

Strategies for Effective Roundabout Approach Speed Reduction

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FINAL REPORT

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EXECUTIVE SUMMARY

Roundabouts are a useful form of intersection design that have applicability in a variety of situations. Roundabouts can be used at low-volume and high-volume intersections as an alternative to traditional intersection control of stop signs and traffic signals, where such control forms are not warranted or efficient. Because roundabouts require a low speed on entry and circulation, they necessitate more adaptation to a high-speed setting, in order to encourage drivers to slow to the lower speeds suitable for entering and circulating the roundabout. Appropriate deceleration on approaches to roundabouts is primarily accomplished through the use of applicable geometric design principles; however, traffic control devices (specifically signing and markings on the approach) also serve a vital role in communicating to the approaching driver what speed profile should be anticipated. Information on suitable treatments to use at these locations is valuable to practitioners and can aid in the decision about which treatment(s) to install and/or study at a given location.

This report provides a resource for engineers to identify and select appropriate speed reduction treatments for high-speed approaches to roundabouts. The research examines best practices and research literature on speed reduction techniques for high-speed approaches for all intersection types, as well as treatments for work zones and horizontal curves. Included in the review is a summary of current design and traffic control device guidance in Minnesota, from the *MnDOT Road Design Manual* and *Minnesota Manual on Uniform Traffic Control Devices*, and a compilation of responses from practitioners with experience in designing and operating roundabouts with high-speed approaches. Guidance from within Minnesota includes discussion of how to determine a roundabout's fastest path and providing appropriate radii for entry, circulation, and exit maneuvers; selecting appropriate design vehicles and approach offsets; landscaping and maintenance concerns; and recommended signs, plaques, and pavement markings.

Feedback from practitioners was in the form of responses to 10 questions about their experiences with roundabouts with high-speed approaches, including geometric treatments, traffic control device treatments, changes in maintenance practices, crash history, and countermeasures considered or applied. Researchers contacted three groups of practitioners, based on input and guidance from the TAP: the Transportation Research Board (TRB) Roundabout Committee and listserv used heavily by more than 400 practitioners, the technical consultants on MnDOT list of pre-qualified contractors for roundabout work types, and the city and county staff who are on MnDOT's state-aid contact list. In total, during the month in which the practitioner request was conducted, researchers received nine responses from the TRB listserv and one updated contact person from the MnDOT prequalified list. Of these responses, four completed questionnaires were received, representing respondents from four states (Minnesota, Arizona, Kansas, and Wisconsin) and were employed by two state DOTs, a city, and a consultant. Common treatments described by the practitioners included splitter islands, approach curves, guide signs and diagrammatic signs (with spacing adjusted for speed-appropriate distances), and illumination. Respondents indicated very little change in routine maintenance, and they indicated that the number and severity of crashes declined after installation of roundabouts.

Researchers also reviewed previous research and existing guidance on speed reduction techniques from national documents (FHWA's *Roundabouts: An Informational Guide*, first and second editions) and guidance documents from four other states (Iowa, Kansas, Wisconsin, and Washington). These documents provide a representative sample of the material available to practitioners seeking guidance on design of high-speed roundabout approaches. Collectively these documents discuss appropriate ranges of values for inscribed circle diameter (90-180 ft) and splitter island length (50-200 ft), as well as considerations for illumination, advance signing and marking, and potential countermeasures to encourage speed reduction.

Based on the findings from the aforementioned efforts, researchers synthesized a selection of treatments, including traditional signs with and without beacons, pavement markings, illumination, speed-activated signs, and transition zones. Information on the effectiveness of these treatments, as well as potential costs of installation and maintenance, are provided for the practitioner to determine which treatment(s) best suit the site under consideration. Guidance is also provided for the methodology of conducting a speed study to determine the speed characteristics of a site, as well as links to resources for additional information.

Finally, the project identifies a number of research needs specific to particular treatments as well as the general need for field research of the recommended countermeasures specifically on approaches to high-speed rural roundabouts. Three general research needs apply broadly to the treatments discussed in this research:

- Establish that these countermeasures would achieve speed reductions on roundabout approaches that are similar to other locations (e.g., horizontal curves) where they are more commonly used.
- Determine the effects of a combination of multiple countermeasures, compared to single treatments used individually.
- Document the effectiveness of a single treatment relative to another single treatment, particularly for treatments of similar cost (e.g., compare two different warning signs, or two pavement marking treatments).

