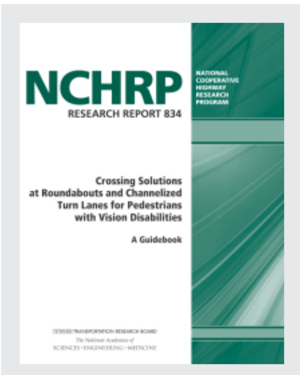

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP RESEARCH REPORT 834

Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities

A Guidebook

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2016

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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

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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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FOREWORD

By Stephan A. Parker
Staff Officer
Transportation Research Board

NCHRP Research Report 834 presents guidance for the application of crossing solutions at roundabouts and channelized turn lanes (CTLs) at signalized intersections for pedestrians with vision disabilities, including individuals with total blindness. The guidebook provides an accessibility assessment framework and a methodology for evaluating treatment alternatives for a proposed crossing, as well as wayfinding accommodations. Guidance is provided based on the feasible range of geometric and traffic operational conditions under which similar treatments have been demonstrated to enhance accessibility.

The guidebook and final report are targeted to an audience of practicing professionals who in some cases may have little or no background in design for accessibility. The guidelines are therefore written in a way that is consistent with other engineering guidebooks, and they are consistent with existing guidance on accessible design of pedestrian facilities and public rights of way. The audience for these products extends well beyond the engineer tasked with designing a particular site, including planners and decision makers at the municipal and state government levels; FHWA; and the U.S. Access Board, which is tasked with writing technical specifications for implementing the American with Disabilities Act, and which has published proposed guidelines in the form of the Notice of Proposed Rulemaking for Accessible Pedestrian Facilities in the Public Right-of-Way. This project also has a broad public interest component, including professionals and researchers in the field of orientation and mobility, as well as private citizens with and without vision impairments.

Accessibility of modern roundabouts and channelized turn lanes to pedestrians with vision disabilities has been a focus of recent and ongoing research. Initial research results documenting the crossing challenges for pedestrians with vision disabilities at these facility types motivated the original NCHRP Project 03-78A research effort (published as *NCHRP Report 674*) and had an influence on language in the Proposed Accessibility Guidelines for Pedestrian Facilities in the Public Right-of-Way (draft PROWAG) published by the U.S. Access Board in 2011. With the impending publication of the final PROWAG and its expected adoption by the U.S. Department of Justice and U.S. Department of Transportation, municipalities and state DOTs need more specific guidance on what may constitute equivalent facilitation to pedestrians with vision disabilities at these facility types.

Under NCHRP Project 03-78B, the research team led by the Institute for Transportation Research and Education (ITRE) at North Carolina State University (NCSU) was tasked with exploring crossing solutions for single-lane and multi-lane crossings at roundabouts and channelized turn lanes. The research was based on the premise that other treatments exist besides an APS-equipped signal that can establish access to these facilities to pedestrians who are blind, while reducing installation cost and impact to vehicular traffic.

CONTENTS

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 www.trb.org) retains the color versions.

CHAPTER 1

Introduction

This report presents a guidebook for the application of crossing solutions at roundabouts and channelized turn lanes to assist pedestrians with vision disabilities. The accessibility of these two complex intersections forms is an important civil rights challenge in the United States that has broad potential implications for engineering practice in this country.

Roundabouts are increasingly adopted by the transportation community in the United States because of their ability to process balanced and unbalanced traffic patterns, aesthetic appeal, relatively low operating costs, and, most importantly, their documented safety benefits (e.g., Rodegerdts et al., 2007; Robinson et al., 2000; Persaud et al., 2000). Similar to channelized turn lanes (CTLs), there are concerns about the accessibility of roundabouts, particularly for pedestrians who are blind (U.S. Access Board, 2003). Crosswalks at roundabouts are typically not signalized. Roundabout accessibility challenges have been documented through extensive research by Guth et al., 2005; Ashmead et al., 2005; Schroeder et al., 2011; and Guth et al., 2013, among others.

CTLs are a common treatment at signalized intersections, intended to allow heavy right-turning movements to bypass the main intersection. Crosswalks at CTLs are often unsignalized in the United States, and pedestrians must therefore make crossing decisions based on their perception of adequate gaps or the presence of a yielding vehicle. Accessible pedestrian signals or other audible devices are typically not available at most CTLs. Accessibility challenges at intersections with CTLs have been documented by Schroeder et al., 2006, and Schroeder et al., 2011, among others.

1.1 Purpose and Scope

The purpose of this guidebook is to present guidance for the application of crossing solutions at roundabouts and CTLs at signalized intersections for pedestrians with vision disabilities, including individuals with total blindness. The guidebook provides an accessibility assessment framework and a methodology for evaluating treatment alternatives for a proposed crossing. Guidance is provided based on the feasible range of geometric and traffic operational conditions under which similar treatments have been demonstrated to enhance accessibility.

While engineers may be faced with retrofit applications, this guidebook focuses on solutions that can be incorporated in the design phase of a new project. Treatments would be fully implemented when a new intersection opens to traffic to ensure it is in compliance with the Americans with Disabilities Act (ADA) and its implementing regulations from the start. The guidebook also considers the trade-offs between the needs of various users of a facility: pedestrians, including those with vision impairments or other disabilities, bicyclists, and vehicular traffic, including heavy vehicles such as trucks and buses. Specifically, the guidebook relies on conveying key principles for the accessibility of a roundabout or CTL, and translating these principles into performance-based checks that can be integrated in the design process for a new site.

This guidebook does not entail any policy recommendations for accessibility, nor does it prescribe standards for accessibility of the intersection types discussed. Rather, the guidebook is intended to be used as a decision-support tool by practicing engineers and planners. Both the decision framework and the methodology are meant to assist agencies with setting their own standards. The guidebook enables accessibility evaluations based on empirically derived models and performance measures. Also, the guidebook can be used to assess the equivalent facilitation potential of various pedestrian access treatments in accordance with the ADA, but without specifying standards for equivalent facilitation or accessibility.

1.2 Accessibility Versus Safety

The primary focus of this guidebook is on the accessibility of intersections for pedestrians with vision disabilities. While the safety of a facility and the access to a facility are related, the two terms are not synonymous. A facility may be considered safe if the frequency of crashes is low. However, accessibility must be judged by the extent to which any individual, or group of individuals, limits or avoids using a facility based upon a real or perceived belief that the facility is unsafe or extraordinarily difficult to use.

Conversely, good accessibility is best evaluated through direct observation of pedestrians with disabilities using a facility without a significant degree of perceived risk beyond that experienced by sighted pedestrians. A facility that is not accessible to and usable by pedestrians who are blind or who have low vision will often be avoided and thus may appear safe due to the lack of crashes involving pedestrians. But little or no pedestrian exposure may be equally or more related to this lack of crashes, as with any safety performance of the intersection. Accessibility is therefore evaluated independently and in addition to the safety record of the intersection. A key motivation of this document is to provide agencies with tools for evaluating the accessibility of a facility, independent of pedestrian crash statistics.

ADA is the underlying legislation that establishes access as a civil right. Requirements for accessibility in state and local government programs and services, including public rights-of-way, are outlined in the implementing regulations for Title II of ADA , which specify that any newly constructed or altered public facility shall be "readily accessible to and usable by individuals with disabilities" (U.S. Department of Justice, 2010) including those with vision loss, mobility impairments, or other disabilities.

The absence of recorded pedestrian crashes, especially those involving older pedestrians, children, or those with visual and/or physical impairments, does not constitute proof that a facility is accessible, nor does the presence of crashes constitute proof that it is inaccessible. An analysis of pedestrian crashes alone therefore is not sufficient to determine the accessibility of complex intersections to pedestrians who are blind.

1.3 Minimum Specifications and Equivalent Facilitation

One of the responsibilities of the U.S. Access Board is to develop minimum technical specifications for transportation facilities to ensure that public rights-of-way are accessible to and usable by all people, and are thereby in compliance with ADA. The U.S. Access Board published a Notice of Proposed Rulemaking for *Accessibility Guidelines for Pedestrian Facilities in the Public Right-of-Way* (referred to as PROWAG-NPRM in this report) on July 26, 2011 (U.S. Access Board, 2011), outlining requirements for making crosswalks and intersections in the public right-of-way compliant with ADA. Specifically, paragraph R306.3.2 requires that, at roundabouts with multilane pedestrian street crossings, a pedestrian-activated accessible pedestrian signal (APS) complying with the *Manual on Uniform Traffic Control Devices for Streets and Highways* (referred to as MUTCD in this report), Sections 4E.08 through 4E.13 (MUTCD, 2009), be provided for each multilane segment of a pedestrian crossing, including the splitter island. A pedestrian-actuated and APS-equipped signal thereby satisfies the accessibility requirement for two-lane roundabout approaches. PROWAG-NPRM R306.4 and R306.5 language for two-lane CTL crosswalks is very similar to the language for two-lane roundabouts, in that a pedestrian signal with APS makes the crossing accessible.

PROWAG-NPRM also requires and specifies a continuous and detectable edge treatment at roundabouts where sidewalks are flush against the curb and pedestrian crossing is not intended (R306.3.1). These edge treatments are designed to reduce the likelihood that individuals with vision impairments cross at locations other than marked crosswalks. Advisory R306.3 describes additional features to delineate the crossing locations at roundabouts. APS devices are required at all crossings equipped with pedestrian signals (R209), and truncated dome detectable warning surfaces are required on the curb ramps to demark the street-sidewalk boundary (R208.1). PROWAG-NPRM does not address crossing treatments or signalization at single-lane roundabouts or single-lane CTLs.

While PROWAG-NPRM specifies a pedestrian-actuated signal at two-lane roundabout crosswalks with pedestrian facilities, ADA allows equivalent facilitation in all implementations of requirements. PROWAG-NPRM allows for equivalent facilitation in Section R102, and defines equivalent facilitation as follows:

> The use of alternative designs, products, or technologies that result in substantially equivalent or greater accessibility and usability than the proposed guidelines is permitted.

Consequently, treatments or geometric configurations that provide equivalent accessibility to treatments or configurations specified in ADA and its implementing regulations are acceptable and in compliance with ADA. This is to allow for improvements in technology, developments in materials or research, or the implementation of new ideas and information. It is up to the designer and/or constructing jurisdiction to provide justification for their installation decisions in the case of an ADA complaint. One of the principal goals of this document is to assist transportation agencies with evaluating the equivalent facilitation of a particular treatment, and to decide whether its provision is likely to conform to ADA.

1.4 Four Components of the Crossing Task

The crossing task for blind pedestrians consists of four principal tasks that need to be mastered to successfully cross the street at roundabouts and intersections with CTLs:

- Finding the crosswalk and identifying the intended crossing location, which includes identifying when and where to turn from the sidewalk toward the crosswalk landing,
- Aligning to cross to establish a correct initial heading at a crosswalk that may or may not be aligned perpendicular with the sidewalk or in the same direction as the slope of the associated curb ramp,
- Deciding when to initiate crossing in an environment of largely uninterrupted traffic flow, requiring the identification of appropriate gaps in traffic or crossing opportunities in front of yielding vehicles (when signals are provided, an audible message should be used to convey to a blind pedestrian when the walk indication is active), and
- Maintaining correct heading while crossing multiple lanes over the length of the entire crosswalk and staying within the crosswalk until the far side of the roadway is reached.

The crossing task at CTLs and roundabouts is often challenging for persons with vision impairments due to the prevailing curved vehicle paths and movement of other nearby vehicles. The task of correctly identifying vehicle positions and trajectories, vehicle gaps, and driver yielding based upon auditory information alone is challenging. The geometric configuration of the intersection can further result in elevated speeds at the crosswalk and heavy traffic volumes can contribute to high ambient noise levels. These factors can also significantly impact crossing difficulty for persons with vision impairments.

Three aspects of the four components of the crossing task are typically characterized as wayfinding tasks: finding the crosswalk, aligning to cross, and maintaining correct heading while crossing. Difficulty in these tasks may result in persons with vision impairments initiating crossing outside the crosswalk area, crossing to the central island of a roundabout, or missing the island at a CTL due to veering. These and other wayfinding challenges can cause confusion and disorientation for the pedestrian. Crossing at a location that is not within the crosswalk and thus where drivers are not expecting pedestrians can be a safety issue as well.

The other component of the crossing task, deciding when to cross, can be more difficult than at a conventional, orthogonal intersection because of the difficulty in interpreting traffic patterns. Traffic sounds are typically the most reliable crossing-related information available to individuals with vision impairments at conventional intersections. When pedestrian crossings are signalized, the addition of an APS, along with traffic sounds, can provide further information to a blind traveler about the location of the pushbutton and the status of the pedestrian signal. The audible information from the accessible pedestrian signal enables pedestrians who are blind to locate the pushbutton, to detect the onset and duration of the walk interval, and to anticipate accurately when vehicles are likely to stop to permit pedestrians to cross.

Recent research on the crossing performance of people with vision impairments at complex intersections, including roundabouts and CTLs, demonstrated that there are unique challenges for this population (Ashmead et al., 2005; Guth et al., 2005; Schroeder et al., 2011). The traffic control at a roundabout entry leg is typically a yield sign, and many drivers are able to enter the circulatory roadway without coming to a full stop or slowing or stopping at the crosswalk. Similarly, traffic exiting the roundabout is often free flowing, resulting in largely uninterrupted traffic flow at the exit crosswalk. Traffic patterns at CTLs are similar in many cases in that the right-turning movement is largely free flowing. The design of a CTL and the location of the crosswalk, whether marked or unmarked, can vary significantly across sites (*NCHRP Report 279*; Newman, 1985). However, recent national survey research revealed that about 70% of CTLs have crosswalks located in the center of the channelized lane (*NCHRP Web-Only Document 208*; Potts et al., 2011). That same research emphasized the importance of design consistency to facilitate crossing and wayfinding task performances by pedestrians who are blind.

Crosswalks at both types of facilities are typically not signalized, and the task of identifying crossing opportunities is thus unassisted by technologies that provide audible information to pedestrians. Depending on the geometric design and the location of the crosswalk, vehicle speeds may be relatively high and, as noted earlier, the interpretation of the sounds of vehicle movement is complicated because the vehicles are moving on a curving path (Ashmead et al., 2005). At conventional signalized intersections, two traffic streams typically move perpendicular to each other, making it easier for pedestrians who are blind to interpret directional traffic movements using hearing alone. Finally, the continuous flow of traffic circulating the roundabout or moving through the CTL and main traffic streams of the intersection can create a difficult auditory environment, and the listening task is complicated by the elevated levels of ambient noise.

1.5 Outline of the Document

This chapter has provided a general overview of the guidebook and of accessibility challenges for pedestrians who are blind at roundabouts and CTLs. The remainder of the document is organized as follows.

Chapter 2 introduces a design process for roundabouts and CTLs, highlighting where analysts can integrate an evaluation of intersection accessibility with references to specific evaluation components presented in other chapters.

Chapter 3 presents a discussion of the general principles for pedestrian access. This chapter contains a summary of wayfinding and alignment principles, a more detailed discussion of the crossing challenges faced by pedestrians who are blind, and guidance on treatments to facilitate accessibility of roundabouts and CTLs for blind pedestrians.

Chapters 4 and 5 present the principles for pedestrian access at roundabouts and CTLs, respectively. The chapters contain discussion of pedestrian-focused designs, crosswalk location and angle, and use of traffic control devices at these locations.

Chapters 6 and 7 provide assessment methodologies for evaluating the accessibility of roundabouts or intersections with CTLs. Chapter 6 provides methods and guidance for assessing wayfinding and alignment treatments at both facility types for a given design. Chapter 7 presents a crossing assessment methodology for evaluating crossing risk, crossing delay, and a crossing confidence score based on various input variables. The chapter also provides guidance on assessing sight distance, visibility, and audibility of designs and any traffic control devices used at the crosswalk.

The main chapters are supported by two appendices that offer supplemental but important information. Appendix A offers additional discussion of noise impacts on accessibility, since the audible environment was found to be a key consideration in the evaluation of a crosswalk. Appendix B presents an assessment of selected accessibility treatments, including a treatment description, estimate of installation cost, and field test results for application to roundabouts and CTLs. The appendix includes detailed cost estimates for several of these treatments.

CHAPTER 2

Design Process

This chapter presents an overall design process for roundabouts and CTLs that fully integrates accessibility. The design process is iterative in nature, as a design may need to be revised throughout its development to achieve a desirable performance. If changes are made to the initial design, these changes may affect performance measures differently. As an example, a raised crosswalk may increase the rate at which drivers yield to pedestrians but it may also decrease the vehicular capacity of the affected lanes. Similarly, a reduction in curve radius may help reduce speeds at the crosswalk, but may also affect the adequate accommodation of the design vehicle.

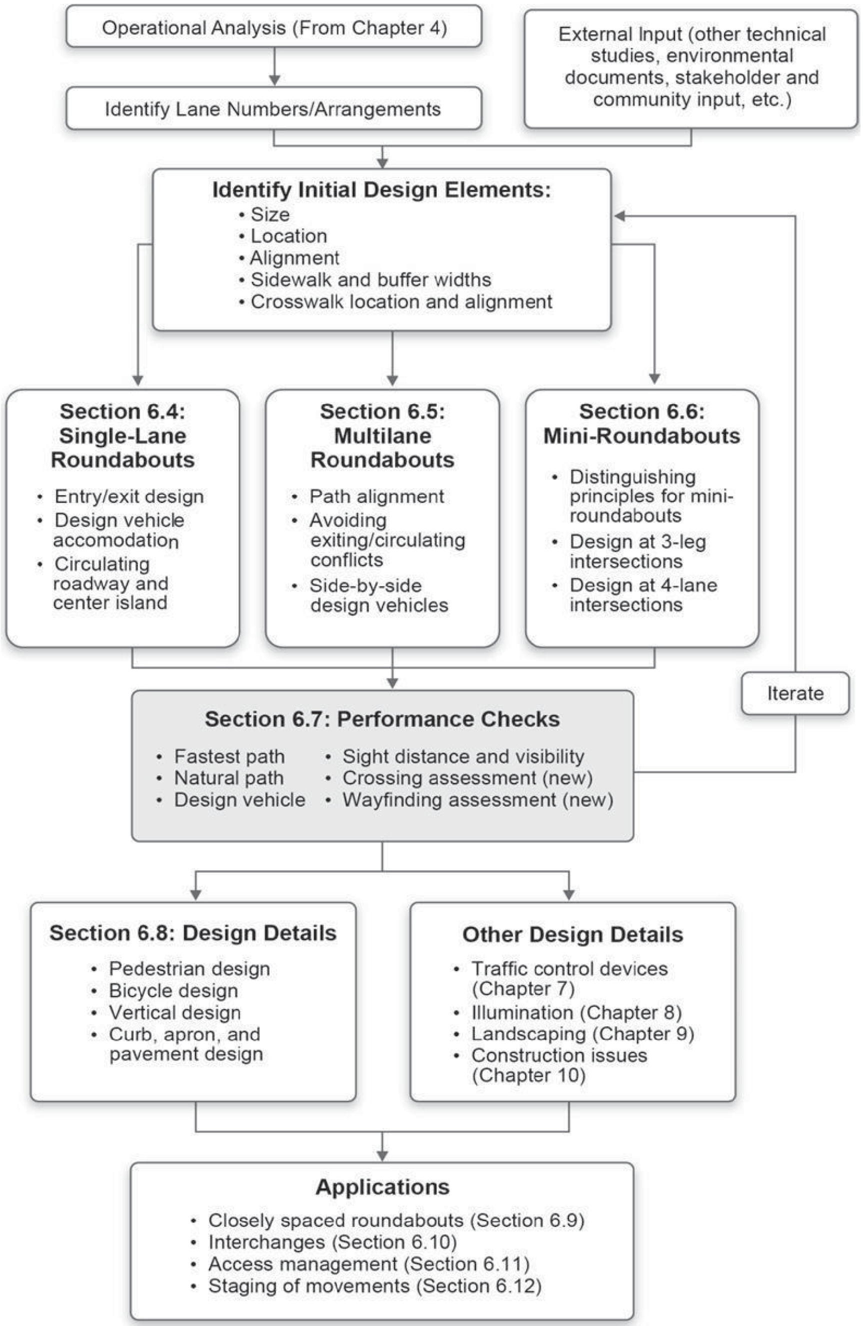
These trade-offs are very similar to others faced by designers in balancing operational performance, safety performance, and costs, to name just three factors. Designers should therefore develop a good understanding of the trade-offs of different geometric configurations and accessibility treatments to minimize the amount of iterations necessary to arrive at an acceptable solution, and to ensure that the needs of all users are reflected in the design.

The design process employed in this guidebook is a performance-based process. A performance-based process recognizes that each project is unique. This approach has been recognized in a number of national documents, including *Flexibility in Highway Design* (FHWA, 2012), and are integrated into the roundabout design process in *NCHRP Report 672* (Rodegerdts et al., 2010). The FHWA document discusses the need for a balanced design. This balance needs to include the accommodation of all road users, including pedestrians of differing abilities. Performance-based checks provide a systematic way for designers to achieve acceptable performance while being tailored to the unique features and constraints of a given project.

2.1 Roundabouts

For roundabouts, *NCHRP Report 672* provides a comprehensive process for designing a roundabout, reproduced here in Figure 2-1. A goal of this guidebook is to expand the "performance checks" portion of the design process (highlighted in Figure 2-1) to include accessibility-related checks.

A key aspect of this figure—and one of the key philosophies presented in *NCHRP Report 672*—is the use of performance checks and the resulting iteration that occurs in the design. For example, the entries and exits of a roundabout should be narrow enough and tight enough to limit fastest path speeds, yet wide enough and with flat enough curvature to accommodate design vehicles. It is challenging for designers to provide appropriate speed control and accommodate design vehicles for all movements on the first attempt. Rather, to meet these performance measures and others, iteration and refinement of an initial design are often needed.



Note: The chapter and section numbers in this figure refer to *NCHRP Report 672*.

Figure 2-1. Roundabout design process (Exhibit 6-1 from* NCHRP Report 672*).

The flowchart in Figure 2-1 shows a multistep roundabout design process with the following components: three data input steps and eight overall design process steps. The data input steps are: (1) operational analysis, (2) identify lane numbers and arrangements, and (3) external input from other studies. The steps in the overall design process are: (4) identify initial design elements, (5) single-lane roundabouts, (6) multilane roundabouts, (7) mini-roundabouts, (8) performance checks, (9) design details, (10) other design details, and (11) applications.

The eighth step—performance checks—is highlighted. The specific performance checks listed in the figure are fastest path, natural path, design vehicle, and sight distance and visibility. This guidebook adds two new checks for accessibility performance—crossing assessment and wayfinding assessment. After performance checks, designers either advance to the next step (design details) or iterate and return to step four to modify the design.

The performance checks outlined in *NCHRP Report 672* can be characterized as follows, with the means to conduct each check given in parentheses:

- Achieve acceptable operational performance (lane numbers and arrangements check),
- Achieve acceptable safety performance (fastest path, path alignment, and sight distance/visibility checks),
- Accommodate the design vehicle (design vehicle check), and
- Accommodate non-motorized users (pedestrians and bicyclist feature check).

This project expands the non-motorized user and sight distance/visibility checks to include accessibility-related issues as follows:

- Pedestrian wayfinding task (Chapter 6 of this guidebook) and
- Pedestrian crossing task and pedestrian-related aspects of sight distance, delay, and risk (Chapter 7 of this guidebook).

Integration of these additional checks into the design process is intended to elevate accessibility to be a normal and integral part of the roundabout design process.

2.2 Channelized Turn Lanes

As stated in *A Policy on Geometric Design of Highways and Streets* (AASHTO, 2011), referred to as the Green Book commonly and in this report, the primary reasons for installing CTLs are as follows:

1. To increase vehicular capacity at intersections,
2. To reduce delay to drivers by allowing them to turn at higher speeds,
3. To reduce unnecessary stops,
4. To clearly define the appropriate path for right-turn maneuvers at skewed intersections or at intersections with high right-turn volumes,
5. To improve safety by separating the points at which crossing conflicts and right-turn merge conflicts occur, and
6. To permit the use of large curb return radii to accommodate turning vehicles, including large trucks, without unnecessarily increasing the intersection pavement area and the pedestrian crossing distance.

When the decision to install a CTL has been made, the design practice generally relies on established techniques and agency preferences rather than an iterative, performance-based process as described previously for roundabouts. Many of these best practices are captured in *NCHRP Web-Only Document 208,* and summarized in Chapter 4 of this document. Figure 2-2 presents the state of practice for CTL design processes, although this process is not formalized as in the case of roundabouts.

The key aspects of this figure are selection of control and design development according to established practices. Operational needs, land use and contextual environment, and agency preferences are all factors influencing the selection of control. The Green Book, agency guidance documents, and typical detail drawings are factors influencing the selection of island size, turning roadway width and radius, and crosswalk location, to name a few of the elements of CTLs. In some cases, site-specific conditions necessitate variations of established practices. For example, if an intersection is skewed, the turning roadway width and radius required to accommodate a design vehicle may need to be determined with vehicle turning template software rather than the orthogonal intersection figures in the Green Book.

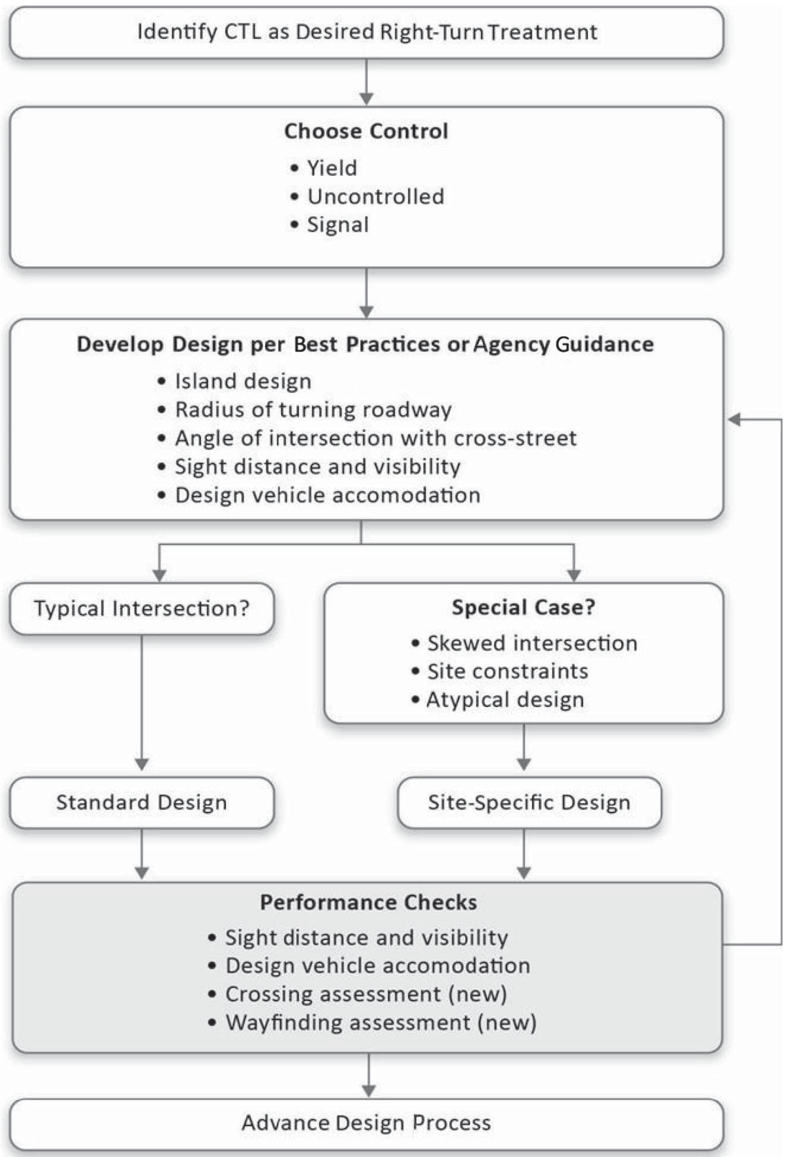


Figure 2-2. Channelized turn lane design process.

The flowchart in Figure 2-2 shows the following steps: 1) identify CTL as desired right-turn treatment, 2) choose control (yield, uncontrolled, or signal), and 3) develop design according to best practices or agency guidance (island design, radius of turning roadway, angle of intersection with cross-street, sight distance and visibility, design vehicle accommodation). After Step 3, there is a decision point in the chart. If the intersection is a typical intersection, a standard design can be used. If the intersection is a special case such as a skewed intersection or has site constraints or an atypical design, a site-specific design is needed. The process converges and performance checks are used to assess sight distance and visibility and design vehicle accommodation, and some iteration may be needed before the design process is advanced. The accessibility checks proposed in this document—crossing assessment and wayfinding assessment—are added to the performance checks.

CHAPTER 3

General Principles for Pedestrian Wayfinding and Crossing Tasks

This chapter presents an overview of the design principles related to accessibility for pedestrians who are blind (subsequently referred to in this document as "blind pedestrians") that should be considered when designing a roundabout or CTL. The chapter is divided into a discussion of wayfinding tasks and an overview of the crossing tasks. In the following chapters, these principles are followed up with design principles specific to roundabouts and CTLs.

3.1 Wayfinding Tasks

3.1.1 Issues and Principles of Wayfinding at Intersections

For pedestrians who are blind, crossing at roundabouts, CTLs, and other intersections consists of four task components, which are required for crossing any street (Guth, Rieser, and Ashmead, 2010):

1. Finding the crosswalk and determining the appropriate crossing location;
2. Aligning to cross and establishing the correct heading at the crosswalk;
3. Deciding when to initiate crossing (requiring the identification of appropriate gaps in traffic or crossing opportunities in front of yielding vehicles); and
4. Maintaining the correct heading while crossing and staying within the crosswalk.

All but the third of these tasks are considered wayfinding tasks of crossing. Failure in any one of the three wayfinding tasks can result in actions such as crossing from a location where pedestrians are outside the crosswalk and thus unexpected by drivers, stepping into the roadway without realizing it, or crossing toward the center island of a roundabout.

These tasks apply both to the initial approach to a crosswalk from the sidewalk as well as to wayfinding on roundabout splitter islands or CTL channelization islands. Failure in wayfinding tasks may lead to unsafe situations when negotiating splitter islands, potentially resulting in disorientation, walking into the street from the island, or aligning in ways that result in crossing into the intersection. Several examples of wayfinding errors are illustrated in Figures 3-1, 3-2, 3-3, and 3-4.

Many strategies taught by certified orientation and mobility specialists to pedestrians who are blind or who have low vision were developed for typical intersection geometries and traffic flow patterns. Pedestrians who are blind may assume, even when crossing streets in unfamiliar areas, that the crossing will be at a corner and that vehicular traffic flow on the street beside them will be parallel to the direction of the crosswalk. They may also assume that the direction of traffic flow will be somewhat predictable due to signal phasing. These strategies and assumptions are

Figure 3-1. Pedestrian initiating crossing outside the crosswalk and toward a roundabout circulatory roadway.

Figure 3-1 shows a blind pedestrian lined up to cross toward the roundabout circulatory roadway during research trials. A cobblestone type of surface between the sidewalk and the roadway was not recognized as a non-walking surface by blind pedestrians. An orientation and mobility specialist is standing nearby. The crosswalk is visible approximately 20 ft to the left of the pedestrian.

not well-suited to the curvilinear traffic flow and large-radius corners that are characteristic of roundabouts and CTLs.

Individuals who are blind usually do not receive ongoing training or orientation and mobility assistance. They typically are provided with training and skills at the time they experience vision loss, or as a child and young adult (if blind since birth), and then use those skills in the future. It is assumed that they will take that training and apply the techniques taught to them

Figure 3-2. Pedestrian disoriented on a large paved CTL island.

Figure 3-2 shows a pedestrian disoriented on a large paved CTL island, walking away from the crosswalk; an orientation and mobility specialist is following close by.

Figure 3-3. Pedestrian walking on a splitter island rather than in a cut-through crosswalk.

Figure 3-3 shows a blind pedestrian walking on the raised portion of the splitter island rather than in the cut-through crosswalk area, disoriented as she walks parallel to traffic. An orientation and mobility specialist is closely following her.

to plan routes and travel in unfamiliar areas independently, and they often do so. If they have a loss of vision or major change in their life circumstances, they may receive more training, but it is not routinely provided. People with more recent training may have had some experience and training on the layout of roundabouts and CTLs, but particularly for wayfinding, training cannot resolve the problem of a design that does not provide adequate cues and information to an individual who cannot see.

Figure 3-4. Pedestrian misaligned to cross at a roundabout.

Figure 3-4 shows a pedestrian using a long cane beginning to cross at a roundabout crossing. She is well-aligned with the detectable warning that denotes the street/sidewalk boundary and gutter but is aligned to the right of the crosswalk direction. Her heading will result in her contacting the raised island outside the crosswalk area and cut-through area. An orientation and mobility specialist is closely following her as she begins to cross.

3.1.2 Typical Wayfinding Techniques and Strategies

3.1.2.1 Determining the Appropriate Crossing Location

In current practice, pedestrians who are blind and approaching an intersecting street with the intent to cross and continue in their current direction of travel, often assume there will be a crosswalk that is at least as wide as the width of the sidewalk on which they are approaching. They also assume that they are within the width of the crosswalk as they approach (Jacobson, 2013; LaGrow and Long, 2011), and that the crosswalk will continue across the street in the same direction that they have been traveling. They also may assume that vehicles idling on the street they want to cross are stopped at a stop line that is parallel to the direction of the crosswalk.

The typical techniques used by a pedestrian intending to continue in their current direction of travel is to stop when they reach a curb or a location that seems to be a curb ramp, check features with their long cane and assess the traffic, and generally maintain their approach heading as their crossing heading. If they are planning to cross the street beside them (their parallel street), they usually continue as described above to the cross street, then turn around and walk back 6 ft to 10 ft and then turn toward the street beside them.

This set of techniques is not effective at finding a crosswalk at a roundabout or CTL. If there is a landscape strip as a traveler approaches the intersection, a blind pedestrian may follow (i.e., trail) along the edge of that strip, looking for the intersecting sidewalk or curb ramp. If there is not a landscape strip, some individuals may follow the curb while using their long cane, looking for a sloped area that may be a curb ramp. This can be more difficult for individuals who are traveling with a dog guide, because dog guide users typically receive less tactile feedback about the walking surface in comparison to long cane users.

There is no reason in general for pedestrians who are blind to use curb ramps, and many prefer to avoid them. Crossing within a crosswalk is important, however, and experienced travelers who are blind understand that curb ramps should be within the width of the crosswalks. Thus they may look for curb ramps with their long cane if they are uncertain about the location of a crosswalk (Barlow et al., 2010; LaGrow and Long, 2011). Figure 3-5 shows an example of a landscaping that is detectable by a blind pedestrian trying to locate a crosswalk at a roundabout. Figure 3-6 shows an example of gravel used to provide adequate separation at a CTL. Figure 3-7 shows an example that is not detectable under foot (for dog guide users) or by the use of a long cane. Figure 3-8 shows an example of a detectable landscape separation that is not carried all the way to the crosswalk, and may thus pose wayfinding challenges.

Detectable warning surfaces (also called truncated domes or truncated dome detectable warnings) are required at the base of curb ramps or where there is a level landing at the street level to provide information to pedestrians who are blind about the location of the edge of the street. They are intended to inform blind pedestrians about the end of the pedestrian way and the beginning of the vehicular way; they are not intended to provide directional information (Bentzen, Barlow, and Tabor, 2000; U.S. Department of Transportation, 2006; U.S. Access Board, 2011). The information intended to be provided by the detectable warning surface is that the next step will be into the street. Since curb ramps are required to be within the width of the crosswalk, some pedestrians who are blind look for the detectable warnings at curb ramps to confirm that they are within the crosswalk.

