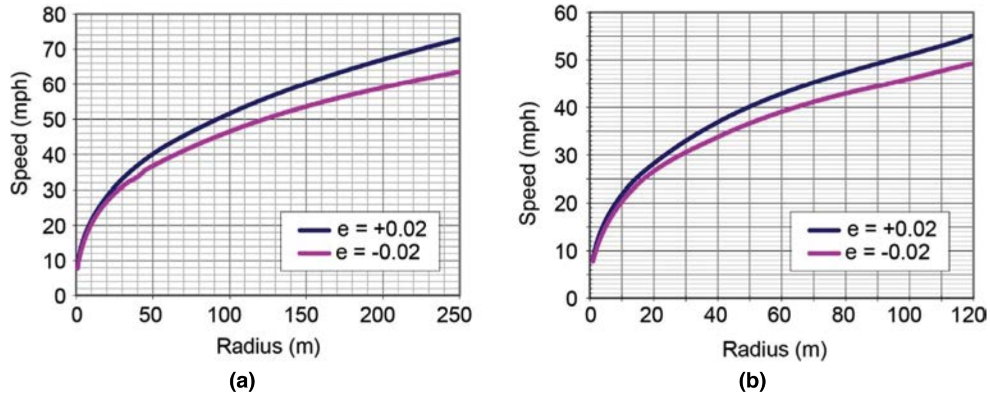
Some roundabout configurations may have exit paths with large radii or tangential alignments. The theoretical speed of the exit (e.g., a tangent) would not represent actual predicted speeds. When identifying the predicted speed for an exit with a large R_3 radius or tangential fastest path, the acceleration 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.

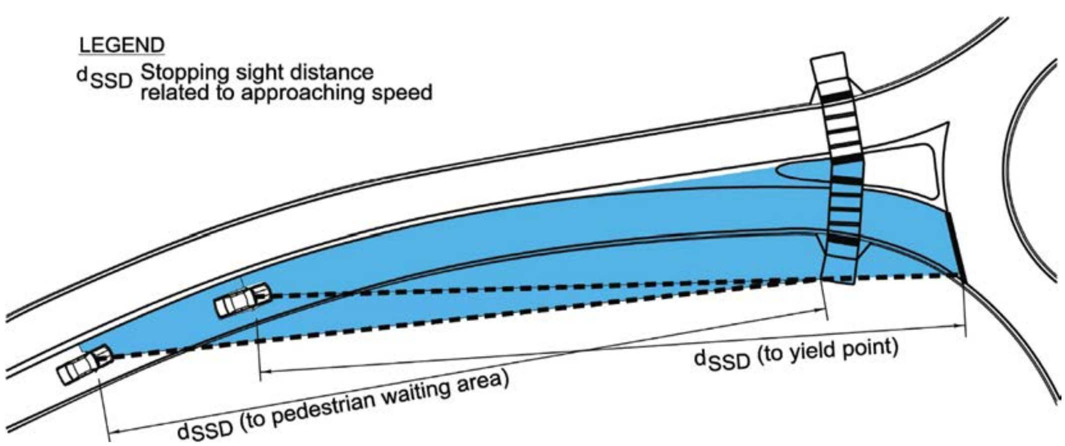
Design Speed (mph)	Design Stopping Sight Distance (ft)	Design Speed (km/h)	Design Stopping Sight Distance (m)
15	80	20	20
20	115	30	35
25	155	40	50
30	200	50	65
35	250	60	85
40	305	70	105
45	360	80	130
50	425	90	160
55	495	100	185

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.

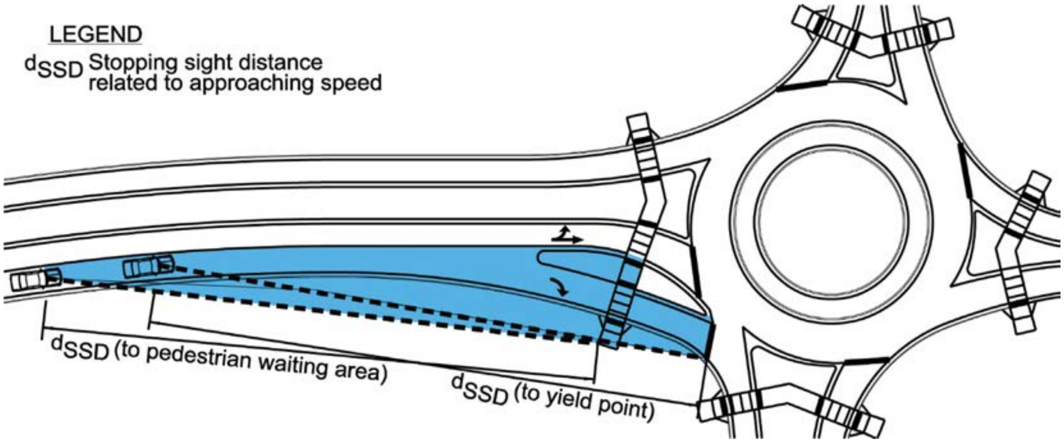
Stopping sight distance is measured using an assumed height of the driver's eye of 3.50 ft (1.080 m) and an assumed height of the object of 2.00 ft (0.60 m). Further details are provided in the Green Book (*5*).

Exhibit 9.12. Stopping sight distance to the pedestrian crossing and entrance line on the approach.



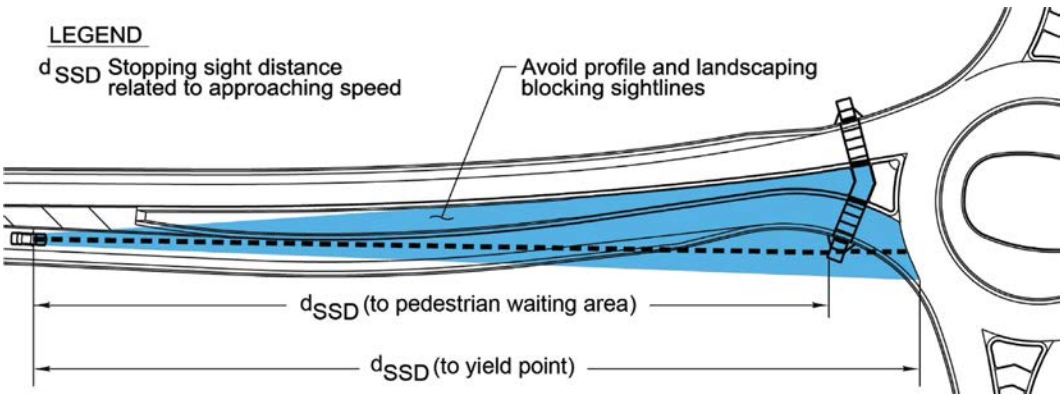
SOURCE: Adapted from Georgia Department of Transportation (*3*).

Exhibit 9.13. Stopping sight distance for a right-turn bypass lane.



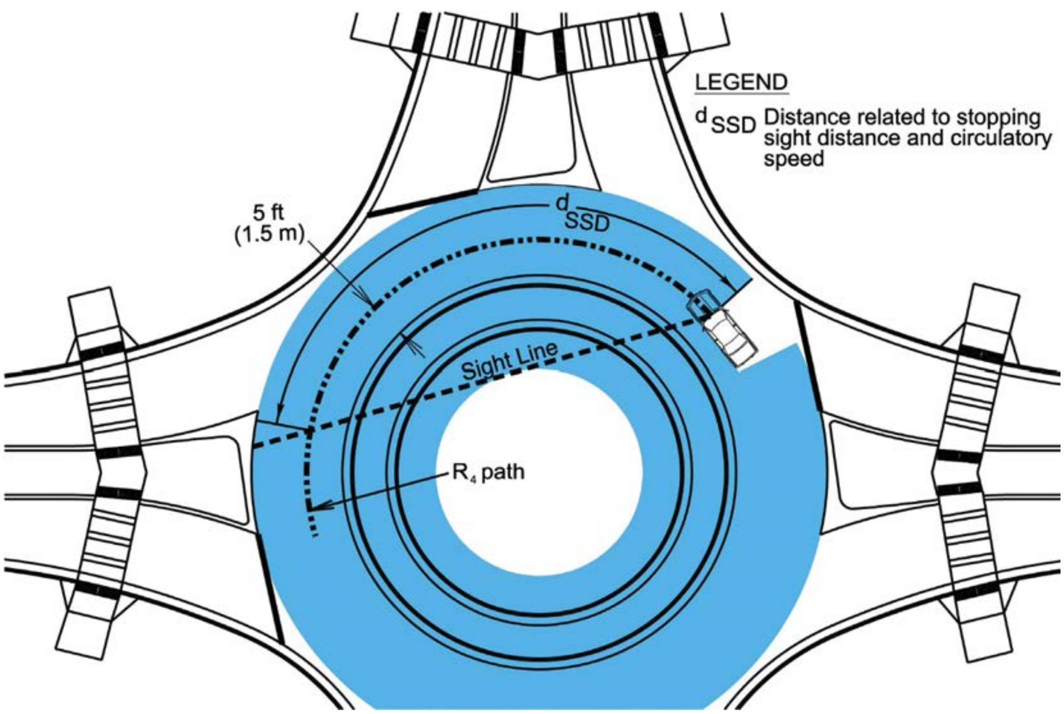
SOURCE: Adapted from Georgia Department of Transportation (*3*).