More specific research needs statements are also provided for infrastructure treatments (gateway treatments, illumination), pavement markings (transverse markings, lane narrowing), and signing (transition zones, long-term effectiveness).

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

Roundabouts are a useful form of intersection design that have applicability in a variety of situations. Roundabouts can be used at low-volume and high-volume intersections as an alternative to traditional intersection control of stop signs and traffic signals, where such control forms are not warranted or efficient. A key feature of roundabouts is their lower speed on entry and circulation, which is easily adaptable to urban, suburban, and neighborhood applications, but requires more adaptation to a high-speed setting, in order to encourage drivers to slow to the lower speeds suitable for entering and circulating the roundabout. Appropriate deceleration on approaches to roundabouts is primarily accomplished through the use of applicable geometric design principles; however, traffic control devices (specifically signing and markings on the approach) also serve a vital role in communicating to the approaching driver what speed profile should be anticipated. Information on suitable treatments to use at these locations is valuable to practitioners and can aid in the decision about which treatment(s) to install and/or study at a given location.

1.2 OVERVIEW OF THE RESEARCH AND REPORT

This report provides a resource for engineers to identify and select appropriate speed reduction treatments for high-speed approaches to roundabouts. The research examines best practices and research literature on speed reduction techniques for high-speed approaches for all intersection types, as well as treatments for work zones and horizontal curves. Based on the findings from those efforts, the report summarizes a selection of treatments, including traditional signs with and without beacons, pavement markings, illumination, speed-activated signs, and transition zones. Information on the effectiveness of these treatments, as well as potential costs of installation and maintenance, are provided for the practitioner to determine which treatment(s) best suit the site under consideration. Guidance is also provided for the methodology of conducting a speed study to determine the speed characteristics of a site, as well as links to resources for additional information.

This report is organized into five chapters:

- Chapter 1 is this introductory chapter.
- Chapter 2 summarizes a review of existing guidance in Minnesota and across the United States, as well as the research team's activities in documenting current practice on roundabout speed reduction.
- Chapter 3 describes analysis of previous research on speed reduction techniques.

- Chapter 4 provides a listing of recommended practices from which a practitioner can choose, as well as a discussion of evaluation methods to determine what specific issues exist at a roundabout and how best to treat them.
- Chapter 5 contains the research team's conclusions and recommendations.

CHAPTER 2: STATE OF THE PRACTICE

2.1 INTRODUCTION

A thorough review of potential treatments and countermeasures for high-speed approaches to roundabouts includes the context in which those treatments and countermeasures would be applied. That context requires an understanding of current practices used by agencies who operate such facilities. Task 1 of this project involved requesting and processing information from practitioners who have experience designing and/or installing roundabouts with high-speed approaches. This technical memorandum describes the activities conducted by the research team to complete the task.

2.2 CURRENT GUIDANCE IN MINNESOTA

2.2.1 MnDOT Road Design Manual

Information on design guidance for at-grade intersections is provided in Chapter 5 of the *MnDOT Road Design Manual (1)*, but Chapter 12 contains more detailed design guidelines for modern roundabouts. There are several sections within Chapter 12 that have particular relevance to this research question and are summarized here.

Section 12-3.02 discusses the feasibility of a roundabout. It says that feasibility for roundabouts begins with specifying a preliminary configuration. The configuration is specified in terms of the minimum number of lanes required on each approach and thus which roundabout category is the most appropriate basis for design: urban or rural, single-lane, or multi-lane. Roundabouts can be appropriate at high-speed intersections, especially those with a poor crash history.

Section 12-4.04 describes design principles for roundabouts. Subsection 12-4.04.01 summarizes the concept of the fastest path principle from the FHWA document *Roundabouts: An Informational Guide (2)* as “the smoothest, flattest path possible for a single vehicle, in the absence of other traffic and ignoring all lane markings, traversing through the entry, around the central island, and out the exit.” This principle is important because its use quantifies the highest speed at which a driver could travel through a roundabout. On a high-speed approach, the fastest path constraint needs to be made clear to the approaching driver to minimize the likelihood of a driver entering the roundabout at an excessive speed. Thus, the next subsection of Chapter 12, Subsection 12-4.04.02, discusses speed consistency. Speed consistency is described as a complementary aspect to the design principles of entry speed and deflection. The *MnDOT Road Design Manual* says that the “elements of the roundabout should be designed so that the relative speeds between consecutive geometric elements as well as between conflicting traffic streams be kept within certain design values. The benefit of achieving these speed consistencies is primarily safety-related, particularly reducing the likelihood of loss-of-control crashes, although entry capacity can benefit by reducing speed differential between entering and circulating traffic.”