If pedestrians who are blind use the strategy of crossing from where they first arrive at the curb at roundabouts without appropriate treatments, they are likely to cross into the circulatory roadway (see Figure 3-1). At CTLs, this strategy may result in crossing at a location that is not within the crosswalk, missing the island entirely, or encountering landscaping at the end of the crossing that makes it very difficult to get out of the lane.

Figure 3-5. Detectable landscape separation at roundabout.

Figure 3-5 shows a roundabout with adequate landscape separation between the sidewalk and the street. The separation is in the form of a 4 ft to 5 ft wide grass strip that follows the curvature of the road.

3.1.2.2 Aligning to Cross and Establishing the Correct Heading

There are two primary strategies that are used by pedestrians who are blind to align to cross at a typical intersection. To establish a heading straight across the crosswalk to the desired location on the opposite side of the street, travelers often assume that they will be continuing to travel in the same direction as they were traveling as they approached the intersection. The first strategy is to use auditory and tactile cues to maintain that line of travel. The second strategy is to align with the sound of traffic proceeding straight ahead on the street beside them (Barlow et al., 2010;

Figure 3-6. Detectable sidewalk separation at a CTL with gravel surface.

Figure 3-6 shows a CTL with adequate landscape separation provided through a gravel surface.

Figure 3-7. Sidewalk separation at a roundabout not detectable under foot or by the use of a long cane.

Figure 3-7 shows a roundabout with separation between the sidewalk and the road provided through paving stones, which are not detectable under foot or by the use of a long cane.

Guth, Rieser, and Ashmead, 2010; Stollof, 2005) and/or to square off (i.e., directly face the loudest point) of traffic moving perpendicular to their path.

When traffic is flowing on the street beside them as they cross, it is assumed to be flowing in the same direction (i.e., parallel) as the crosswalk, helping with both initial alignment and maintaining alignment during crossing. This is a very effective strategy at intersections having typical geometry because the traffic is normally moving parallel to the crosswalk. However, at roundabouts and CTLs, the crosswalk is seldom straight ahead in line with the sidewalk as one

Figure 3-8. Sidewalk separation at a CTL not carried to the crosswalk.

Figure 3-8 shows a CTL with gravel landscape separation between the sidewalk and the street that is not carried all the way to the crosswalk, and thus does not provide adequate wayfinding guidance.

approaches an intersection; instead, it is usually some distance around a large-radius corner and to one's side. At roundabouts, there typically is no traffic traveling parallel to the crosswalk. Traffic also may not be traveling perpendicular to the crosswalk, depending on the location of the crosswalk and the geometry of the roundabout or CTL. Some individuals may attempt to align with the traffic traveling across their path, which may work at some CTLs and roundabouts. The success of this strategy depends on the angle and location of the crosswalk in relation to the traffic movement and the curvature of the roundabout entry or exit or the CTL.

Pedestrians who are blind may also cue on the street gutter and align themselves so that they are perpendicular to the gutter or the curb line on each side of the ramp. Curb ramps may or may not slope in line with the direction of crosswalks, and although slope may have some influence on alignment, it does not result in more accurate alignments (Scott et al., 2011a). In optimal design for wayfinding by pedestrians who are blind, curb ramps should slope in the direction of travel on the associated crosswalk. As noted earlier, detectable warning surfaces are not intended as an alignment cue and neither the pattern nor the edge of the detectable warning results in an accurate alignment for crossing (Scott et al., 2011b). Therefore, although they may affect alignment and crossing heading, neither the slope of the curb ramps nor the way in which the truncated dome detectable warnings are installed are usually considered to be reliable sources of information for aligning to cross. Despite that, many blind pedestrians attempt to use a combination of the slope of the curb ramp, the gutter of the street, and the detectable warning surface as additional alignment information. While this is a strategy that does not work at all locations, it may be used by some blind pedestrians in the absence of other cues.

Figure 3-9 is an example of a roundabout crosswalk aligned too far to the left of the crosswalk landing on the splitter island. Figure 3-10 is an example of a blind pedestrian aligning to cross at a CTL.

Other cues for alignment include landmarks (objects or edges that are either parallel or perpendicular to the crosswalk), although these usually require some familiarity with the specific intersection. More general alignment cues include other pedestrians, the direction of travel on the street to be crossed, and the location of idling cars. Physical cues such as grass lines and returned curbs (curbs along the edges of curb ramps) that are perpendicular to the street that is about to be crossed can be used if travelers are aware of their presence and know that they are aligned in the direction of the crosswalk (Hill and Ponder, 1976; Barlow et al., 2010). If such features are consistently available, pedestrians who are blind will begin to expect and use them. Some secondary cues for alignment may be useful at familiar roundabouts, but they are quite idiosyncratic and hard to anticipate and use in unfamiliar environments.

3.1.2.3 Maintaining the Correct Heading While Crossing and Staying Within the Crosswalk

The primary strategy used by pedestrians who are blind to maintain their heading and travel straight across crosswalks at signalized and stop-controlled intersections is to travel parallel to the traffic moving straight ahead on the street beside them as they cross (Hill and Ponder, 1976; Jacobson, 2013). Straying from the crosswalk is a common problem for blind pedestrians and typically results from initial misalignment (Guth, Hill, and Rieser, 1989) or from veering from the initial alignment while crossing (Guth and LaDuke, 1994; Kallie, Schrater, and Legge, 2007; Rouse and Worchel, 1955). This is illustrated in Figure 3-11.

The strategy of traveling parallel to traffic moving straight ahead on the street parallel to the direction of travel of the pedestrian is not useful at roundabouts because there is no traffic moving straight ahead, parallel to the crosswalk. At a CTL, this strategy may work for the main part of the intersection, but again there is no parallel street for crossing the actual CTL.

Figure 3-9. Roundabout crosswalk aligned too far to the left of the island landing.

Figure 3-9 shows a roundabout with a crosswalk that is aligned too far to the left of the island for a wide three-lane crossing of a roundabout exit.

An accessible pedestrian signal or other treatment with audible message may serve as a far side audible beacon if present to help with maintaining heading. But for most crossings at CTLs and roundabouts, the accuracy of the initial alignment is likely to have a strong impact on the direction of travel, with limited audible or tactile cues available to correct initial alignment errors while crossing.

As mentioned above, some individuals may attempt to align with traffic traveling across their path, or yielding to them near the crosswalk. The success of this strategy depends on the angle and location of the crosswalk in relation to the traffic lanes and the curvature of the roundabout entry or exit or the CTL.

Figure 3-10. Blind pedestrian aligning to cross at a CTL.

Figure 3-10 shows a blind pedestrian aligning to cross at a CTL with detectable warning surfaces, ramp and gutter aligned with crossing, and the crosswalk perpendicular to the traffic flow.

Figure 3-11. Blind pedestrian maintaining crossing heading at signalized intersection.

Figure 3-11 shows a blind pedestrian crossing a wide street in the crosswalk, with traffic moving on the street parallel to the crosswalk at a signalized intersection.

3.2 Crossing Tasks

3.2.1 Issues and Principles for Determining When to Cross

The task of determining the appropriate or safe time to cross the street is a key concern for the accessibility of roundabout and CTL crossings by individuals who are blind. The crossing task is a key focus, given that this task is likely to be the most risky of the four wayfinding and crossing tasks (i.e., determining crossing location, aligning to cross, determining when to cross, and maintaining the correct heading while crossing), because it directly exposes a pedestrian to the conflicting vehicle traffic stream.

At unsignalized roundabout or CTL crossings, pedestrians who are blind have two types of crossing opportunities: (1) when there is a gap in traffic such that no approaching vehicle can reach the crosswalk before the crossing is completed or (2) when vehicles have yielded (Long et al., 2005). The yield crossing can be in the form of a voluntary yield maneuver by drivers or may involve crossing in front of vehicle(s) that have stopped or are stopping just upstream of the crosswalk for other reasons (e.g., roundabout entry queuing).

For individuals who have total blindness, these decisions must be made using sound cues alone. Individuals with low vision may be able to visually observe vehicles stopping or visually detect a gap in traffic within certain distances or locations in relation to the crosswalk.

3.2.2 Typical Crossing Techniques and Strategies

Strategies typically taught and used by pedestrians who are blind at both familiar and unfamiliar street crossings may not be effective at roundabouts and CTLs. For example, crossing decisions at traditional intersections, such as stop-controlled or signalized intersections, are based on auditory cues from the somewhat predictable flow of traffic that aids blind travelers in selecting a relatively low risk time to begin crossing. At unfamiliar signalized intersections, pedestrians who are blind listen to determine the pattern of traffic movement, often for more than one signal cycle. They typically cross with the beginning of the movement of traffic in the near parallel lane of the street beside them, using that surge of traffic to indicate that the traffic parallel to their path has a green indication. They listen for traffic turning from the street beside them into the cross street across the crosswalk, since they know that many drivers do not yield to pedestrians, although pedestrians have the right-of-way. Accessible pedestrian signals further simplify the crossing decision by providing an audible indication of the onset of the walk interval. Learning the strategies for listening and making crossing decisions at signalized intersections is a common part of the orientation and mobility instruction for blind individuals.

At unsignalized crosswalks, the typical technique taught to pedestrians who are blind or who have low vision is to cross when there is no traffic audible on the street they are crossing (Allen, 1997; Hill and Ponder, 1976; Jacobson, 2013). This applies to crossing the uncontrolled leg of a two-way stop-controlled intersection, crossing at a mid-block crosswalk, or crossing at a roundabout or CTL. In other words, the recommended strategy is to wait for a long gap or an all-quiet period, which is a technique observed by several participants in roundabout studies as well (Schroeder et al., 2011). Of course, this strategy tends to become less effective as traffic volume increases and large gaps become rare (Figure 3-12).

Individuals with visual impairments may have received instruction in timing strategies to determine that they can hear all vehicles far enough to be sure that a gap is adequate to cross the street (Barlow et al., 2010; Sauerburger, 2006). The timing strategy involves listening to or observing a number of vehicles and calculating the time that it takes for the vehicle to reach the crosswalk from the first moment that they hear each vehicle (Barlow et al., 2010). If it takes vehicles longer to reach the crosswalk following detection than the time it takes for pedestrians to cross the street, the assumption is that pedestrians will be able to cross using their hearing to determine a time to cross with minimal risk. To use this strategy safely, there must be gaps in traffic of adequate lengths of time as well as no other traffic that might mask the sound of a quieter, closer vehicle. At a very low volume roundabout or CTL, or at a low volume time of day, this may be an adequate strategy.

Although some individuals will begin crossing an uncontrolled crosswalk when they perceive that a vehicle has yielded, others are reluctant to do so. Many certified orientation and mobility specialists instruct their clients not to cross in front of stopped vehicles. This is probably due to

Figure 3-12. Single-lane roundabout with frequent all-quiet periods.

Figure 3-12 shows a single-lane roundabout in Charlotte, North Carolina, that typically has frequent all quiet periods that allow pedestrians to cross when there are long gaps in traffic.

the inability of most clients to make eye contact with the driver, leading to difficulty in discerning the driver's intentions and confirming that the driver is stopping for the pedestrian. It is not always clear whether the driver has indeed stopped to allow a pedestrian to cross or for some other reason, such as a stopped vehicle ahead.

Some individuals who are blind or those who have low vision may elect to wait for a gap in traffic in the closest lane, then extend their long cane and begin crossing when they detect that a vehicle is yielding (slowing or stopped upstream) (Willoughby and Monthei, 1998). While more recent orientation and mobility textbooks mention crossing in front of vehicles that have yielded at single-lane locations, they caution against using that technique at multilane locations due to multiple threat concerns (LaGrow and Long, 2011). Travelers with visual impairments in these situations may use other strategies such as soliciting assistance or locating a nearby crossing that is signalized or stop-controlled.

CHAPTER 4

Design Principles for Pedestrian Access at Roundabouts

This chapter presents an overview of the design elements that are specific to roundabouts.

4.1 Geometric Design

This chapter presents the proposed best practices for the design of roundabouts, applying the wayfinding and crossing tasks discussed in Chapter 3 to specific applications at roundabouts. Figure 4-1 shows the typical dimensions and placement of a crosswalk at a roundabout.

Crosswalks pass through the splitter islands, creating a two-stage crossing for pedestrians.

They are set back from the yield line by one or more car lengths to:

- Shorten crossing distance (lane widths generally flare out approaching the circulatory roadway),
- Separate vehicle-vehicle and vehicle-pedestrian conflict points,
- Help pedestrians distinguish between exiting traffic and circulating traffic, and
- Allow the second entering driver to devote attention to crossing pedestrians while waiting for the driver ahead to enter the circulatory roadway (Rodegerdts et al., 2010).

At most roundabouts in the United States, crosswalks have been set back one car length from the circulatory roadway on both the entry and the exit. This section presents several crosswalk configuration options and associated trade-offs.

There are three general principles for developing design solutions to optimize wayfinding information for people who rely on nonvisual information:

1. Landscaping, fences, or other features should restrict the ability of pedestrians to cross at locations other than crosswalks, or at least make it very clear where crossing is not intended, and provide guidance to the crosswalk location.
2. Curb ramps should be oriented so that the running slope is in the same direction as the crosswalk and/or the edges of landscaping or ramps should be aligned in the direction of travel on the crosswalk.
3. The far side of the crosswalk and any channelization and splitter islands should be aligned with the nearside ramp and should be designed to compensate for the expected error in the crossing angle.

Specific treatments to maximize wayfinding information will be described and illustrated in this section, and their potential benefits for pedestrians who are blind will be explained.

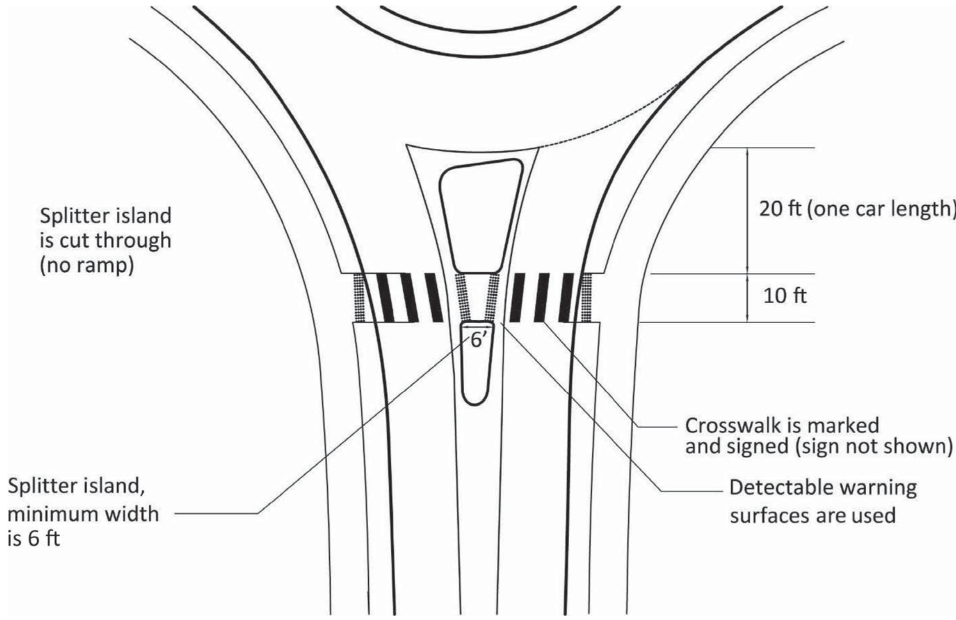


Figure 4-1. Typical crosswalk dimensions and features of a single-lane roundabout.

Figure 4-1 shows a crosswalk at a roundabout with a number of specific design features called out. The crosswalk passes through a splitter island, creating a two-stage crossing. The crosswalk is set back one car length (20 ft) from the circulatory roadway, the sidewalk is 10 ft wide, the crosswalk is marked and signed, detectable warning surfaces are used in the splitter island and on the outside of the roadway, the splitter island is cut through (pedestrians do not travel up and down a ramp), and the splitter island is a minimum of 6 ft wide at the crosswalk location.

4.1.1 Crosswalk Location and Angle Options

The geometric design of a crosswalk can directly influence its effectiveness, regardless of the type of traffic control devices used at that crosswalk. There are several conflicting challenges to balance:

- *The crosswalk should be located conveniently close to the roundabout to minimize out-of-direction travel for pedestrians.* Pedestrians are increasingly likely to cross closer to the roundabout if the designated crossing location is too far away, insufficient channelization is provided to encourage crossing at the appropriate location, and the pedestrian does not perceive a risk of crossing away from the designated location.
- *Positive wayfinding guidance to the crosswalk is critical, regardless of location.* The curvilinear nature of roundabouts makes it substantially more difficult for a pedestrian with vision disabilities to locate the appropriate crossing location and to maintain the correct heading through the crosswalk. Positive channelization also assists pedestrians without vision disabilities by encouraging them to cross at the appropriate crossing location and discouraging them to cross at inappropriate locations. This is a requirement in PROWAG-NPRM.
- *The crosswalk should be located such that approaching drivers have time to see a pedestrian in it, react and apply their brakes, and stop their vehicles before reaching the crosswalk.* This distance, which is a function of speed, is referred to as stopping sight distance and has numerous applications in roadway design. Stopping sight distances are provided in the Green Book (Table 3-1, Stopping Sight Distance on Level Roadways, and Table 3-2, Stopping Sight Distance on Grades). A portion of Table 3-1 has been reproduced as Table 4-1.

Table 4-1. Stopping sight distance on level roadways (Table 3-1, AASHTO, 2011).

Design Speed (mph)	Brake Reaction Distance (ft)	Braking Distance on Level (ft)	Stopping Sight Distance (calculated) (ft)	Stopping Sight Distance (design) (ft)
15	55.1	21.6	76.7	80
20	73.5	38.4	111.9	115
25	91.9	60.0	151.9	155
30	110.3	86.4	196.7	200
35	128.6	117.6	246.2	250
40	147.0	153.6	300.6	305
45	165.4	194.4	359.8	360

Note: Based on brake reaction distance of 2.5 s and deceleration rate of 11.2 ft/s^2.

- *For crosswalks with traffic control device, minimum stopping sight distance needs to be provided.* MUTCD specifies a minimum sight distance for the visibility of traffic signal heads in Table 4D-2. The distances are derived from the stopping sight distance (shown in Table 4-1) and the assumed queue length for a short signal cycle length. Therefore, the distances are greater than the stopping sight distance values shown in Table 4-1. Section 4D.12 of MUTCD states that the distances in Table 4D-2 should be provided for traffic signals (unlikely at a roundabout crosswalk) and Section 4F.02 of MUTCD notes that Section 4D.12 is applicable to pedestrian hybrid beacons as well. Table 4D-2 has been reproduced as Table 4-2.

These principles can be challenging to balance in retrofit situations where optimal crosswalk locations may not be achievable. Note that there is also a potential concern over having a variety of crosswalk configurations (distance, orientation, etc.) used at the same type of intersection (roundabout or signal) or within the same community, although there is no research at the time of this writing to confirm this.

Table 4-2. Minimum sight distance for signal visibility (Table 4D-2, MUTCD, 2009).

85th-Percentile Speed	Minimum Sight Distance
20 mph	175 feet
25 mph	215 feet
30 mph	270 feet
35 mph	325 feet
40 mph	390 feet
45 mph	460 feet
50 mph	540 feet
55 mph	625 feet
60 mph	715 feet

Note: Distances in this table are derived from stopping sight distances plus an assumed queue length for shorter cycle lengths (60 to 75 seconds).

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The following section presents the most common crossing alignment options and the advantages and disadvantages associated with each option.

4.1.1.1 Entry and Exit Crosswalks Equidistant from the Circulatory Roadway

Figure 4-2 shows a straight crosswalk alignment cutting directly through the splitter island, and Figure 4-3 shows a similar crosswalk alignment but with an angle point within the splitter island (sometimes referred to as a chevron style crosswalk). In both cases, the entry and exit crosswalks are approximately the same distance from the circulatory roadway. The requirement that the slope of the wheelchair ramp is perpendicular to the edge of the street may influence the alignment of the crosswalk. This type of crosswalk is generally placed one car length (20 ft) back from the yield line, although more separation (two car lengths) between the crosswalk and yield line can be advantageous if signals or beacons are used.

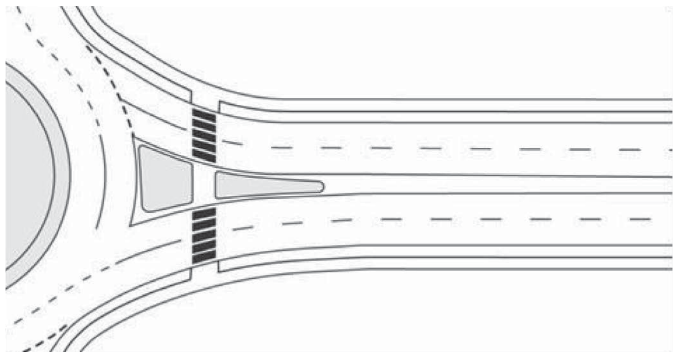

Figure 4-2. Entry and exit crosswalks same distance from roundabout with straight alignments.

Figure 4-2 shows a crosswalk on a roundabout leg that is set back one car length from the yield line. The entry and exit are both two lanes. The crosswalk is straight, and passes through the splitter island but does not bend at the splitter island.

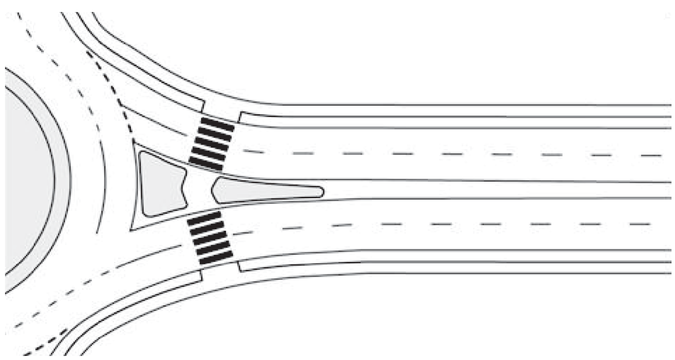

Figure 4-3. Entry and exit crosswalks same distance from roundabout with angled alignment.

Figure 4-3 shows a crosswalk on a roundabout leg that is set back one car length from the yield line. The entry and exit are both two lanes. The crosswalk bends at the splitter island, allowing the crosswalk to cross the entry and exit perpendicularly.

Advantages of straight crosswalks

- Generally meets driver and pedestrian expectations for roundabout crosswalks,
- Minimizes the potential for out-of-direction travel distance for pedestrians, and
- Vehicle speeds are generally low at crosswalks because of roundabout geometry.

Disadvantages of straight crosswalks

- More likely for pedestrians to treat as one-stage crossing (pedestrians may continue without stopping).
- More difficult to establish visual separation between pedestrian signal displays and audible separation between APS units in the splitter island, and
- Difficult to build curb ramps that are accessible; ramp must meet gutter at a 90 degree angle.

Advantages of angled crosswalks

- More likely that blind pedestrians will align correctly when crossing from the curb because the crosswalk is perpendicular to the traffic on the leg, and square to the gutter;
- May make it easier to separate pedestrian signal indications because they are not in line with one another;
- Potentially less likely for pedestrians to treat as one-stage crossing than a straight alignment;
- Generally meets driver and pedestrian expectations for roundabout crosswalks;
- Minimizes the potential for out-of-direction travel distance for pedestrians; and
- Vehicle speeds are generally low at crosswalks because of roundabout geometry.

Disadvantages of angled crosswalks

- Angle point on splitter island cut-through needs to be substantial enough (i.e., raised) to be detectible (subtle changes in angle may not be detected by a blind pedestrians and they may not adjust their alignment for the second crossing).

4.1.1.2 Exit Crosswalk Farther from Circulatory Roadway

Figure 4-4 shows a staggered crosswalk alignment with the exit crosswalk farther from the roundabout. This design is typically constrained by the location of the exit side crosswalk, which can benefit from more separation (40 ft) between the crosswalk and the yield line when

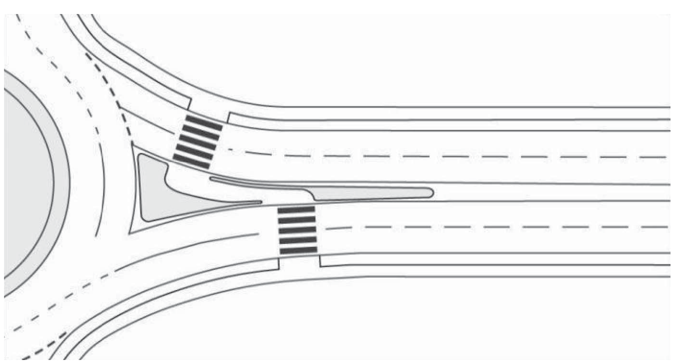

Figure 4-4. Staggered crosswalk with exit crosswalk further from roundabout.

Figure 4-4 shows a staggered crosswalk on a roundabout leg. The exit crosswalk is set back two car lengths from the roundabout, and the entry crosswalk is set back one car length from the roundabout (yield line). The entry and exit are both two lanes. The crosswalk has two 90-degree turns at the splitter island.

signal/beacon equipment is present. The pedestrian path within the raised splitter island needs to be clearly channelized to provide wayfinding guidance.

The staggered design is contrary to common guidance for pedestrian mid-block crossings, which typically offset the crossing to the right. Offsetting the crossing from the splitter island to the right makes pedestrians naturally turn toward oncoming traffic and is believed to improve visibility. In the case of roundabouts, the offset to the left (in the direction of pedestrian travel) is deliberate as it achieves greater separation between the exit portion of the crosswalk and the circulating lane. The added benefits of increased driver reaction distance (especially for right-turning vehicles), the added queue storage, and the improved auditory information for blind pedestrians are believed to outweigh concerns that the design is different from a typical mid-block configuration.

Figure 4-5 shows an example of this crosswalk placement option at a roundabout in Gatineau, Quebec. This photo is provided only for the purpose of showing an existing staggered crosswalk at a roundabout. Some design details, such as different crosswalk widths and island opening widths and the use of bollards as a buffer, are not desirable from an accessibility standpoint.

Advantages of staggered crosswalks

- More vehicular storage space between the circulatory roadway and the exit crosswalk,
- Exiting drivers have more time to react to the crosswalk conditions,
- Right-turning vehicles from the upstream approach have additional time to react, and
- Motorist attention to the crosswalk may be improved as they can focus on the crosswalk after exiting the roundabout.

Disadvantages of staggered crosswalks

- Higher vehicle speeds may result from locating the crosswalk further away from the central island and the circulatory roadway than usual (this is most commonly a challenge at exit crosswalks),

Figure 4-5. Staggered crosswalk with exit crosswalk further from roundabout in Canada.

Figure 4-5 is a photograph of the crosswalk placement option shown diagrammatically in Figure 4-4. This figure illustrates the signal placement and configuration of the splitter island in a real-world site in Canada. Other aspects of this crossing would not be deemed accessible by the guidance in this document. Potential problems include the lack of landscape separation to guide pedestrians to the crosswalk (bollards without fence are not sufficient), the lack of detectable warning surfaces at the curb and on the island, and the lack of audible information and APS in the pedestrian push-button.

- Pedestrians are turned away from the flow of vehicular traffic that they will cross next as they negotiate the splitter island, and
- Pedestrians may benefit from channelization by fences or other treatments to discourage crossing at inappropriate locations.

4.1.2 Sidewalk Alignment

At roundabouts where pedestrian access is provided, pedestrians are accommodated around the perimeter of the roundabout. Sidewalks are located outside of the circulatory roadway and crosswalks are located on the entry and exit legs. The speed-limiting geometry of roundabouts is a key element of safety for all modes, including pedestrians, which is not inherent in other intersection forms. The channelization of movements at roundabouts prevents many erratic vehicle maneuvers.

Figures 4-6 and 4-7 show two examples of sidewalk placements at roundabouts. In both cases, a buffer is provided between the sidewalk and the roadway. The buffers help to:

- Direct pedestrians, especially those with vision impairments, to the crosswalks;
- Discourage the use of the central island by pedestrians; and
- Reduce conflicts between overhanging vehicles and pedestrians.

Buffers should be a minimum of 2 ft wide and preferably 5 ft wide. If there is insufficient right-of-way for a buffer, fencing may be used. Sidewalks at roundabouts should be a minimum of 5 ft wide and preferably 6 ft wide. If the sidewalk is intended to be used as a multiuse path, as is

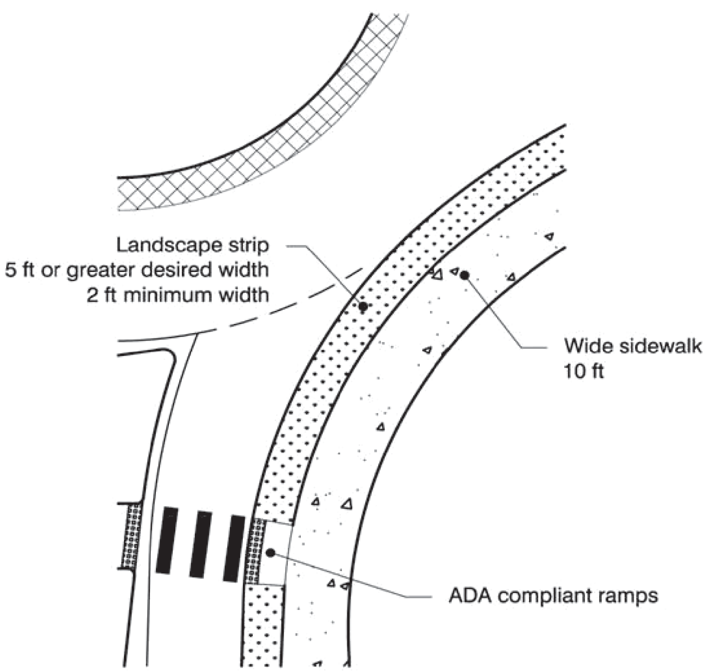

Figure 4-6. Roundabout with landscape buffer following roadway curvature.

Figure 4-6 shows a sidewalk that follows the curvature of the roadway in the roundabout but is separated by approximately a 4 ft to 5 ft wide landscaping buffer.

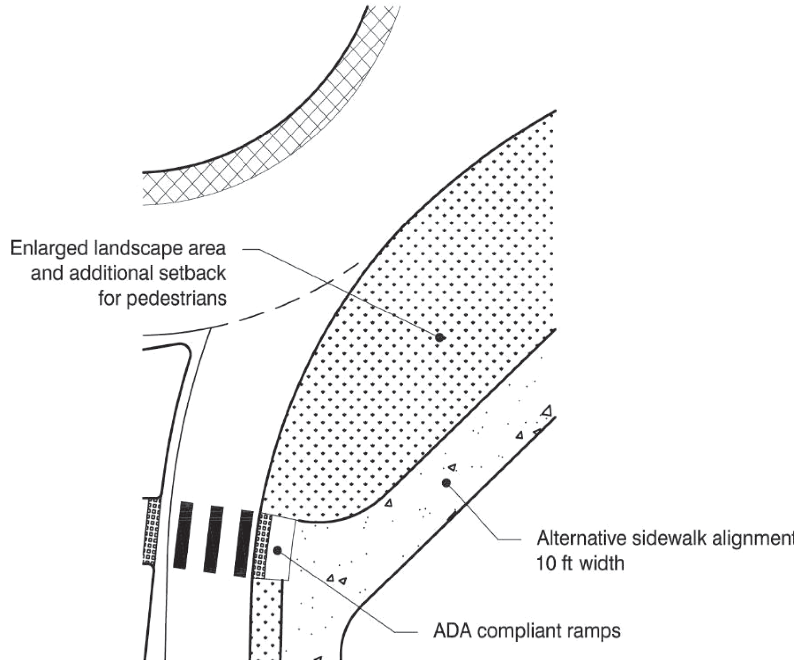

Figure 4-7. Roundabout with straight sidewalk and wide landscape buffer.

> Figure 4-7 shows a straight sidewalk on the outside quadrant of a roundabout. The buffer is several times wider and the overall footprint is larger than if the sidewalk curved to follow the alignment of the outside curb of the roundabout.

sometimes done at roundabouts, the sidewalk functions as a shared use path and the sidewalk should be a minimum of 10 ft wide.

Where the sidewalk is routed entirely away from the corner, pedestrians are unlikely to cross from an unintended location. Pedestrians, including those with visual impairments, will be “channeled” directly to the crosswalk; and there is minimal opportunity for failure to find the crosswalk. The sidewalk can approach the crosswalk in a direction that is in line with the direction of the crosswalk, which can also assist pedestrians who are blind with aligning to cross. Figure 4-8 shows a single-lane roundabout where this sidewalk location technique was used. The example also shows good use of landscaping and placement of detectable warnings on the curb side and the splitter island. The cut-through of the splitter island is further wide enough to compensate for errors in maintaining the crossing heading.

4.1.3 Buffering

4.1.3.1 Landscaping

Grass or a landscaping strip at the outer edge of the sidewalk indicates to pedestrians who are blind that they are not intended to cross in that location. It also provides a surface that can be trailed with a long cane to locate the crosswalk. This treatment, shown in Figure 4-9, may also decrease the likelihood that other pedestrians will cross from unintended locations.

Pedestrians who are blind are unlikely to cross to the central island of a roundabout if there is continuous grass or a landscaping strip that is interrupted only by a curb ramp at a crosswalk.

Figure 4-8. Sidewalk curving away from the corner to guide pedestrians directly to the crosswalks.

At the roundabout corner visible in Figure 4-8, the sidewalk between the crosswalks on either side of the corner curves in the opposite direction from the curb line. This results in a very wide area of grass and other landscaping between the sidewalk and the curb of the circulatory roadway, making it unlikely that any pedestrian will be inclined to cross to the central island. A pedestrian who is traveling toward the roundabout from either approach will find that the grass strip along the curb line ends where the crosswalk begins to cross the street beside them. If they wish to cross the intersecting street, the continuation of the sidewalk turns away from the roadway and curves around to lead them directly to, and in line with, the crosswalk for the intersecting street. As noted in the text, the splitter island cut-through is as wide as the crosswalk and there are low plants on the non-walking areas of the island.

Figure 4-9. Landscaping that discourages crossing to the central island and provides an edge that blind pedestrians can follow (i.e., trail) with the long cane to locate a curb ramp.

Figure 4-9 shows a narrow landscaping strip of low plants between the wide sidewalk and the travel lanes at this two-lane roundabout. Landscaping is present on both sides of the curb ramp.

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Figure 4-10. Example of surface material that was not recognized as a non-walking surface by blind participants.

Figure 4-10 shows a roundabout approach with surface material that was not recognized as a non-walking surface by blind participants. The cobblestone surface was installed at this roundabout between the concrete paved sidewalk and the curb, but it did not provide guidance (that might have been intended). The inset on the right shows the size of the cobblestones in comparison to a foot; each cobblestone is approximately the width of the foot, with an inch or more of grout between the stones.

Such a landscaping strip could be gravel, grass, or some other surface that is detectable under foot. However, rough brick or a cobblestone type of surface between the sidewalk and the curb or on an island was often not recognized by participants in this research as a non-walking surface. Such a surface did not provide the desired cues to the crosswalk location or prevent crossing from the wrong location. An example is shown in Figure 4-10.

A grass or landscaping strip where pedestrians are not intended to cross satisfies the PROWAG-NPRM requirement for separation between the sidewalk and the street (R306.3.1).

If pedestrians who are blind choose to follow the edge of the grass or landscaping nearest the street, it will lead them to an opening at the crosswalk. However, if they are not actively using the technique of following (i.e., trailing) the grass or landscaping but are traveling in the center of the sidewalk or following the edge of the sidewalk on the side farthest from the street, they may fail to find the crosswalk. It is important that the landscaping is kept low enough so that it does not obstruct the driver's view of pedestrians waiting to cross, especially pedestrians of short stature or who are traveling with the aid of a wheelchair.