Exhibit 9.14. Stopping sight distance for approach curvature.



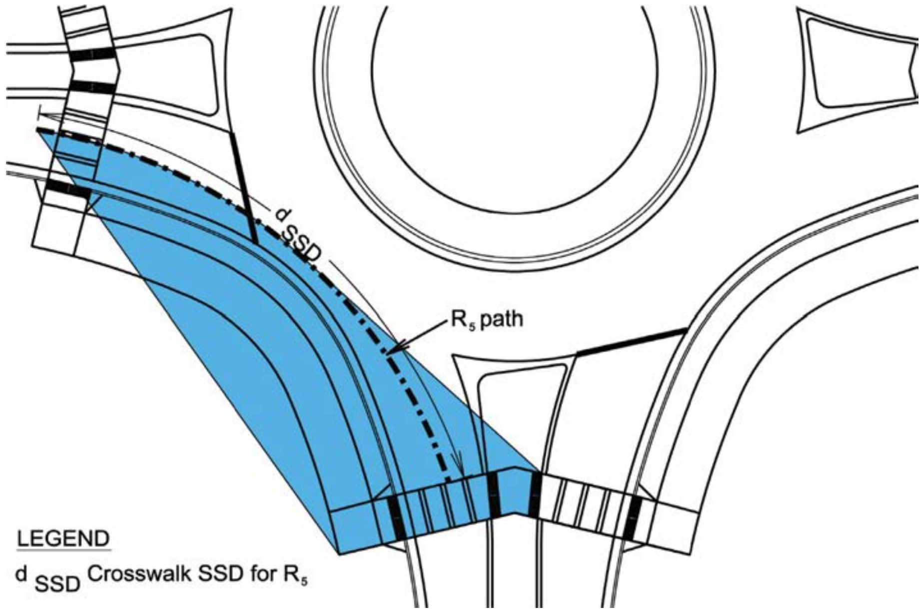
SOURCE: Adapted from Georgia Department of Transportation (*3*).

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.

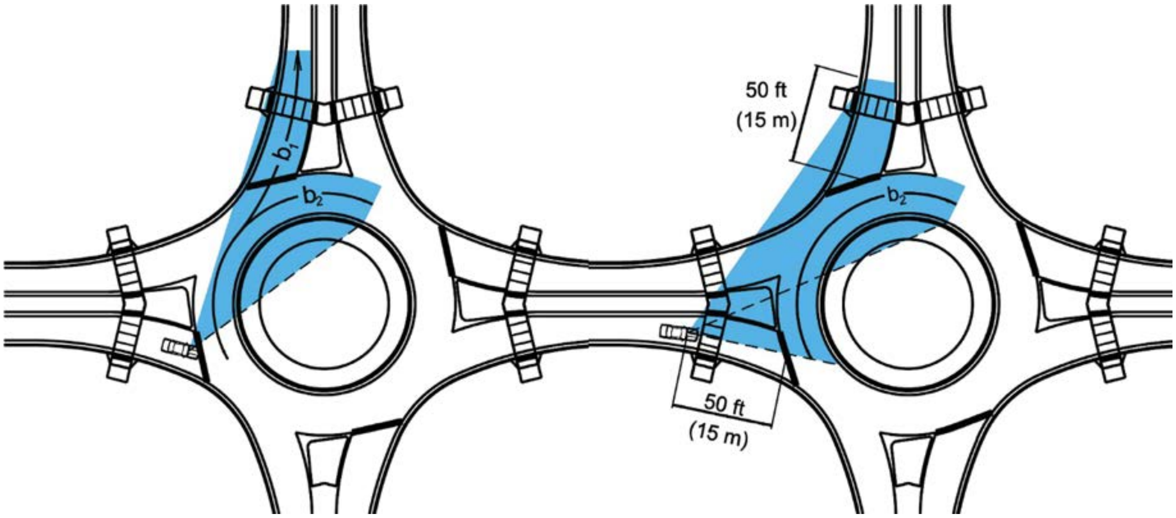
Intersection sight distance is measured by determining *sight triangles*. This triangle is bounded by a length of roadway defining a sight distance limit away from the intersection on each of the two conflicting approaches and by a line connecting those two limits. For roundabouts, these "legs" may be 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 $$b_1 = 1.47 V_{ent}\, t_g$$	Equation 9.13 $$b_1 = 0.278 V_{ent}\, t_g$$
Equation 9.12 $$b_2 = 1.47 V_{circ}\, t_g$$	Equation 9.14 $$b_2 = 0.278 V_{circ}\, t_g$$
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

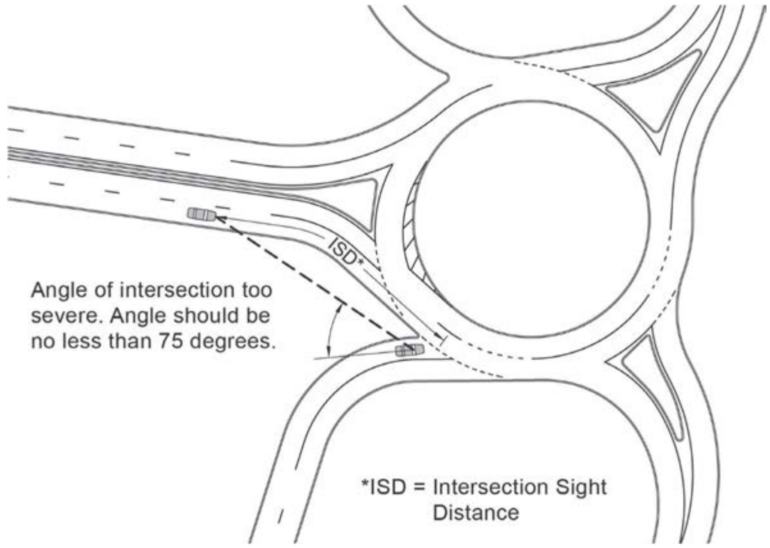
A *view angle* is the angle to the left, measured between the trajectory of the subject driver's vehicle and the line of sight for the driver to see an oncoming vehicle. A driver's ability to turn their head to the left is limited by human anatomy and becomes more difficult for older drivers and drivers 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.

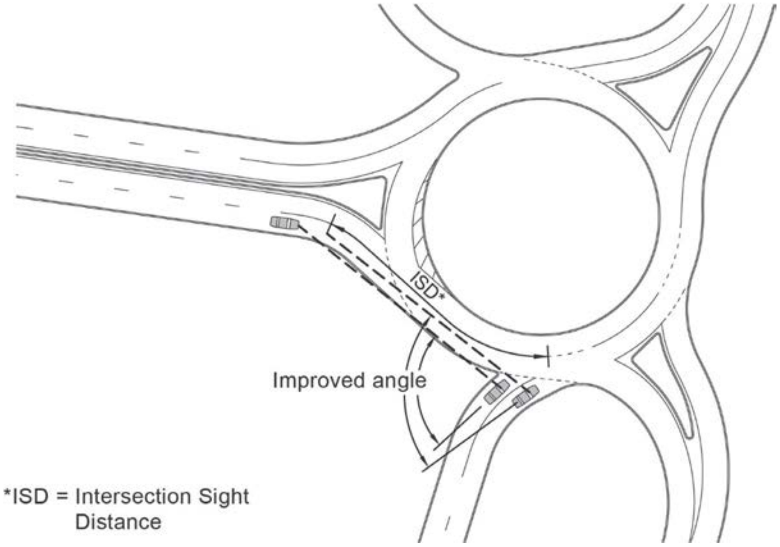
Performance checks conducted early in roundabout planning and design help inform these types of design decisions and trade-offs.