The fastest path concept is used as a geometric basis for checking speed consistency, which underscores the importance of the design of the approach in providing a roundabout that is safe for drivers. Traffic control devices supplement the design and help to inform the driver what is expected, but the design provides the conditions on which the driving environment is based.

Using information from *Roundabouts: An Informational Guide (2)*, the *MnDOT Road Design Manual* describes the critical path radii in the fastest path concept, as well as their relationships. Figure 2.1 is a reproduction of Figure 12-4.04A in the *MnDOT Road Design Manual*, and Table 2.1 replicates Table 12-4.04A, describing the key design elements in the fastest path evaluation.

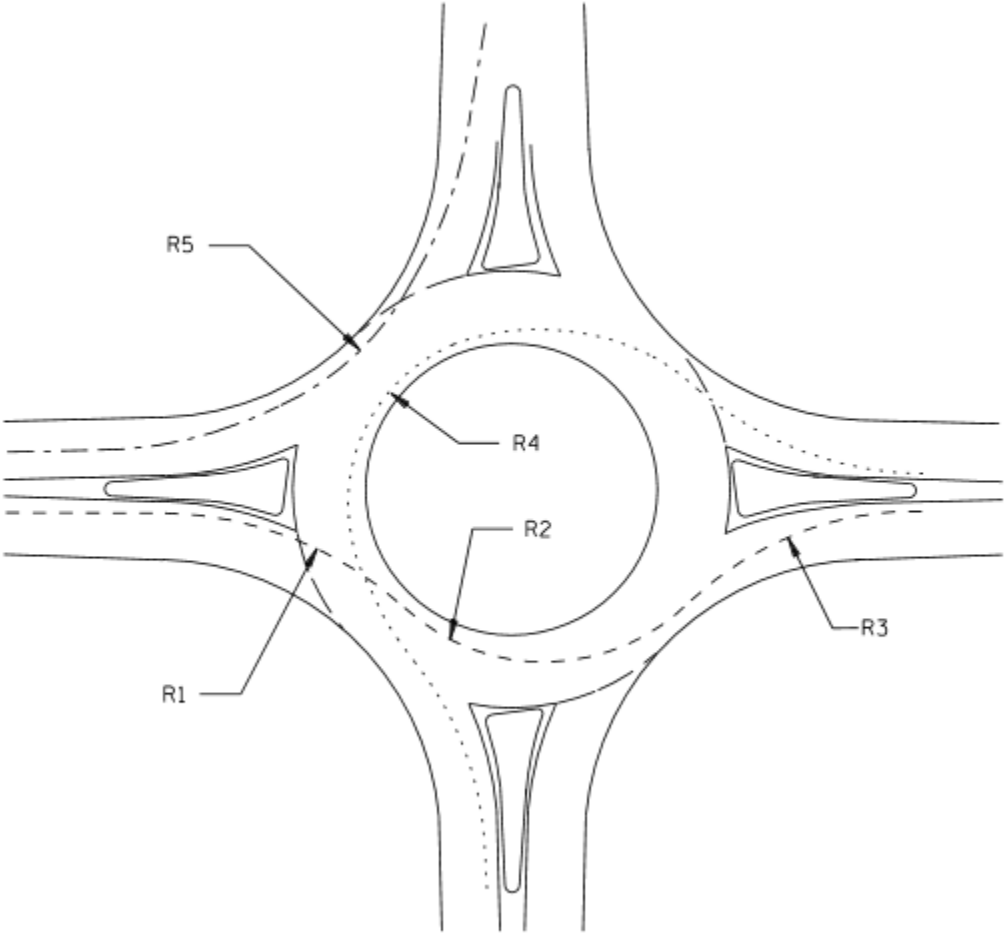


Figure 2.1 Fastest vehicle path radii. (1)

Table 2.1 Radii used to define the fastest path through a roundabout. (1)

Variable	Description
Entry Path Radius, R1	The minimum radius on the fastest through path prior to the yield line. This is not the same as Entry Radius.
Circulating Path Radius, R2	The minimum radius on the fastest through path around the central island.
Exit Path Radius, R3	The minimum radius on the fastest through path into the exit.
Left Turn Path Radius, R4	The minimum radius on the path of the conflicting left-turn movement.
Right Turn Path Radius, R5	The minimum radius on the fastest path of a right-turning vehicle.