4.1.3.2 Fencing and Bollards

Fencing, shown in Figure 4-11, or bollards connected by chains where crossing is not intended, indicates to all pedestrians that they should not cross in locations so marked. Bollards alone are not sufficient indications to blind pedestrians that they are in a non-crossing location (unless they are less than approximately 24 in. apart) as they may pass through without encountering a bollard. When chains are used between bollards, the lower edge should be no higher than 15 in. above the sidewalk, as required by PROWAG-NPRM R306.3.1. Chains that are more than 15 in. above the sidewalk may not be detected by a user, because the long cane may slide under the chain without touching it. A higher chain should also be provided so it is readily visible to aid pedestrians who are not using a long cane in detecting it. Bollards and chains should contrast with surrounding surfaces so that they can be seen by travelers with reduced vision who do not use a long cane or dog guide.

Figure 4-11. Fencing and grass strip at a roundabout corner.

At the roundabout in Figure 4-11, a wide brick sidewalk is separated from the circular roadway by a 3 ft high metal fence that ends where the crosswalk begins. On the approach to the crosswalk leading up the street toward the roundabout, there is a wide grass strip terminating with a tall brick pillar at the beginning of the crosswalk. Both the grass and the fence can be trailed by a blind pedestrian using a long cane.

Well-designed bollards connected by chains satisfy the PROWAG-NPRM requirement for separation between the sidewalk and the street (R306.3.1).

4.1.3.3 Central Island Treatments

The central island of a roundabout is not to be used by pedestrians because access to it requires crossing the circulatory roadway. Design techniques to discourage pedestrians from using the central island include:

- Use of different materials for sidewalks and the truck apron and
- No placement of objects that would attract pedestrians to the central island.

4.1.4 Detectable Warning and Guidance Surfaces

At crossing points on the curb and on splitter islands with no difference in level between the sidewalk curb line and the street, detectable warning surfaces are needed to alert blind pedestrians to the edge of the street (i.e., the street/sidewalk boundary). A detectable warning surface is a pattern of small truncated domes with specific size and location characteristics specified by ADA guidelines. It must be detectable under foot as well as with a long cane because people with low vision or dog guide users may not be using a long cane. They serve as a hazard warning for blind pedestrians (and may serve this function for other pedestrians). Detectable warning surfaces should be installed in pairs, like parentheses, one at the beginning of a crossing and one at the end. When detectable warnings surfaces are not provided at the edges of splitter islands, blind pedestrians will not know they have reached a refuge area.

If a two-stage crossing is desirable, as is usually the case at roundabouts, detectable warning surfaces are required on both ends of the crosswalks (within the splitter island and on the outside of the roundabout). On the splitter island, two separate detectable warnings are required to distinguish the entry and exit portions of the crossing. Each detectable warning surface needs to be 2 ft wide, with at least 2 ft of separation between the two sets of warning surfaces, resulting in an island width of at least 6 ft.

The detectable warning surface must cover the entire curb ramp area that is level with the street in order to be reliably detected. As shown in Figure 4-12, a pedestrian can step past the detectable warning surfaces that do not extend across the entire width of the cut-through island and into the street without realizing it.

Even though good landscaping at roundabouts and CTLs prevents pedestrians who are blind from crossing at an unintended location, if they are not trailing and looking for a break in the landscaping, they may fail to notice the break in the landscaping to the street side and the associated curb ramp and crosswalk. It is not uncommon for pedestrians who are blind to miss curb ramp entries and continue walking around wide-radius corners characteristic at roundabouts and CTLs without realizing that they have done so.

PROWAG-NPRM states that "European and Australian roundabouts provide a 610 mm (24 in.) width of tactile surface treatment from the centerline of the curb ramp or blended transition across the full width of the sidewalk to provide an underfoot cue for identifying pedestrian street crossings" (Advisory R306.3.1). This tactile surface treatment referred to by the U.S. Access Board is a bar tile surface or guidance tile, as shown in Figure 4-13, which is used in Australia.

A variation of the tile shown in Table 4-13, with bars perpendicular to the direction of the crosswalk, is shown in Figure 4-14, as both an indication of the location of the crosswalk and to provide alignment information to blind pedestrians. Bar tiles are optional treatment and are not subject to the same requirements as detectable warning surfaces.

Figure 4-12. Example of incorrect detectable warning surface installation at a roundabout crossing.

Figure 4-12 shows an example of a pedestrian stepping past an incorrect installation of a detectable warning surface at a roundabout crossing. The detectable warning surface does not cover the entire cut-through area at a splitter island, and the pedestrian's left foot is just to the left of the detectable warning surface in the picture on the left. In the picture on the right, the pedestrian has taken a step and the right foot is past the detectable warning at the street edge. The pedestrian thus may not detect the edges of the island and may continue into the travel lanes.

Figure 4-13. Australian bar tile surface.

Figure 4-13 shows an example of an Australian bar tile surface installed across a sidewalk to indicate the location of the crossing at the roundabout (outside of frame on the left). A person using a long cane is approaching the surface with the cane tip contacting the bar tile surface. The bar tile surface is 2 ft wide in the direction of pedestrian travel and extends across the entire width of the sidewalk. Bars are aligned with the direction of the crosswalk.

Figure 4-14. Experimental bar tile with bars perpendicular to the direction of the crosswalk.

Figure 4-14 shows an experimental bar tile application from the Raleigh pilot data collection, with bars perpendicular to the crosswalk direction. The curb ramp, gutter, and detectable warning surface at this location are not aligned with the direction of travel at the crosswalk but the bar tile treatment is aligned with the direction of the crosswalk. The treatment is a temporary surface installed for research about the usefulness of bar tiles to provide an indication of the crosswalk location and alignment.

4.1.5 Curb Ramps

4.1.5.1 Curb Ramp in Line with Crosswalk to Provide Alignment Cue

While travelers who are blind are not usually able to align precisely with the running slope of a curb ramp, ramp slope does influence alignment (Scott et al., 2011a). Therefore when curb ramps slope in the same direction as travel on the crosswalk, alignment and subsequent crossing by pedestrians who are blind are likely to be more accurate.

Pedestrians who are blind may also cue on the street gutter and align themselves so that they are perpendicular to the gutter or the curb line on each side of the ramp. They may be more likely to align correctly if the crosswalk is perpendicular to the gutter. In an optimal design for wayfinding by pedestrians who are blind, curb ramps slope in the direction of travel on the associated crosswalk. However, curb ramps must intersect the roadway and the roadway gutter as near to 90 degrees as possible to accommodate assistive devices such as wheelchairs, which may otherwise be unstable as they transition between the pedestrian and the vehicular way. In some designs and locations, that requirement may conflict with aligning the ramp slope with the direction of the crosswalk.

At roundabouts, moving the location of the crosswalk away from the circulatory roadway may enable associated crosswalks to both intersect the roadway at 90 degrees and slope in the same direction as the crosswalk.

4.1.5.2 Returned Curb in Line with Crosswalk to Provide Alignment Cue

Where a grass strip or landscaping is used at the sidewalk edge, a curb ramp having returned curbs that are parallel to the direction of the crosswalk can be used to assist pedestrians who are blind with aligning to cross. They may trace (i.e., take a line of direction) from the direction of a returned curb with a long cane or with the side of the foot. Figure 4-15 shows a roundabout with curb returns on the ramp. There is no need for flare on the sides of ramps that are bordered by grass or landscaping. Flares are only necessary to eliminate tripping hazards at locations where other pedestrians may walk across the ramp on the sidewalk.

4.1.5.3 Parallel Curb Ramps

Parallel ramps are used in situations where sidewalks are narrow, not allowing for a compliant curb ramp perpendicular to the curb. This is quite common at CTLs and at some roundabouts. Note that when installed at roundabouts without landscape strips, as shown in Figure 4-16, they do not comply with PROWAG requirements for separation unless some type of fencing is installed. For a parallel ramp, the entire sidewalk is sloped down to the level landing at the crosswalk, and then slopes back up. For wheelchair users and individuals with mobility impairments this can be a disadvantage if they are continuing along the sidewalk, because they have to travel up and down ramps unnecessarily. For individuals who are blind, parallel ramps can be confusing in terms of detecting the slope and determining the correct direction of travel on the crosswalk. Detectable warning surfaces must be installed where the level landing meets the street to provide an indication of the edge of the street.

An example of a parallel curb ramp is shown in Figure 4-16. The lack of landscape separation or fencing in the figure poses accessibility challenges.

4.1.6 Crosswalk Markings to Provide Cue to Maintain Travel Within the Crosswalk

For pedestrians with low vision, marked crosswalks can provide useful cues to the crosswalk location and can assist with maintaining travel within the crosswalk. Pedestrians with low vision

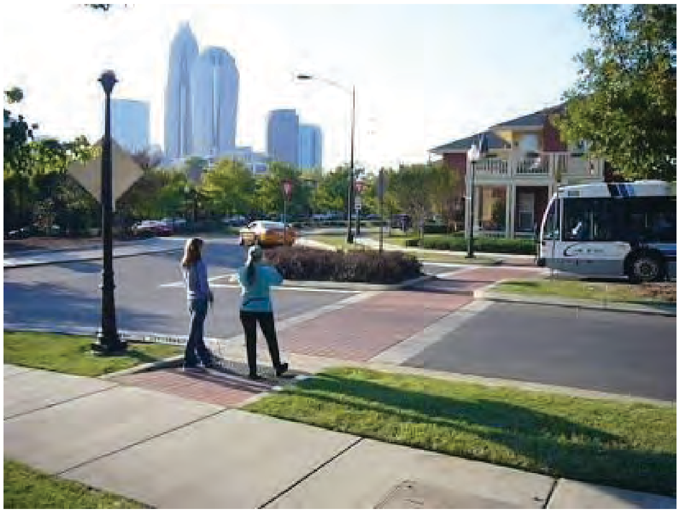


Figure 4-15. Curb ramp with returned curbs.

Figure 4-15 shows a pedestrian waiting to cross an exit lane from the corner to the splitter island. On each side of the curb ramp is a sloping curb with vertical sides between the ramp and the grass, which is aligned with the direction of travel on the crosswalk. The cut-through in the splitter island is also bounded by returned curbs so that following the curbing all the way across the island could aid in maintaining crossing direction. There is grass on both sides of the ramp, which reduces the likelihood of pedestrians approaching the ramp from a less than optimal direction.

Figure 4-16. Parallel curb ramp.

Figure 4-16 shows a parallel curb ramp at a roundabout crossing. A parallel ramp is often used when there is a narrow sidewalk at the back of curb. The entire sidewalk slopes down to a level landing at the crosswalk location. The detectable warning surface is installed along the curb line for the entire width of the level area. As noted in the text, there is no landscaping or barrier between the sidewalk and the curb, so a blind person is not guided to the crosswalk location.

Figure 4-17. Ladder crosswalk marking.

Figure 4-17 shows ladder crosswalk markings at a roundabout. Ladder markings have both transverse and longitudinal lines, with two lines on the outside edges of the crosswalk aligned with the direction of crossing and bars across between those two lines in the vehicle travel direction, making it easier for a person with low vision to follow a line across the crosswalk. The longitudinal lines make the crosswalk more visible to drivers.

have stated a preference for the ladder type crosswalk markings. Ladder markings have both transverse and longitudinal lines, making it easier for a person with low vision to follow a line across the crosswalk. The longitudinal lines make the crosswalk more visible to drivers. Crosswalks that are brick colored may not be distinguishable from the asphalt street color for individuals who are color blind, and are not as visible to drivers. An example of a ladder-style crosswalk marking is shown in Figure 4-17.

4.1.7 Island Design

The principles of splitter island design are discussed in the Green Book and *NCHRP Report 672.* Splitter islands should be at least 6 ft or more wide where the crosswalk passes through, allowing storage for a person pushing a stroller, walking a bicycle, or using a wheelchair. Splitter islands are usually, but not always, raised above the surface of the roadway, with cut-throughs to the street level to accommodate wheelchair users. Where the crosswalk passes through the splitter island, it is preferred that the splitter island be cut so that pedestrians remain on the elevation of the road surface rather than passing up a ramp and then immediately down another; edges on the cut-through can also assist blind pedestrians with wayfinding. To distinguish the island surface to the left and right of the cut-through crosswalk from a sidewalk, the raised area of the island should be landscaped or have a gravel surface to clearly indicate that it is not an intended walking environment.

Pedestrians who are blind or who have low vision need appropriate guidance through the island area to the other crosswalk or crosswalks from the island. A completely paved island with no landscaping materials present in areas adjacent to the crosswalk can be disorienting, as was observed at several sites studied in this research (Figure 4-18). In addition and as noted earlier, detectable warning surfaces must be provided at the boundary between the island and the street to alert individuals to the location of the street/island boundary.

Paths across refuge islands are typically cut-through (level with street) or ramped. Some participants in this research expressed a preference for ramped pathways, so that they could detect more easily that they had reached the island with an upward slope as well as the detectable warning surface. Even when detectable warning surfaces were installed correctly at cut-through and ramped refuge islands, some participants missed them.

Figure 4-18. All-paved roundabout splitter island.

The blind pedestrian in Figure 4-18 is standing at the edge of the splitter island approximately 20 ft from the crosswalk at a roundabout island with a zig-zag crosswalk and a cut-through pedestrian channel. He has stepped up on the paved area out of the cut-through. A second person, who is an orientation and mobility specialist involved in the research, is walking toward him. The raised portion of the splitter island is not distinguishable from the unraised portion, as a result of which the island provided insufficient wayfinding information to the blind participant, who stepped up onto the island from the cut-through area and is preparing to cross the street outside the crosswalk area.

Islands with ramps must be wide enough in the direction of pedestrian travel to allow for two curb ramps with a level landing area between the ramps. The minimum width then depends on the vertical elevation of the sloped ramp. Between the sloped ramps, at least a 4 ft^2 landing needs to be provided. If the island is not wide enough to accomplish this, a cut-through island may be the only feasible alternative. A short ramp, raising the cut-through area by an inch or two, may provide some information to blind pedestrians and reduce water and debris from gathering in the cut-through area.

Cut-through islands need to be at least 6 ft wide in the direction of pedestrian travel to allow for a 2 ft detectable warning at each road transition point, with a gap of at least 2 ft between sets of detectable warnings. The island opening also needs to be at least 5 ft wide in the direction of vehicle travel to allow two wheelchairs to pass one another (required by proposed PROWAG). Ideally, the island opening should be as wide as the crosswalk. These dimensions are illustrated in Figure 4-19 for a cut-through island, and in Figure 4-20 for an island with ramps.

The area outside the prescribed path should also be detectable as a non-walking surface. At roundabouts, landscaping is commonly used on the splitter islands to serve this purpose.

4.1.8 Right-Turn Lanes

Some roundabouts have right-turn lanes, which are generally designed in one of two ways:

- The lane is a bypass lane—separated from other entry lanes with a raised island—and does not yield to traffic in the circulatory roadway. Bypass lanes may yield to exiting traffic, have a merge area, or have a dedicated receiving lane.
- The lane is exclusively for right-turning vehicles, but enters the roundabout and yields to circulating traffic like other entry lanes do. There may or may not be painted separation between

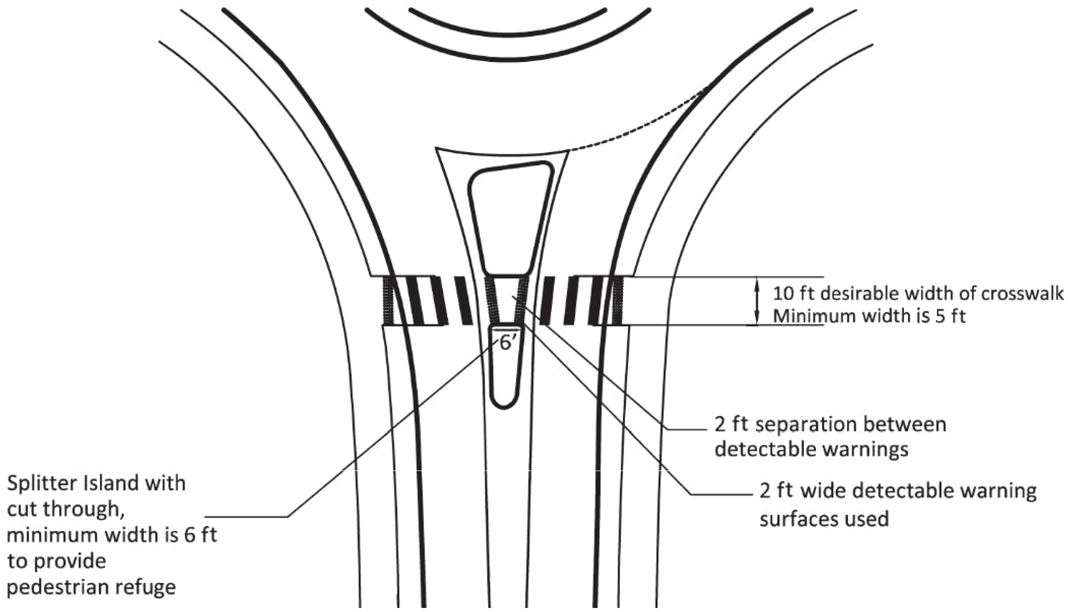


Figure 4-19. Minimum refuge island dimensions for a cut-through island.

Figure 4-19 shows a 6 ft minimum width island with a cut-through pedestrian path. Within the cut-through area of the island for the full width of the cut-through is a 2 ft section of detectable warning surface, then 2 ft of smooth surface, and then another 2 ft section of detectable warning surface.

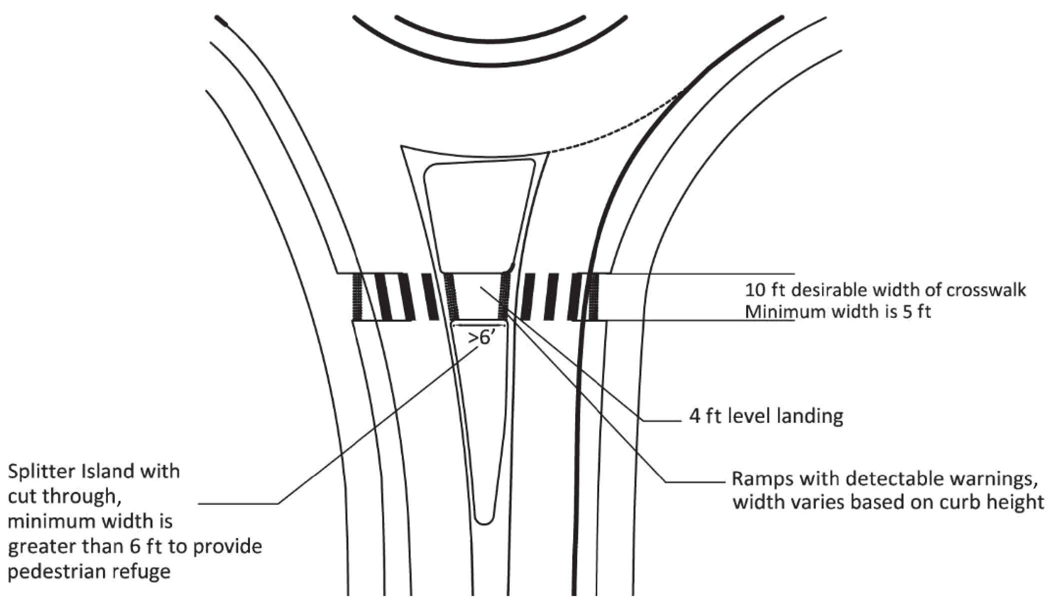
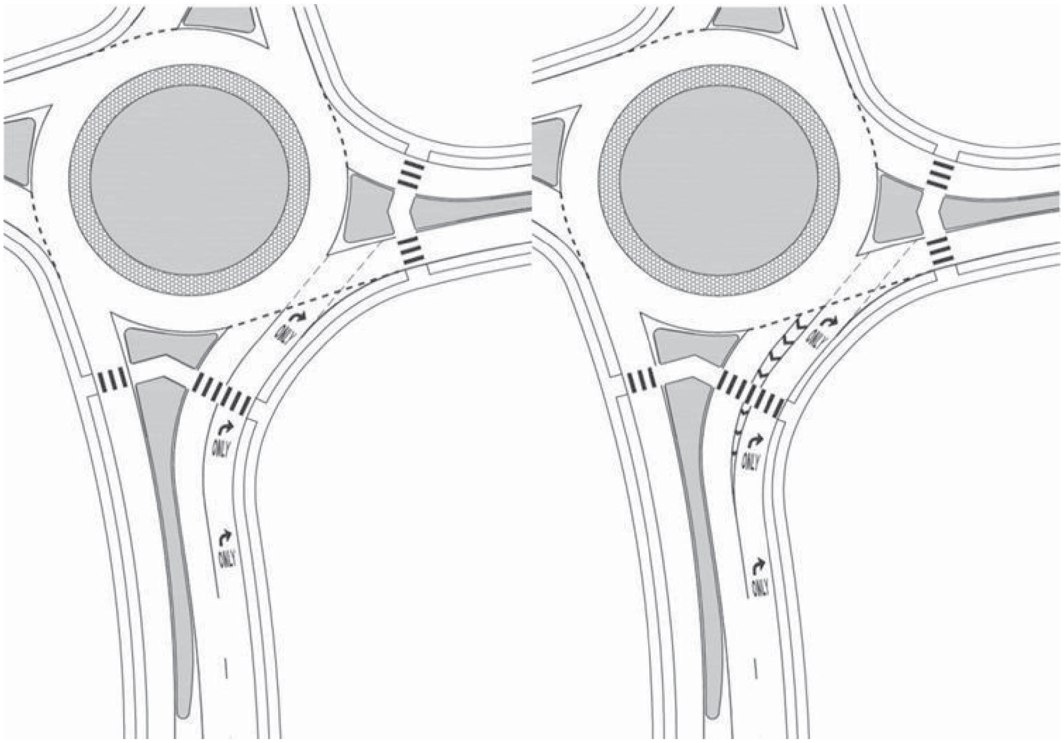


Figure 4-20. Minimum refuge island dimensions for an island with ramps.

Figure 4-20 shows a wider island than a cut-through (dimensions not given) with curb ramps sloping up on each side with detectable warnings surfaces at the base of the ramps at each street edge. A 4 ft level landing between the ramps is shown.



(a) (b)

Figure 4-21. Types of non-bypass right-turn lanes at roundabouts.

Figure 4-21 shows two types of non-bypass right-turn lanes at roundabouts. Figure 4-21(a) shows a lane that is exclusively for right-turning vehicles, but enters the roundabout and yields to circulating traffic like other entry lanes do. Figure 4-21(b) shows a variation of this configuration, with additional gore striping to accommodate truck traffic. Neither is considered a bypass lane—which would have to be separated from other entry lanes with a raised island. Bypass lanes may yield to exiting traffic, have a merge area, or have a dedicated receiving lane.

the lanes, but there is no pedestrian refuge. Two types of non-bypass right-turn lanes are shown in Figure 4-21.

Right-turn bypass lanes at roundabouts present many of the same challenges for pedestrians as CTLs at signalized intersections.

4.2 Traffic Control Device Applications

Three major types of traffic control devices are considered in this section: standard pedestrian signals, pedestrian hybrid beacons (PHBs), and rectangular rapid-flashing beacons (RRFBs). In general, all three devices may be used at roundabouts. In addition, this section discusses signing and marking at roundabouts, as well as other treatments including raised crosswalks.

4.2.1 Type of Traffic Control Device

A standard pedestrian signal as defined in this section displays a red-yellow-green indication to motorists (resting in green) and a walking person–upraised hand (resting in upraised hand) indication to pedestrians. A standard pedestrian signal can be implemented in the vicinity of roundabouts, provided that the signal is located far enough from the circulatory roadway to minimize potential confusion between the green indication and the yield sign at the entry to the roundabout. Current judgment suggests that a separation of 150 ft or more should be sufficient to minimize driver confusion, but further research is needed to confirm or refine this suggestion.

A PHB displays a sequence to drivers and pedestrians as described in MUTCD, Chapter 4F. It requires a signal controller with a conflict monitor/malfunction management unit because of potentially conflicting vehicle and pedestrian displays. Hardwire connections to displays are needed to enable conflict monitor/malfunction management units to operate. In addition, multiple controllers may be needed to operate a full and independently operated set of PHBs on all the entries and exits of a roundabout because of limitations in the numbers of rings available within a controller's software. Figure 4-22 shows a photograph of a PHB at a roundabout in Golden, Colorado, and Figure 4-23 shows the sequence of operation for the vehicular and pedestrian signal heads. Since this beacon provides a walk indication, a standard APS can be used to provide information to pedestrians who are blind or to those who have low vision.

The RRFB is significantly different from the standard pedestrian signal and the PHB in that it does not display either a red indication to the motorist or a walk indication to the pedestrian. Rather, it is a visually enhanced warning device that is activated by the pedestrian. Because of their differences in operation, an RRFB does not require a signal controller with a conflict monitor/malfunction management unit because there are no pedestrian displays. However, in order to be usable by a pedestrian who is blind or who has low vision, an audible information device should be integrated into the pushbutton. This device does not provide a walk signal, but instead provides information about the functioning of the device, with a pushbutton locator tone to let a person who is blind know the device is there, and be able to find it easily. An audible message when the lights are flashing should state "yellow lights are flashing" as recommended by MUTCD on its FAQ page. A vibrotactile indication, such as is provided by an APS, is not appropriate since that could be mistaken for a walk indication. Figure 4-24 shows an RRFB at a roundabout in Oakland County, Michigan.

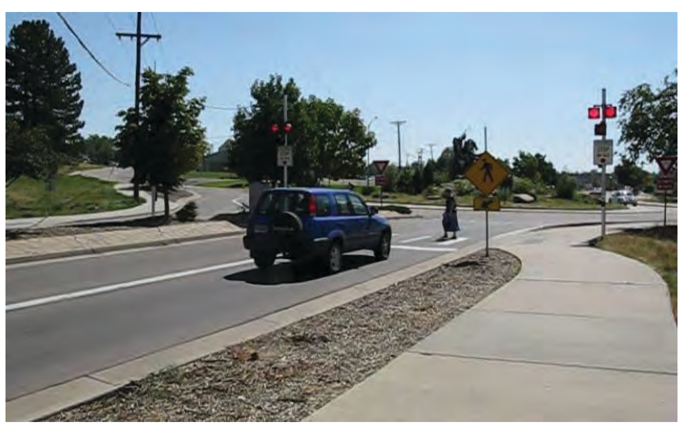


Figure 4-22. Pedestrian hybrid beacon at roundabout in Golden, Colorado.

Figure 4-22 shows a vehicle stopped at a red indication at the crosswalk on a roundabout entry. The red indication is displayed on two side-by-side ball signals on top of the display. A sign on the signal post states "stop on red." A pedestrian is crossing in the crosswalk.

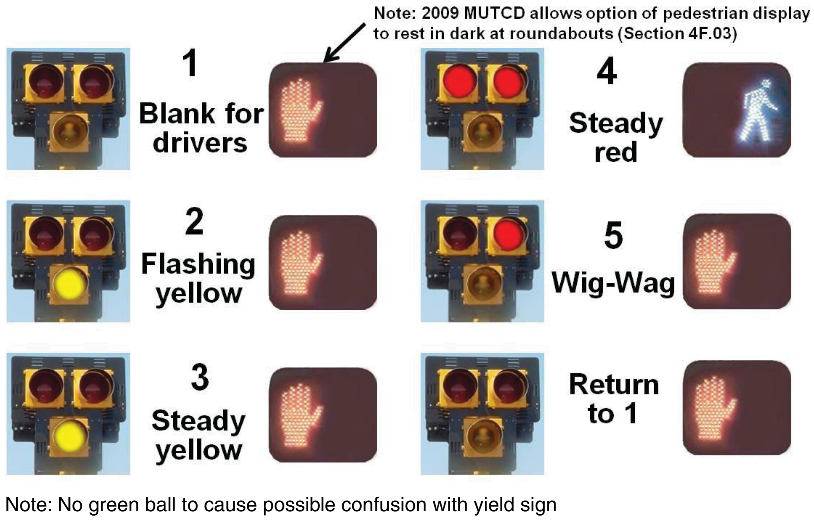


Figure 4-23. Sequence of displays at a Pedestrian Hybrid Beacon.

Figure 4-23 shows the six intervals in a sequence for a PHB. Each interval is shown as a signal face having three lenses: two horizontally aligned with a third centered under them.

The first interval is labeled "1 Blank for Drivers." It shows two dark (black) signal faces with one dark signal face centered below them. Beside the interval is a pedestrian signal display with an orange hand symbol. An arrow points to the pedestrian display with the text information: "Note: 2009 MUTCD allows the option for the pedestrian display to rest in dark at roundabouts. (Section 4F.03)." The second interval is labeled "2 Flashing Yellow." It shows two dark signal faces above an illuminated circular yellow signal. Beside the interval is a pedestrian signal display showing an orange hand symbol. The third interval is labeled "3 Steady Yellow." It shows two dark signal faces above an illuminated circular yellow signal. Beside the interval is a pedestrian signal display with an orange hand symbol. The fourth interval is labeled "4 Steady Red." It shows two illuminated circular red signals on top with one dark signal face centered below them. Beside the interval is a pedestrian signal display with a walking person symbol, indicating walk. The fifth interval is labeled "5 Wig-Wag." It shows two signals on top with one dark signal face centered below them. The right signal face of the top display is illuminated red. Beside that is a pedestrian signal display with an orange hand symbol. The sixth interval is labeled "Return to 1." It shows two dark (black) signal faces with one dark signal face centered below them. Beside the interval is a pedestrian signal display with an orange hand symbol.

A note at the bottom of the graphic states: No green ball to cause possible confusion with the yield sign.

4.2.2 Location of Vehicle Signal/Beacon Faces

MUTCD, Section 4D.12, governs the visibility, aiming, and shielding of signal faces, with guidance on the minimum sight distance. The design speeds (based on the fastest path radii of a roundabout per *NCHRP Report 672*) should be used to determine the minimum sight distances required.

In addition, at least one and preferably two signal/beacon faces shall meet the lateral positioning requirements of MUTCD, Section 4D.13. At roundabouts, this can be more challenging on the exit side, given the relatively close proximity of a typical crosswalk to the circulatory roadway and to vehicles that may be coming as right turns from the upstream entry. The traffic control device needs to be sufficiently visible to both sources of upstream traffic.

Figure 4-24. Rectangular rapid flash beacon at a roundabout in Oakland County, Michigan.

Figure 4-24 shows a crosswalk on a roundabout entry with an RRFB. Arrows added to the photograph point to a light bar installed below the pedestrian warning sign, which is on a post beside the crosswalk, on the downstream side. This light bar is where the rapid flashing beacon lights are displayed.

Furthermore, the use of overhead signals can also influence placement. A driver's visibility of an overhead signal can be restricted by the roof of a vehicle if the vehicle is less than 40 ft from the stop line associated with the signal.

Beacons can be mounted on poles along the side of the roadway (side-mounted), placed overhead using a mast arm or span wire installation (overhead), or a combination of the two. As discussed in Section 4D.13 of MUTCD, at least one and preferably both of the primary signal faces shall be within 20 degrees to the left or the right of the center of the approach, as measured from a point 10 ft prior to the stop bar. This section of MUTCD governs traditional green/yellow/red signals and also applies to PHBs. It is appropriate for other types of beacons (RRFBs, flashing beacons, etc.) to be located in this manner as well. Figure 4-25 shows the use of side-mounted

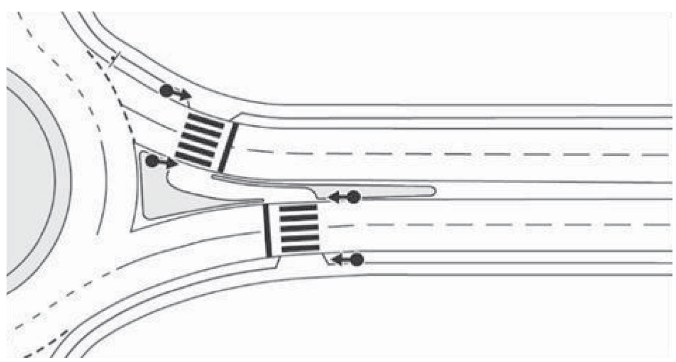


Figure 4-25. Use of side-mounted vehicle displays only at roundabouts.

Figure 4-25 shows the placement of side-mounted traffic signals or beacons on a roundabout leg. For both the entry and the exit, one pedestal-mounted signal is placed in the splitter island and one pedestal-mounted signal is placed immediately beyond the outside curb. Both signals and signal poles are on the downstream side of the crosswalk. The entry and the exit are both two lanes.

vehicle displays at a roundabout. Although not shown in the figure, a supplemental nearside signal head may also be beneficial.

If overhead signals are used, the signal mounting height is governed in MUTCD, Section 4D.15. For overhead signals, the top of the face cannot exceed 25.6 ft over the roadway, and the bottom of the face cannot be below 15 ft over the roadway. For side-mounted signals, the bottom of the signal shall be a minimum of 8 ft and a maximum of 19 ft above the sidewalk.

The following mounting locations are recommended for crosswalks at roundabouts depending on the number of travel lanes that the crosswalk is spanning:

- One-lane crossings: side-mounted vehicle displays
- Two-lane crossings: either side-mounted or overhead vehicle displays
- Three-lane crossings: overhead and side-mounted vehicle displays recommended for visibility to center lane

4.2.3 Location of Pedestrian Signal Faces and Accessible Pedestrian Signals

Pedestrian signal face locations and APS are governed in MUTCD, Chapter 4E. Specific attention should be paid to the location of APS units next to the crosswalk and in proximity to one another, especially within the splitter island. Refer to MUTCD, Sections 4E.08 to 4E.13, for further guidance on this topic.

APS, as well as audible information devices that may be used with RRFBs, have a pushbutton locator tone to indicate to a blind pedestrian the existence of a pushbutton and to help them find it. The pushbutton locator tone is emitted from a speaker in the pushbutton housing and is supposed to be audible 6 ft to 12 ft from the button. Pushbutton locator tones repeat constantly at an interval of once per second. Other features of APS include a tactile arrow aligned with the direction of travel on the crosswalk, ambient sound response, and audible and vibrotactile walk indications. Audible information devices at RRFBs have a pushbutton locator tone and a speech message providing a message that “yellow lights are flashing.”

If a crosswalk has a signal or beacon and APS or audible information devices are provided in the splitter island for a two-stage crossing, a wider splitter island is needed. The pushbuttons and audible messages must be separated by at least 10 ft, and poles must be set back from the curb by 2 ft to reduce the likelihood of being struck by vehicles and to properly locate pedestrian pushbuttons (see MUTCD, Sections 4D.16 and 4E.08 through 4E.10). Therefore, with a signal or beacon and a straight pedestrian crossing, the minimum recommended width of the splitter island at the crosswalk location is 14 ft. Moving the exit portion of the crosswalk further away from the roundabout in a zig-zag island design can aid with providing adequate space for the required separation of entry and exit traffic control devices for pedestrians. The zig-zag may also allow for an island that is less than 14 ft wide, while still providing adequate separation, as illustrated in Figure 4-26.