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.

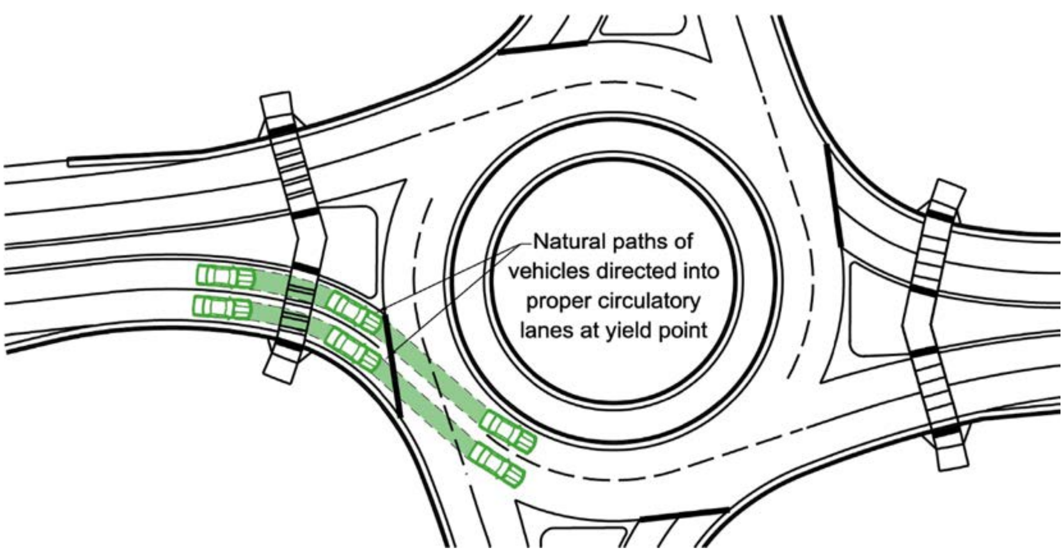


SOURCE: *NCHRP Report 672* and Tian et al. (*2, 6*).

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.

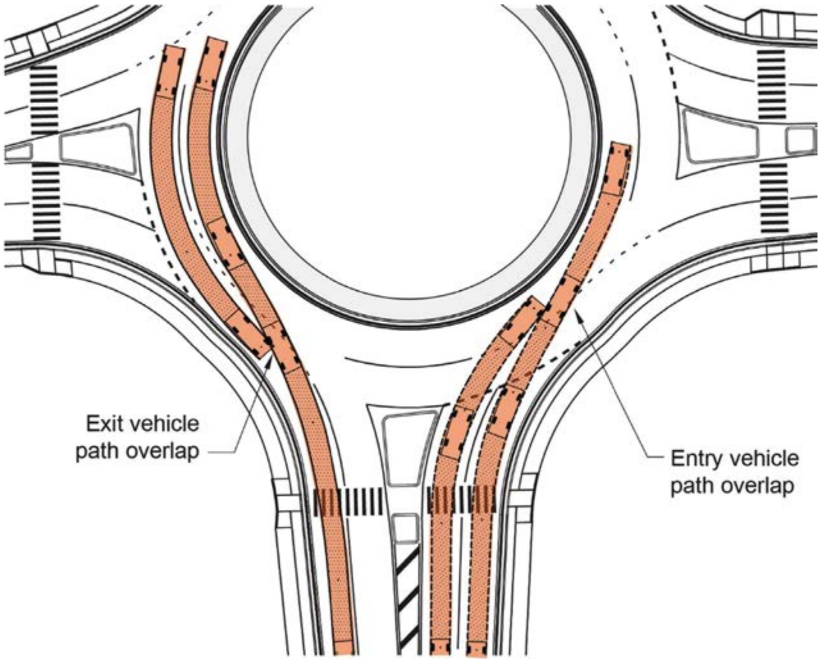


Exhibit 9.24. Examples of poor vehicle path alignment at a multilane roundabout.

(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.

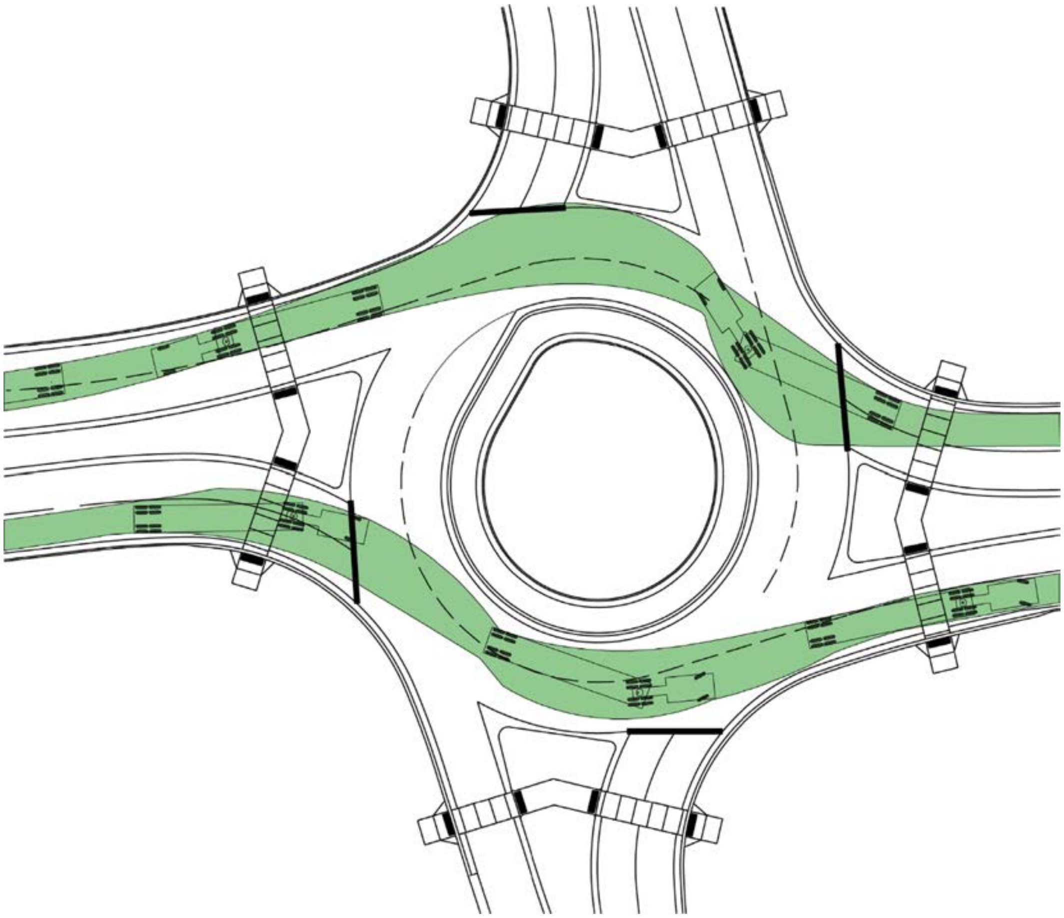
The associated geometric details and traffic control devices to support these two design cases are presented in Chapter 10 and Chapter 12, respectively.

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*).