The Manual states that, typically, the speed relationships between R1, R2, and R3 as well as between R1 and R4 are of primary interest. Along the through path, the desired relationship is $R1 > R2 < R3$, where R3 should not be less than R1. Similarly, the relationship along the left-turning path is $R1 > R4$. The difference in achieved design speed from R1 to R2 or R4 should be 6-8 mph (10-15 km/h) desirable and 12 mph (20 km/h) absolute maximum. For most designs, the R1/R4 relationship will be the most restrictive for speed differential at each entry. However, the R1/R2/R3 relationship should also be checked, particularly to ensure the exit design speed is not restrictive.

Subsection 12-4.04.03 of the Manual provides guidance on the design vehicle. It refers the reader to Chapter 5 for the four primary design vehicles, but it adds that the restrictive nature of roundabout geometry makes this decision a critical one, even though selection of the appropriate vehicle is dictated by site-specific circumstances. For this reason, the Manual says that a consideration of the consequences of usage of any roundabout approach by WB-62 vehicles –even where they are not the designated design vehicle – is strongly recommended. Additionally, usage or possible usage of the facility by unconventional vehicles (e.g. farm vehicles, oversized loads) must be researched and the design tailored to accommodate them accordingly.

Section 12-4.05 discusses geometric design criteria. Subsection 12-4.05.07 focuses on setting the approach offset to increase entry deflection, an important feature in encouraging drivers to slow to appropriate speeds on high-speed approaches. The Manual advises that the technique of offsetting the approach alignment left of the roundabout center is effective at increasing entry deflection (see Figure

2.2). However, this also decreases the entry angle Φ , which if decreased too far can create reduced capacity, unsafe entry conditions, line of sight issues, or unbalanced lane use. It also reduces the deflection of the exit on the same leg, which will increase the fast path speed at the entry. Therefore, the distance of the approach offset from the roundabout center should generally be kept to a minimum to maximize its effectiveness in design. Another effective method may be to increase the inscribed diameter slightly.

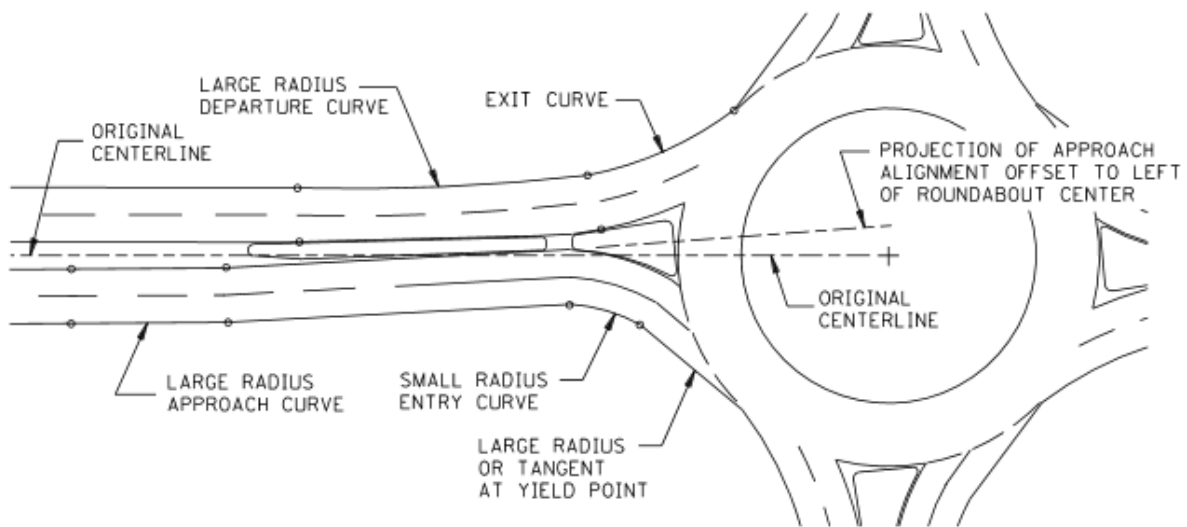


Figure 2.2 Approach offset. (1)

In Subsection 12-4.05.08, the Manual states that curbs are required at rural roundabouts also. It is important to modify the rural cross-section by introducing a curb/gutter as the highway approaches the roundabout. Curbs are used in the rural roundabout area to define the roundabout entry, calm approach speeds, and indicate a change in roadway environment. Designers should reduce the shoulder width by tapering a Design B curb and gutter toward the travel lane.