This separation is required to place the pushbutton and the audible tone or message close to the crossing to which it applies and to prevent confusion between two crosswalks on the same corner or island. There is an exception in MUTCD 4E.08, paragraph 8, which allows pushbuttons to be placed closer, if speech walk messages are used. However, there has been no research on what the speech messages should say to clarify which leg of the roundabout the signal applies to. The designation, entry lane or exit lane, is not well understood by the general public, with a high likelihood of confusion for pedestrians who are blind if audible devices are

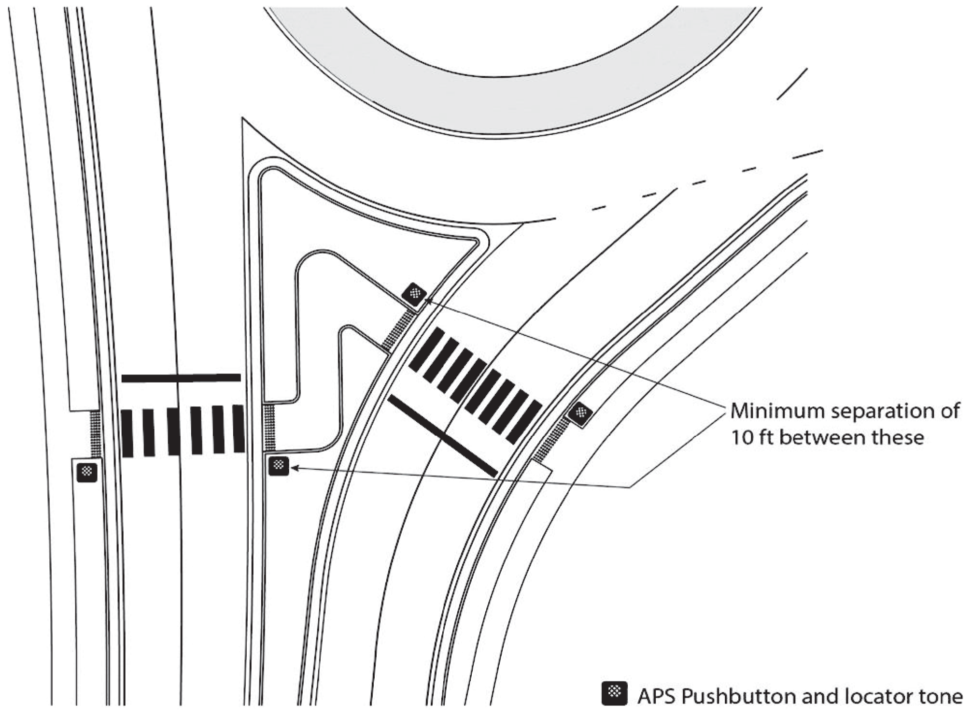


Figure 4-26. Location of pedestrian pushbuttons for zig-zag crossings.

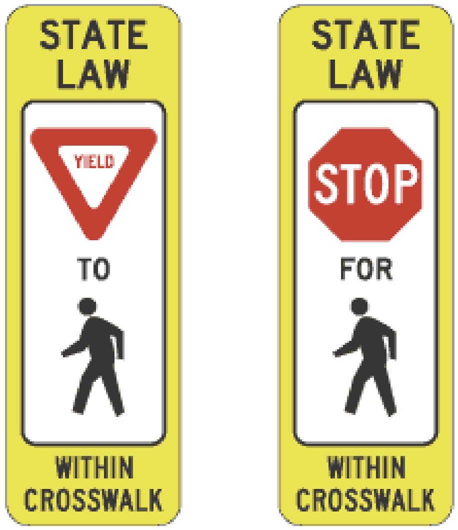
Figure 4-26 shows proposed locations of APS or audible information devices with push button, audible message and locator tones at a two-lane roundabout. Pushbuttons and devices for entry and exit are located downstream of the crosswalk, which separates the sound of the devices from that of approaching vehicles. On the splitter island, it also provides maximum separation between the two components of the crossing. Note that no vehicular signal heads are shown in the image.

placed closer together. Although not specified by MUTCD, audible devices should be placed on the downstream side of the crosswalk (relative to the direction of vehicle travel) to avoid the audible message masking the sound of approaching vehicles.

4.2.4 Signing and Markings

MUTCD, Section 3B.16, provides language on the placement of stop bars associated with crosswalks. MUTCD, Section 4D.14, indicates that signal faces shall not be less than 40 ft from the stop bar "except where the width of the intersecting roadway or other conditions makes it physically impractical." If signal faces for a signalized crosswalk on a roundabout exit are less than 40 ft from the roundabout, it would be physically impractical to place the stop bar 40 ft or more from the signal face because it would be within the circulatory roadway. The crosswalk design should account for where vehicles will queue based on the location of the stop bar when determining the crosswalk location.

High visibility crosswalk markings (also referred to sometimes as "zebra" markings, in contrast to having two transverse lines on either side of the crosswalk) may make drivers more aware of the pedestrian crosswalk and provide guidance to pedestrians with low vision about the crossing location. On the other hand, transverse lines can help low vision travelers maintain their straight



R1-6
(a)

R1-6a
(b)

Figure 4-27. In-road pedestrian signs.

Figure 4-27 shows two examples of in-road signs reminding drivers of the state law to either yield or stop for pedestrians within the crosswalk. Near the top of each sign are the words "state law." Figure 4-27(a) includes a small yield sign, the word "to," and the pedestrian symbol with the words "within crosswalk" below the pedestrian symbol. Figure 4-27(b) includes a small stop sign, the word "for" and the pedestrian symbol with the words "within crosswalk" below the pedestrian symbol. The yield and stop signs are listed in MUTCD as numbers R1-6 and R1-6a, respectively.

line of travel while crossing (as noted in the section on wayfinding). As a result, a "ladder" type crosswalk (see figure 4-17), featuring both transverse lines and zebra stripes (or continental style markings), may be the most effective crosswalk marking to assure access to blind travelers and travelers with low vision, although research on the effect of the different markings is limited.

An in-road sign reminding drivers that it is a state law to yield to pedestrians within the crosswalk (Figure 4-27) may increase yielding behavior. Research at non-roundabout locations has shown that these signs are effective in increasing the yielding behavior of drivers (Fitzpatrick et al., 2006) and they have been used effectively at some roundabout installations.

The sign, yield here to pedestrians, in Figure 4-28, is intended to be used in conjunction with an advance yield line to encourage drivers to stop further from the crosswalk. However, vehicles stopping further from the crosswalk may make it harder for blind pedestrians to detect the vehicle that has yielded and may lead to unexpected conflicts. However, having a sign clearly indicating to drivers where they are intended to yield presumably enhances the predictability of where to listen for yields.

4.2.5 Other Treatments

Numerous treatments are intended to increase pedestrian visibility and encourage drivers to yield to pedestrians. They can range from typical warning signs and crosswalk markings to pedestrian-actuated flashing beacons. Higher yielding rates may result in more opportunities

R1-5
(a)

R1-5a
(b)

Figure 4-28. Sign for yielding to pedestrians.

Figure 4-28 shows two examples of roadside signs indicating to drivers where to yield to pedestrians. Figure 4-28(a) is square and Figure 4-28 is rectangular. Within the black and white sign is a red yield sign, the word "here," a downward pointing arrow, the word "to," and a pedestrian symbol or the word "pedestrians." The square and rectangular signs are listed in MUTCD as numbers R1-5 and R1-5a, respectively.

for crossing for pedestrians who are blind or who have low vision. However, as noted above, the pedestrian has to be able to detect that a vehicle has yielded, the driver has to wait long enough for the pedestrian to make that decision, and the pedestrian has to be willing to cross in front of a yielding vehicle. At multilane crossings, the second lane has the potential for multiple threat events and is a big concern for pedestrians who are unable to visually ascertain the status of the second lane before crossing.

Non-signalized treatments can be considered to improve the accessibility of crosswalks at roundabouts. Treatments that provide vertical deflection and thus reduce speeds such as raised crosswalks and speed humps, may improve the likelihood of drivers yielding to pedestrians. Testing of a raised crosswalk at a multilane roundabout is reported in *NCHRP Report 674* and showed beneficial results in terms of the pedestrian level of risk and driver yielding. Evaluations in NCHRP Project 03-78B further found that raised crosswalks can help reduce vehicle speeds, increase driver yielding, and reduce pedestrian risk and delay. The potential impact of a raised crosswalk at roundabouts on the slowing down of vehicles needs to be considered before installation. Further testing is needed to understand the range of conditions under which a raised crosswalk may be effective.

At roundabouts, it may be possible to keep raised crosswalks closer to the circulatory roadway compared to a signal as discussed above. This tends to reduce out-of-direction travel for pedestrians. Detectable warnings are essential to help a blind pedestrians identify the street or sidewalk boundary. Figure 4-29 shows a raised crosswalk at a two-lane roundabout.

Design considerations for raised crosswalks specific to roundabouts have not been developed. Generally, a raised crosswalk refers to the crosswalk walking surface being elevated relative to the vehicular travel lanes across the entire width of the crosswalk (as opposed to a more narrow speed hump or bump). The key design dimension of the raised crosswalk are the vertical elevation (typically between 3 in. and 5 in. higher than travel lanes) and the transition slope (typically between 1:10 to 1:15). In general, a higher vertical difference and a steeper transition slope will result in a slower design speed for vehicles.

Figure 4-29. Raised crosswalk at a two-lane roundabout.

Figure 4-29 shows an installation of a raised pedestrian crosswalk at the entry leg of a two-lane roundabout in Golden, Colorado. This location was studied as part of *NCHRP Report 674*.

It is further possible to combine a flashing beacon or RRFB with a raised crosswalk. The beacons are primarily intended to increase driver awareness of the crosswalk, alert them of the presence of a pedestrian, and encourage drivers to yield. A raised crosswalk can be effective in supplementing these treatments, by reducing vehicle speeds at the crosswalk, which can help reduce sight distance requirements, improve yielding, and reduce risk. Care is needed in ensuring an appropriate set of signs and pavement markings to accompany the combined treatments.

CHAPTER 5

Design Principles for Pedestrian Access at Channelized Turn Lanes

The Green Book defines channelization as "the separation or regulation of conflicting traffic movements into definite paths of travel by traffic islands or pavement marking to facilitate the orderly movement of both vehicles and pedestrians." *NCHRP Report 279* presents nine principles of channelization, one of which is that channelization can provide refuge for non-motorized users. For purposes of this project, CTLs are defined as right-turn lanes having raised islands separating them from other lanes at an intersection.

Oftentimes, CTLs are installed for geometric reasons, and particularly to accommodate design vehicles at skewed intersections. In other cases, CTLs are used to increase the capacity for right-turning traffic.

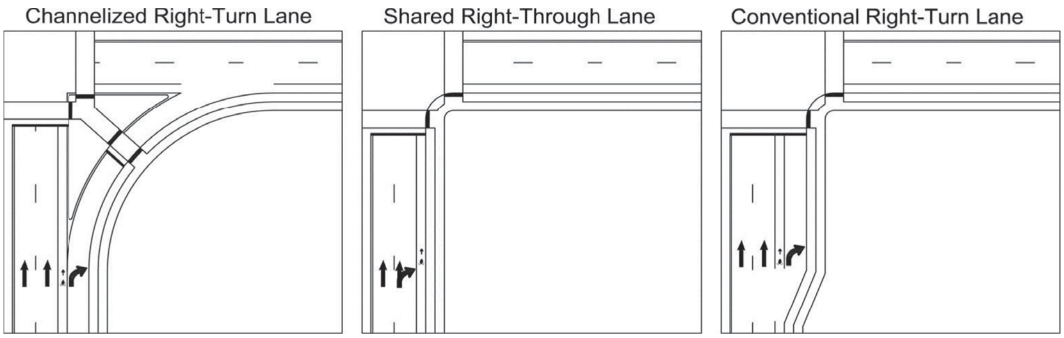
Recent research (Potts et al., 2011) found that CTLs had a lower motor vehicle crash frequency than conventional right-turn lanes and higher motor vehicle crash frequency than shared right-through lanes. In other words, once a decision has been made that a designated right-turn lane is needed for capacity, a CTL provides a safer configuration than an exclusive right-turn lane without channelization. Figure 5-1 depicts these three types of right-turn lanes.

The effects of CTLs on pedestrian safety have historically been poorly documented. To date, the largest study of pedestrian safety at CTLs analyzed data from 400 intersection approaches in Toronto (Potts et al., 2011). The study found that pedestrian crash frequency was approximately the same on approaches with CTLs and approaches with shared through-right lanes. Approaches with conventional right-turn lanes had 70% to 80% more pedestrian crashes. These findings, coupled with the auto safety findings noted earlier, suggest that where right-turn lanes are needed for capacity purposes, it may be appropriate to channelize them even if pedestrian activity is anticipated.

However, as emphasized in Chapter 1.2, pedestrian safety and accessibility are two different questions, and while safety performance is important, the focus of this document is on the accessibility performance of CTLs.

Advantages and disadvantages of CTLs for pedestrians compared to conventional right-turn lanes are presented in Table 5-1.

Some of the design elements of CTLs that are advantageous for pedestrians in general are problematic for blind pedestrians. For example, the benefit of a refuge island is offset by the navigational and wayfinding tasks that must be performed to reach the island and subsequently leave it. The curved nature of CTLs makes it more challenging for blind pedestrians to locate crosswalks, remain in crosswalks, hear vehicles, know if their crossing is controlled by a signal or not, and know when they have reached the other side of the street. The typical lack of signalization for the CTL requires that blind pedestrians base decisions about when to begin crossing on acoustic information about gaps in traffic and yielding vehicles. These challenges are similar to the challenges that blind pedestrians face at roundabouts (see Chapter 3).



(a) (b) (c)

Figure 5-1. Types of right-turn lanes.

> Figure 5-1 shows three similar intersections. Figure 5-1(a) has a dedicated right-turn lane that is channelized on the northbound leg with an island separating it from the adjacent through lane. Figure 5-1(b) has a single northbound lane that is used by right-turning drivers and through drivers. Figure 5-1(c) has a dedicated right-turn lane on the northbound leg; it is not physically separated from the adjacent through lane.

5.1 Geometric Design

This chapter presents the proposed best practices for the design of CTLs, applying the way-finding and crossing tasks discussed in Chapter 3, to specific applications at CTLs.

CTLs generally have been designed in accordance with best practices and agency preferences rather than a performance-based approach as is used with roundabouts. However, while this design process is less formalized than for roundabouts, the same performance-based principles are adopted for CTLs.

This chapter presents key design elements and associated best practices. Two elements of design of particular importance to blind pedestrians—traffic control devices and crosswalk location—are discussed in detail later.

Table 5-1. Advantages and disadvantages of CTLs for pedestrians.

Advantages	Disadvantages
• Island serves as a refuge for pedestrians. • Compared to crossings having a conventional right-turn lane, the length of the main crosswalk is shorter. • Right turn on red maneuvers are removed from the main crosswalk spanning through and left lanes. • Right turn on green maneuvers are removed from the main crosswalk spanning through and left lanes. • Larger turn radii can decrease the likelihood of large vehicles encroaching or off-tracking onto sidewalks.	• In most cases, the crossing of the CTL is unsignalized. • Pedestrians must make decisions about the speed of vehicles and driver yielding behavior • Channelization may enable higher speeds for right-turn vehicles • Curvature of the channelized lane may create sight distance and visibility issues for drivers and pedestrians. • Crosswalk location varies and angles may be confusing for pedestrians with vision disabilities. • Drivers may be focused on conflicting traffic and searching for gaps rather than focusing on pedestrians.

5.1.1 Island Design

Section 9.6.3 of the Green Book provides guidance on island design. Islands should be a minimum of 50 ft^2 in urban areas and 75 ft^2 in rural areas, to assure that the island is readily visible to approaching drivers. Additional considerations for island size include expected storage space, especially if frequent use by (groups of) pedestrians and bicycles is expected. An example of an island barely large enough to accommodate two cyclists and a pedestrian on roller skates is shown in Figure 5-2.

The leading and trailing ends of the island should be designed in accordance with principles of channelization shown in Figures 9-38 and Figure 9-39 of the Green Book. The same principles discussed in the design of splitter islands at roundabouts apply to the channelization islands at CTLs. Pedestrians who are blind or who have low vision need appropriate guidance through the island area to the other crosswalks from the island. A completely paved island with no landscaping materials present in areas adjacent to the crosswalk can be disorienting, as was observed at several sites studied in this research (see Figure 5-3). In addition and as noted earlier, detectable warning surfaces must be provided at the boundary between the island and the street to alert individuals to the location of the street or island boundary.

The general design principles for CTL islands are similar to roundabouts, and the principles discussed in Chapter 4.1 generally apply to CTL islands as well. Desirable design dimensions for CTL islands are illustrated in Figure 5-4.

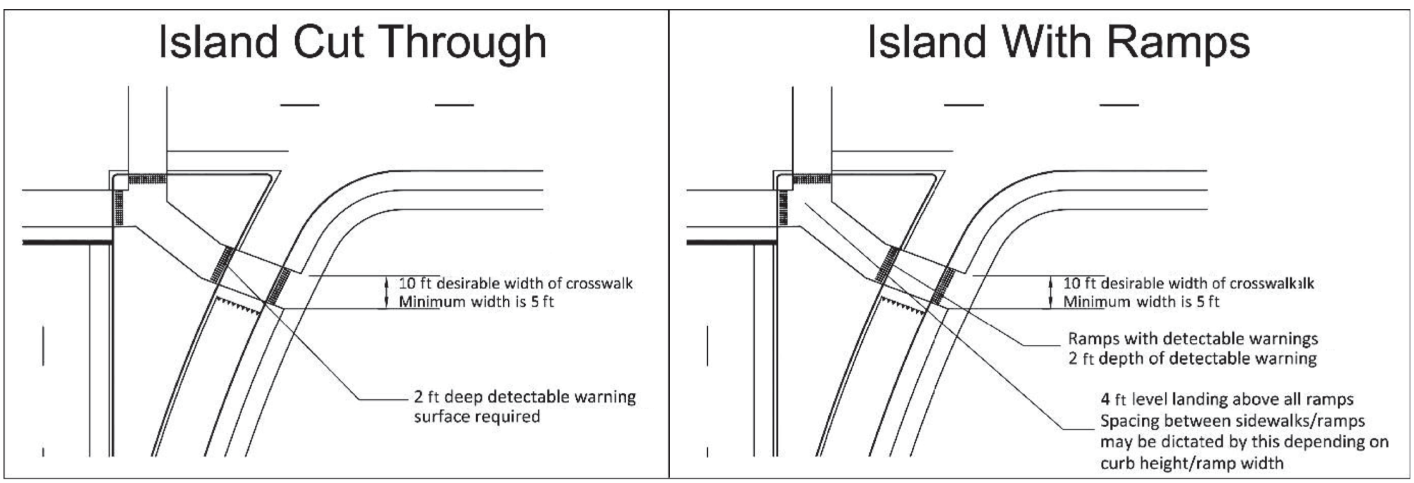
Similar to roundabouts, the area outside the prescribed path on CTL islands should be detectable as a non-walking surface. Research has shown that some participants were slightly misaligned when crossing and reached the island outside the crosswalk area (NCHRP Project 03-78B). When reaching the island, individuals who were blind were typically taught to step up onto the island to get out of the street as quickly as possible rather than to look for a cut-through area or curb ramp. If the island was grass or an obvious non-walking surface such as

Figure 5-2. A crowded CTL island with pedestrians and bicycles.

Figure 5-2 shows an island with two cyclists and a pedestrian on roller skates. One of the bicycles has a trailer attachment, and the island is barely large enough to accommodate it.

Figure 5-3. Blind pedestrian disoriented on an all-paved CTL island.

Figure 5-3 shows a blind pedestrian (followed closely by an orientation and mobility specialist) on an all-paved island, approaching the curb near the end of the island, not at the crosswalk.



(a) **(b)**

Figure 5-4. Minimum CTL island and crosswalk dimensions.

Figure 5-4(a) shows a 5 ft minimum width of the crosswalk with a cut-through pedestrian path. Within the cut-through area of the island for the full width of the cut-through is a 2 ft section of detectable warning surface, then at least 2 ft of smooth surface, and then another 2 ft section of detectable warning surface. The actual separation between the two detectable warning surfaces is significantly larger on this island.

Figure 5-4(b) shows an island with ramps sloping up on each side with detectable warning surfaces at the base of the ramps at each street edge. A 4 ft level landing between the ramps is required, although the area in the figure is significantly larger than that.

Figure 5-5. Island with ramps to paved walkways and gravel outside the pedestrian path area.

Figure 5-5 shows an island with detectable warning surfaces along the edge of the island and wide paved paths across the island in two directions: to the two main street crossings, with a bench along the path as well. Outside the path area, the surface of the island is crushed stone.

pebbles, they tended to look for and found the paved path or cut-through area. Figure 5-5 shows an example with gravel treatment outside the intended walking area, and other examples exist with grass or landscaping on the islands.

When the entire island was raised but had a concrete or brick surface, blind pedestrians were often unable to reorient or maintain their orientation in crossing the island (see Figure 5-3). If the island had a cut-through pedestrian path, they were unable to discern whether the cut-through was the pedestrian path or the street, causing further disorientation and failure to locate the crosswalk to complete crossing the street.

5.1.2 Radius of the Turning Roadway

The radius of the turning roadway in a CTL is a function of turning speeds, truck considerations, pedestrian crossing distances, and island sizes. In locations where pedestrians are expected, the radius of the turning roadway should be minimized. This reduces vehicle speeds and has been shown to increase yielding to pedestrians by drivers (Potts et al., 2011).

5.1.3 Angle of Intersection with the Cross Street

The Green Book historically recommended that CTLs be designed with flat angle entries to the cross street, as shown in Figure 5-6(a). This design may be appropriate at CTLs without pedestrian facilities, and with yield control or no control and an acceleration lane (Potts et al., 2011). However, where pedestrians are expected to cross the CTL, a design similar to the one in Figure 5-6(b) is preferred. This guidance is also consistent with the guidance provided in the *Guide for the Planning, Design and Operation of Pedestrian Facilities* (AASHTO, 2004).

The "pork chop" or "lamb chop" island design shown Figure 5-6(b), provides improved sight distances between the pedestrian and approaching vehicles, and further is likely to enhance the visibility of traffic control devices at the crosswalk. The design is generally believed to result in slower vehicle speed than Figure 5-6(a), although the actual design speed depends on the geometry and curve radii used. Islands and CTLs should be designed to encourage slow vehicle speeds, minimize the need of drivers to turn their heads far to the left, and place the pedestrian crossing point before

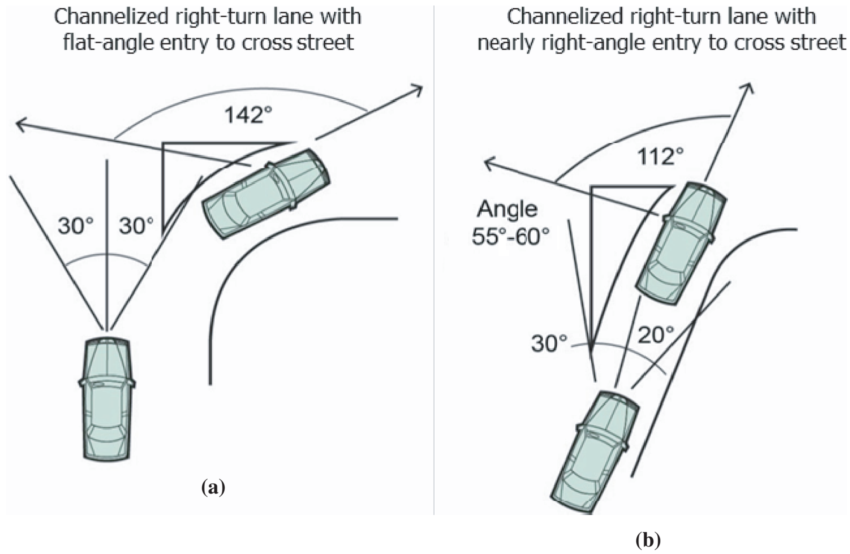


Figure 5-6. Typical CTLs with different entry angles to the cross street.

> Figure 5-6 shows two types of angles and curvatures for a CTL. In Figure 5-6(a), the lane turns to the right continuously and vehicles are nearly parallel with the downstream roadway at the end of the CTL, creating a very flat-angle entry to cross the street. In Figure 5-6(b), the CTL diverges from the entering, and vehicles are nearly perpendicular to the downstream roadway at the end of the CTL.

the downstream yield point for vehicles. This last feature separates driver decisions of interacting with pedestrians (yielding) and interacting with the downstream traffic stream (searching for gaps). Similar to the placement of crosswalks at roundabouts, crosswalks at CTLs should be placed one-vehicle length back from the downstream yield line for vehicles for that reason.

5.1.4 Deceleration and Acceleration Lanes

Use of a deceleration lane is often advantageous for a safe crossing environment to slow vehicles before they enter the CTL, reduce the speed differential between right-turning traffic and the traffic on the downstream through lanes on the entering roadway, and reduce the likelihood of queues blocking the entrance to the CTL. This may also make it easier for blind pedestrians to detect a vehicle in the lane approaching the crosswalk.

Use of acceleration lanes should be avoided at locations where pedestrians are expected, because they are believed to increase vehicle speeds and decrease yielding.

5.1.5 Sight Distance and Visibility

Stopping sight distance values for CTLs are the same as the values for an open highway, and are presented in Table 9-21 of the Green Book. At all points along a CTL, visibility to the downstream roadway and any crosswalks should be available.

5.1.6 Design Vehicle Accommodation

Figure 9-43 and Table 9-18 of the Green Book provide edge of way designs for different vehicles and two types of curves: simple curve radius with taper and three-centered curves. For situations in which other types of curves are used or roadways that do not intersect at a right angle, software-generated vehicle turning templates can be used to determine the necessary edge-of-traveled-way designs.

5.1.7 Crosswalk Location and Angle Options

The geometric design of a crosswalk can directly influence its effectiveness, regardless of the type of traffic control devices used at that crosswalk. *Guide for the Planning, Design and Operation of Pedestrian Facilities* (AASHTO, 2004) provides criteria that pedestrian crossings to triangular islands should meet:

1. Pedestrian crossings should be at 90 degrees across the turn lane and be placed where the motorist can easily see the pedestrian crossing ahead;
2. Pedestrians and motorists must be able to easily see each other; and
3. The design should encourage low vehicle turning speeds (Potts et al., 2011).

For CTLs, the first and second objectives are sometimes in conflict. A crosswalk that is 90 degrees across the turn lane (perpendicular to a tangent of the turn lane) may be too far downstream in the CTL where the line of sight and visibility are compromised. Generally, the use of a larger island with a pork chop design is more likely to provide adequate space to properly locate the pedestrian crossing to meet both objectives. For smaller islands, the crosswalk may need to be angled at more than 90 degrees, which is less desirable.

Also, NCHRP Project 03-78B found that it is critical for the crosswalk to reach the island in a "centered" location, which provides sufficient island surface area on the left and right side of where the crosswalk meets the islands. For crosswalks too close to either edge of the island, blind pedestrians were observed to sometimes miss the island entirely, and walk into the main travel lanes.

The third objective of low turning speed may conflict with the need to accommodate for a specific design vehicle. But even for large design vehicles, the CTL design and crosswalk location should aim to achieve slow speeds in the vicinity of the crosswalk. *NCHRP Web-Only Document 208* discussed five options for crosswalk placement and alignment at a CTL, which have been re-ordered here, starting with the most preferred option based on this research. These possible configurations are shown in Figure 5-7.

- **Option 1. At the center, and perpendicular to the sidewalk and CTL;**
- Option 2. At the upstream end, and parallel to the entering road;
- Option 3. At the upstream end, and perpendicular to the sidewalk and CTL;
- Option 4. At the downstream end, and parallel to the exiting road; or
- Option 5. At the downstream end, and perpendicular to the sidewalk and CTL.

When choosing a configuration, there are several conflicting challenges to balance from a pedestrian perspective:

- *The crosswalk should be located conveniently close to non-channelized lanes and their crosswalks to minimize out-of-direction travel for pedestrians.* Pedestrians are increasingly likely to cross closer to the parallel street if the designated crossing location is too far out of their direction of travel, if insufficient channelization is provided to encourage crossing at the appropriate location, and if the pedestrian does not perceive a risk of crossing away from the designated location. This can be particularly problematic for larger turning radii associated with a flatter-angle entry CTL. A centered crosswalk is likely to balance out-of-direction travel for pedestrians approaching from different directions.
- *The crosswalk should minimize crossing distances and thereby exposure to traffic in the CTL.* In general, a crosswalk close to a 90-degree angle across the turn lane will result in the shortest

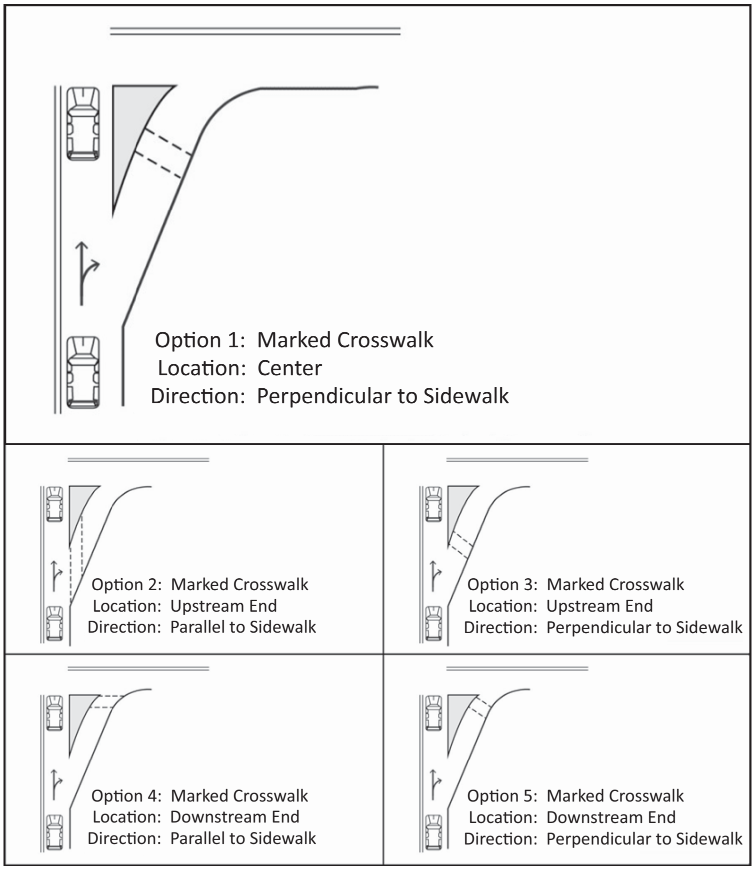


Figure 5-7. CTL crosswalk location options (adapted from* NCHRP Web-Only Document 208*).

Figure 5-7 shows five crosswalk location options at CTLs. The preferred option is (1) crosswalk at the center and at 90 degrees across the right-turn lane. Other options are less desirable for reasons discussed in the text, and include (2) crosswalk at the upstream end and parallel to the roadway entering the intersection, (3) crosswalk at the upstream end and at 90 degrees across the right-turn lane, (4) crosswalk at the exit and parallel to the roadway exiting the intersection, and (5) crosswalk at the exit and at 90 degrees across the right-turn lane.

crossing. AASHTO recommends that pedestrian crossings should be placed at a 90-degree angle across the CTL and located so that pedestrians and drivers can see one another (AASHTO, 2004). Crossings at a 90-degree angle also minimize the crossing distance and thus reduce exposure. They also enable curb ramps to be both perpendicular to the sidewalk and aligned with the crosswalk, thus benefitting both pedestrians who use wheelchairs and pedestrians who are blind.

- *Good visibility of conflicting vehicle traffic needs to be provided to allow pedestrians to detect gaps.* Having good visibility is oftentimes correlated with an improved audible environment. A crosswalk located toward the downstream end of the CTL is less likely to have good visibility and audibility.
- *Positive wayfinding guidance to the crosswalk is critical, regardless of location.* Like roundabouts, the curvilinear nature of CTLs makes it substantially more difficult for a blind pedestrian to locate the appropriate crossing location and to maintain alignment through the crosswalk. Positive channelization also assists pedestrians without vision disabilities by encouraging them to cross at the appropriate crossing locations.

- *The channelization island itself needs to be designed following the same principles as the curbside crosswalk landing.* Most islands have three crosswalk landings, and each landing needs to follow the accessibility principles. In addition, clear wayfinding guidance between these crossing points needs to be provided.

From a driver's perspective, there are also several conflicting challenges to balance:

- *Visibility of the crosswalk itself and of pedestrians in or about to enter the crosswalk.* A crosswalk that is located toward the downstream end of the CTL can be less visible to approaching drivers than one located closer to the upstream entry point into the CTL.
- *Separation of decision points of interacting with pedestrians and downstream vehicles.* At some point, drivers are expected to look left to screen the conflicting vehicle traffic for gaps to leave the CTL, which can make it more difficult to see a pedestrian waiting to cross from the right. This research found that separating these decision points can improve pedestrian safety and accessibility, by allowing drivers to focus on pedestrians before and independent of interacting with the downstream vehicular traffic stream.
- *Visibility of traffic control devices present at the crosswalk.* This is particularly important for traffic control devices that change indication, such as pedestrian-activated flashing beacons, PHBs, and red-yellow-green traffic signals.
- *Driver speeds through the crosswalk area.* Research suggests a strong relationship between the speed at which drivers are driving and their willingness to yield to a pedestrian. Research also shows a strong relationship between vehicle speed and the severity of any collisions that may occur.

With regard to visibility, a guide for identifying the appropriate locations for a crosswalks is provided in Table 3-1, Stopping Sight Distance on Level Roadways, and Table 3-2, Stopping Sight Distance on Grades, of the Green Book. A portion of Table 3-1 is reproduced below as Table 5-2.

These principles can be challenging to balance in retrofit situations where an optimal crosswalk location may not be achievable. There is also the potential concern of having a variety of crosswalk configurations used at the same intersection or within the same community, although there is no research at the time of this writing to confirm the safety impacts of this. Examples of good and poor crosswalk placement are shown in Figure 5-8 and Figure 5-9, respectively.

5.1.8 Recommended Crosswalk Placement

Based on observations in this study, a centered crosswalk location is preferred at CTLs. While there are always exceptions and reasons to favor one of the other options described in Figure 5-7,

Table 5-2. Stopping sight distance on level roadways (Table 3-1, AASHTO, 2011).

Design Speed (mph)	Brake Reaction Distance (ft)	Braking Distance on Level (ft)	Stopping Sight Distance (calculated) (ft)	Stopping Sight Distance (design) (ft)
15	55.1	21.6	76.7	80
20	73.5	38.4	111.9	115
25	91.9	60.0	151.9	155
30	110.3	86.4	196.7	200
35	128.6	117.6	246.2	250
40	147.0	153.6	300.6	305
45	165.4	194.4	359.8	360

Note: Based on brake reaction distance of 2.5 s and deceleration rate of 11.2 ft/s^2.

Figure 5-8. Example of a properly placed and aligned crosswalk at a CTL.

Figure 5-8 shows an example of a properly placed and aligned crosswalk at a CTL. The crosswalk is located at the center of the CTL at a 90-degree angle across the turn lane, and leads to a sufficiently large and landscaped island. This installation however does not have adequate landscape separation on the curb.

Figure 5-9. Example of a poorly aligned crosswalk at a CTL.

Figure 5-9 shows an example of a poorly aligned crosswalk at a CTL. The slope of the ramp and detectable warnings do not point in the direction of the island, but rather into the street left of the island. The island size is further not sufficiently large, thus pedestrians in the research missed the island and walked into the intersection.

placing the crosswalk at the center of the CTL (Option 1, see in Figure 5-10) is recommended in most cases for the following reasons:

- The crossing is at a 90 degree angle.
- Out-of-direction travel is equally distributed among pedestrian routes.
- Ramps can be both perpendicular to the sidewalk and aligned with the crosswalk.
- The crosswalk is visible to approaching drivers and a clear line of sight is provided between pedestrians and approaching drivers.
- The crosswalk is likely to be upstream of a stop or yield line if one is present, and may provide sufficient space for one-vehicle length of storage between the crosswalk and the stop or yield line (similar to the entry to a roundabout).