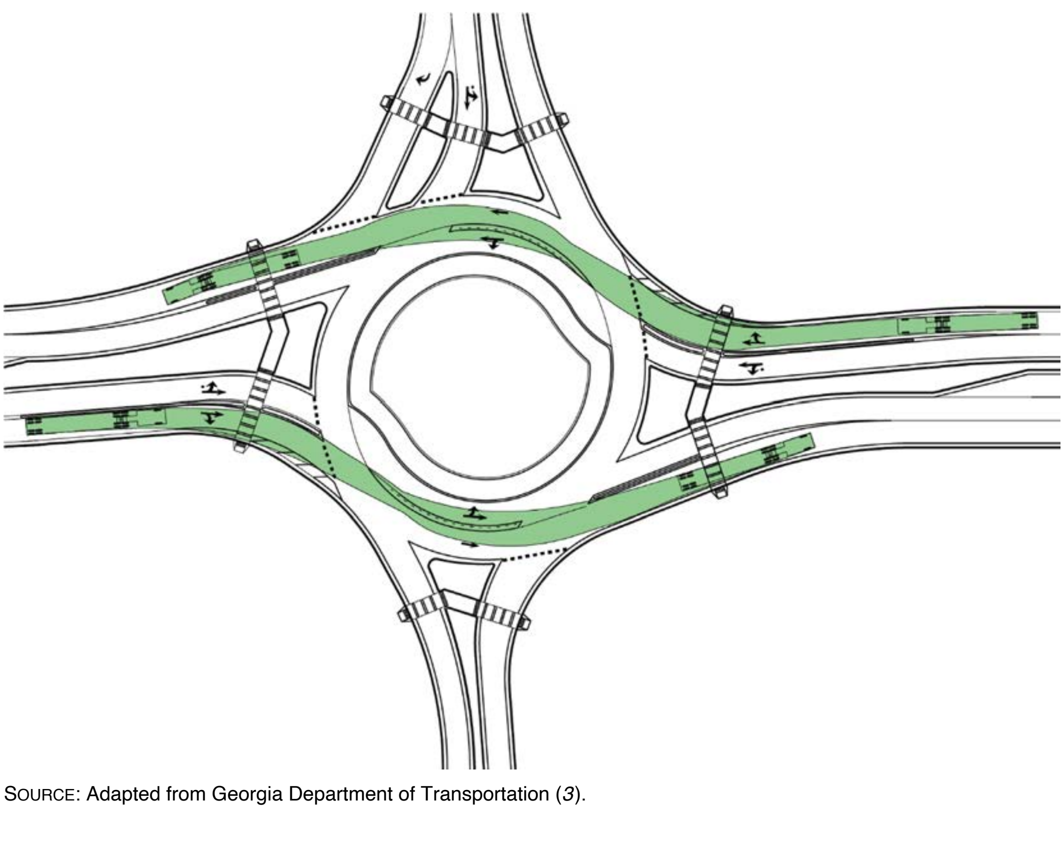
Exhibit 9.27 and Exhibit 9.28 demonstrate typical swept paths for through movements for the cases of straddling lanes and staying in-lane, respectively. Swept paths are to be drawn and

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:

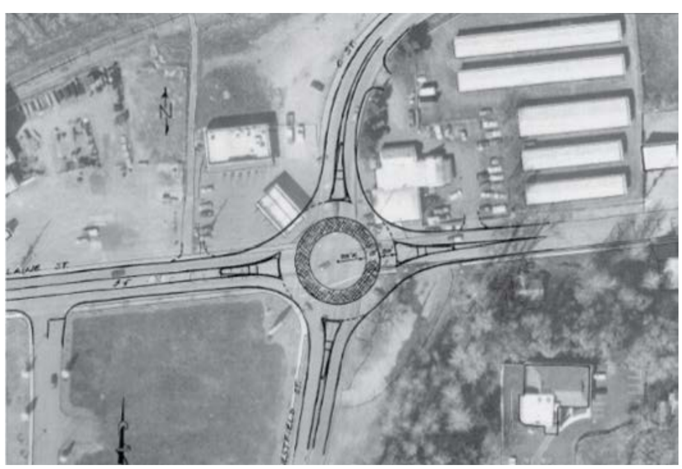
- Roundabouts requiring exclusive left-turn lanes may require spirals in the circulatory roadway so drivers can maintain appropriate lane assignments while traversing the circulatory roadway. Applying spirals (presented in Section 10.7.7) will typically result in a non-circular central island shape.
- 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.

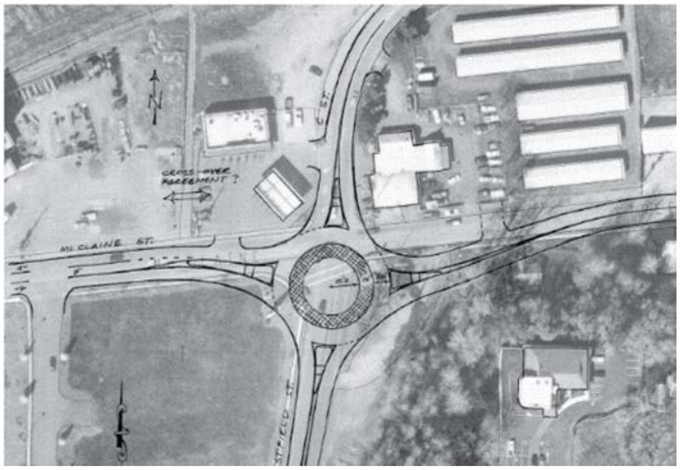
Exhibit 10.9, Exhibit 10.10, and Exhibit 10.11 provide an example of a design using three possible circle locations with the same ICD. Centering the roundabout on the existing intersection provides a baseline from which to consider project issues. The location as shown in Exhibit 10.9 affects developed 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.



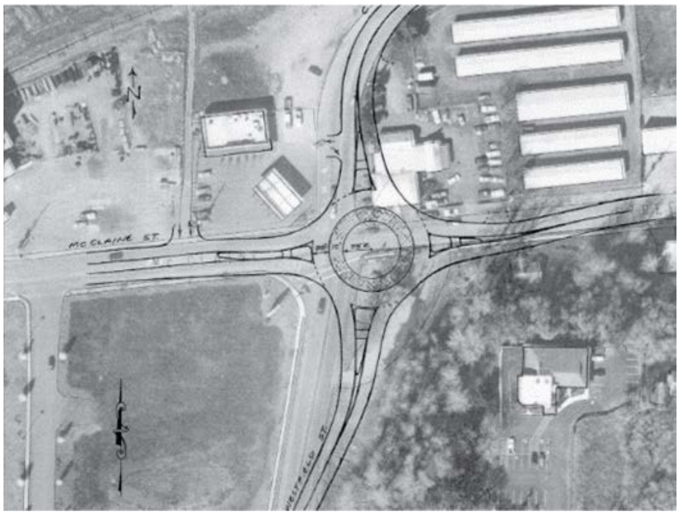
SOURCE: *NCHRP Report 672* (*2*).

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.

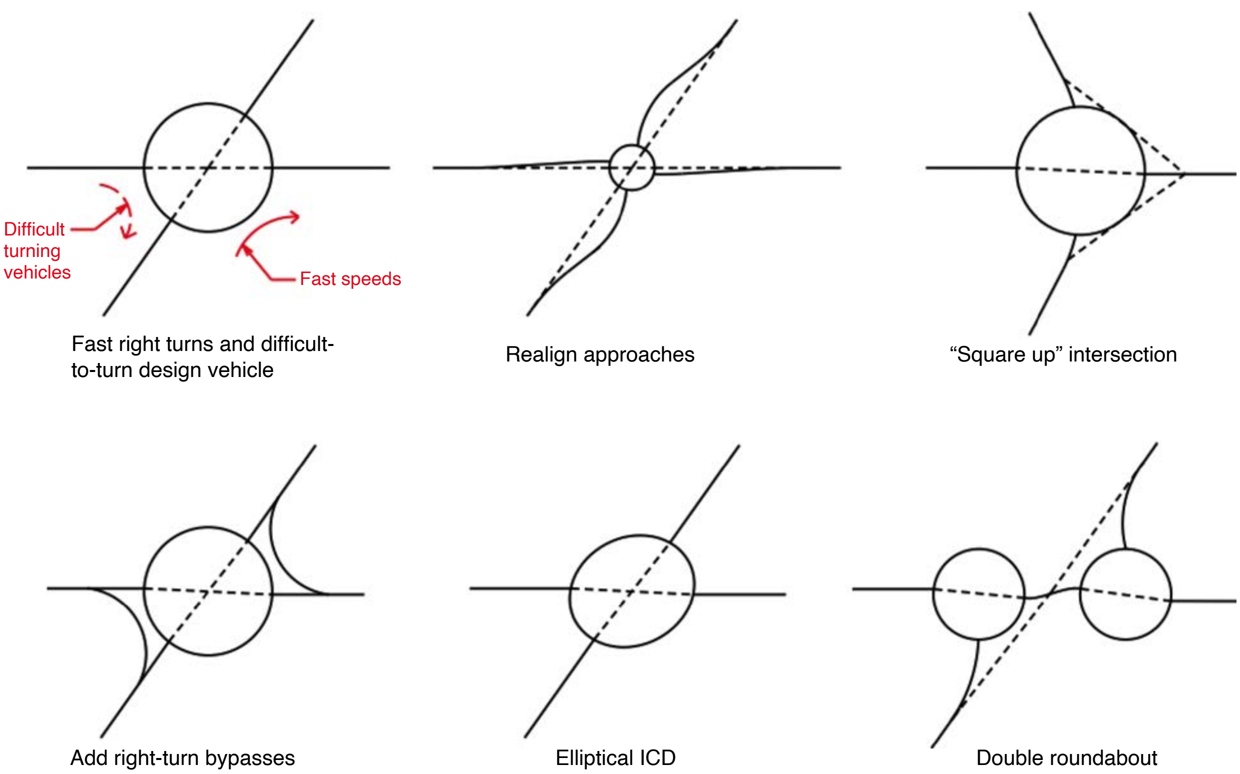
Intersection skew affects any intersection form, including roundabouts. As with other intersections, it is generally preferable for the approaches to intersect at perpendicular or near-perpendicular intersection angles. An acute skew angle can make navigation difficult for right-turning trucks and could 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).