Subsection 12-4.06.03.2 describes the interaction between driver behavior and geometric elements. The designer is reminded that drivers approaching a roundabout must slow to a speed that will allow them to safely interact with other users of the roundabout and to negotiate the roundabout. The width of the approach roadway, the curvature of the roadway, and the volume of traffic present on the approach govern this speed. As drivers approach the yield point, they must check for conflicting vehicles already on the circulatory roadway and determine when it is safe and prudent to enter the circulating stream. The widths of the approach roadway and entry determine the number of vehicle streams that may form side-by-side at the yield point and govern the rate at which vehicles may enter the circulating roadway. The size of the inscribed circle affects the radius of the driver's path, which in turn determines the speed at which drivers travel through the roundabout. The width of the circulatory roadway determines the number of vehicles that may travel side-by-side through the roundabout.

Section 12.5 discusses some common maintenance considerations. Subsection 12-5.01 focuses on snow and ice operations, stating that a goal of snow and ice operations is to effectively mitigate the visual impact that snow may have on the recognition of the roadway surface. When the visual perception of the roadway is lost, it is important for snowplow operators to have landmarks available to successfully navigate the roundabout approach and intersection. Without this guidance, unnecessary damage from the plow (or the snow it is moving) may occur to curbs, medians, light poles, and signage. Subsection 12-5.02 describes considerations for routine maintenance, with an emphasis on the central island and landscaping; in particular, the Manual states that all roundabouts must provide some form of visual conspicuity in the central island to promote safety. It also says that maintenance of pavement markings is important to provide positive feedback to drivers and may require a great deal of effort, but different pavement types, colors, surfacing and transitional curbing can provide visual feedback to the drivers and facilitate movement through the roundabout in lieu of pavement markings.

Section 12-7.0 further discusses the advantages and recommended guidelines of landscaping, including recommendations to make the central island and splitter islands more conspicuous, and to visually reinforce the geometry, intended circulation paths of all modes, and necessary decision-making. Proper landscaping helps to avoid obscuring the form of the roundabout, the signing, and pedestrian crossings, and it clearly indicates to drivers that they cannot travel straight through the intersection.

2.2.2 Minnesota MUTCD

The *Minnesota Manual on Uniform Traffic Control Devices* (MN MUTCD) (3) also contains some information specific to roundabouts. Chapter 2B provides standards and guidance for regulatory signs, and it states that a roundabout is the only type of intersection at which all approaches can be controlled by YIELD signs. If a raised splitter island is available on the left-hand side of a roundabout approach, an additional YIELD sign should be placed on the left-hand side of a multi-lane approach, and an additional YIELD sign may be placed on the left-hand side of a single-lane approach. Where the central island allows for the installation of signs, Roundabout Directional Arrow signs should be used to inform drivers of the appropriate direction of travel; ONE WAY signs may be used instead of or to supplement Roundabout Directional Arrow signs. Where the central island does not provide a reasonable place to install a sign, Roundabout Circulation Plaques should be placed below the YIELD signs on each approach. Figure 2.3 is a reproduction of Figure 2B-22 from the MN MUTCD and illustrates examples of regulatory and warning signing for a single-lane roundabout.

Chapter 2C, on warning signs, provides guidance that if an approach to a roundabout has a statutory or posted speed limit of 40 mph or higher, the Circular Intersection (W2-6) symbol sign (see Figure 2.4) should be installed in advance of the circular intersection. A ROUNDABOUT (W16-17P) educational plaque may be mounted above or below a Circular Intersection symbol sign on the approach to a roundabout but may not be used on an approach to a traffic circle. A TRAFFIC CIRCLE (W16-12P) educational plaque may be mounted above or below a circular intersection symbol sign on the approach to a traffic circle but may not be used on an approach to a roundabout. The relative importance of the

intersecting roadways may be shown by different widths of lines in the symbol. An advance street name plaque (see Section 2C.58) may be installed above or below an Intersection Warning sign.