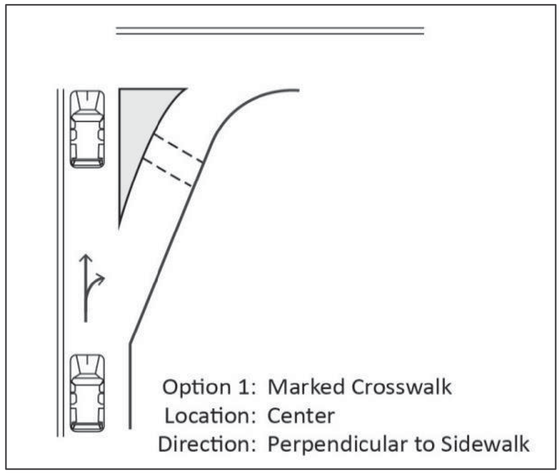


Figure 5-10. Recommended crosswalk location and configuration for CTLs.

> Figure 5-10 shows the preferred crosswalk location and configuration for CTLs, with the crosswalk located in the center of the CTL and oriented perpendicular to the approach. This configuration minimizes crossing distance, aids with alignment, provides good visibility of the crosswalk for motorists, and reduces wayfinding challenges once the island is reached.

- The crosswalk location is likely to separate driver decision points of (1) interacting with the pedestrian and (2) interacting with downstream vehicle traffic. This allows the driver to focus on the interaction with pedestrians, before scanning for gaps in downstream traffic.
- The channelization island provides sufficient raised area on either side of the crosswalk to minimize the chance of pedestrians missing the island and stepping into the travel lanes.

An example of a well-placed and configured CTL crosswalk is shown in Figure 5-8. The installation has the crosswalk in the center of the turn lane at a 90 degree angle across the turn lane. The installation is missing landscaping to delineate the crosswalk on the curb side, which should be retrofitted. On the island, the design features properly installed detectable warnings and crushed stone surface on areas not intended for walking, providing good channelization and wayfinding cues for pedestrians on the island.

Figure 5-9 shows an example of a poorly located and configured CTL crosswalk. The curb ramp is at the upstream end of the CTL and slopes toward the left of the channelization island. A pedestrian lining up with the detectable warning and curb ramp slope is likely to miss the island and cross into the intersection. This was observed for several participants in experimental wayfinding trials as part of this research.

5.2 Traffic Control Device Applications

A variety of traffic control devices can be used at the crosswalk to increase pedestrian visibility and encourage drivers to yield to pedestrians. They can range from typical warning signs and crosswalk markings to pedestrian-actuated flashing beacons. Higher yielding rates may result in more opportunities of crossing for pedestrians who are blind or who have low vision. However, as noted above, the pedestrian has to be able to detect that a vehicle has yielded, the driver has to wait long enough for the pedestrian to make that decision, and the pedestrian has to be willing to cross in front of a yielding vehicle. At multilane crossings, the second lane has the potential for multiple threat events and is a big concern for pedestrians who are unable to visually ascertain the status of the second lane before crossing. The proposed PROWAG requires a pedestrian-activated signal in those locations.

5.2.1 Vehicle Control Options for CTLs

There are many vehicle control options for CTLs available that govern the interaction between vehicles in the CTL and the downstream merge point with the cross street. The primary treatments include yield control, free-flowing operation with a dedicated receiving lane, stop-control, signalization, and pedestrian-actuated beacons. Most state and local agencies do not have policies related to traffic control devices for CTLs (Potts et al., 2011), so a wide variety of control options may be in use in the same area. Variety creates challenges for blind pedestrians, because they may not be able to discern the configuration of a CTL at an intersection with which they are not familiar.

In observations of driver behavior at CTLs, it has been repeatedly seen that the speed and compliance behavior of drivers varied depending on the phase of the signal at the adjacent intersection. Driver speeds were noted to be higher and yielding compliance lower when the parallel through movement had a green indication than when it was red. Presumably, drivers knew that they had no downstream conflicts during the adjacent green phase, and as a result traveled faster and yielded less than when there was a chance for a downstream conflict. This is a characteristic likely to apply to most CTLs with yield control, no control, or signal control, and should be considered in any evaluation.

The following sections present the advantages and disadvantages of different control devices for CTLs and are adapted from *NCHRP Web-Only Document 208*.

5.2.1.1 Yield Control

Yield control may be the most common form of traffic control at CTLs that do not have an acceleration lane.

Advantages

- Enables vehicles to proceed without stopping in the absence of conflicting vehicles and pedestrians and
- Well-suited for the flat angle entry design presented in the Green Book.

Disadvantages

- Potential for high speeds by vehicles,
- Potential for queues to stack across the crosswalk (assuming the crosswalk is placed in the middle of the CTL), and
- The yield control and lack of a pedestrian signal can be especially challenging for blind pedestrians.

5.2.1.2 No Control

For CTLs with acceleration lanes, oftentimes there may be no traffic control device. Instead, traffic through the CTL flows freely and merges with downstream traffic.

Advantages

- Enables vehicles to proceed without stopping and
- Well-suited for the flat angle entry design presented in the Green Book.

Disadvantages

- Potential for high speeds by vehicles,
- Requires right-of-way for the receiving lane on the downstream roadway, and

- Lack of a control device can be challenging for pedestrians, especially for those who are blind.

5.2.1.3 Stop-Control

Stop-control at CTLs is uncommon, unless the stop sign is required because of considerations for vehicular sight distance or other safety considerations. The configuration is similar to a yield-controlled CTL, but with a stop sign and a stop bar at the merge point.

Advantages

- Stop requirement for all vehicles is beneficial to pedestrians and
- Stop requirement for all vehicles can enhance vehicle safety if sight distances are compromised by the CTL design.

Disadvantages

- Imposes delay on all vehicles even without pedestrians present, which may lead to drivers ignoring the traffic control device over time;
- Uses traffic signals at the same intersection, which may be confusing to or unexpected by some pedestrians; and
- Lack of a signal may be challenging for blind pedestrians.

5.2.1.4 Signal Control

Signal control is common at two-lane CTLs to allow both lanes to safely merge into the downstream traffic stream. However, even single-lane CTLs may be signalized for safety considerations or to provide a clearly defined crossing interval for pedestrians.

Advantages

- Signalized crosswalks are beneficial to pedestrians (APS devices are needed to make the signals accessible),
- Enables pedestrians who are blind to accurately determine the onset of an intended crossing time and eliminates multiple lane threat, and
- Enables designs with two or more right-turn lanes.

Disadvantages

- Imposes delay on vehicles, especially if right turn on red is prohibited;
- If the movement operates with overlap phasing, it may be necessary to prohibit U-turns from the associated left-turn lane to avoid conflicts on the exit leg; and
- Signal equipment increases the cost of CTLs.

5.2.2 Pavement Markings

For pedestrians with low vision, marked crosswalks can provide an essential cue to the crosswalk location and assist with maintaining travel within the crosswalk. Pedestrians with low vision have stated a preference for ladder-type crosswalk markings. Ladder markings have both transverse and longitudinal lines. The transverse lines make it easier for a person with low vision to follow a line across the crosswalk and the longitudinal lines enhance crosswalk visibility to drivers. Crosswalks that are brick colored may not be distinguishable from the asphalt street color under low illumination as well as for individuals who are color blind, and they are not as visible to drivers. An example of ladder-style crosswalk markings was shown in Figure 4-17.

MUTCD, Section 3B.16, provides language on the placement of stop bars associated with crosswalks. MUTCD, Section 4D.14, indicates that signal faces shall not be less than 40 ft from the stop bar "except where the width of the intersecting roadway or other conditions makes it physically impractical." The crosswalk design should account for the location of the stop bar and where vehicles will queue when determining crosswalk location.

5.2.3 Signs

A number of signs are appropriate at CTLs as discussed below.

5.2.3.1 STOP (R1-1) and YIELD (R1-2) Signs

If the CTL is sign-controlled, then either a stop or an yield sign must be used at the exit of the CTL. If sight lines and crosswalk placements allow, it may be advantageous to place the stop or the yield sign in advance of the crosswalk.

5.2.3.2 In-Street Pedestrian Crossing Signs (R1-6 and R1-6a)

An in-street sign reminding drivers that it is a state law to yield to or stop for pedestrians within the crosswalk (Figure 5-11) may increase yielding behavior. Research at non-roundabout locations has found these signs are effective in increasing the yielding behavior of drivers (Fitzpatrick et al., 2006).

5.2.3.3 Yield Here to Pedestrians (R1-5 and R1-5a) Signs

The yield here to pedestrians sign, Figure 5-12, is intended to be used in conjunction with an advance yield line to encourage drivers to stop further from the crosswalk. However, vehicles stopping further from the crosswalk may make it harder for blind pedestrians to detect the vehicle that has yielded and may lead to unexpected conflicts. However, having a sign clearly indicating to drivers where they are intended to yield presumably enhances the predictability of where to listen for yields.

Figure 5-11. In-road pedestrian signs.

Figure 5-11 shows two examples of in-road signs reminding drivers of the state law to either yield or stop for pedestrians within a crosswalk. The signs are listed in MUTCD as numbers R1-6 and R1-6a, respectively.

R1-5

R1-5a

Figure 5-12. Yield here to pedestrian signs.

Figure 5-12 shows two examples of roadside signs indicating to drivers where to yield to pedestrians. The signs are listed in MUTCD as numbers R1-5 and R1-5a, respectively.

5.2.4 Rectangular Rapid-Flashing Beacons

RRFBs are typically activated by a pedestrian pushbutton. The flashing display is associated with identifying the presence of a pedestrian by drivers and may result in more yielding. In the research, blind pedestrians noted that they liked knowing they had activated a beacon that was highly visible to drivers, and it gave them greater confidence that a vehicle might yield. Pedestrians who are blind still need to be able to recognize that vehicles have yielded, drivers have to wait long enough for the detection, and pedestrians have to be willing to cross in front of a stopped vehicle. The multiple threat issue is also not resolved.

For usability by a pedestrian who is blind, an RRFB must be equipped with an audible information device, providing a pushbutton locator tone to help the pedestrian find the pushbutton, and an audible message telling the pedestrian that "yellow lights are flashing." Figure 5-13 shows an example of an RRFB at a roundabout entry, but the device could similarly be used at a CTL.

5.2.5 Pedestrian Signals and Pedestrian Hybrid Beacons

For pedestrians who are blind or who have low vision, a pedestrian-activated signal that provides a red indication to vehicles and a walk indication to the pedestrian is most definitive and more comfortable. To provide access for pedestrians who are blind, the pedestrian signals must include APS to provide information about the signal phases. Research at mid-block locations also showed that devices with a red indication resulted in the highest driver yield compliance of all treatments, typically well above 90% (Fitzpatrick et al., 2006).

Pedestrian signal face locations and APS are discussed in MUTCD, Chapter 4E. Specific attention should be made to the location of APS units next to the crosswalk and separated from one another, especially within the splitter island. Refer to MUTCD, Sections 4E.08 to 4E.13, for further guidance on this topic.

If the CTL is itself signalized for vehicular traffic, then a standard pedestrian signal with a red-yellow-green indication for drivers and a walk/flashing don't walk/don't walk sequence for

Figure 5-13. RRFB at a two-lane roundabout.

Figure 5-13 shows an RRFB at a two-lane roundabout. The device could also be applied to CTLs to increase driver awareness of a pedestrian wanting to cross.

pedestrians (along with audible information) can be used. If the CTL is yield-controlled, a PHB may be a good option. The PHB is a device that is geared at enhancing the operational efficiency compared to a standard signal, but still provides similar safety benefits due to a steady red indication. The PHB provides much of the same benefit as a standard pedestrian signal, but does not show a green indication that could be confused with the yield sign.

5.2.6 Treatments to Facilitate Wayfinding

The same philosophy and many of the same treatments used at roundabouts to facilitate wayfinding also apply to CTLs. This section presents examples specific to CTLs. Chapters 4.1 and 4.2 refer to the treatments discussed in the context of roundabouts.

5.2.6.1 Detectable Warning Surface (truncated domes) to Indicate the Edge of the Street

An example of a detectable warning surface at a CTL is shown in Figure 5-14. The bollards to the left and right of this crosswalk limit vehicular travel on the sidewalk, but do not provide wayfinding guidance for blind pedestrians in the task of locating the crosswalk.

5.2.6.2 Raised Crosswalk Slopes to Provide Cue to Maintain Travel within the Crosswalk

A raised crosswalk, shown in Figure 5-15, can assist pedestrians who are blind in staying within the crosswalk for the entire crossing. Pedestrians may be able to detect the sloping sides of a raised crosswalk and use the slopes as boundaries. While a detectable warning surface covering the width of the crosswalk is present at this CTL, blind pedestrians had difficulty locating the crosswalk because landscaping was not provided on either side of the crosswalk. More than one pedestrian walked into the street without realizing it because the curb was not detectable (less than an inch of vertical separation) near the crosswalk because of the raised crosswalk.

Figure 5-14. Detectable warning surface installed at a CTL crossing.

Figure 5-14 shows an example of a detectable warning surface installed at the base of the curb ramp at the crossing of a CTL toward the island. The detectable warning surface extends the full width of the ramp that is level with the street. Large bollards approximately 10 ft to 12 ft apart are visible along the curb line near the crosswalk.

It is critical that detectable warning surfaces be used to define the boundary between the pedestrian and vehicular ways at raised crosswalks, which create a blended transition area, or raised crosswalks are likely to result in blind pedestrians being within the vehicular way without being aware of it or taking appropriate steps to determine a safe crossing time. Detectable warnings are required at curb ramps by the Department of Transportation's ADA Standards and by PROWAG-NPRM R208.1, "Curb ramps and blended transitions at pedestrian street crossings." A raised crosswalk results in a blended transition between the pedestrian and vehicular way.

Figure 5-15. Raised crosswalk at a CTL.

At the CTL in Figure 5-15, the crosswalk across the lane is level with the sidewalk and a detectable warning surface is installed across the area where the sidewalk is level with the street. There are chevrons on the upslope to alert drivers. Detectable warnings are present at the boundary between the pedestrian and vehicle way, but no landscaping is provided on either side of the crosswalk.

Some municipalities are adopting standardized treatments of their CTLs, including the City of Boulder, Colorado, which uses raised crosswalks at almost all of their CTLs to reduce vehicle speeds and enhance pedestrian safety.

5.2.6.3 Pushbutton Locator Tones may Provide a Cue for Locating the Crosswalk and for Maintaining Correct Heading while Crossing

The pushbutton locator tones that are a required feature in APS indicate the location of the pedestrian pushbutton. In addition, pushbutton locator tones may be used on other push-buttons, such as those for RRFBs. Pushbuttons, shown in Figure 5-16, should be located as close as possible to the crosswalk (see MUTCD, Section 4E.8); therefore, pedestrians who are blind can be guided to the approximate location of the crosswalk by pushbutton locator tones. In addition, most crossings at CTLs are one-lane wide, and it is likely that blind pedestrians will be able to hear the pushbutton locator tone from the device at the far end of the crosswalk as they cross, helping them to stay within the width of the crosswalk. Pushbuttons and APS or audible information devices should be located downstream of the crosswalk, so they are not in-between the pedestrian and the approaching traffic they are trying to listen for, and so they do not block the view of drivers that need to see the pedestrian waiting.

5.2.7 Other Traffic Control Devices and Pedestrian Treatments

The control options described in Chapter 5.2.1 are primarily intended for motor vehicle control. At some CTLs, control devices and treatments to assist and increase driver awareness of pedestrian crossings have been added. Control devices include flashing beacons, PHBs, and RRFBs, which were discussed earlier.

Figure 5-16. Pushbuttons with pushbutton locator tones assist with locating the crosswalk and maintaining correct heading while crossing.

In Figure 5-16 pushbuttons with pushbutton locator tones are visible at the side of the curb ramp at this entry lane roundabout crossing. In addition, there is a pushbutton with a pushbutton locator tone on the splitter island. Detectable warnings are visible at the base of each curb ramp.

Additionally, the following treatments have been used to enhance accessibility at CTL crosswalks:

- Sound strips (road surface treatments similar to rumble strips), specifically for blind pedestrians, and
- Raised crosswalks or other vertical deflection to slow vehicles.

However, some municipalities are adopting standardized treatments of their CTLs, including the City of Boulder, Colorado, which uses raised crosswalks at almost all of their CTLs to reduce vehicle speeds and enhance pedestrian safety.

Sound strips across deceleration lanes have been tested at CTLs to provide additional auditory information to pedestrians who are blind (Figure 5-17). The sound strips may enable pedestrians who are blind to auditorily distinguish turning traffic from through traffic when a deceleration lane is present, as well as allow some inferences about vehicle speed (shorter intervals between sounds indicate faster speeds). Sound strips may further assist in the identification of yield events, as a slowing vehicle generates different sound patterns from a vehicle traveling at constant speed. In NCHRP Project 03-78A and 03-78B, different rumble strip materials were used for sound strips at CTLs. In order to be effective, the sound treatment must be placed far enough to give audible cues in time for the pedestrian to make a decision. Strips were installed across the CTL deceleration lane at 30-ft intervals beginning 150 ft before the crosswalk (distance determined by the speed of approaching vehicles). However, for both materials, sound was not generated if vehicles were traveling very slowly over the strips. This inconsistency in cues led to confusion for blind participants in the research. While this might be a feasible solution, more research is needed to determine appropriate materials and installation to provide consistent sound cues in the noisy intersection environment.

Treatments that provide vertical deflection, such as raised crosswalks and speed humps, may improve the likelihood of drivers yielding to pedestrians. Design considerations for raised crosswalks specific to CTLs have not been developed. It is believed to be possible to combine either

Figure 5-17. Sound strips installed at a CTL.

Figure 5-17 shows sound strips installed across the deceleration lane approaching an intersection. Three strips are visible as low foot-wide bars across the deceleration lane in this photograph. The crosswalk is just out of view as the lane curves.

Figure 5-18. Raised crosswalk at a CTL.

At this large 4-way signalized intersection in Boulder, Colorado (Figure 5-18), a CTL has a raised crosswalk. It is marked with chevrons that are visible on the up-slope. There is no landscaping or barrier between the wide sidewalk and the curb line that can help pedestrians with visual impairments find the crosswalk. However, there are large bollards at each side of the crosswalk that blind pedestrians who are familiar with this crossing might be able to use to identify the location of the crosswalk.

the PHB or the RRFB with a raised crosswalk. Care is needed in ensuring an appropriate set of signs and pavement markings to accompany the combined treatments.

Raised crosswalks or speed humps force drivers to slow down (Figure 5-18). Lower speeds have also been linked to increased yielding behavior (Geruschat and Hassan, 2005; Scroeder et al., 2015).

Like roundabouts, the curvilinear nature of CTLs makes it substantially more difficult for a blind pedestrian to locate the appropriate crossing location and to maintain the correct heading through the crosswalk.

CHAPTER 6

Wayfinding Assessment

This chapter provides a methodology for assessing wayfinding and alignment challenges for pedestrians who are blind. The most important underlying principle in the design of pedestrian crosswalks is that the design should be intuitive for its users. Many pedestrians who are blind or who have low vision have received orientation and mobility instruction and training for independent travel, but their training may not have covered roundabouts and intersections with CTLs, particularly if they received the training several years ago. Furthermore, pedestrians likely did not receive training at the specific location they may be trying to cross. An intuitive design of the crosswalk therefore is critical to make sure that pedestrians understand the purpose of the crosswalk and the rules governing the interaction between pedestrians and drivers.

As discussed in Chapter 3, pedestrians who are blind or who have low vision may not be aware of the presence of a roundabout where two roads intersect or of a CTL at the intersection. If the design and wayfinding features of the sidewalk do not guide them to the correct crossing location, or provide cues to the proper crosswalk heading, they may cross at a location where crossing is not intended, or veer out of the crosswalk and possibly along the vehicular travel lanes or into the roundabout circulatory roadway. It's important to evaluate each crossing from each approach direction in light of the three wayfinding tasks outlined in Chapter 3, determining the crossing location (or locating the crossing), aligning to cross, and maintaining correct heading while crossing.

6.1 Determining the Appropriate Crossing Location

The first task of the pedestrian is to determine the appropriate crossing location or to locate the crosswalk. Sidewalks, curb ramps, and other features should guide pedestrians to the point where the designer wants them to cross the roadway and to discourage or prevent pedestrians from crossing at other locations. This should also be considered in the design of islands.

As shown in Figures 6-1 and 6-2, the zone discussed is on the approach to the roundabout or CTL as pedestrians walk toward the crossing location from either direction, including crossing from islands to the sidewalk.

In evaluating wayfinding features for determining the crossing location, six basic questions should be considered by designers, as presented in Table 6-1. Each question is discussed further with additional details and graphics provided in Chapters 4 and 5.

6.1.1 Do the Sidewalks Lead to the Crosswalks?

Sidewalks should lead to the crosswalks, particularly in designs where the sidewalks are not beside the roadway. On islands, the walkway should be defined to give clear guidance to all pedestrians about the appropriate crossing location (see Chapter 6.4).

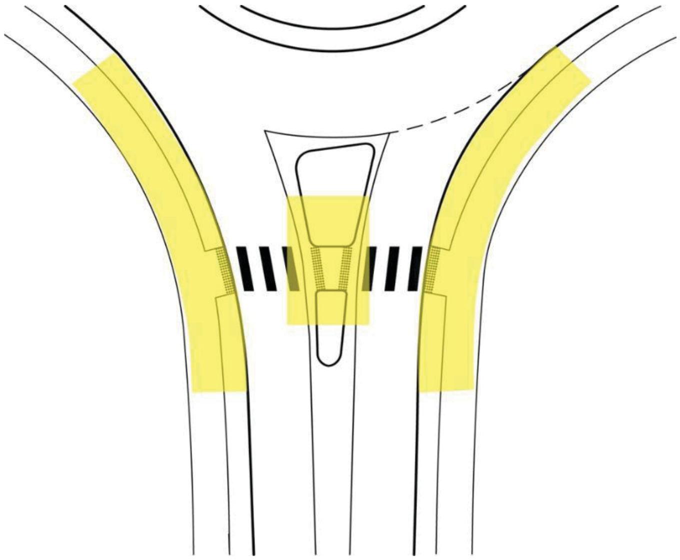


Figure 6-1. Illustration of zone to determine the crossing location at roundabouts.

Figure 6-1 shows a drawing of a single-lane roundabout. Yellow shaded zones are seen on the sidewalk approaching the crosswalk on both entry and exit sides, denoting the region where wayfinding features to assist in determining the crossing location should be considered. Yellow shaded zones are also seen on the splitter island.

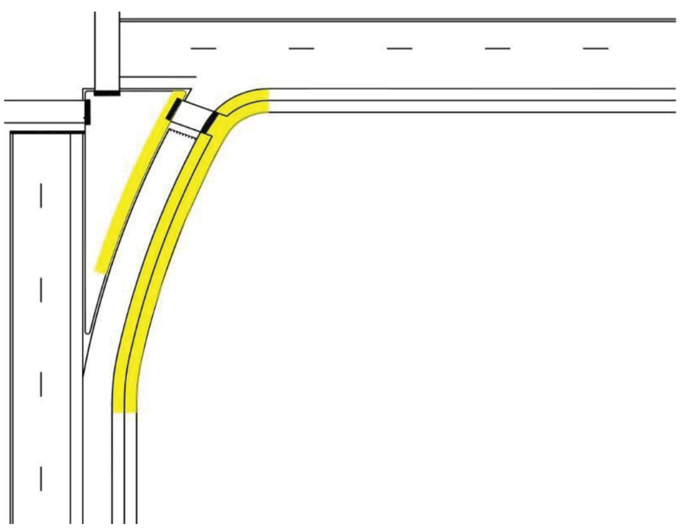


Figure 6-2. Illustration of zone to determine the crossing location at CTLs.

Figure 6-2 shows a drawing of a CTL. Yellow shaded zones are seen on the sidewalk approaching the crosswalk on both curb and island sides, denoting the region where wayfinding features to assist in determining the crossing location should be considered.

Table 6-1. Considerations for determining the crossing location.

Question	Notes
1. Do the sidewalks lead to the crosswalks?	See Chapters 4.1 and 5.1 for details.
2. Is separation provided between the sidewalk and the curb?	See Chapters 4.1 and 5.1 for details. This is required by PROWAG-NPRM at round-abouts and is considered a good practice at CTLs.
3. Is the edge of the street clearly defined by detectable warning surfaces?	See Chapters 4.1 and 5.1 for details. This is required by the Department of Transportation's ADA regulations and PROWAG-NPRM.
4. Are there other features that could be mistaken for curb ramps?	See Chapters 4.1 and 5.1 for details.
5. Are traffic control devices accessible?	See Chapters 4.2 and 5.2 for details. This is required by PROWAG-NPRM. The specifications are in MUTCD 4.E.
6. Are other treatments needed or desired to assist with locating the crosswalk?	See Chapters 4.2 and 5.2 for details.

6.1.2 Is Separation Provided Between the Sidewalk and the Curb (required by PROWAG-NPRM)?

Sidewalks should be separated from the curbs by a landscape strip, except at the crosswalks. A landscape strip at least 2 ft wide should be provided between the sidewalk and the curb on each side of the curb ramp, and should be a surface that is detectable under foot, such as grass, gravel, pebbles, or small shrubs. Bricks, cobblestone-type pavers, or colored paved surfaces do not provide sufficient cue to prevent blind pedestrians from crossing into the circulatory roadway. This should be provided on the approach to the crosswalk from either direction (see Figure 6-1).

If there is insufficient right-of-way to provide a landscape strip as described above, fencing or bollards and chain should be provided on either side of the crosswalk to prevent crossing into the circulatory roadway. PROWAG-NPRM requires a lower edge or chain that is not more than 15 in. above the walking surface; a higher chain or fence may be needed to avoid tripping by sighted pedestrians. If bollards are used, they must be connected by chains or other material to prevent pedestrians from walking between them.

6.1.3 Is the Edge of the Street Clearly Defined (required by the Department of Transportation's ADA Regulations and PROWAG-NPRM)?

A detectable warning surface (truncated domes) should be provided for the width of the ramp or for the area that is level with the street. The surface must be a minimum of 2 ft deep in the direction of pedestrian travel covering the entire area that is level with the street so that a pedestrian does not easily step over or around the surface. When a raised crosswalk is installed that brings the crosswalk up to sidewalk level, the detectable warning surface is the only indication of the street or sidewalk boundary to a blind pedestrian.

6.1.4 Are There Other Features that Could be Mistaken for Curb Ramps?

If bike ramps are planned, they must be carefully designed to avoid misleading pedestrians. The ramp should be angled at a more than 45-degree angle toward the roadway rather than parallel to the sidewalk. Detectable warning surfaces should be installed at the top of the ramp and at the junction with the sidewalk and aligned with the edge of the sidewalk to alert blind pedestrians of the presence of the ramp.

6.1.5 Are Traffic Control Devices Accessible (required by PROWAG-NPRM and specifications in MUTCD 4.E)?

If a pedestrian signal is present, an APS with an appropriate audible pushbutton locator tone has to be provided. Pedestrians need to be able to locate and use a pedestrian pushbutton without having to deviate far from the path of travel or the crosswalk. Audible indications, including a pushbutton locator tone to assist blind pedestrians in locating a pushbutton, should be provided even on devices such as RRFBs, which do not provide a walk indication. The sound of the pushbutton locator tone can also provide information about the location of the crosswalk.

6.1.6 Are Other Treatments Needed or Desired to Assist with Locating the Crosswalk?

Bar tiles or guidance tiles are used in other countries to notify pedestrians of the location of the crosswalk at roundabouts and CTLs. These types of surfaces provide information about the crosswalk location to pedestrians who use dog guides or long canes but are not trailing the edge of the sidewalk with their canes. Pilot research suggested that bar tiles may work well to address concerns of wheelchair users while helping pedestrians who are blind locate crosswalks and align to cross.

6.2 Aligning to Cross and Establishing the Correct Heading

Aligning to cross is the necessary task after finding the crosswalk. The technique most commonly used by blind pedestrians at a typical intersection is aligning with traffic traveling parallel to the crosswalk. At roundabouts and CTLs this technique is generally not available since there is no parallel traffic. Blind pedestrians must use a combination of sidewalk and curb ramp features and the movement of traffic (perpendicular to their path) as primary cues to the direction of travel on the crosswalk. A mistake in alignment may put pedestrians who are blind outside the crosswalk area, or headed toward the circulatory roadway, and could be a dangerous, as well as confusing, mistake. Figure 6-3 shows the areas where this task takes place and where the designer needs to focus in considering alignment cues.

In evaluating wayfinding features for the task of aligning to cross and for establishing the correct heading, six basic questions should be considered by designers, as presented in Table 6-2. Each question is discussed further, with additional details provided in Chapters 4 and 5.

6.2.1 Is the Curb Ramp Width the Same as the Crosswalk Width?

The width of the curb ramp and the sidewalk leading to the crosswalk should be the same width as the crosswalk. If the sidewalk on either end of the crosswalk is wider than the crosswalk, pedestrians who are blind may cross outside the crosswalk area. If the ramp or cut-through area is narrower than the crosswalk, the curb can be a tripping hazard and can cause confusion as pedestrians who are blind may think that they have veered outside the crosswalk when they have not. Detectable warning surfaces must also be the full width of the area that is level with the street, so it also must be the full width of the crosswalk.

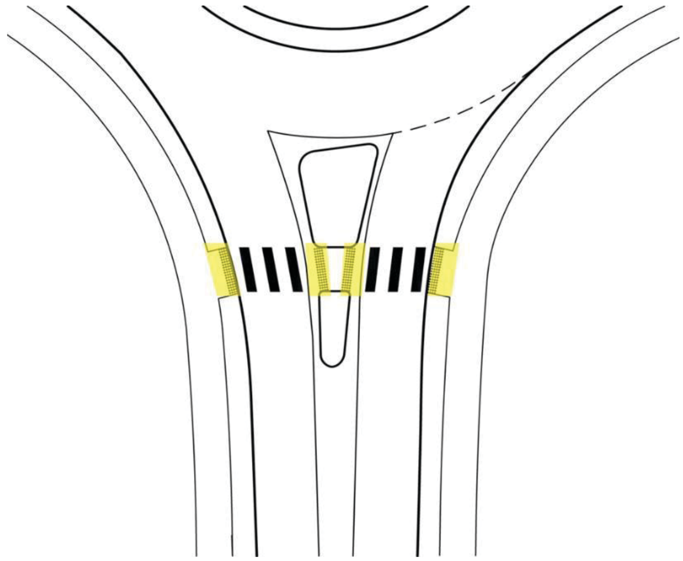


Figure 6-3. Illustration of zone for aligning to cross at roundabouts.

Figure 6-3 shows a drawing of a single-lane roundabout. Yellow shaded zones are seen on the crosswalk landing on both entry and exit sides, as well as on the curb and island. The shaded areas denote the regions where wayfinding features to assist in aligning to cross should be considered.

6.2.2 Are the Curb Ramp Slopes Aligned with the Crossing?

All curb ramps should be oriented so that the running slope is in the same direction as the direction of travel on the crosswalk. The slope of the ramp can influence the direction of travel of blind pedestrians on the crosswalk, so it should align with the direction of the crosswalk. The greater the slope, the more potential influence there is. In addition, it can be difficult for wheelchair users to make a turn at the base of the curb ramp and stay within the crosswalk; at best, it slows them and distracts them as they enter the street.

Curb ramps and crosswalks should further be aligned perpendicular to the curb, gutter, and the travel lanes. To prevent tipping problems for wheelchair users, it is essential that the base

Table 6-2. Considerations for aligning to cross and establishing a correct heading.

Question	Notes
1. Is the curb ramp width the same as the crosswalk width?	See Chapters 4.1 and 5.1 for details.
2. Are the curb ramp slopes aligned with the crossing?	See Chapters 4.1 and 5.1 for details.
3. Are the ramp edges aligned with the crossing?	See Chapters 4.1 and 5.1 for details.
4. Is the detectable warning surface aligned with the slope of the curb ramp?	See Chapters 4.1 and 5.1 for details. This is required by PROWAG-NPRM.
5. Are the push buttons in correct locations?	See Chapters 4.2 and 5.2 for details.
6. Is there a need for additional treatments?	See Chapters 4.2 and 5.2 for details.

of the ramp be square to the gutter or grade break at the base of the ramp. Pedestrians who are blind also tend to use the gutter and curb line as an alignment cue and will often travel across the roadway on a path that is perpendicular to the curb line.

On islands, both at roundabouts and CTLs, when the island is not a cut-through, the curb ramp slope can provide help with the detection of the crossing location and with the alignment for the crossing. See Chapter 6.4 for a detailed discussion.

6.2.3 Are the Ramp Edges Aligned with the Crossing?

Returned edges on the curb ramp should be aligned with the direction of the crosswalk. If there are returned edges on the curb ramps, they may serve as a cue to blind pedestrians and should be in line with the crosswalk. Returned curbs should not be used in locations without landscaping or other features where they may be a tripping hazard to pedestrians walking across the ramp area.

Flares (sloped areas beside the ramp) are not needed if there is landscaping beside the ramp. The ramp should be the width of the entire crosswalk, and the flares, if needed, can be outside the crosswalk area.

6.2.4 Is the Detectable Warning Surface Aligned with the Slope of the Curb Ramp (required by PROWAG-NPRM)?

The domes of the detectable warning surface should be aligned with the slope of the ramp (required by PROWAG-NPRM). This is to make it easier for wheelchair users to travel between the domes on the slope of the ramp. The alignment of the detectable warning surface is not intended to be a cue for the direction of travel on the crosswalk, but some pedestrians who are blind will try to align with it, nonetheless. It is not possible for most people who are blind to accurately align themselves with the truncated dome surface. Nonetheless, aligning the detectable warning surface edges, the curb/gutter, and the ramp slope with the direction of travel on the crosswalk can provide consistency that can lead to better alignment.

6.2.5 Are the Pushbuttons in Correct Locations?

When a pedestrian pushbutton is used, either with a pedestrian signal, a PHB, or an RRFB, it should be next to the crossing and beside a level area to allow access for wheelchair users. Most pushbutton devices include a tactile arrow that must be aligned with the direction of travel on the crosswalk. That arrow must be located within 5 ft of the crosswalk line and should be no further than 6 ft from the curb, if possible. Audible devices, either APS or audible information devices, provide a pushbutton locator tone and that tone may be audible across a short crossing and may help with alignment and maintaining the correct heading when crossing. The pushbutton locator tone is supposed to be audible no more than 12 ft from the pushbutton, so it may not provide alignment help on longer crossings.

6.2.6 Is There a Need for Additional Treatments?

For approaches that do not meet the above criteria, additional treatments may be needed to assure that a blind pedestrian is able to correctly align with the crossing. A tactile bar tile–type surface perpendicular to the direction of travel on the crosswalk was found in pilot research to lead to better initial alignment. There is a need for more research on the appropriate placement of such surfaces and the potential effect on wheelchair users.

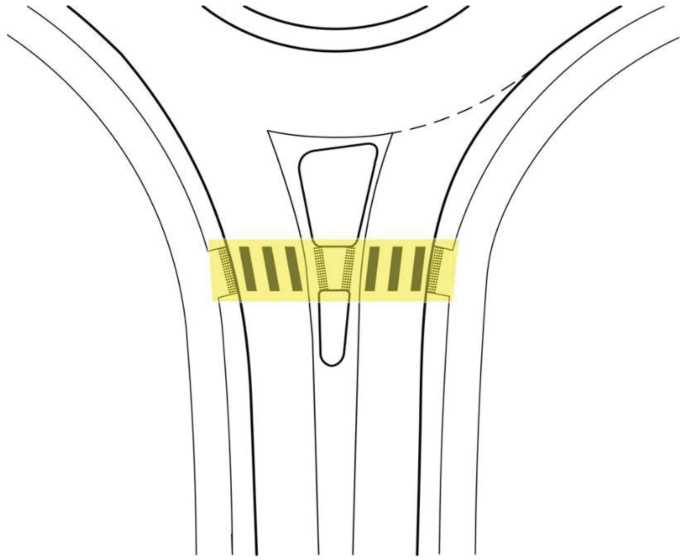


Figure 6-4. Illustration of zone for maintaining the correct heading at roundabouts.