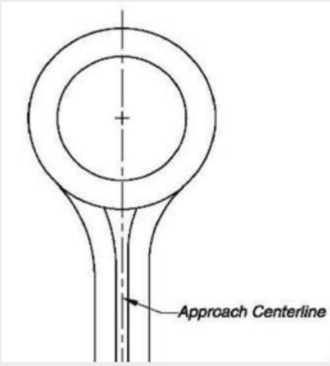
The roundabout addressed safety performance needs with a resulting alignment that better serves design vehicles. A secondary benefit is successive curves on the approach alignment that

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



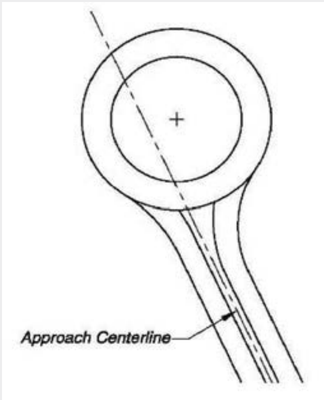
When It Might Be Appropriate

- 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



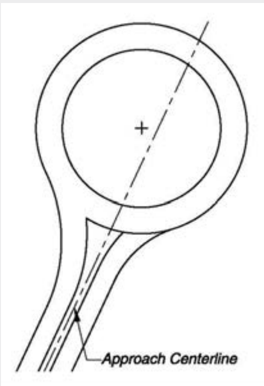
When It Might Be Appropriate

- 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.

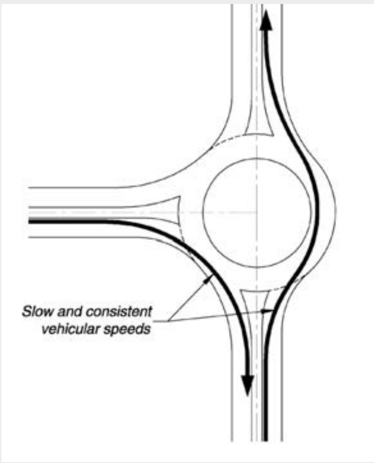
Question

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.

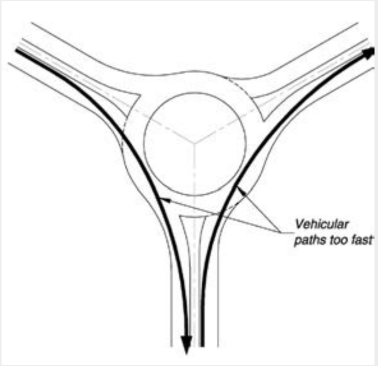
Perpendicular Legs



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.

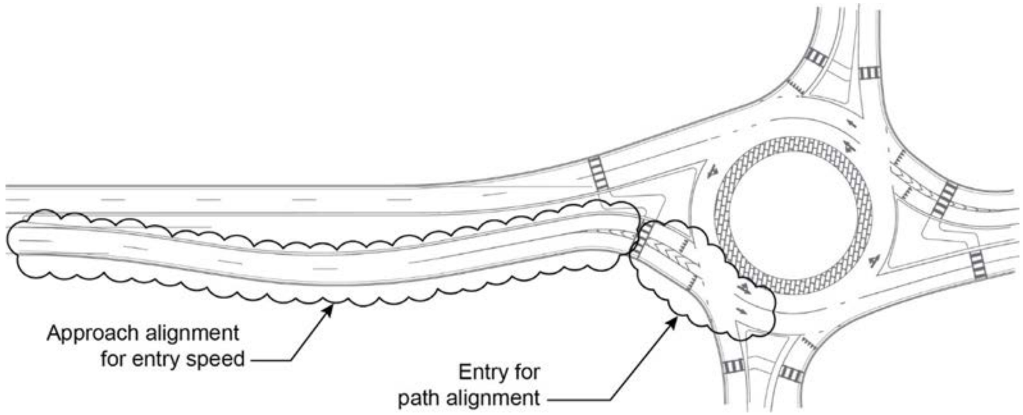
10.3.4 Facilities for Pedestrians and Bicyclists

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

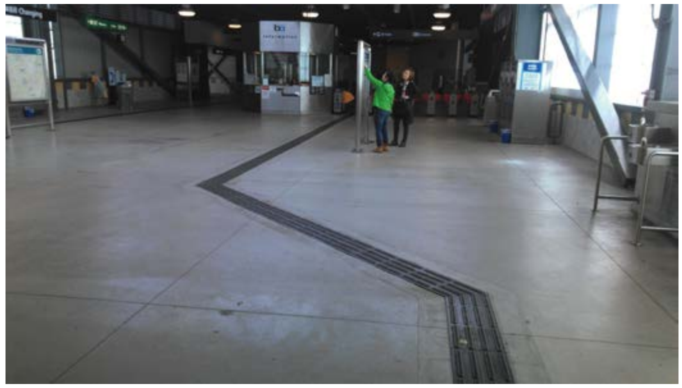
In addition to geometric treatments, tactile walking surface indicators (TWSIs) are used to aid wayfinding by people who are blind or have low vision. These indicators have been demonstrated to be readily detectable under foot and with a long cane. They should provide visual contrast with the surrounding 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.

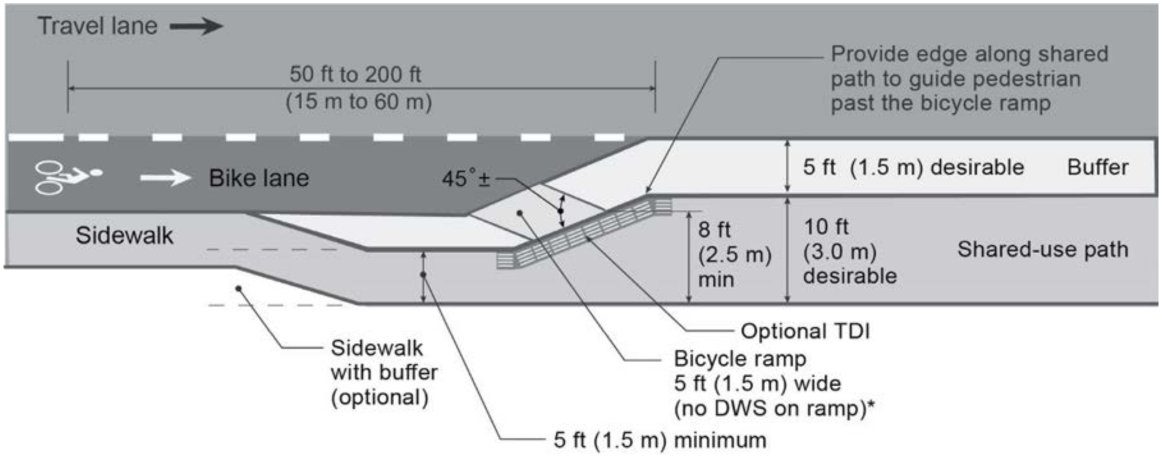
Where shared use by both bicyclists and pedestrians is intended, the desirable shared-use path width is at least 10 ft (3 m). If facilities around the perimeter of a roundabout are less than 8 ft (2.4 m) wide, they are too narrow for shared use and are treated as pedestrian-only facilities; see Section 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.