Figure 6-4 shows a drawing of a single-lane roundabout. A yellow shaded zone is shown across the entire crosswalk for both entry and exit sides, denoting the region where wayfinding features to assist in maintaining the correct heading should be considered.

6.3 Maintaining the Correct Heading While Crossing

Staying within the crosswalk area while crossing can be critical to safety, driver expectation, and orientation. Critical zones for this task are the area of the crosswalk within the street as shown in the Figure 6-4.

In evaluating wayfinding features for the task of maintaining the correct heading while crossing and staying within the crosswalk, four basic questions should be considered by designers, as presented in Table 6-3. Each question is discussed further, with additional details provided in Chapters 4 and 5.

Table 6-3. Considerations for maintaining the correct heading while crossing and staying within the crosswalk.

Question	Notes
1. Is the crossing configured at the shortest distance practical?	See Chapters 4.1 and 5.1 for details.
2.Is the crossing aligned perpendicular to the curb and splitter edges?	See Chapters 4.1 and 5.1 for details.
3. Are markings clearly visible?	See Chapters 4.1 and 5.1 for details.
4. Is there need for additional treatments?	See Chapters 4.2 and 5.2 for details. Required by PROWAG-NPRM.

6.3.1 Is the Crossing Configured at the Shortest Distance Practical?

The shorter the crossing, the less exposure and less opportunity there is for the pedestrian to veer outside the crosswalk area.

6.3.2 Is the Crossing Aligned Perpendicular to the Curb and Splitter Edges?

Good initial alignment makes it more likely that blind pedestrians will complete their crossing within the crosswalk. As noted in the alignment discussion, the crossing and the crosswalk need to be aligned with the edge of the street.

6.3.3 Are Markings Clearly Visible?

For low-vision pedestrians, crosswalk markings provide critical information to assist them in staying within the crosswalk. Ladder markings with both longitudinal and transverse lines are preferred by individuals with low vision.

6.3.4 Is There a Need for Additional Treatments?

For approaches that do not meet the above criteria, additional treatments may be needed to assure that a blind pedestrian is able to maintain correct heading during crossing. Raised crosswalks provide additional cues to assist blind pedestrians in staying within the crosswalk if they recognize the slope on the edges of the crosswalk. Detection is dependent on the steepness of that slope but slight changes in cross slopes are detectable by many pedestrians who are blind. As a pedestrian is crossing, the pushbutton locator tone of an APS or audible information device may provide a cue to the end of the crosswalk and heading direction.

Tactile guide strips are used in some countries and have been experimented with in the United States to provide guidance, particularly if the crossing is more than two lanes.

6.4 Crossings from Channelization and Splitter Islands

The second half of the crossing from triangular islands at CTLs or splitter islands of roundabouts can be problematic if the island does not provide crossing and alignment cues as noted above. Additional principles also need to be considered for the island environment. Figures 6-5 and 6-6 show the channelization island zone for a roundabout and a CTL, respectively.

In general, the same wayfinding features that were discussed in the previous sections also apply to channelization islands. In addition, the following four questions should be considered by designers, as presented in Table 6-4. Each question is discussed further, with additional details provided in Chapters 4 and 5.

6.4.1 Are Islands Wide Enough to Provide Safe Refuge?

The minimum width of an island (length in direction of pedestrian travel) should be 6 ft. The minimum width of cut-through areas should also be 6 ft (or the same width as the crosswalk if the crosswalk is wider than 6 ft). For areas with heavier pedestrian traffic (greenways, shared use paths, etc.), consider larger islands to provide adequate storage.

6.4.2 Are Transitions to the Roadway Clearly Defined?

Detectable warning surfaces that denote street/sidewalk boundaries are needed on all edges of the islands where it is level with the street. All islands should be raised to clearly separate them

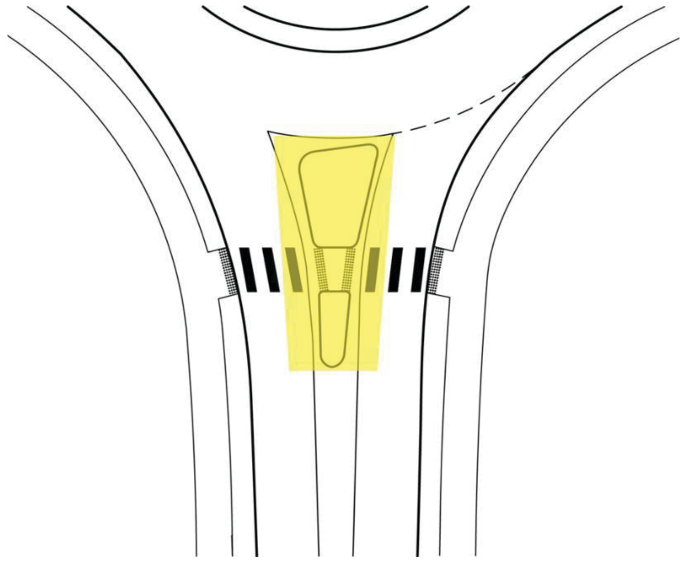


Figure 6-5. Illustration of zone for island crossings at a roundabout.

Figure 6-5 shows a drawing of a single-lane roundabout. A yellow shaded zone is shown covering the island, denoting the region where wayfinding features to assist in navigating the splitter island should be considered.

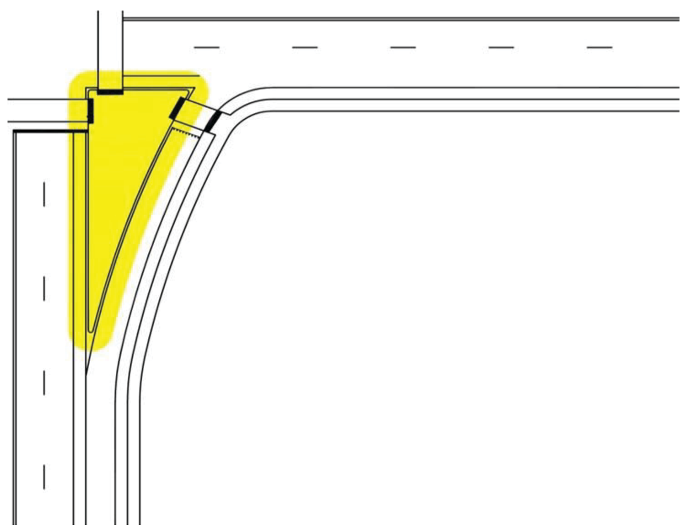


Figure 6-6. Illustration of zone for island crossings at a channelized turn lane.

Figure 6-6 shows a drawing of an intersection with a channelized right turn lane. A yellow shaded zone is shown covering the island, denoting the region where wayfinding features to assist in navigating the splitter island should be considered.

Table 6-4. Considerations for crossings from channelization and splitter islands.

Question	Notes
1. Are the islands wide enough to provide safe refuge?	See Chapters 4.1 and 5.1 for details.
2. Are transitions to the roadway clearly defined?	See Chapters 4.1 and 5.1 for details.
3. Are paths through the islands clearly defined?	See Chapters 4.1 and 5.1 for details.
4. Are pushbuttons accessible?	See Chapters 4.2 and 5.2 for details.

from the vehicular right-of-way. Painted islands are inaccessible (not detectable) to blind users and should not be used. The island size should be large enough to be visible to approaching drivers, and as required by AASHTO.

6.4.3 Are Paths Through the Island Clearly Identifiable?

To define the path through the island and prevent disorientation, if a blind pedestrian veers from the crosswalk on approach to the island, it is most desirable to have landscaping outside of the walkway that is detectable under foot such as gravel, grass, or shrubs. Detectable landscaping clearly directs pedestrians to stay on the planned path through the island rather than take a different path or shortcut. Completely paved islands, even with rough pavers or bricks, can result in confusion and disorientation for pedestrians who are blind.

If the island is cut-through, the approach to the curb line of the cut-through areas needs to be aligned with the direction of travel on the crosswalk. If the island is not cut-through, attention should be paid to the alignment of curb ramps, detectable warnings, and gutters to provide alignment cues.

6.4.4 Are Pushbuttons Accessible?

There are somewhat different location needs for APS at signalized intersection than there are for audible information devices at unsignalized crosswalks. MUTCD 4E.08 requires pushbuttons and APS to be installed within 5 ft of the crosswalk line furthest from the center of the intersection. There are no specific requirements in MUTCD for audible information devices, such as those installed at RRFBs. However, it is desirable for the device to be close to the crosswalk and to be downstream from the crosswalk to avoid having the device sounds between blind pedestrians and the vehicles they need to hear. In addition, devices also must be separated by at least 10 ft to allow pedestrians to distinguish which one is sounding. On small islands, that can be challenging to design and may require additional stub poles.

Pushbutton information messages, a type of speech message provided when the pushbutton is held for more than one second, can be configured to provide street name information. This could be a very helpful orientation aid on islands at CTLs to differentiate the main street crossings.

CHAPTER 7

Crossing Assessment

7.1 Assessment of Pedestrians Crossing at Roundabouts and Channelized Turn Lanes

This chapter provides a method for the assessment of a pedestrian crossing at a roundabout or intersection with CTLs. The method is divided into thirteen principal steps geared at quantifying the performance of a given site. The method is based on input variables available to the analyst, including site geometry, traffic volumes, and other factors. These inputs are used to estimate operational characteristics, including vehicle speed, driver yielding, gap availability, and utilization rates of crossable yields and gaps.

These operational characteristics feed into three performance checks that are integrated into the overall design processes for roundabouts and CTLs discussed in Chapter 2. These new performance checks for pedestrian accessibility are: (1) crossing sight distance, (2) pedestrian delay, and (3) level of risk.

Many of the models and interim steps used to predict these performance measures are sensitive to the effects of crossing treatments and can be used to predict performance for new and existing sites.

This chapter provides the overall methodology used for crossing assessment, while details for the various models are given in *NCHRP Web-Only Document 222*.

7.1.1 Crossing Performance Checks

The crossing assessment method is geared at estimating three key performance checks, which jointly attempt to describe the accessibility of a site. These performance measures are (1) the crossing sight distance, (2) the estimated level of crossing delay, and (3) the expected level of risk for blind travelers. These measures are combined with other performance checks on wayfinding presented in Chapter 6 to allow for an overall accessibility evaluation of a site.

The first performance check, crossing sight distance, is a design parameter used to provide clear lines of sight between the driver and the pedestrian to provide appropriate reaction and braking time. A driver with adequate time to see the pedestrian can make adequate decisions about yielding. More generally, the driver has sufficient time to react should the pedestrian step into the roadway. For sighted pedestrians, adequate sight distance is directly linked to their ability to make gap acceptance decisions. But for blind pedestrians, having a clear line of sight is critically linked to the amount and quality of audible information that is available to make crossing decisions. Crossing sight distance is determined from the design of the roundabout and CTL, and is a function of the approaching vehicle speed, the crossing width, and the walking speed of pedestrians. In general, faster vehicle speed, longer crossings, and slower walking speed result in an increase in the crossing sight distance requirements.

The second performance check, pedestrian delay, is one commonly used by transportation analysts to evaluate the level and quality of service of pedestrian facilities for sighted pedestrians. In the context of this method, the delay is focused on the expected experience of a pedestrian who is blind. Crossing delay is a direct function of the availability of crossing opportunities in the form of crossable gaps and yields. With more crossing opportunities, delay is expected to decrease. Differences in delay between sighted and blind pedestrians may be associated with differences in the rate of utilization of the crossing opportunities. The utilization rates are in turn related to attributes of the vehicle stream, the auditory environment, and ultimately the individual making the decision. It is noted here that in many of the crossing trials performed in this and prior research, the experienced delay did not seem to be as important to blind participants as the level of risk. Accordingly, the relative weight of delay is conceptually less important than the weight of the risk score. Nonetheless, extraordinarily high delays are considered an impediment to accessibility, which is why the measure is included in this methodology. Extraordinary delays may also lead to acceptance of risky crossing opportunities.

The last performance check, level of risk, is arguably the most important performance measure for any crossing, as it estimates the likelihood of a poor crossing decision given attributes of the site. For the field studies that form the empirical basis of this research, risk was estimated through intervention events (participants being physically stopped from stepping into the roadway by a certified orientation and mobility specialist), through expert ratings of crossing risk, and through measurements of time-to-contact—a measure of time between a pedestrian decision and the next vehicle arrival. All three metrics are surrogate safety measures, as no actual crash data are available for this analysis. However, all three metrics are documented in the literature as valid measurements of pedestrian risk and have been previously used in accessibility assessment studies.

Together, the three performance checks (as well as the various operational characteristics used as inputs in their calculation) are intended to provide a multifaceted look at the expected crossing performance of the studied crosswalk. As with any performance measure, their usefulness is limited by their ability to be measured objectively and predicted from available data.

7.1.2 Setting Performance Targets

The three performance checks are intended to enable a quantitative assessment of the accessibility of a crosswalk at a roundabout or a CTL at an intersection. Through the quantitative nature of the performance checks, it is generally possible to (1) conduct a relative comparison of two sites or (2) conduct a before-and-after assessment of the same site. Regardless of the type of assessment, the performance targets should yield evidence as to which site or treatment results in better relative accessibility performance.

It is much more challenging to use these checks to conduct an absolute assessment of accessibility. In other words, once a crossing assessment has been completed, and once estimates for risk, delay, and confidence score performance measures have been obtained, can a given site be classified as being "accessible"?

The question of whether a performance level is acceptable is ultimately a policy decision by the appropriate agency. As an example, for general pedestrian delay, the *Highway Capacity Manual 2010* (TRB, 2010) provides a letter-grade assessment of the Levels of Service (LOS) of a pedestrian crossing based on the estimated average pedestrian delay. Pedestrian delay at two-way stop-controlled intersections less than 5 seconds per pedestrian is considered LOS A, while a delay greater than 45 seconds is considered LOS F. For signalized intersections, LOS thresholds are based on a user-perception score, which incorporates delay as one of several factors. However, even with the letter-grade LOS being determined by the *Highway Capacity Manual 2010* methodologies,

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the decision of what LOS is acceptable is an agency decision. In other words, the performance target for pedestrian LOS is an agency policy decision.

In the context of this research, the performance target for accessibility also lies with the appropriate implementing agency or agencies. The performance checks and prediction tools presented in this document are intended to support these policy decisions through quantitative metrics, but as a research publication, this document does not set the standard. Minimum standards for accessibility, as a civil rights issue in the United States, are set by the U.S. Access Board and adopted by other agencies.

7.1.3 Limitations of the Methodology

It is important to emphasize the limitations of the crossing assessment method and the performance checks presented in this chapter. The predictive models and performance estimation methods are based on a limited number of study sites that are believed to be representative, but nonetheless describe only a small subset of all roundabouts and CTLs that exist around the country. Further, all field studies showed high variability of performance across participants.

The field-measured performance is thus only a snapshot of the true complexity of pedestrian decision-making, especially for pedestrians who are blind. The methods put forth in this chapter are intended to provide an approximation of the expected performance to aid engineers and planners in evaluating design alternatives and assist in the selection of crossing treatments to enhance the accessibility of a given or proposed site.

The limitations of the methodology are primarily due to two factors: (1) variability in the geometry, signing, marking, and other features of roundabouts and CTLs chosen for the study and (2) high variability of performance across participants.

Variability in the geometry of studied sites may affect the range of observed vehicle speed, conflicting traffic volume, and local and regional differences of driver behavior. These site attributes may, in turn, affect yielding rate and gap availability, which are key inputs in the performance estimation. Variability in participant behavior and skill level may, in turn, affect yield and gap utilization rate, which are also critically linked to the performance measures.

The analyst is encouraged to check for these limitations by comparing local data to the field measurements presented in this research, and details published in *NCHRP Web-Only Document 222*. For example, results from a region with general high driver yield compliance and frequent pedestrian activity are likely not transferable to areas with low compliance and low expectancy of a driver encountering a pedestrian and vice versa.

7.1.4 Value of Direct Field Measurements

The procedures and models presented in this chapter present a way to estimate the expected accessibility of a new intersection based on available geometric and traffic operational input variables. However, in some instances, an analyst may be interested in evaluating the accessibility of an existing site and in identifying treatments that may enhance the accessibility performance of such sites. For existing sites, direct field measurements of accessibility may represent a viable and preferred alternative to predicting performance.

The clear benefit of direct field measurements is that any bias and error from applying national models to a local site are avoided. In that sense, driver behavioral difference, driving culture, and local context are uniquely tied to the site in question; this can be a big advantage. Given local context, participants may be accustomed to crossing at single-lane roundabouts due to frequent use of this intersection form in the local area. Similarly, certain treatments may be very effective in an area, where such treatments are used routinely at other intersection forms. In short, locally observed accessibility performance data is likely to be more accurate and representative of the “true” accessibility of a site in question.

On the other hand, a field accessibility assessment is resource intensive, requires trained staff, and may involve the use of human subjects, which requires approval from an Institutional Review Board. As such, a full-scale accessibility audit may be out of scope for many sites in question. *NCHRP Web-Only Document 222* provides detailed field protocols for conducting this accessibility audit using the methods that also form the basis of this report.

As an alternative to a full accessibility audit, an agency may select a subset of studies, as permitted by the available resources, to calibrate for local context. For example, if a crossing indicator study with blind participants is not possible due to resource constraints or Institutional Review Board approval requirements, one or more of the input variables may be measured directly in the field. A field study of driver yielding behavior is generally very feasible and requires minimal resources. Similarly, a local study of gap availability is generally feasible. In some cases, a local gap study may even be desirable if conditions at adjacent intersections (such as an upstream signal) are expected to affect the gap availability distribution.

As general guidance, direct measurements of driver and pedestrian behavior under local operating conditions are expected to provide a better accessibility assessment than national-scale predictive models, provided that the local studies are executed by trained and qualified staff and follow the study protocols put forth in the final project report (or comparable).

7.2 Methodology

The crossing assessment methodology consists of thirteen principal steps that are evaluated sequentially. The methodology obtains key input and performance targets from the overall site design process described in Chapter 2. A key characteristic of the method is that it is iterative. Should a performance check fail to meet a specified performance target, it may require changes to the design and recalculation of the performance checks as described in Chapter 2. The methodology flow chart is shown in Figure 7-1 and discussed in detail in the following sections.

To use the crossing assessment methodology, initial site-related data need to be gathered. The data are entered into various models developed as part of crossing assessment and eventually the model results are used for final crossing assessment performance measures. A summary of the required input data and their application in each of the crossing models is shown in Table 7-1.

7.3 Methodological Steps

In this section, each of the steps shown in Figure 7-1 is described in more detail. For steps with significant computations, only the key equations are shown here, with additional information on model derivation provided in the *NCHRP Web-Only Document 222*. The methodology is applied to each approach of the roundabout, and separately to entry and exit legs, as well as to CTLs.

Before embarking on the steps, the analyst needs to obtain geometry inputs and performance targets. In the overall design process described in Chapter 2, the analyst defines the candidate design and crossing configuration of the roundabout or CTL to be evaluated for accessibility. The initial design should contain sufficient detail to specify the number of lanes, design radii, crosswalk location, and other geometric details. The initial design may be obtained from an engineering design project at approximately the 10% to 25% completion level. At this stage, the design is expected to provide sufficient geometric and operational details, while still allowing flexibility

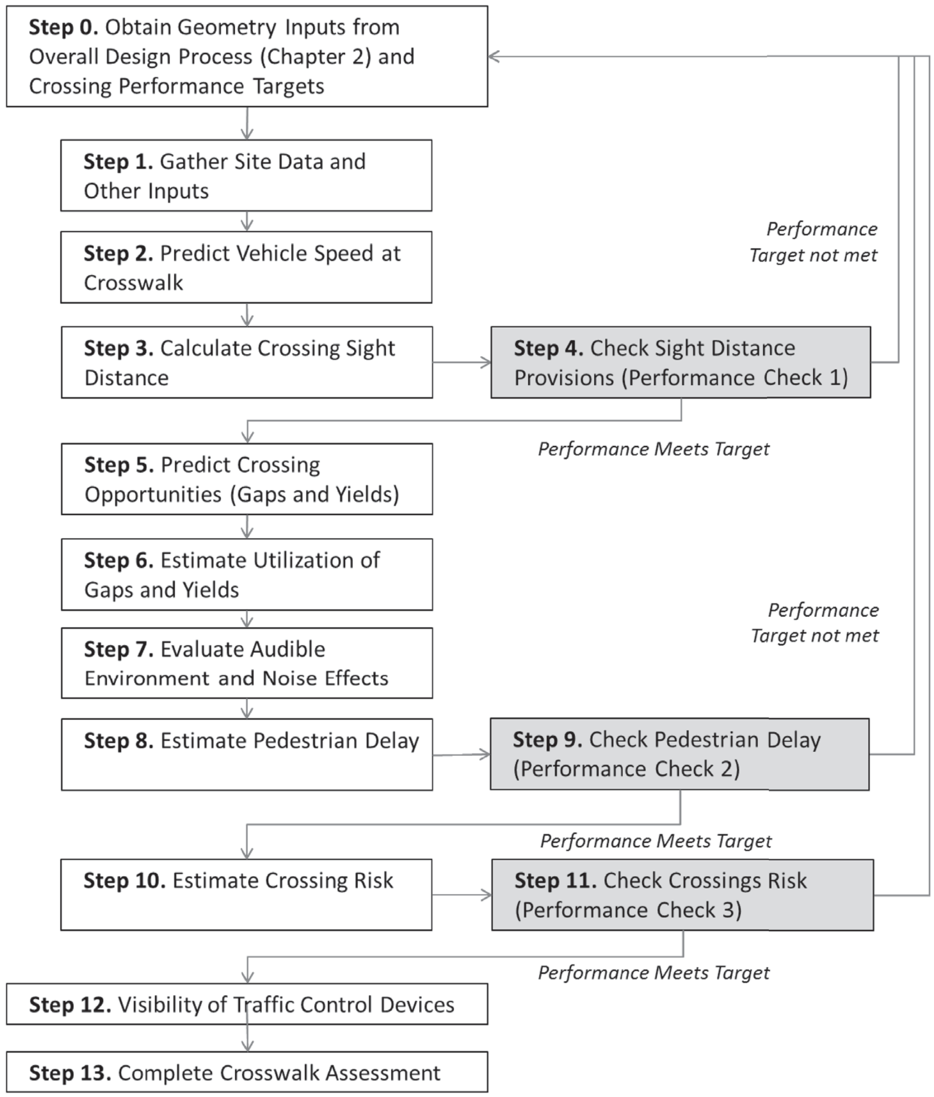

Figure 7-1. Methodology flow chart.

Figure 7-1 showing a thirteen-step methodology for assessing crossing performance. Step Zero obtains design data from the overall process described in Chapter 2, as well as performance targets set by the agency. The twelve principal steps of the methodology are as follows: (0) obtain geometry inputs, (1) gather site data and other inputs, (2) predict vehicle speed at crosswalk, (3) calculate crossing sight distance, (4) check sight distance provision, (5) predict crossing opportunities in the form of gaps and yields, (6) estimate utilization of gaps and yields, (7) evaluate audible environment and noise effects, (8) estimate pedestrian delay, (9) check pedestrian delay, (10) estimate crossing risk, (11) check crossing risk, (12) check visibility of traffic control devices, and (13) complete crosswalk assessment. The analysis sequence is linear, with potential for iteration after each of the three performance checks in steps 4, 9, and 11.

Table 7-1. Required inputs for the crossing assessment method.

Step	Equation/Table	Required User Input
Step 2. Predict speed at crosswalk	Equation 7-1 Table 7-2 and Table 7-3	Fastest path radius Treatment effect
Step 3. Calculate crossing sight distance	Equation 7-2 Equation 7-3	Vehicle speed at crosswalk (from Step 2) Approach geometry Pedestrian walking speed
Step 4. Check Sight Distance Provisions	Expert judgment	CAD drawing Crossing sight distance (from Step 3)
Step 5. Calculate crossing opportunity (gaps and yields)	Equation 7-4 Equation 7-5 Equation 7-6 Equation 7-7	Approach geometry and treatment, Gap acceptance parameters Pedestrian walking speed Traffic volume on approach Vehicle speed at crosswalk (from Step 2)
Step 6. Estimate utilization of gaps and yields	Table 7-4 Table 7-5	Approach geometry
Step 7. Evaluate audible environment and noise effect	Expert judgment Appendix A	Local observation Surrounding lane uses
Steps 8 and 9. Estimate pedestrian delay	Equation 7-9 through Equation 7-11	Gap and yield opportunities (from Step 5) Gap and yield utilization (from Step 6)
Steps 10 and 11. Estimate crossing risk	Equation 7-12	Vehicle speed at crosswalk (from Step 2) Noise (from Step 7) Sight distance (from Step 4)

for design adjustments and treatment provision as needed. Key design elements needed for the crossing assessment include the number of lanes, lane widths, crosswalk location, treatment details, and design radii for the intersection itself. The initial design should also be sensitive to other performance elements that are specified in various guidelines or standards (e.g., design vehicle). The initial design may or may not include specialized treatments intended to enhance the accessibility of the site.

Before starting with the principal procedure, the analyst reviews and notes performance targets for the three accessibility performance checks based on agency guidelines or standards. Pedestrian accessibility performance objectives based on federal guidelines and previously conducted studies can serve as target values, but the specification of target standards is the responsibility of the agency conducting the assessment. This report intends to provide the quantitative assessment methodology to estimate the performance measures needed in those standards.

7.3.1 Step 1. Gather Site Data and Other Inputs

The analyst gathers engineering inputs or selects default conditions specified by the methodology. These inputs include traffic conditions and roadway factors, as well as geometric details of the roundabout or CTL in question. The overall design of the roundabout or CTL in question was transferred to the crossing assessment in step 0. In this step, design details necessary for the crossing assessment are extracted, along with other traffic operational factors. See Table 7-1 for a listing of required input data.

7.3.2 Step 2. Predict Vehicle Speed at Crosswalk

Vehicular speed has been identified as a key measure affecting pedestrian accessibility. This step predicts the free-flow speeds under low volume conditions that can be expected in the vicinity of the crosswalk. The analyst may obtain speed estimates through field measurements at comparable sites, or use the speed prediction equations presented below.

Speed prediction is required for computing other aspects of accessibility such as calculating the required crossing sight distance and driver yielding rate at the crosswalk, and predicting the rate of intervention and risk events.

The model for predicting the speed of the crosswalk is the theoretical fastest path speed method described in *NCHRP Report 672* for roundabouts. It was found to also apply to vehicle free-flow speeds through CTLs.

The vehicle speed model in Equation 7-1 estimates the free-flow speed at the crosswalk, FFS, as a function of the fastest path radius, R, for a curve with positive superelevation e = +0.02 (drainage toward the outside, which is most common).

Equation 7-1. Fastest path radius calculation for vehicle speed.

$$FFS = 3.4415\, R^{0.3861}, \quad \text{for } e = +0.02$$

The equation predicts the 85th percentile free-flow speed expected at the crosswalk as a function of fastest path radius (in feet) that is believed to control the speed at the crosswalk. For roundabout entries, this speed is generally calculated using the entry path radius, R_1. For roundabout exits, a composite equivalent radius may be used to estimate the speed under consideration of both the radii in the circle and on the exit itself.

At a roundabout entry, this speed is principally a function of the R_1 radius shown in Figure 7-2. For exiting vehicles, the analyst can estimate an equivalent composite radius from the terms R_2, R_4, and R_5 depending on whether the conflicting movement is a right-turning vehicle from the immediate upstream entry, or a through, or left-turning vehicle from another entry. Since vehicles

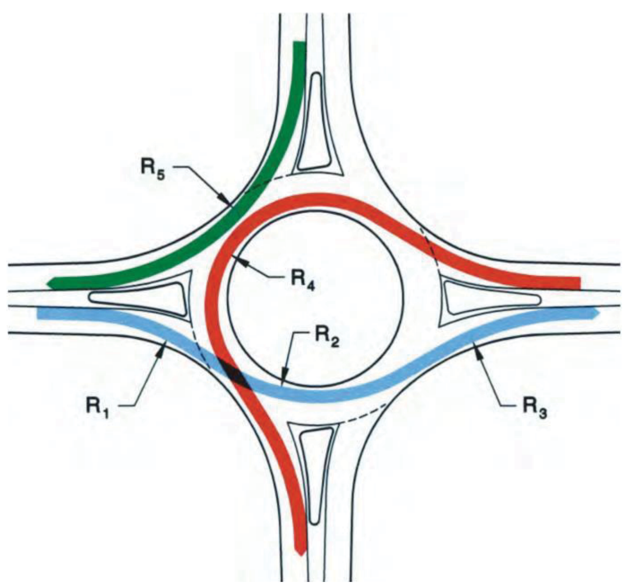

Figure 7-2. Roundabout vehicle path radii (Source:* NCHRP Report 672*).

Table 7-2. Equivalent composite radius for speed estimation.

Approach	Vehicle Movement	Equivalent Composite Radius
RBT Entry	Right, through, and left	R_1
RBT Exit	Right	R_5 with acceleration constraint
RBT Exit	Through	R_2 with acceleration constraint
RBT Exit	Left	R_4 with acceleration constraint
CTL	Right	R_1 equivalent at CTL

have an opportunity to accelerate leaving the roundabout, their actual speeds at the crosswalk are expected to be higher than those predicted by the respective controlling radii. As such, the speed is estimated at the fastest path radii, adjusted by the acceleration of vehicles as described in *NCHRP Report 672*.

For CTLs, the equivalent of the R_1 radius is used to estimate the speed. The equivalent radius computations are summarized in Table 7-2.

The free-flow speed at the crosswalk can also be impacted by certain treatments that are installed specifically with the goal of reducing vehicle speeds. Several sites were evaluated in prior research with various forms of raised crosswalks or speed tables installed to slow traffic, and some sites even had speed humps in advance of the crosswalk with a similar goal. The *Traffic Control Devices Handbook* provides some guidance for estimating the speed-reducing effects of traffic-calming measure as shown in Table 7-3 (Seyfried, 2013).

Specific design attributes of the traffic-calming measure (e.g., height of the speed hump or speed table, transition slope) are not reflected in the *Traffic Control Devices Handbook* guidance. Further, the *Traffic Control Devices Handbook* data refer to standard intersections, and do not consider the speed-reducing impacts of roundabout or CTL geometry. As such, it is advisable to use the average reduction or percentage reduction in speed as an approximation of the effect, rather than the absolute measured speed.

7.3.3 Step 3. Calculate Crossing Sight Distance

The crossing sight distance corresponds to the distance required by pedestrians to recognize the presence of conflicting vehicular traffic and determine crossing opportunities at intersections and roundabouts. The distance is established through sight triangles that allow a pedestrian to evaluate potential conflicts with approaching vehicles. Similarly, the resulting sight triangles also assure that the driver has a clear view of a pedestrian waiting to cross or approaching the crosswalk. For pedestrians who are blind, the crossing sight distance applies in that any visual

Table 7-3. Speed impacts due to traffic-calming measures (adapted from the *Traffic Control Devices Handbook*).

Traffic-Calming Measure	Sample Size	85th Percentile Speed after Calming in mi/h (Std. Dev.)	Average Change in Speed after Calming in mi/h (Std. Dev.)	Average Percentage Change (Std. Dev.)
12 ft hump	179	27.4 (4.0)	-7.6 (3.5)	-22% (9%)
14 ft hump	15	25.6 (2.1)	-7.7 (2.1)	-23% (6%)
22 ft table	58	30.1 (2.7)	-6.6 (3.2)	-18% (8%)
Longer tables	10	31.6 (2.8)	-3.2 (2.4)	-9% (7%)

obstructions are also expected to impact the audible environment at the crosswalk and the ability to hear approaching vehicles without sound obstructions or deflections.

The methodology developed to determine crossing sight distance adequacy at a roundabout or CTL has been adapted from the sight distance performance checks for vehicles at roundabouts from *NCHRP Report 672,* calculations and definitions from the Green Book, and the pedestrian mode methodology in Chapter 19 of the *Highway Capacity Manual 2010.*

The four pedestrian movements at a roundabout—crossing from the curb to the splitter island at entry, crossing from the splitter island to the curb at entry, crossing from the curb to the splitter island at exit, crossing from the splitter island to the curb at exit—are all different for several reasons, including:

- Traffic is approaching from the left when crossing from the curb, but from the right when crossing from the splitter island;
- Traffic is moving only in front of the pedestrian when crossing from the curb (quiet behind the pedestrian), while it is moving both in front of and behind the pedestrian when crossing from the splitter island; and
- Entering traffic is decelerating in approach of the yield line, while exiting traffic is accelerating as drivers exit the roundabout.

Since traffic patterns at each conflicting approach are judged independently, there are sight distances and sight triangles associated with each location and its conflicting approaches. The entry crossing locations have one potential conflict with vehicles entering the roundabout. The exit crossing locations are subject to two conflicting movements with different trajectories: traffic from the immediate upstream entry approach (right turns), and traffic circulating from other upstream approaches (through and left turn movements).

The sight distance (d) is calculated as a function of the conflicting vehicle speed (V) and the pedestrian critical headway (t_c)

Equation 7-2. Crossing sight distance calculation.

$$d_n = (1.467)(V_n)(t_{n,c})$$

where,

d_n = distance along approach leg n upstream of the crosswalk for crossing, ft;
V_n = free-flow speed of conflicting vehicle movement on approach n, mph; and
$t_{n,c}$ = critical headway required by a pedestrian crossing approach n.

The critical headway describes the minimum amount of time necessary for a pedestrian to cross the roadway. The critical headway calculation is directly derived from the pedestrian analysis method covered in the two-way stop-controlled intersection methodology of the *Highway Capacity Manual 2010.*

Equation 7-3. Estimating pedestrian critical headway.

$$t_{n,c} = (L_n / S_p) + t_s$$

where,

L_n = crosswalk length for a specific traffic stream, ft;
S_p = average pedestrian walking speed, ft/s (default = 3.5 ft/s);
t_s = pedestrian start-up time and end clearance time, s (default = 2 s).

The vehicle speed parameter is the same as was estimated in Step 2. At a roundabout entry, this speed is principally a function of the R_1 radius shown in Figure 7-2. For exiting vehicle, the analyst

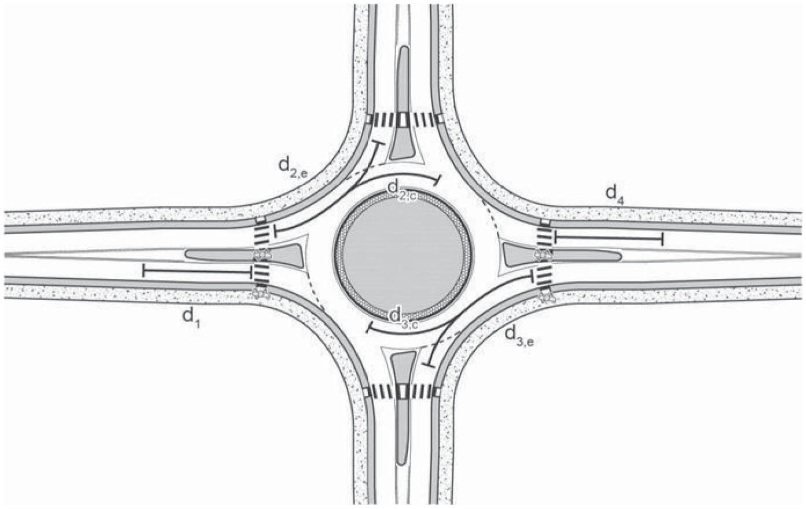

Figure 7-3. Minimum sight distance along the actual vehicle path for roundabouts.