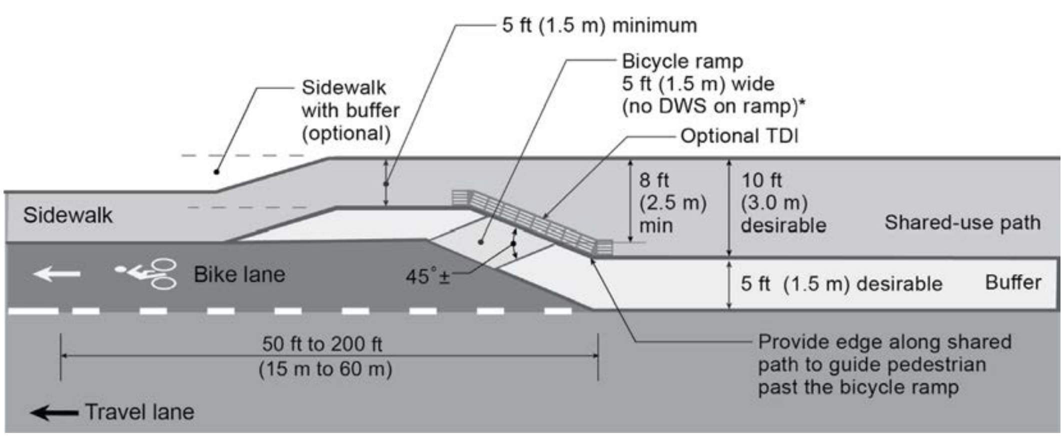


*DWSs are no longer recommended on bicycle ramps. If desired, optional TDIs can be used to delineate the desired path for pedestrians near the ramp. See FHWA (*12*).

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.

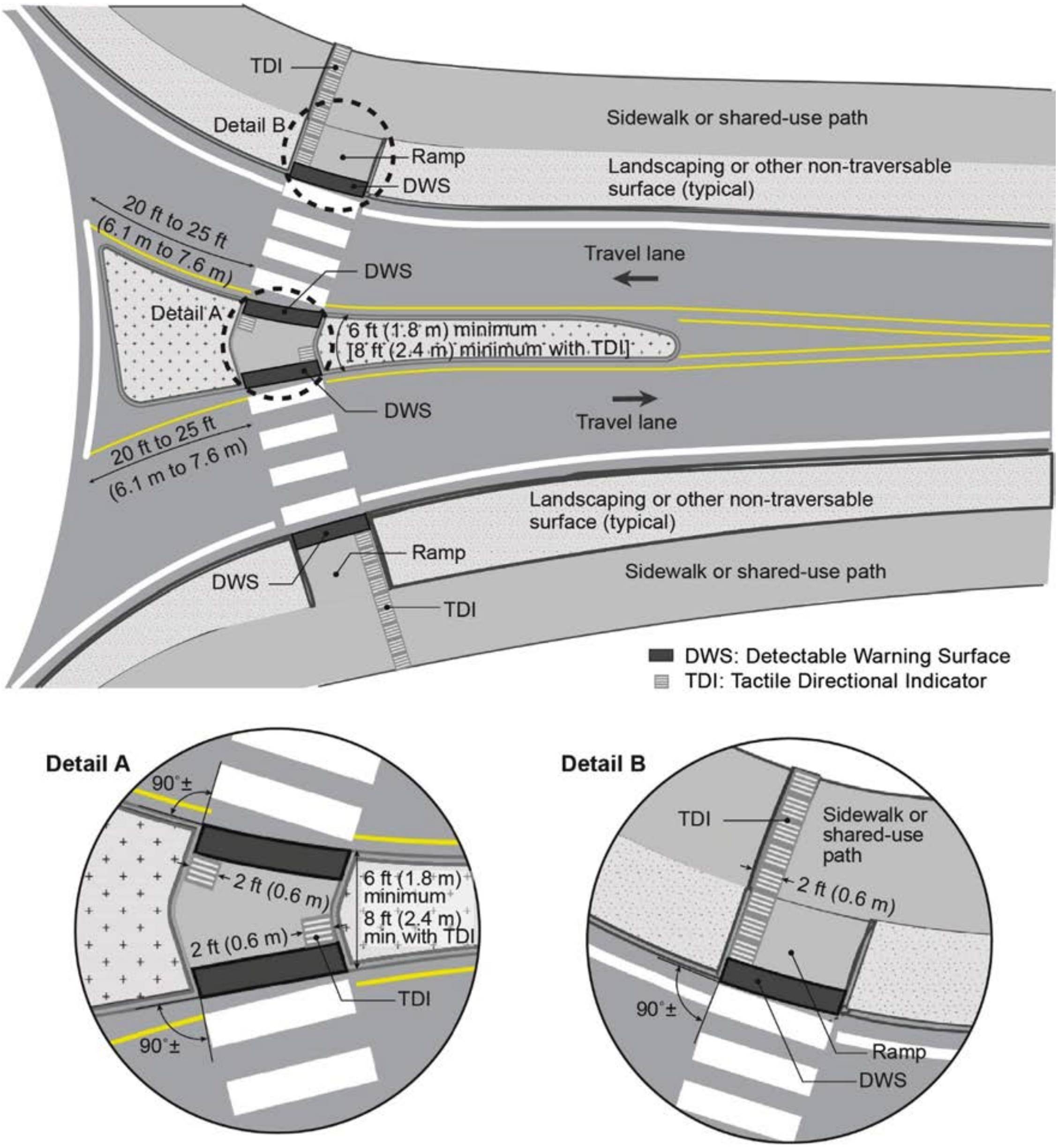
All roundabout pedestrian crossings have features in common:

- 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

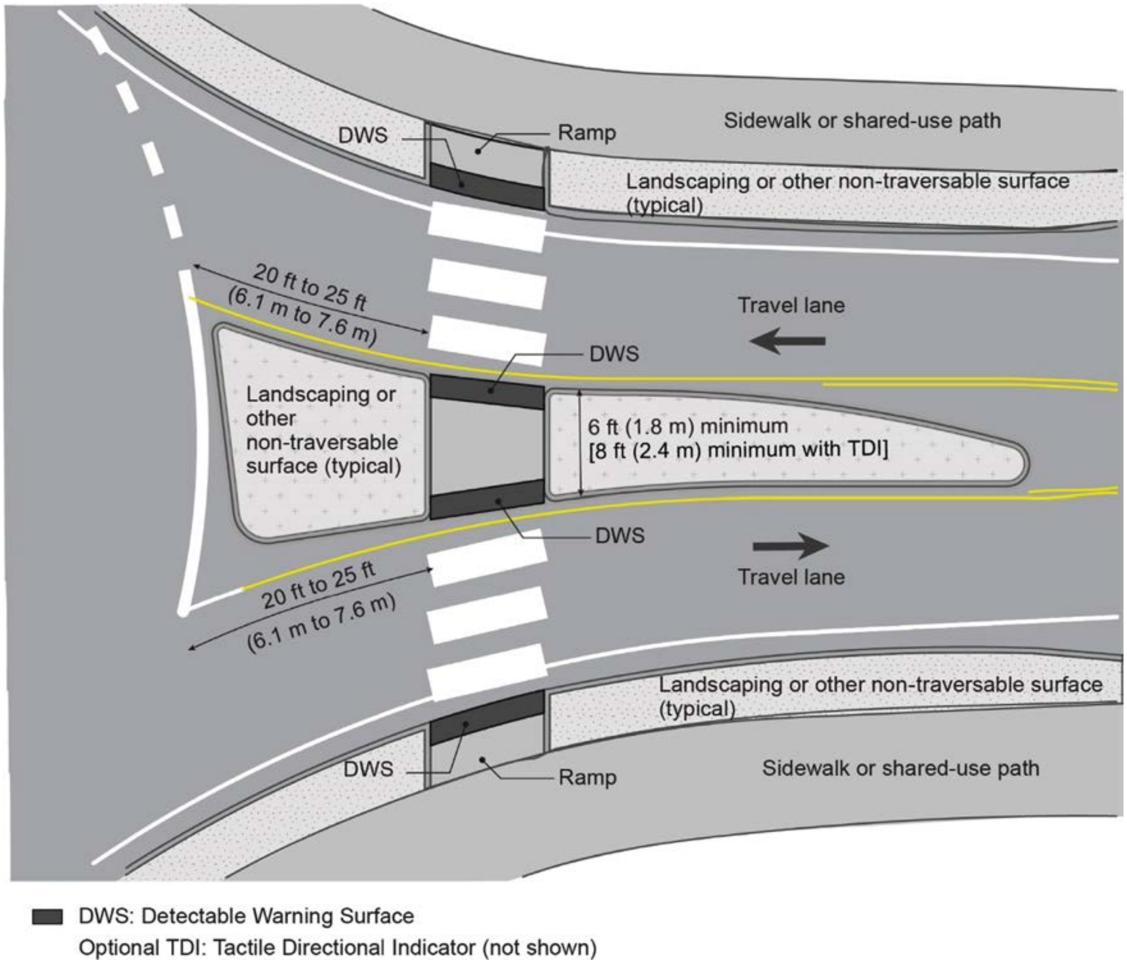
Exhibit 10.27. Typical features and dimensions of angled crossing.