Figure 7-3 shows a schematic of a roundabout with calculated sight distances drawn for entry and exit legs, and for both crossings from the curb and crossings from the splitter island.

uses the controlling radius for the particular movement from radii R_2, R_4, and R_5 depending on whether the conflicting movement is a right-turning, through, or left-turning vehicle. For all exit-leg movements, the actual speed is adjusted to account for the vehicle's ability to accelerate before reaching the crosswalk as shown in Table 7-2.

Once the minimum distance, *d,* is determined for all possible conflicting movements, the designer should plot the distance along the centerline of the direction of travel. Figure 7-3 shows the necessary sight distance, *d,* for each crossing location at the entry and exit of a roundabout. The length of each *d* may be longer or shorter than shown relative to the roundabout geometry, depending on the speed and critical headway times used in the calculation.

After plotting the distance from the pedestrian location, the sight triangle is determined as shown in Figure 7-4. Any sight obstruction should be eliminated from the sight triangles for better pedestrian visibility. The figure focuses on showing examples for just two of the crosswalks. But just like the rest of the crossing assessment method, the evaluation needs to be performed for each crosswalk, entry and exit, and both for crossings originating from the island and originating from the curb.

7.3.4 Step 4. Check Sight Distance Provisions

In this step, the calculated required crossing sight distance is checked against the design of the roundabout or CTL to see if sufficient sight distance is provided. The required length of sight distance is measured along the center of the approaching roadway in advance of the crosswalk. Figure 7-5 illustrates this for a roundabout for both entry and exit legs. The figure includes a two-lane entry (south entry, shown in blue), a two-lane exit (north exit, shown in red), and a three-lane entry and exit (east entry and exit, shown in green). Sight distances are shown based on the field-measured vehicle speed at the crosswalk, which was approximately 13 mi/h to 15 mi/h because of the raised crosswalks installed on the tested approaches. Without this treatment, the sight distance requirements would have been significantly longer. The figure further shows

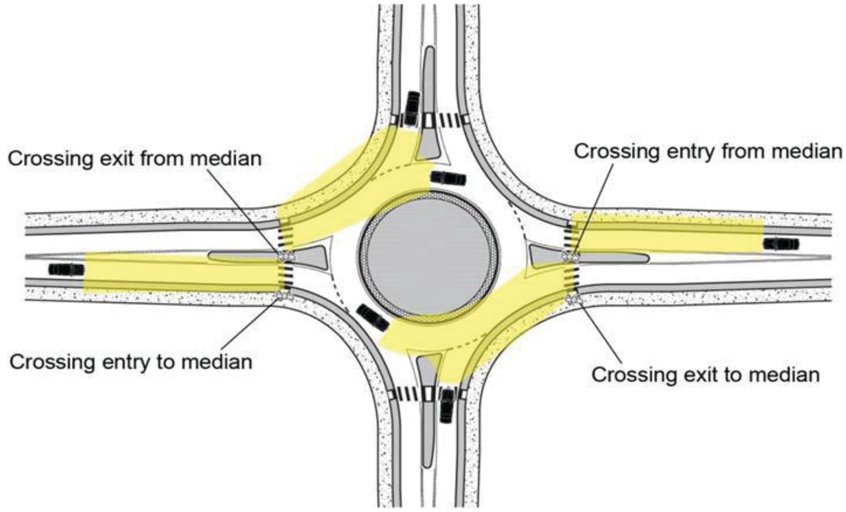

Figure 7-4. Pedestrian sight triangles for each crossing location.

Figure 7-4 shows a schematic of a roundabout with estimated sight triangles drawn based on the calculated sight distances. Sight triangles are drawn for entry and exit legs, and for both crossings from the curb and crossings from the splitter island.

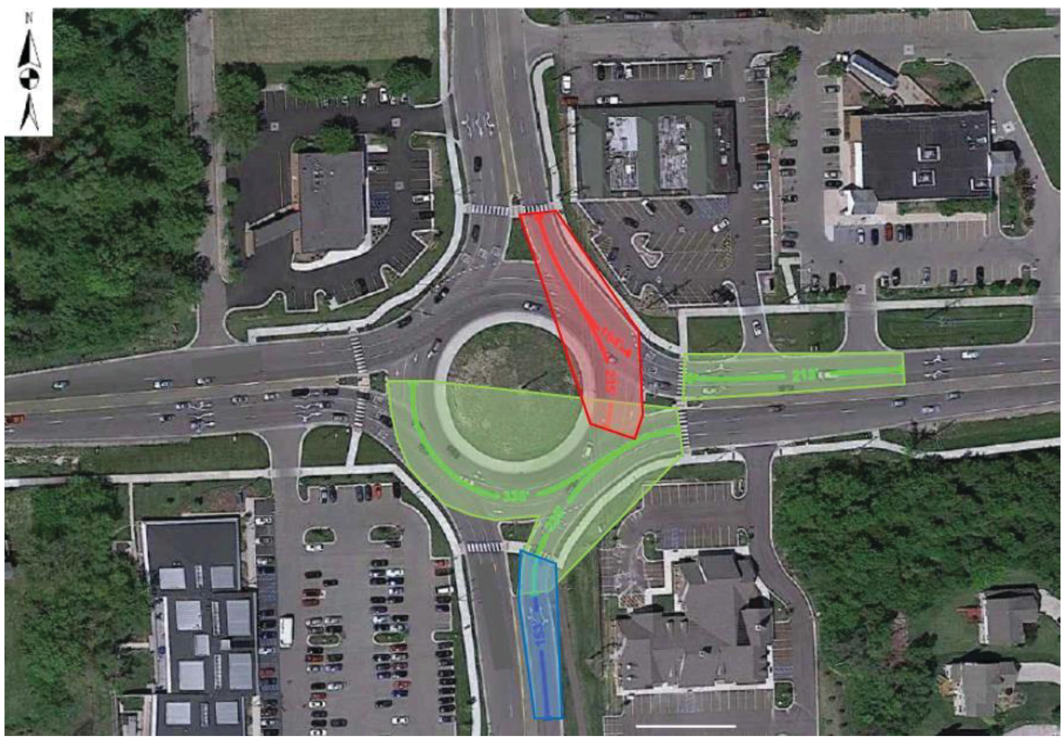

Figure 7-5. Sight distance for two-lane and three-lane roundabout approaches.

Figure 7-5 shows an example application of the sight distance calculations for a two-lane entry (south entry, shown in blue), a two-lane exit (north exit, shown in red), and a three-lane entry and exit (east entry and exit, shown in green). Sight distances are shown as arrows based on the field-measured vehicle speed at the crosswalk, which was approximately 13 mi/h to 15 mi/h because of the raised crosswalks installed on the tested approaches. The figure further shows the resulting sight "triangles" drawn relative from the respective waiting positions (on both curb and island) for a pedestrian to the end of the measured sight distance.

the resulting sight "triangles" drawn relative from the respective waiting positions (on both curb and island) for a pedestrian to the end of the measured sight distance.

It is evident from this example that the three-lane crossings result in a longer required sight distance (336 ft for traffic exiting from circle, 236 ft for traffic exiting from south to east right turn, and 213 ft for traffic entering the circle) relative to the two-lane crossings (235 ft, 164 ft, and 153 ft for the corresponding distances). This is intuitive, as the required crossing time for pedestrians (exposure time in the street) is longer for a three-lane crossing, thereby increasing the sight distance requirements.

The sight triangles between the pedestrian crosswalk landing and the end of the measured sight distance should be clear of obstacles and obstruction, including tall bushes, signal controller cabinets, walls, or buildings. If the crossing sight distance is not provided, pedestrians will not be able to see (and presumably hear) far enough to be able to accept a sufficiently large gap in traffic. Similarly, drivers may not be able to see a pedestrian waiting to cross or beginning to cross, which is expected to impact their propensity to yield as well as their ability to react in time to avoid a potential collision.

Increased vehicle speeds, longer crossing distances, and slower pedestrian walking speeds all contribute to longer sight distance requirements. If the sight distance check fails, the designer has the choice of modifying the design to reduce the sight distance requirements (e.g., through tighter radii, fewer lanes, or a raised crosswalk to reduce speeds) or may decide to move the crosswalk (e.g., further from the circulating lane for an exit crossing).

Figure 7-5 illustrates the effect of crossing distances for a roundabout with two-lane and three-lane crossings. Figure 7-6 shows two CTL approaches to a signalized intersection. The east approach has a required crossing sight distance of 203 ft for a single-lane crossing. For the north approach, the presence of a raised crosswalk reduces vehicle speeds and thereby the sight distance to 129 ft.

7.3.5 Step 5. Predict Crossing Opportunities (Gaps and Yields)

This step predicts the availability of crossing opportunities in the form of crossable gaps between moving vehicles, as well as vehicle yields.

The availability of crossable gaps can be estimated from traffic flow relationships by taking into account platooning or bunching effects that may result from signals upstream of the crosswalk in question. A predictive equation for gap opportunities is presented below.

Pedestrian crossable gap opportunities $P(CG\text{-}Opp)$ are predicted as shown in Equation 7-4 as a function of critical headway for crossable gap (t_c) and average headway (t_{avg}). The equation shows the equation that can be used to estimate the probability of encountering a gap greater than the critical gap.

Equation 7-4. Estimating Pedestrian Crossable Gap Opportunities from Traffic Flow Theory (May, 1990).

$$P(CG - Opp) = P(headway \geq t_c) = e^{-\frac{t_c}{t_{avg}}}$$

where,

t_c = critical headway for crossable gap (s)
t_{avg} = average headway, defined as (3,600 s/h)/(vehicular volume in vehicles/hour)

In the absence of pedestrian platoons, the critical headway for pedestrians can be calculated by Equation 7-5 following the pedestrian delay methodology at two-way stop-controlled intersections in the *Highway Capacity Manual 2010.*

Figure 7-6. Sight distance for CTLs with and without raised crosswalks.

Figure 7-6 shows an example application of the sight distance calculations at a CTL. Sight distances are shown as arrows and the resulting sight "triangles" drawn relative from the respective waiting positions (on both curb and island) for a pedestrian to the end of the measured sight distance.

Equation 7-5. Pedestrian critical headway from the Highway Capacity Manual, Chapter 19.

$$t_c = \frac{L}{S_p} + t_s$$

where,

L = crosswalk length (ft)
S_p = average pedestrian walking speed (ft/s), and
t_s = pedestrian start-up and clearance time (s), default = 2 sec.

In addition to crossable gaps, driver yielding events also present crossing opportunities. A predictive equation for estimating the likelihood of driver yielding is given below, as a function of geometry and other prevailing traffic conditions.

Yield opportunities are predicted, as shown in Equation 7-6, as a function of fastest path radius at the crosswalk *(Rcrosswalk)* and the presence of an RRFB at the approach. The fastest path radius (in feet) is a continuous variable and RRFB is a binary variable that is 1 if a roundabout approach is equipped with RRFB and 0 if no RRFB is present.

Equation 7-6. Estimating probability of yielding.

$$P(Yield) = (-0.065) * (Rcrosswalk) + (11.9) * (RRFB) + 82.6$$

The model predicts a base yield probability of 82.6%, which is reduced by 6.5% for each 100 ft increase in the fastest path radius. The presence of an RRFB increases the yield probability by 11.9% after controlling for radius. The model has been calibrated from data at two-lane roundabouts. It is expected that yield rates at single-lane roundabouts are higher than the estimate from Equation 7-6, while yield rates at three-lane roundabouts are lower.

The probability of yield crossing opportunity *P(Y-Opp)* is different than the probability of driver yielding, *P(Yield)*. The term *P(Y-Opp)* is calculated on the basis of all encountered vehicles, and it is a better representation of the yield encountered rate that a pedestrian is likely to experience.

A reasonable approach for estimating *P(Y-Opp)* from *P(Yield)* is to subtract the probability of crossable gaps from the total number of vehicle events (see Equation 7-7):

Equation 7-7. Estimating yield opportunities from yield probabilities.

$$P(Y\text{-}Opp) = P(Yield) * (100\% - P(CG\text{-}Opp))$$

This approach assures that the sum of $P(Y\text{-}Opp)$ and $P(CG\text{-}Opp)$ is less than or equal to 1 as is required by definition.

7.3.6 Step 6. Estimate Utilization of Gaps and Yields

In this step the analyst estimates the rate of utilization of gap and yield crossing opportunities. The utilization rate of gaps is calculated as the ratio of the number of crossings a blind pedestrian is expected to take in a gap over the total estimated number of gap crossing opportunities available. Yield utilization is similarly calculated as the ratio of the number of yields utilized or accepted over the total number of yields available.

The gap utilization rate of pedestrians who are blind is generally more conservative than that of sighted pedestrians, with the biggest differences being additional latency time after a vehicle passes the crosswalk until a decision to cross is made. Sighted pedestrians will often visually identify a gap in traffic approaching the crosswalk and initiate crossing as soon as the gap opens in front of them. Research has generally shown that a blind pedestrian requires additional time for the noise of the vehicle to subside before choosing to cross in a gap. The additional decision latency time results in blind travelers rejecting gaps that a sighted person may have utilized.

Gap opportunity utilization is estimated from the average gap opportunity utilizations observed at study locations in NCHRP Project 03-78B, and are shown in Table 7-4. There is presently insufficient data in the literature to derive more sophisticated gap utilization models, but

Table 7-4. Estimated average gap utilization for blind pedestrians.

Approach	Average Gap Utilization	Sample Size	Std. Error
1 Lane Entry	66.5%	6	2.55%
1 Lane Exit	60.8%	6	2.92%
2 Lane Entry	82.3%	12	2.21%
2 Lane Exit	65.7%	11	3.00%
CTL	57.9%	12	2.05%

Table 7-5. Estimated average yield utilization for blind pedestrians.

Approach	Average Gap Utilization	Sample Size	Std. Error
1 Lane Entry	67.0%	6	2.79%
1 Lane Exit	68.5%	6	3.30%
2 Lane Entry	72.7%	17	22.09%
2 Lane Exit	70.5%	16	1.22%
CTL	35.7%	12	1.24%

analysts are encouraged to use local data or estimates should those be available. It is also noted that the relatively high gap utilization of 82.3% at two-lane entries compared to other locations may be biased by the specific sites studied in the research.

Similar to the concept of gap utilization, not all yield events may result in a utilized crossing. Pedestrians who are blind may not utilize a yield crossing opportunity because of high ambient noise, quiet vehicles, uncertainty of driver intent, or other reasons that result in not having confidence in their judgment. A non-utilized yield is not necessarily an event "missed" by the pedestrian, as the decision to reject the yield may be made consciously.

Yield opportunity utilization is estimated from the average yield opportunity utilizations observed at study locations and is shown in Table 7-5. There is presently insufficient data in the literature to derive more sophisticated yield utilization models, but analysts are encouraged to use local data or estimates should those be available.

7.3.7 Step 7. Evaluate Audible Environment and Noise Effects

Research has linked the accessibility of a site for a pedestrian who is blind to the availability of adequate audible cues. This is intuitive, as a blind traveler relies on hearing to navigate and make crossing decisions. An adequate audible environment is therefore critical to assure that a blind traveler can independently and safely navigate a crossing. In this step, the analyst should identify and flag any concerns about the audible environment. The outcome is a yes/no check on whether audibility is likely to be compromised at the site. To date, no quantitative method exists to accomplish this, but some guidance is provided below, as well as in Appendix A.

The availability of audible cues is related to the presence of noise sources in the vicinity of the site, as well as obstacles that may interfere with the ability to clearly hear approaching vehicles. Such obstacles may include signs, poles, or landscaping that may impact audibility in a matter similar to their impact on sight distance. The principal question is whether the person can adequately hear the approaching vehicle (referred to as the signal in human factors research) to the background noise. Having an adequate signal-to-noise ratio is critical to assure that the conflicting vehicle can be heard and distinguished from other noise sources.

In evaluating the audible environment, the first and foremost audibility consideration is the location of the crosswalk relative to sources of noise. In the case of a CTL, most of the traffic noise is generated at the main intersection. It is generally expected that smaller radius CTLs result in smaller channelization islands, which, in turn, place the pedestrian closer to that noise source. In a similar fashion, crossing from the channelization island to the curb is expected to have higher levels of interfering noise (from behind the pedestrian) than crossings from the curb to the island.

For roundabouts, the separation between the crosswalk and the circulatory roadway affects the level of noise at the crosswalk. Noise levels are further expected to be different between entry legs (quiet traffic slowing down in approach of the roundabout) and exit legs (louder traffic accelerating away from the roundabout). Similar to CTLs, the splitter island is expected to have the highest levels of noise, with traffic traversing in front of and behind the waiting pedestrian. Landscaping has the potential to minimize the noise behind the waiting pedestrian when installed on the splitter island, but may limit lines of sight from the driver to the pedestrian.

Other noise sources may exist in the vicinity of the site that have high impact on the blind person's ability to hear conflicting traffic and distinguish it from background noise. Common examples of this include nearby freeways (especially at interchanges), work zones or construction activity, or general industrial activity. Noise levels are also often amplified in locations with a high percentage of trucks and other heavy vehicles.

7.3.8 Step 8. Estimate Pedestrian Delay

The second accessibility performance check is pedestrian delay. *NCHRP Report 674* showed a link between pedestrian delay and the probability of crossing at a crosswalk. The probability of crossing at a crosswalk, *P(Cross),* is described in Equation 7-8 as a function of the probability of yielding, *P(Y),* the probability of yield utilization, *P(GO | Y),* the probability of encountering a crossable gap, *P(G),* and the probability of utilizing that crossable gab, *P(GO | G).*

Equation 7-8. Estimating the probability of crossing.

$$P(Cross) = P(Y\_Opp) * P(GO|Y\_Opp) + P(CG\_Opp) * P(GO|CG\_Opp)$$

The components of *P(Cross)* were all estimated in previous steps. This research developed models to predict pedestrian delay at roundabouts and intersections with CTLs as a function of *P(Cross).* These models allow analysts to estimate pedestrian delay for new sites if the input variables are known. Since the models are sensitive to the utilization measures, the delay estimation can distinguish between blind and sighted pedestrians, who may be presented with the same gap and yield opportunities, but have different rates of utilizing these opportunities.

Separate models were developed for single-lane CTL approaches, single-lane roundabout approaches, and two-lane roundabout approaches. Pedestrian delay for single-lane CTL approaches is predicted as shown in Equation 7-9 as a function of *P(Cross).*

Equation 7-9. Calculating pedestrian delay for single-lane CTL approaches.

$$d_p = 10.75 - 9.95 * LN(P(Cross))$$

Pedestrian delay for single-lane roundabouts is predicted, as shown in Equation 7-10, as a function of *P(Cross).*

Equation 7-10. Calculating pedestrian delay for single-lane RBT approaches.

$$d_p = 9.37 - 9.78 * LN(P(Cross))$$

Pedestrian delay for two-lane approaches (two-lane roundabouts) is predicted, as shown in Equation 7-11, as a function of *P(Cross).*

Equation 7-11. Calculating pedestrian delay for two-lane RBT approaches.

$$d_p = 6.14 - 8.53 * LN(P(Cross))$$

The delay term, d_p, in Equation 7-9 through Equation 7-11, is measured in seconds per pedestrian. The equations are applied separately to each portion of the crossing, which in the case of a roundabout means the total delay or the sum of delay for the entry and exit legs.

The quantity increases with a decreasing probability of crossing, $P(Cross)$, which in turn decreases with reduced availability and utilization of gaps and yields. As such, a low-volume site (i.e., with lots of gaps) or a high-yielding site is expected to result in low delay, provided that the utilization of crossing opportunities is adequate. As traffic volumes increase (reducing the availability of gaps) and as vehicle speeds increase (reducing the number of yields), the delay per pedestrian is expected to increase. As an alternative to this pedestrian delay methodology, the analyst may choose to refer to the method in the *Highway Capacity Manual 2010*, or conduct a simulation study. However, it is emphasized here that the *Highway Capacity Manual 2010* method does not account for opportunity utilization of less than 100%. For simulation, a method for considering varying gap and yield availability and utilization distributions is described in Schroeder, Rouphail, and Hughes (2008).

7.3.9 Step 9. Check Pedestrian Delay

The calculated pedestrian delay has to be compared to the agency performance target to determine whether it is acceptable. The *Highway Capacity Manual 2010* defines pedestrian LOS for unsignalized intersections on the basis of the average delay per pedestrian, although these performance thresholds are not calibrated for blind travelers. Table 7-6 shows the *Highway Capacity Manual 2010* thresholds for delay.

The LOS in Table 7-6 is defined on a per approach basis. In the case of a roundabout, this means that the entry and exit leg delays should be added together before applying the thresholds. For a CTL, the total crossing delay should be considered, which adds whatever delay the pedestrian experiences crossing one or more of the intersecting streets to the calculated CTL delay. The analyst may use the *Highway Capacity Manual 2010* methodology for signalized intersections to estimate the pedestrian delay of the full crossing.

In Table 7-6, it is further shown that the likelihood of risk-taking increases significantly with longer wait times. While this refers primarily to sighted pedestrians (no studies with blind travelers have been conducted to date), high delay times are nonetheless cause for concern and should be avoided. The agency may thus choose to adopt stricter performance thresholds than those shown in the table.

7.3.10 Step 10. Estimate Crossing Risk

The third, and arguably most critical, accessibility performance check is the expected level of pedestrian risk. The level of risk is determined in field studies from certified orientation and mobility specialist intervention events, observer ratings, time-to-contact measurements, and

Table 7-6. Pedestrian LOS thresholds for unsignalized intersections from the Highway Capacity Manual.

LOS	Control Delay (s/ped)	Comments
A	0-5	Usually no conflicting traffic
B	5-10	Occasionally some delay due to conflicting traffic
C	10-20	Delay noticeable to pedestrians, but not inconveniencing
D	20-30	Delay noticeable and irritating, increased likelihood of risk-taking
E	30-45	Delay approaches tolerance level, risk-taking behavior likely
F	>45	Delay exceeds tolerance level, high likelihood of pedestrian risk-taking

video observations. These risk assessment factors are correlated to the characteristics of the studied crosswalk to arrive at a risk prediction model. The model predicts the likelihood of a risky decision as a function of different variables.

The intervention model predicts the likelihood of the crossing decisions a blind pedestrian might make, which would have resulted in a certified orientation and mobility specialist intervention. The intervention model, *P(INT)* is predicted as shown in Equation 7-12 as a function of noise *(NOISE),* average crosswalk speed *(XSPD_AVE),* and sight distance *(SIGHT_D).* Variables *NOISE* and *SIGHT_D* are binary variables and equal to 1 if the noise level is high and the required crossing sight distance is not provided, respectively. Noise level and sight distance were estimated in Steps 4 and 7, respectively. XSPD_AVE is a continuous variable and is defined for speeds higher than 10 mph.

Equation 7-12. Estimating the probability of interventions.

$$P(INT) = 0.0629 * (NOISE) + 0.0020 * (XSPD\_AVE) + 0.0230 * (SIGHT\_D) - 0.0177$$

7.3.11 Step 11. Check Crossing Risk

The calculated crossing risk has to be compared to the agency performance target to determine whether it is acceptable. There is presently no standardized guidance for what level of risk or what rate of interventions is acceptable. Clearly, an intervention rate of zero would be desirable to reduce the risk as much as possible. In the language of the ADA legislation, however, a crossing should provide equivalent access to persons with and without a disability. To date, no comprehensive study exists comparing the rate of interventions between blind and sighted pedestrians, therefore guidance is limited.

Based on research conducted for FHWA at two-lane roundabouts (Schroeder et al., 2015), researchers concluded that an intervention rate of 3% or less is similar to the rate of interventions at single-lane roundabouts, and may be considered accessible in many cases. Rates of intervention above 5% were considered as likely to present a significant barrier for blind travelers crossing at these locations, and rates of intervention above 10% were considered as representing a challenging and risky crossing environment.

It is emphasized here that these thresholds are not based on any formal guidance available, nor should they be used as the basis for policy and categorization of roundabouts. These thresholds are merely introduced to help distinguish and categorize sites for the purpose of analysis and discussion. An agency should set its own thresholds for the purpose of evaluating sites and deciding on the need for further treatments.

7.3.12 Step 12. Visibility of Traffic Control Devices

The accessibility framework and method presented in this chapter may result in the provision of treatments intended to enhance accessibility of pedestrians who are blind at roundabouts and CTLs. These treatments encompass a range of geometric and design changes in the roundabouts, as well as the installation of traffic control devices in the form of traffic signals, beacons, signs, and markings. Traffic control devices on roads open to public travel have important functions in providing guidance and information to road users. The visibility of such physical aids is especially important for motorists, bicyclists, and pedestrians navigating complex roundabouts and intersections with CTLs.

The basic question in this context of visibility is whether traffic control devices can be seen by drivers as they approach the crosswalk and whether pedestrians can see or hear the device.

An underlying consideration of whether traffic control devices are understood by drivers and pedestrians also plays into the question of visibility. The key difference between visibility and sight distance (discussed in the another step of the crossing assessment method) is that visibility considers weather drivers and pedestrians can see (and properly interpret) traffic control devices, while crossing sight distance is strictly tied to physical obstructions and the line of sight between drivers and the pedestrian.

The principles underlying the visibility performance checks presented in this section are compiled from MUTCD, the *Traffic Control Devices Handbook, NCHRP Report 672,* and other sources.

7.3.12.1 Visibility Considerations for Signs and Markings

Traffic signs and pavement markings are designed and placed in a way that they are legible to the road user for whom it is intended. Proper visibility of these traffic control devices assures that they are understandable in time to provide information for a proper decision. This decision can be for the purpose of navigation, warning, guidance, or advisory purposes. Important aspects include, but are not limited to, consistent design, daytime and nighttime visibility, proper size, and correct placement.

Two key considerations exist for signage and markings, both of which test for adequate separation of traffic control devices at the crosswalk with the traffic control devices controlling the downstream merge point at the CTL or the entry at a roundabout.

1. The first consideration is whether there is sufficient separation between the crosswalk markings and the markings for the yield line or stop bar downstream of the crosswalk at the roundabout entry or at the CTL merge point. The two sets of markings should be separated by at least one-vehicle length. This assures a visual separation and distinction of the two sets of markings. It also provides a one-vehicle length of storage between the yield line or stop line and the crosswalk, so that a waiting vehicle does not obstruct the crosswalk. Any subsequent vehicles can then queue upstream of the crosswalk, leaving the crossing area free (in principle). If a longer separation is needed, a separation in multiples of vehicle lengths (i.e., 20 ft, 40 ft, 60 ft) is desirable to maximize the potential for vehicles blocking the crosswalk.
2. The second consideration is whether there is appropriate separation of signs at the crosswalk from signs at the yield or stop line. In addition to checking for separation, the designer should also check for potential occlusion effects with a sign blocking one or more downstream signs. Visual obstruction may also affect the visibility of the pedestrian, but that aspect should have been identified in the crossing sight distance step.

7.3.12.2 Visibility Considerations for Signals and Beacons

Six considerations exist for signal and beacon installations at roundabouts and CTLs, as follows:

1. Are signals visible to an approaching driver to provide adequate stopping sight distance per MUTCD requirements? Stopping sight distance is calculated from the approaching vehicle speed and assumed driver reaction times and deceleration rates. If stopping sight distance is not adequate, a supplemental (upstream) signal head may be needed. This visibility concern is especially important at roundabout exit-leg signals and CTLs, where the roadway curvature upstream of the signal may limit its visibility.
2. Are mounting heights correct? Overhead traffic signals need to be mounted at a sufficient height to allow large design vehicles (trucks) to pass underneath them. The general mounting height of overhead mounted signals is 15 ft. In addition, side-mounted signals need to be mounted at least 8 ft high to assure proper visibility, and to not act as a potential obstacle for pedestrian traffic.
3. Is the stop bar set back enough? MUTCD requires a separation between the vehicle stop bar and any overhead signal to assure that drivers stopped at the stop bar can comfortably see

the signal display (without having to lean forward in their seat). This setback requirement may result in the need for a full or partial crosswalk relocation at roundabouts to meet this criterion at the exit leg.

4. Is the stop bar located upstream of the crosswalk? Pedestrians should cross downstream of the stop bar where vehicles wait for a red signal. For multilane crossings, where there is a high potential for multiple threat situations, an additional setback distance from the crosswalk is desirable. A stop bar downstream of the crosswalk would result in vehicles queuing onto the crosswalk, which is undesirable. This is a principle for signalized and unsignalized crosswalks and their position relative to the vehicular stop bar or yield line, respectively.
5. Is the signal or beacon control separated from other traffic control devices? Both roundabouts and CTLs have additional traffic control devices that control yielding and merging behavior at the roundabout entry and at the downstream end of the CTL. Any signals or beacons at the crosswalk need to be visibly separated to avoid driver confusion. For example, a green vehicle signal at a roundabout entry crosswalk may be misunderstood by drivers as providing a protected movement into the circulating lane, unless the signal is sufficiently separated from the circulatory roadway.
6. Are audible messages provided and sufficiently separated? Any pedestrian signal or beacon installation requires the use of APS or other audible devices that convey the presence and functionality of the traffic control device to a pedestrian who is blind. These devices should be installed immediately adjacent to the crosswalk, aligned with the crossing direction, and downstream of the approaching vehicles. Any audible devices further need to be separated from each other by at least 10 ft, or must have special speech messages, to uniquely tie the audible message to a crossing point. This is especially critical on splitter or channelization islands, which exist for both roundabout and CTLs. In some cases, larger island designs may be required to assure a separation of entry and exit devices, or of devices controlling the CTL versus the main intersection. Additional discussion on audibility considerations at both facility types is given in the next section.

7.3.13 Step 13. Complete Crosswalk Assessment

When the candidate design satisfies the performance targets, the design can be finalized and the treatments can be implemented as applicable. As part of this assessment, the analyst conducted three explicit performance checks (Steps 4, 9, and 11), and compared estimates to the performance targets established by the agency to evaluate whether or not the candidate design meets the desired level of accessibility. The result of the crosswalk assessment is iterative by definition and will prompt the analyst to accept, reject, or modify the candidate design. Depending on the outcome of the performance checks, the analyst may complete the crosswalk assessment (Step 13) or may repeat the process with a modified design after iterations in Steps 4, 9, or 11.

While not explicitly called for, an assessment of vehicle impacts may be considered in this step. Chapter 2 of this guidebook presents the context of the accessibility evaluation within the broader intersection design process, which considers the expected operational and safety performance of each mode. By conducting the assessment of vehicle impacts in this step, the analyst may check for these impacts within the accessibility assessment.

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APPENDIX A

Discussion of Audible Environment and Noise Effects

A key component of accessibility for a pedestrian who is blind is the availability of adequate audible cues to assure that a blind traveler can independently navigate the roundabout or CTL. The availability of audible cues is related to the presence of noise sources in the vicinity of the site, as well as obstacles that may interfere with the ability to clearly hear approaching vehicles. Such obstacles may include signs, poles, or landscaping, which may impact audibility in a matter similar to their impact on sight distances.

However, a clear difference is that while these obstacles generally impede sight distances, they may in some cases improve audibility. For example, heavy landscaping in the splitter island may help separate audible cues from the two directions of traffic, and thus enhance audibility for a blind pedestrian waiting on the splitter island (*NCHRP Report 674*).

In general, audibility is less understood than sight distance, which makes an audibility assessment more challenging due to limited available guidance. This section introduces concepts of audibility and high-level principles that should be considered in the design of a roundabout or a CTL. The analyst should identify and flag any concerns about the audible environment. The outcome is a yes/no check on whether audibility is likely to be compromised at the site. To date, no quantitative method exists to accomplish this, but some guidance is provided below.

Location of Crosswalk Relative to Noise Sources

The first and foremost audibility consideration is the location of the crosswalk relative to sources of noise. In the case of a CTL, the majority of traffic noise is generated at the main intersection. It is generally expected that smaller radius CTLs result in smaller channelization islands, which in turn place the pedestrian closer to that noise source. In a similar fashion, crossing from the channelization island to the curb is expected to have higher levels of interfering noise (from behind the pedestrian) than crossings from the curb to that island.

For roundabouts, the separation between the crosswalk and the circulatory roadway impacts the level of noise at the crosswalk. Noise levels are further expected to be different between entry legs (quiet traffic slowing down in approach of the roundabout) and exit legs (louder traffic accelerating away from the roundabout). Similar to CTLs, the splitter island is expected to have exceptionally high levels of noise, with traffic traversing in front of and behind the waiting pedestrian. Wider islands and landscaping on the island may help with reducing noise levels on the splitter islands, although this has not been documented in research. Landscaping further has the potential of limiting lines of sight from the driver to the pedestrian.

Other noise sources that have a high impact on the ability to hear conflicting traffic may exist in the vicinity of the site; these make it difficult for a person to distinguish conflicting traffic from background noise. Common examples of this include nearby freeways (especially at interchanges), work zones or construction activity, and general industrial activity. Noise levels are also oftentimes amplified in locations with a high percentage of trucks and other heavy vehicles.

Considering Curvature and Directionality of Traffic

A key commonality between roundabouts and CTLs is roadway curvature. Research has shown that pedestrians can have difficulties distinguishing noise generation from through traffic and turning traffic at a CTL, or exiting and circulating traffic at a roundabout exit leg (Ashmead et al., 2012). With trajectories of these movements being similar, the sound patterns generated are also similar. As such, a blind pedestrian waiting to cross at a CTL, or at the exit leg of a roundabout, will likely have a difficult time distinguishing between vehicles that conflict directly with the crosswalk from those that proceed through the main intersection or continue to circulate. Additional separation between the crosswalk and the point where the two trajectories separate is expected to enhance the ability to identify conflicting traffic accurately.

Absolute and Relative Noise Levels

One key principle in acoustics research is the difference between absolute and relative noise levels. Research on the ability of blind travelers to identify quiet hybrid vehicles, as well as internal combustion engine vehicles, was shown to be highly correlated to the level of ambient noise (Emerson et al., 2015). In other words, even a “quiet” vehicle can be audible at low ambient noise levels. Similarly, even a “loud” vehicle can be difficult to hear when the level of background noise is elevated.

The notion of relative sound levels makes the audibility assessment of a new site difficult, as the designer needs to make assumptions about the level of ambient noise. For example, a very rural location is likely to have lower ambient noise levels than a busy downtown location, although unusual noise generators like agricultural equipment or industrial developments may pose an exception to that rule.

Many audible traffic control devices and Audible Pedestrian Signal (APS) systems include adjustments for the level of ambient noise that increase the decibel level of the audible indication in loud environments.

Impact of Grades

There is some evidence that roadway grade may impact the audibility at the crosswalk. Specifically, a crosswalk located in a downhill portion may provide better acoustic information about an approaching vehicle than a crosswalk approached in an uphill section. This pattern was suggested by research performed at two CTLs on opposing approaches at a signalized intersection in *NCHRP Report 674*. With the main roadway having a notable grade (3% to 4%), one CTL was approached by downhill traffic, while the other was approached by uphill traffic. Blind study participants and researchers noted that identical sound strip treatments installed in the CTL were more audible on the downhill section than on the uphill section. A potential explanation for this is that vehicle engine noises can propagate toward the crosswalk in a downhill approach, while the sound waves get trapped between the vehicle and the roadway on uphill approaches.

Location and Separation of Traffic Control Devices

The location of traffic control devices and the separation of two or more (audible) devices can impact audibility at the crosswalk, as well as how well the devices themselves can be heard and distinguished from each other.

MUTCD provides specifications for installation of APS devices at signals, which should have a minimum separation of 10 feet between two devices or the installation of speech walk messages and additional features. This guidance applies at any location where APS are installed.