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.

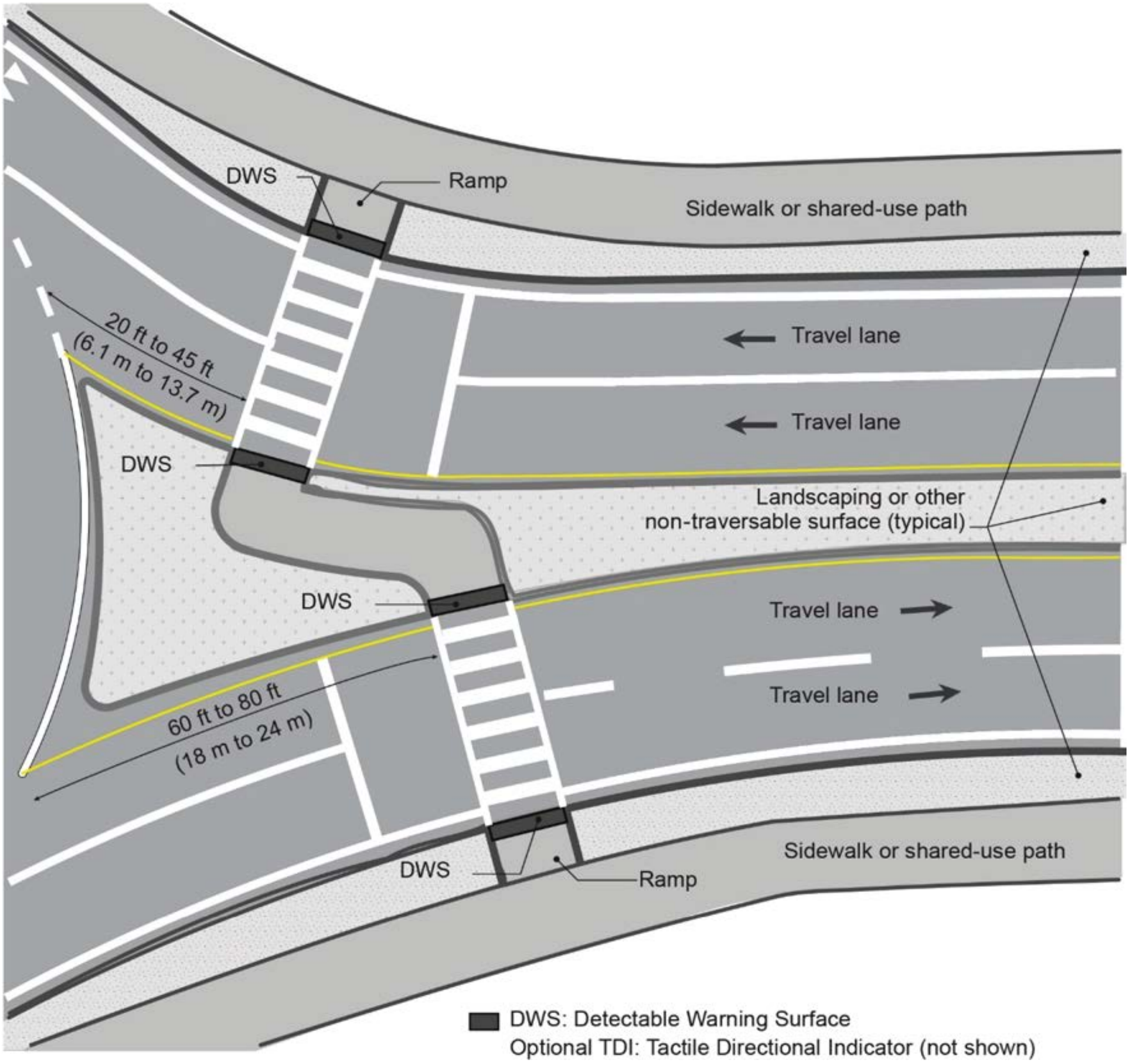


bicyclists. If separated bicycle and pedestrian crossings are provided, the pedestrian walkway can be narrower, to a minimum of 6 ft (1.8 m), to provide better wayfinding for people who are blind or have low vision. Exhibit 10.30 provides design details for splitter island pedestrian refuges for cut-through (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).

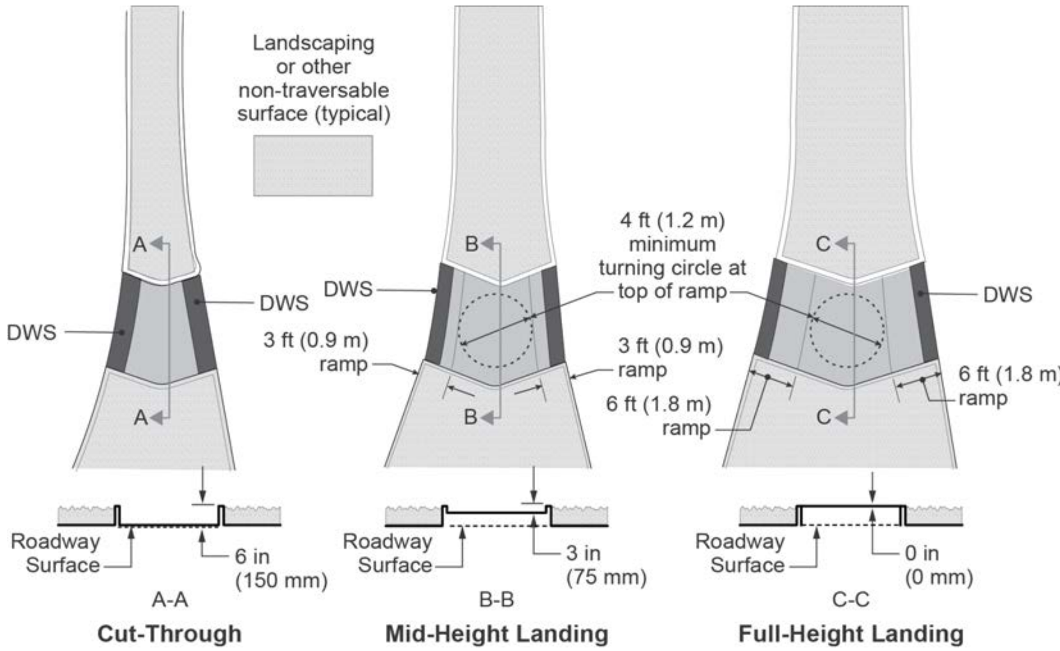


In all cases, determining the crossing configuration early in planning and design helps establish the roundabout footprint. For example, a staggered crossing placement at the exit and associated wider splitter island could result in a straighter alignment for motor vehicles that results in higher vehicle 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.

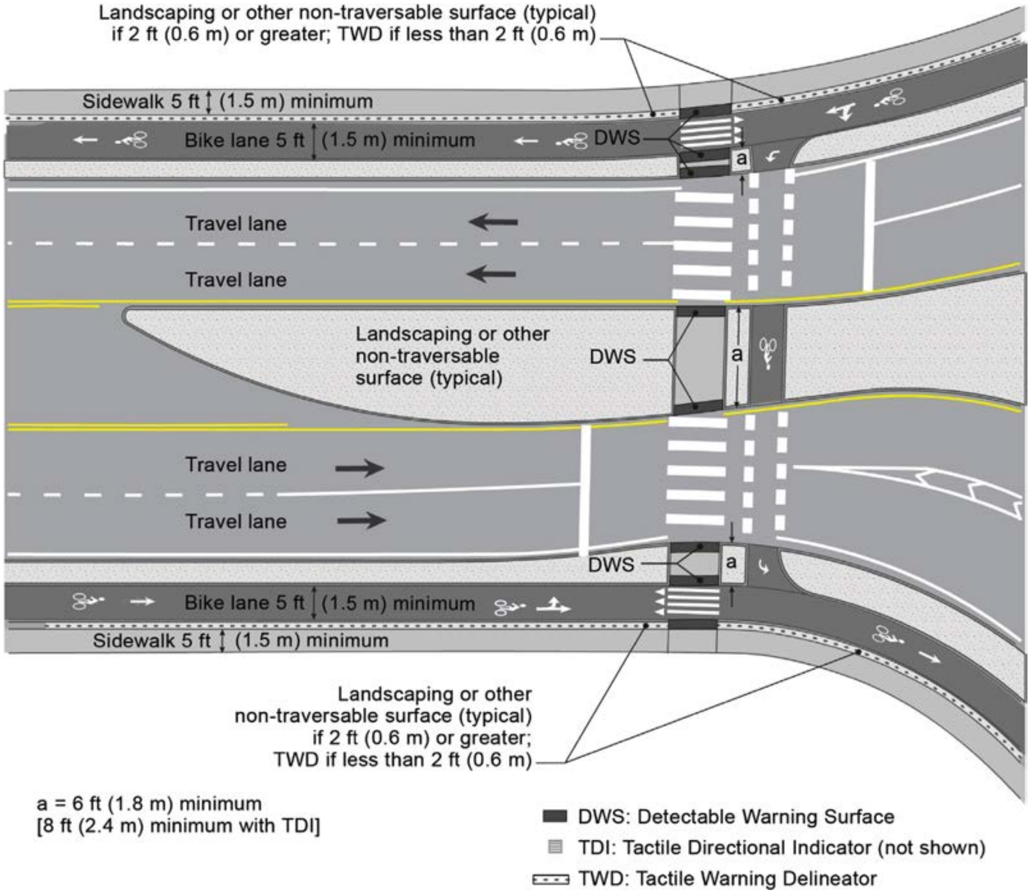
The separated bike lane approach to the bicycle crossing needs to result in bicyclists arriving at the queuing area at a perpendicular angle to approaching motorists. Channelizing islands would maintain separation between the bicycle and pedestrian crossings. When a separated bicycle crossing or a wider 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:

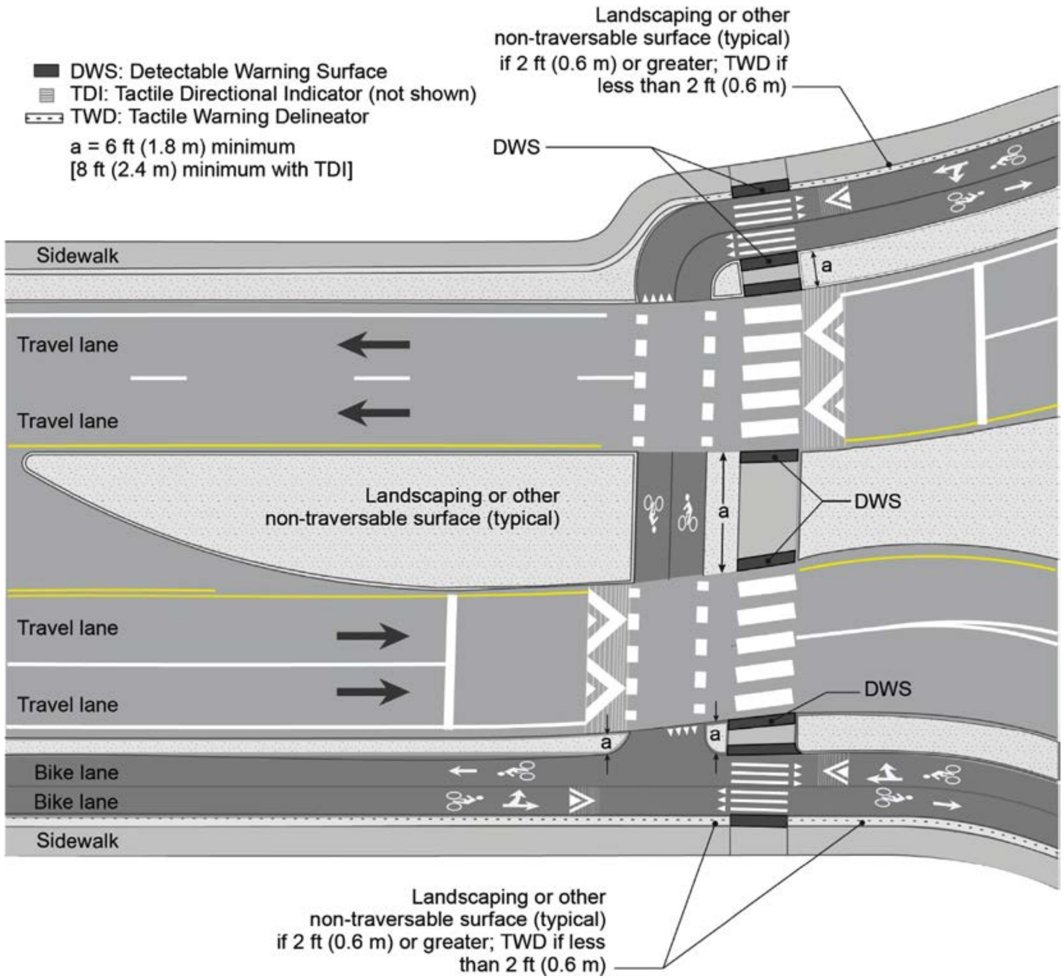
- The pedestrian crossing is farther from the roundabout, resulting in more out-of-direction travel for some movements.
- Depending on the overall length of the crossing, the pedestrian clearance time under one-stage operation is much longer than a typical two-stage crossing because of the additional 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.

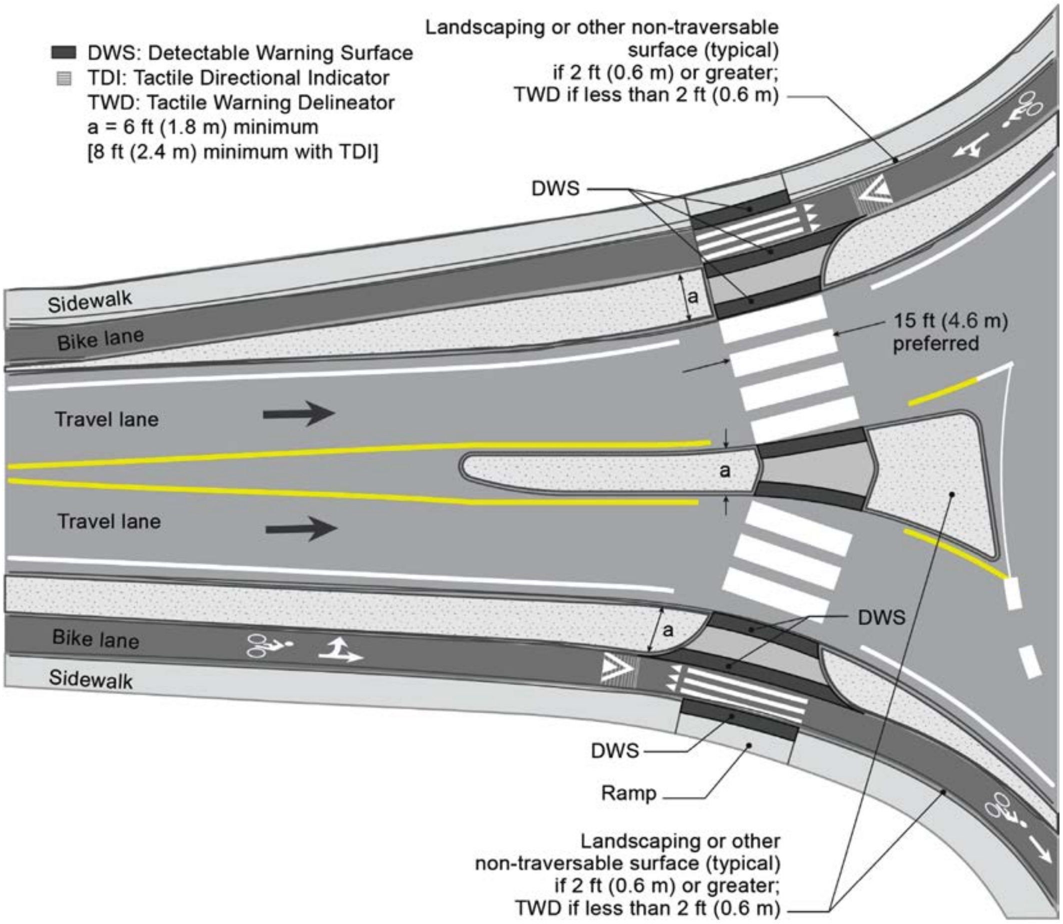


- The pedestrian crossing is closer to the roundabout, resulting in less out-of-direction travel for some movements.
- The alignment allows the bicycle and pedestrian crossings to be operated as a one-stage crossing to minimize delay for bicyclists and pedestrians.

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