For the placement of other traffic control devices like crosswalk signs, MUTCD specifies that the signs need to be placed adjacent to the crosswalk, but is silent on whether they should be placed on the upstream or downstream side. Prior research and significant feedback from blind travelers suggests that a downstream sign placement is preferable. Specifically, a downstream placement assures that the sign does not block the view or sound between the pedestrian and oncoming traffic.

Impacts of Landscaping and the Built Environment

As discussed above, landscaping can impact the audibility of a crosswalk in two critical ways. Landscaping can block critical audible information about an approaching and conflict vehicle and can thus have a harmful impact on audibility. However, landscaping can also block unwanted or distractive traffic noise (for example from behind the pedestrian, or from across the other side of the roundabout) and may thus have a positive impact on audibility.

The built environment surrounding the crosswalk is similarly expected to impact audibility. The presence of (tall) buildings close to the crosswalk can cause traffic sounds to be reflected and amplified and thereby impact the ability to clearly distinguish directionality of conflicting traffic. Bridges or expressways nearby also affect audibility.

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APPENDIX B

Summary of Crossing Treatments

This appendix provides an overview of pedestrian crossing treatments that were evaluated in this and prior research. The discussion for each treatment includes a description of its functionality and purpose, an estimate of installation cost, field test results for application to roundabouts and/or CTLs, limitations of the treatments, and links to additional resources and information.

Pedestrian Hybrid Beacon

Crossing improvement category: Driver information treatment
Purpose(s): Pedestrian signal to stop vehicular traffic
Cost of initial leg: $68,000–$133,000
Cost of subsequent legs: $29,000–$80,000

Pedestrian hybrid beacons (PHBs) or HAWK signals aim to be more efficient than a conventional signal by allowing vehicular traffic to move during the pedestrian flashing do not walk interval. PHBs are user-actuated beacons that give pedestrians a calculated time to cross streets when activated.

PHBs could also be used at a mid-block location or in a zig-zag arrangement, combining advantages of the extra queue storage capacity at the exit leg of the roundabout with more efficient signal phasing. Depending on pedestrian route patterns, these configurations may result in an increase in the travel time for pedestrians compared to a crossing at the traditional splitter island. The location of the mid-block crosswalk requires a median refuge island to be used if a two-stage crossing is necessary.

Functionality and Purpose

PHBs are installed to stop vehicular traffic during the pedestrian phase. When the pushbutton is activated, a flashing yellow starts followed by a solid yellow and solid red. The solid red phase coincides with the WALK interval, which last approximately 4 to 7 seconds. During the pedestrian clearance interval when a flashing do not walk interval is displayed for pedestrians, an alternating flashing red indication is displayed to the driver. The flashing red indication for drivers allows traffic to proceed after stopping, if no pedestrian is in the crosswalk. This phasing scheme allows for less vehicular delay while providing similar pedestrian-related benefits of a regular signal.

Effectiveness

Results from before-and-after treatment studies assessing the effectiveness of PHB treatments at roundabouts have been summarized below. The measures of effectiveness were defined in

Figure B-1. PHB at a two-lane roundabout.

Figure B-1 shows an installation of a PHB at the entry leg of a two-lane roundabout in Golden, Colorado. This location was studied as part of *NCHRP Report 674*.

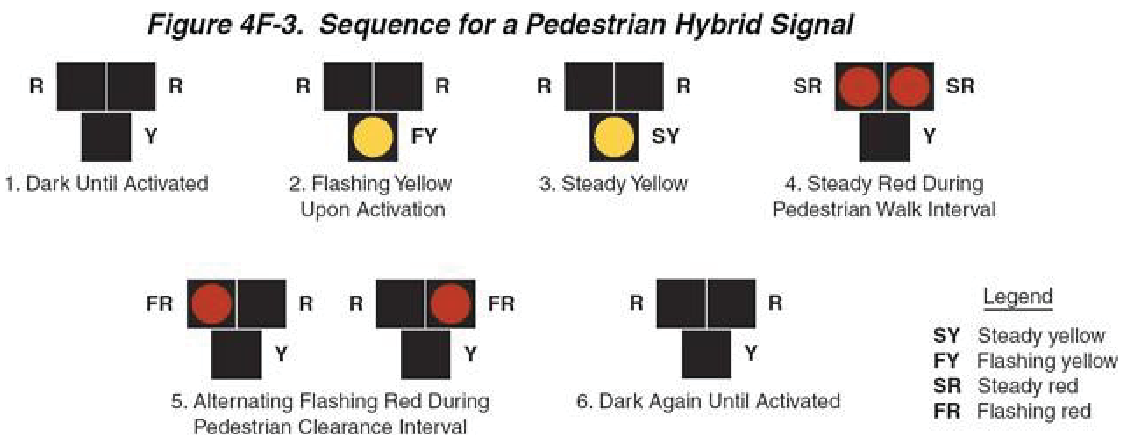

Figure B-2. PHB sequence.

Figure B-2 shows the phasing sequence of a pedestrian hybrid beacon. The sequence involves six phases: (1) dark until activated, (2) flashing yellow upon activation, (3) steady yellow, (4) steady red during pedestrian walk interval, (5) alternating flashing red during pedestrian clearance interval, and (6) dark again until activated.

terms of orientation and mobility interventions and the average delay experienced by blind subjects, and are summarized in Tables B-1 and B-2.

PHBs were effective in reducing both interventions and delay in all studied conditions. PHBs reduced the rate of interventions to zero at the Golden, Colorado, roundabout, a feat nearly replicated at two-lane and three-lane entry legs at an Oakland County, Michigan, roundabout. For the two-lane and three-lane exit legs in Oakland County, some interventions remained even in the PHB posttest condition, although at a statistically significant reduction over the pretest, where intervention rates were extremely high. PHB installations also had a consistent impact on the average pedestrian delay, which was reduced in all tested installations.

Table B-1. Summary of PHB effectiveness—orientation and mobility interventions (%).

Location	No. of Lanes	Entry/Exit	No Treatment	With Treatment
Golden, CO	Two	Combined	2.4%	0.0%
Oakland County, MI	Two	Entry	1.9%	0.0%
Oakland County, MI	Two	Exit	8.7%	1.7%
Oakland County, MI	Three	Entry	7.7%	0.0%
Oakland County, MI	Three	Exit	9.6%	0.8%

Table B-2. Summary of PHB effectiveness—pedestrian delay (sec).

Location	No. of Lanes	Entry/Exit	No Treatment	With Treatment
Golden, CO	Two	Combined	16.0	5.8
Oakland County, MI	Two	Entry	15.4	11.5
Oakland County, MI	Two	Exit	19.0	11.2
Oakland County, MI	Three	Entry	20.1	14.2
Oakland County, MI	Three	Exit	22.3	11.7

Limitations

Driver education may be required for the alternating flashing red signals; drivers are more likely to stop for a familiar control device such as a traffic signal. Driver unfamiliarity with a treatment, as well as installation of a treatment in an unexpected location, may result in reduced compliance with the red signal indication. Most state laws require drivers to treat dark signals, other than ramp meters, like a four-way stop, so drivers may stop unnecessarily when the signal is dark. A re-configured signal is currently in development to reduce driver confusion about dark signals. However, PHBs seem to be effective. According to an 8 month study conducted by the City of Tucson, the PHBs increased driver yielding to pedestrians from 30% in the before case to 93% stopping at the red signal in the after installation case. Similarly high rates of driver compliance with the PHB have been observed at roundabout entry legs. However, compliance rates were only about 85% at two tested two-lane roundabout exit legs, and only 70% at a tested three-lane exit, causing some concern for elevated risk of red-light running at multilane roundabout exits.

Cost Summary

Table B-3. Summary of cost estimate for a PHB installation.

Infrastructure	Cost Range (2014$)	Cost Unit
PHBs with mast arms (initial leg)	$98,000–133,000	Per leg
PHBs with mast arms (subsequent Legs)	$59,000–80,000	Per leg
PHBs with pedestal poles (initial leg)	$68,000–93,000	Per leg
PHBs with pedestal poles (subsequent legs)	$29,000–40,000	Per leg

Table B-4. Cost estimate details for a PHB installation.

Item	Unit	Assumed Unit Cost	Quantity	Need
Signal cabinet + controller + foundation	Each	$24,000	1 per intx	Required
Service cabinet + foundation	Each	$3,000	1 per intx	Required for direct power connection.
Signal pole, mast arm, anchor bolts	Each	$10,000	2 per leg	Required for mast arm installation
Signal pole foundation	Each	$3,000	2 per leg	Required for mast arm installation
Push Button post + foundation	Each	$750	2 per leg	Required for mast arm installation
Pedestrian signal pole (no mast arm) + foundation	Each	$1,250	4 per leg	Required for non-mast arm installation
PHB signal display head	Each	$900	4 per leg	Required
Pedestrian signal display head	Each	$600	4 per leg	Required
Audible push button assembly	Each	$950	4 per leg	Required
Audible push button control unit	Each	$2,500	1 per intx	Required
Aluminum sign assembly	Each	$300	8 per leg	Number may vary based on agency standards.
Conduit trench + conduit + wiring	Linear foot	$30	100 feet per leg	Required for wired power/communication, specific length will vary based on project
Junction box	each	$450	4 per leg	Required for wired power/communication, specific number will vary based on project
Contingency	--	20%	--	Unforeseen items
Engineering	--	10% to 50%	--	Varies based on project

Assumptions

- Installation at existing multilane roundabout
- One signal cabinet (with controller) and service cabinet per roundabout (included in initial leg cost), cost increases if multiple controllers are used
- Accessible (audible) pedestrian signals
- Direct power connection (no solar power)
- Signing costs included
- Illumination, striping, traffic control, and other miscellaneous costs not included
- Engineering cost varies from 10 to 50% of construction cost. This can vary greatly depending on the contracting mechanisms used.

Additional Information and Links

- FHWA Pedestrian Hybrid Beacon Guide. http://safety.fhwa.dot.gov/ped_bike/tools_solve/fhwasa14014/.
- FHWA Pedestrian Hybrid Beacon Overview and Links. http://safety.fhwa.dot.gov/proven countermeasures/fhwa_sa_12_012.cfm.
- *NCHRP Report 674*. http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_674.pdf.
- Oakland County hawk and RRFB Study. http://www.rcocweb.org/Lists/Publications/Attachments/126/HAWK%20Final%20Report%202011.pdf.

Rectangular Rapid-Flashing Beacon

Crossing improvement category: Driver information treatment
Purpose(s): User-actuated supplement for static warning signs
Cost (per leg): $26,000–$49,000

Also known as LED rapid-flash systems, rectangular rapid-flashing beacons (RRFBs) seek to reduce crashes between vehicles and pedestrians at unsignalized intersections and mid-block pedestrian crossings by increasing driver awareness of pedestrians preparing to or actively crossing the vehicle's path.

Functionality and Purpose

RRFBs are installed at intersections or mid-block crosswalks to supplement warning signs on two-lane or multilane roads. The beacons are user-actuated by manual push activation or automatic pedestrian detection. The amber LEDs flash in an irregular pattern similar to that of emergency vehicles. RRFBs have reduced costs compared to traffic signals and pedestrian hybrid signals, and have been found to improve driver yielding behavior when supplementing standard pedestrian crossing signs and other treatments.

Effectiveness

Results from a detailed FHWA study assessing the effectiveness of RRFB treatments at two-lane roundabouts have been summarized in Table B-5. The measures of effectiveness were defined in terms of orientation and mobility interventions, the average and 85th percentile delay experienced by blind subjects, and the average yield rate by drivers.

The results showed that of the twelve studied entries, the worst performance was observed at a channelized turn lane, which showed a 13.5% intervention rate. Of the remaining 11 entry legs, none had 10% or more interventions, and nine had 5% or less interventions.

Figure B-3. RRFB at a two-lane roundabout.

Figure B-3 shows an RRFB at a two-lane roundabout.

Table B-5. Summary of RRFB effectiveness from FHWA study (Schroeder et al., 2015).

City, State	Approach	Entry/Exit	Average Estimated Intervention (%)	Average Participant Delay	85th Percentile Participant Delay	Average Yielding Rate+ (%)
Albany, NY	Fuller North	Entry (n=59)**	13.6	9.8	24.4	36.0
Albany, NY	Fuller North	Exit (n=60)	21.7	28.2	70.4	0.0
Albany, NY	Fuller South	Entry (n=60)	1.7	8.5	19.1	39.0
Albany, NY	Fuller South	Exit (n=62)	12.9	10.2	31.6	11.0
Carmel, IN	Clay Terrace	Entry (n=52)	3.8	16.4	26.7	60.0
Carmel, IN	Clay Terrace	Exit (n=50)	4.0	13.3	19.1	61.0
Davidson, NC	Griffith East	Entry (n=23)	4.3	9.1	13.9	96
Davidson, NC	Griffith East	Exit (n=23)	0.0	10.1	16.8	80
Davidson, NC	Griffith West	Entry (n=23)	0.0	14.2	23.0	100
Davidson, NC	Griffith West	Exit (n=24)	8.3	10.7	20.4	96
Olympia, WA	14th	Entry (n=42)	7.1	2.3	3.4	95.0
Olympia, WA	14th	Exit (n= 42)	2.4	2.9	4.6	100.0
Olympia, WA	4th	Entry (n=45)	2.2	4.3	6.5	89.5
Olympia, WA	4th	Exit (n= 35)*	3.0	2.8	4.8	97.0
Olympia, WA	Olympic	Entry (n=45)	6.7	4.5	6.9	94.0
Olympia, WA	Olympic	Exit (n= 45)	0.0	2.9	4.8	94.0
Oshkosh, WI	Jackson	Entry (n=48)	2.1	12.4	20.7	83.0
Oshkosh, WI	Jackson	Exit (n=50)	16.0	17.3	27.5	20.0
Oshkosh, WI	Murdock	Entry (n=40)	0.0	13.1	19.5	90.0
Oshkosh, WI	Murdock	Exit (n=40)	15.0	17.0	26.7	20.0
Springfield, OR	Hayden	Entry (n=45)	2.2	8.9	12.6	100.0
Springfield, OR	Hayden	Exit (n= 41)	12.2	9.3	11.4	100.0
Springfield, OR	Pioneer	Entry (n=48)	4.2	5.7	8.3	90.0
Springfield, OR	Pioneer	Exit (n= 44)	11.4	10.4	15.1	64.0

** This exit is only a single lane*

*** This entry is a channelized turn lane*

+ *Percent yielding rate estimated from 30 trials in naturalistic yielding study for sighted pedestrian with RRFB activated*

Two of the studied entry legs had 0% interventions. Of the twelve studied exit legs, six had 10% or more interventions and five out of 12 had 5% or less interventions. Two exit legs had 0% interventions.

The study found a strong effective of the roundabout controlling radius at the crosswalk, and results suggest that a threshold may exist at an entry and exit radius of around 91.4 m (300 ft). At entry crosswalks, where all approaches had a radius of less than 91.4 m (300 ft), all percent interventions were less than 10%, and nine out of 11 approaches had less than 5% intervention. Similarly, the study suggests that the observed percent interventions changes noticeably at a vehicular free-flow speed of around 35 km/h (22 mph). For sites with free-flow speed below 35 km/h (22 mph), all but one location had less than 10% intervention, and 12 out of 14 had less than 5% intervention. For sites with free-flow speeds greater than 35 km/h (22 mph), five out of seven had more than 10% intervention, and six out of seven had more than 5% intervention.

This finding does not imply that all crosswalks with a controlling vehicle path radius of greater than 91.4 m (300 ft) or a speed greater than 35 km/h (22 mph) are assured to be less accessible, nor that all crosswalks with a controlling vehicle path radius of less than 91.4 m (300 ft) or speed less than 35 km/h (22 mph) are assured to be more accessible.

In a series of studies performed in Oakland County in this and prior projects, the effectiveness of RRFBs was tested with and without raised crosswalks at a two-lane and three-lane roundabout approach as summarized in Tables B-6 and B-7.

Table B-6. Summary of RRFB effectiveness—orientation and mobility iterventions (%).

Location	No. of Lanes	Entry/ Exit	No Treatment	RRFB Only	RRFB and Raised Crosswalk
Oakland County, MI	Two	Entry	7.5%	0.0%	0.0%
Oakland County, MI	Two	Exit	23.8%	16.4%	7.1%
Oakland County, MI	Three	Entry	12.5%	7.6%	0.0%
Oakland County, MI	Three	Exit	23.2%	18.9%	0.0%

Table B-7. Summary of RRFB effectiveness—pedestrian delay (s).

Location	No. of Lanes	Entry/ Exit	No Treatment	RRFB Only	RRFB and Raised Crosswalk
Oakland County, MI	Two	Entry	20.8	17.1	9.3
Oakland County, MI	Two	Exit	22.2	18.8	8.2
Oakland County, MI	Three	Entry	35.2	19.8	9.3
Oakland County, MI	Three	Exit	30.5	24.8	10.9

The Oakland County results show improvements in interventions and delay with installation of the RRFB only, but show that the addition of the raised crosswalk made a more drastic difference in the accessibility performance. Consistent with findings from the FHWA study, the speed-reduction effect of the raised crosswalk greatly reduced interventions and delays for this location.

Although the number of studies is too limited to make generalized implications at this time, the evidence found in the FHWA and Oakland County studies show promise in improving accessibility by treating roundabout entries with RRFBs. The results for exit lanes of multilane roundabouts are mixed, with high intervention rates remaining at some sites even after installation of the RRFB treatment, especially for those with large curve radii or high vehicle speeds.

Limitations

- Care should be taken so as to only activate beacons when manually actuated or automatically triggered; false calls may result in reduced yielding behavior.
- RRFBs are generally sufficient on standalone solar panel units, but may require additional power under low light conditions. The use of an audible device with a pushbutton locator tone, a requirement to make RRFBs accessible, is an important consideration in the estimation of required power.

Cost Summary

Table B-8. Summary of cost estimate for a RRFB installation.

Infrastructure	Cost Range (2014$)	Cost Unit
Rectangular rapid-flashing beacon—direct power (initial leg)	$26,000—$36,000	Per leg
Rectangular rapid-flashing beacon—direct power (subsequent legs)	$31,000–$42,000	Per leg
Rectangular rapid-flashing beacon—solar power (any leg)	$36,000–$49,000	Per leg

Table B-9. Cost estimate details for a RRFB installation.

Item	Unit	Assumed Unit Cost	Quantity	Need
Service cabinet + foundation	Each	$3,000	1 per intx	Required for direct power connection.
Solar power unit	Each	$250	4 per leg	Required for solar power connection.
RRFB controller + cabinet	Each	$2,500	2 per leg	Required
Pedestrian signal pole (no mast arm) + foundation	Each	$1,250	4 per leg	Required
RRFB display head	Each	$800	4 per leg	Required
Audible push button assembly	Each	$950	4 per leg	Required
Aluminum sign assembly	Each	$300	6 per leg	Number may vary based on agency standards
Conduit trench + conduit + wiring	Linear foot	$30	100 feet per leg	Required for wired power/communication, specific length will vary based on project
Junction box	Each	$450	4 per leg	Required for wired power/communication, specific number will vary based on project
Contingency	--	20%	--	Unforeseen items
Engineering	--	10 to 50%	--	Varies based on project

Assumptions

- Installation at existing multilane roundabout
- Pole-mounted installation
- One RRFB cabinet/controller per approach direction (two per leg)
- Accessible (audible) pedestrian signals
- Estimate provided for both direct power connection (one service cabinet per intersection) and solar power connection (one solar unit per controller)
- Wired communication between RRFB controller and RRFB heads (no wireless communication)
- Signing costs included
- Illumination, striping, traffic control, and other miscellaneous costs not included
- Engineering cost varies from 10% to 50% of construction cost. This can vary greatly depending on the contracting mechanisms used.

Additional Information and Links

- FHWA's Intersection Safety Technologies. http://safety.fhwa.dot.gov/intersection/resources/techsum/fhwasa09009/.
- FHWA Report: FHWA-SA-15-069—Accelerating Roundabouts in the U.S.: Volume I of VII—Evaluation of Rectangular Rapid-Flashing Beacons at Multilane Roundabouts Final Report.
- Oakland County HAWK and RRFB Study. http://www.rcocweb.org/Lists/Publications/Attachments/126/HAWK%20Final%20Report%202011.pdf.

Raised Pedestrian Crossing

Crossing improvement category: Traffic calming treatment
Purpose(s): Physical cue to encourage the reduction of vehicular speeds
Cost: $8,000–$39,000 (Drainage improvements not included)

Figure B-4. Raised crosswalk at two-lane roundabout.

Figure B-4 shows an installation of a raised pedestrian crosswalk at the entry leg of a two-lane roundabout in Golden, Colorado. This location was studied as part of *NCHRP Report 674*.

Raised pedestrian crossings (RPC) or raised crosswalks are essentially speed tables installed at crossings on approaches of an intersection or mid-block locations. Construction involves the installation of an elevated crossing platform, along with transition slopes connecting the raised platform to the pavement. Pavement markings and signage are generally used to make the raised crossing visible to drivers. RPCs can be constructed from asphalt or concrete, and even some temporary plastic treatment exists. The treatment alternatives further differ in the RPC's vertical elevation (relative to the pavement), and the transition slope between pavement and RPC (a flatter slope corresponds to a longer transition, given the same vertical elevation of the RPC).

Functionality and Purpose

Raised crosswalks are installed to reduce vehicle speeds as a function of the height relative to pavement surface and the degree of the transitional slope. A low and a gently sloping raised crosswalk would likely have higher speeds as vehicles easily maneuver over the crosswalk. Likewise, a steep incline to a high raised crosswalk could result in significant speed reductions; however, the reduced lane capacity may outweigh the benefit of the reduction in speed. Raised crosswalks also introduce vertical obstructions for emergency vehicles and snow plows that need to be considered; however, these treatments have been installed in some extreme snow fall locations. Studies show that drivers are more likely to yield to pedestrians when traveling at slower speeds.

Effectiveness

At a two-lane roundabout in Golden, RPCs were installed on the entry and exit lanes of one approach. Before installation, the orientation and mobility intervention rate was about 2.4%, and pedestrians experienced an average delay of 16.0 seconds. After treating the site with raised crosswalks, the intervention rate was reduced to 0.0%, and the average delay to 5.8 seconds. The 85th percentile delay was reduced from 31.0 to 13.4 seconds. Additional raised crosswalk results in combination with RRFBs were summarized in Tables B-6 and B-7.

In this research, raised crosswalks were tested at five CTLs, with three of those resulting in 0% to 2% interventions. For two sites, the intervention rates were 8%, which was attributed to added effects of poor pedestrian visibility and high ambient noise.

RPCs are also accessible for mobility impaired pedestrians and help pedestrians who are blind to stay within the crosswalk as they cross. RPCs require detectable warning surfaces on the pedestrian way where it transitions to the vehicular way, both on the corner and on the splitter island.

Limitations

- Raised crosswalks should not be used when sight distance is limited or vertical grade is steep.
- RPCs may hinder the maneuverability of heavy trucks, buses, and emergency vehicles depending on the slope and height of the RPC.
- Multiple raised devices at each approach can be disruptive to traffic and may reduce the overall capacity of the intersection or street.
- Drainage, runoff, and general maintenance will need to be considered in designing RPCs.

Cost Summary

Table B-10. Summary of cost estimate for a RPC.

Infrastructure	Cost Range (2014$)*	Cost Unit
Raised pedestrian crossing (asphalt)	$8,000–$15,000	Per leg
Raised pedestrian crossing (brick pavers)	$16,000–$39,000	Per leg

*Cost range does not include drainage improvements, which may be necessary.

Assumptions

- Installation at existing multilane roundabout
- 3.5 in. maximum height for RPC
- RPC dimensions in direction of travel: 6 ft long slope from existing grade to 3.5 in. height, 10 ft long full height, 6 ft long slope from 3.5 in. height to existing grade
- Roundabout approach width = 30 ft
- Concrete pedestrian area within splitter island raised 3.5 in. to match RPC elevation
- Splitter island width at pedestrian area = 10 ft
- No grinding/milling of existing pavement surface
- Curb ramp modifications may be needed. The cost estimate assumes ramps are present on the outside and modifications are needed, but ramps are not present at the splitter island (but through design)
- Drainage improvements may be required due to RPC installation, but are not included in the cost estimate
- Engineering cost varies from 10 to 50% of construction cost. This can vary greatly depending on the contracting mechanisms used

Additional Information and Links

- PEDSAFE's Countermeasure Selection System. http://www.walkinginfo.org/pedsafe/pedsafe_curb1.cfm?CM_NUM=27.
- *NCHRP Report 674*. http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_674.pdf.
- NCHRP 03-78B Final Report.

Table B-11. Cost estimate details for a RPC installation.

Item	Unit	Assumed Unit Cost	Quantity	Need
Raised Pedestrian Crossing (asphalt)				
Asphalt pavement	Ton	$70–$100	~20 tons per leg	Required
Concrete pavement	Square yard	$30–$50	~25 square yards per leg	Required
Asphalt tack coat	Gallon	$5–$10	~200 gallons per leg	Required
Ramp modification	Each	$1500	2 (assumes splitter island is cut-through)	Varies by site
Contingency	--	20%	--	Unforeseen items
Engineering	--	10% to 50%	--	Varies based on project
Raised Pedestrian Crossing (brick pavers)				
Brick pavers	Square foot	$10–$20	~600 square feet per leg	Required
Excavation (12 in. below grade)	Cubic yard	$10–$15	~50 cubic yards per leg	Required, but depth may vary
Aggregate base (3/4 in. minus @ 12 in. thickness)	Ton	$10–$20	~100 tons per leg	Required
Ramp modification	Each	$1500	2 (assumes splitter island is cut-through)	Varies by site
Concrete pavement	Square yard	$30–$50	~65 square yards per leg	Required
Contingency	--	20%	--	Unforeseen items
Engineering	--	10 to 50%	--	Varies based on project

Sound Strips

Crossing improvement category: Pedestrian information treatment
Purpose(s): Provide pedestrians with audible information to make informed crossing decisions
Installation cost: Less than $5000 per leg

Sound strips are installed at roundabouts and CTLs primarily to provide auditory cues to blind pedestrians. As a vehicle traverses a sound strip, the tires rolling over the surface produce sound patterns that provide information about the approach speed of the vehicle.

Functionality and Purpose

A number of strips are installed across the roadway on the approach to the crosswalk at prescribed distances to generate auditory cues of approaching and/or yielding vehicles. At one installation in Charlotte, North Carolina, a spacing of 30 ft was used to generate an audible tone in one-second intervals for a vehicle traveling 30 ft per second (approximately 20 miles per hour). As the vehicle slows down (to yield) the time between sounds increases, thereby giving the pedestrian additional information about vehicle dynamics. The treatment can also provide

Figure B-5. Sound strips at a CTL.

Figure B-5 shows an installation of sound strips in a channelized right turn-lane in Charlotte, North Carolina. This location was studied as part of NCHRP Report 674.

information about the availability of crossable gaps. As an added benefit, the driver may be more cautious when approaching the crosswalk due to the additional sound cue provided by the treatment.

Effectiveness

Newly installed sound strips were studied at intersections with CTLs in Charlotte and Boulder, Colorado. Charlotte was a before-and-after study at the same locations, one with sound strips only, and one with sound strips and a flashing beacon. The Boulder study evaluated two CTLs at the same intersection, with one having sound strips installed.

The Charlotte results found a decrease in orientation and mobility interventions as well as average pedestrian delay as shown in Tables B-12 and B-13. However, the resulting accessibility performance showed some challenges remaining even with the treatment. The Boulder site showed no interventions in either condition but a slightly lower delay with the sound strips. The sample size for the assessment of sound strips at CTLs was limited with only two locations, and thus, the results are not conclusive.

Table B-12. Summary of sound strip effectiveness at CTLs—orientation and monitoring interventions (%).

Location	Treatment Type	No Treatment	With Treatment
Charlotte, NC	Sound strip only	9.4%	2.9%
Charlotte, NC	Sound strip and beacon	5.6%	1.4%
Boulder, CO	Sound strip only	0.0%	0.0%

Table B-13. Summary of sound strip effectiveness—pedestrian delay (sec).

Location	Treatment Type	No Treatment	With Treatment
Charlotte, NC	Sound strip only	26.2	18.5
Charlotte, NC	Sound strip and beacon	23.4	12.2
Boulder, CO	Sound strip only	13.0	9.8

Limitations

Sound strips have not been fully developed as a functional crossing treatment and should be further investigated. The treatment studied at the Charlotte intersection was a temporary raised marking strip approximately ¼ in. thick (height above pavement) and 4 in. wide. Permanent treatment materials are available to study and are under consideration. In addition, several milled rumble strip configurations exist that may provide audible cues with minimal disruption to vehicular traffic.

Cost Summary

Cost is dependent on the material used and installation method. For milled rumble strip configurations the costs may increase due to the specialized equipment needed to mill, the availability of this equipment, whether the work is contracted or done by in-house resources, and the type of configuration used.

Additional Information and Links

- FHWA Sound Strip Evaluation Study. http://www.fhwa.dot.gov/publications/research/safety/pedbike/05080/03.cfm.
- *NCHRP Report 674*. http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_674.pdf.
- NCHRP 03-78B Final Report.

Flashing Beacon

Crossing improvement category: Driver information treatment
Purpose(s): Improvement to static warning signage
Cost (per leg): $25,000–$46,000

Flashing beacons are installed on overhead signs, in advance of the crosswalk, or on signs at the entrance of a crosswalk to make it more visible to drivers. The flashing beacon should be installed in an "active-when-present" mode, where the device rests in dark, and begins flashing after a push button (or passive) activation by a pedestrian. They can utilize a single beacon, or multiple beacons in a "wig-wag" configuration.

Functionality and Purpose

Flashing beacons are typically installed at uncontrolled intersections when used for pedestrian crossings.

Figure B-6. Flashing beacon at CTL.

Figure B-6 shows an installation of a yellow flashing beacon in a channelized right-turn lane in Charlotte, North Carolina. This location was studied as part of *NCHRP Report 674*.

Effectiveness

A flashing yellow beacon was studied at an intersection with CTLs in Charlotte, North Carolina, as a supplement to sound strips. The results found a decrease in orientation and mobility interventions, as well as average pedestrian delay over the pre-treatment condition, as well as some added benefit over the sound strip only location. The sample size for the assessment of sound strips at CTLs was very limited; thus, the results are not conclusive. Results of the Charlotte flashing beacon were summarized in the section on sound strips.

Pedestrian-actuated beacons with audible information devices are likely to be more effective for improving the accessibility to pedestrians who are blind because they provide a clear indication of when vehicles are most likely to yield.

Limitations

A standard yellow flashing beacon is believed to be less visible to drivers than an RRFB.

Cost Summary

Table B-14. Summary of cost estimate for a flashing beacon installation.

Infrastructure	Cost Range (2014$)	Cost Unit
Flashing beacon—direct power (initial leg)	$34,000– $46,000	Per leg
Flashing beacon—direct power (subsequent legs)	$30,000–$40,000	Per leg
Flashing beacon—solar power (all legs)	$25,000–$33,000	Per leg

Table B-15. Cost estimate details for a flashing beacon installation.

Item	Unit	Assumed Unit Cost	Quantity	Need
Service cabinet + foundation	Each	$3,000	1 per intx	Required for direct power connection
Solar power unit	Each	$250	4 per leg	Required for solar power connection
Flashing beacon controller + cabinet	Each	$2,500	2 per leg	Required
Pedestrian signal pole (no mast arm) + foundation	Each	$1,250	4 per leg	Required
Flashing beacon display head	Each	$500	4 per leg	Required
Audible push button assembly	Each	$950	4 per leg	Required
Aluminum sign assembly	Each	$300	6 per leg	Number may vary based on agency standards
Conduit trench + conduit + wiring	Linear foot	$30	100 feet per leg	Required for wired power/communication, specific length will vary based on project
Junction box	Each	$450	4 per leg	Required for wired power/communication, specific number will vary based on project
Contingency	--	20%	--	Unforeseen items
Engineering	--	10 to 50%	--	Varies based on project

Assumptions

- Installation at existing multilane roundabout
- Pole-mounted installation
- One flashing beacon cabinet/controller per approach direction (two per leg)
- Accessible (audible) pedestrian signals
- Estimate provided for both direct power connection (one service cabinet per intersection) and solar power connection (one solar unit per controller)
- Wired communication between flashing beacon controller and flashing beacon heads (no wireless communication)
- Signing costs included
- Illumination, striping, traffic control, and other miscellaneous costs not included
- Engineering cost varies from 10 to 50% of construction cost. This can vary greatly depending on the contracting mechanisms used.

Additional Information and Links

- *NCHRP Report 674*. http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_674.pdf.

Cost Database Information

The University of North Carolina Highway Safety Research Center maintains a database of costs for pedestrian and bicycle improvements (Bushell et al., 2013). This database was searched for the treatments described in Appendix B, and aggregate results are shown below in Table B-16. The treatments were not installed at roundabouts, and the costs are provided here as a secondary source of information for gauging the relative cost differences between the various treatments. Most costs in the database appear to be based on studies and cost estimates, rather than bids for construction projects.

Table B-16. Summary of cost estimates from UNC pedestrian and bicycle database (Bushell, 2013).

Infrastructure	Median	Average	Minimum	Maximum	Cost Unit	Number of Sources (Observations)
Pedestrian hybrid beacon	**$51,460**	$57,680	$21,440	$128,660	Each	9 (9)
Rectangular rapid-flashing beacon	**$14,160**	$22,250	$4,520	$52,310	Each	3 (4)
Raised crosswalk	**$7,110**	$8,170	$1,290	$30,880	Each	14 (14)
Flashing beacon	**$5,170**	$10,010	$360	$59,100	Each	16 (25)

References

Bushell, M.A., B.W. Poole, C.V. Zeeger, D.A. Rodriguez. 2013. "Costs for Pedestrian and Bicyclist Infrastructure Improvements." University of North Carolina Highway Safety Research Center, Chapel Hill, North Carolina.

Schroeder, B., K. Salamati, N. Rouphail, D. Findley, E. Hunter, B. Phillips, J. Barlow, and L. Rodergerdts. 2015. Accelerating Roundabout Implementation in the United States—Volume I of VII: Evaluation of Rectangular Rapid-Flashing Beacons (RRFB) at Multilane Roundabouts. FHWA-SA-15-069. Federal Highway Administration, Washington, D.C.

Summary Table of Pedestrian Crossing Treatments

Treatment Category	Purpose and Functionality	Pedestrian Crossing Treatment	Cost	Effectiveness
Driver information treatments	*Improvements to standard pedestrian signage. May include APS-equipped signals or beacons that can be effective at stopping traffic and at providing the pedestrian with visual and auditory cues of when the crossing phase is active*	Continuous flasher	$$	*
		In-roadway warning sign	$	**
		Active-when-present flasher	$$	**
		RRFB	$$	**
		Pedestrian-actuated traditional signal	$$$	***
		Pedestrian hybrid beacon	$$$	***
Traffic calming treatments	*Traffic calming is a method of designing streets using visual or physical cues to encourage drivers to reduce speeds. May include modification of crosswalk location or an alternative crossing location at roundabouts*	Posting lower speed	$	**
		Raised crosswalks	$$	***
		Traffic calming at crosswalk	$$	***
		Offset exit crossing	$$	***
		Adding deceleration lane	$$$	**
		Acceleration lane removal	$$	***
Pedestrian information treatments	*Treatments that provide pedestrians with audible information that can be used to make more informed decisions*	Surface alterations/rumble strips	$	**
		Active-when-present flasher with APS	$$	**
		Pedestrian hybrid signal with APS	$$$	***
Grade separated crossing	*Grade separation allows pedestrians to cross the road without affecting the movement of vehicles*	Pedestrian overpass	$$$	**
		Pedestrian underpass	$$$	**

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TDC	Transit Development Corporation
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation

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