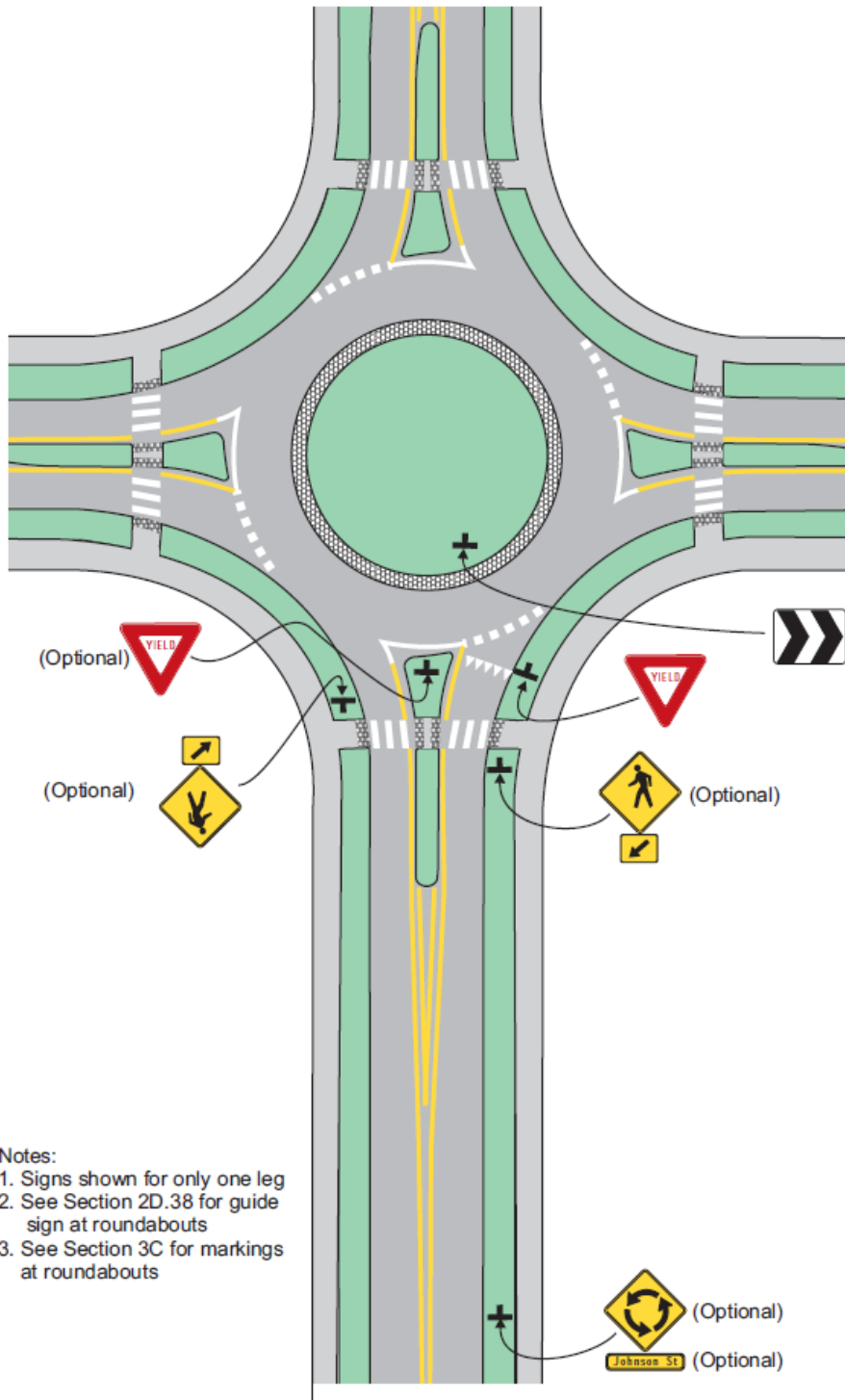


Figure 2.3 Example of regulatory and warning signs for a one-lane roundabout. (3)

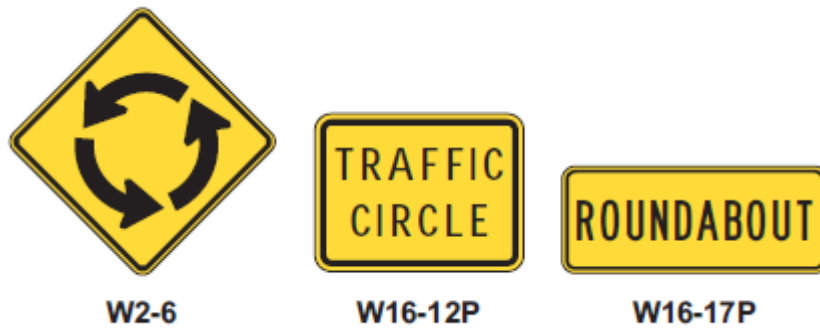


Figure 2.4 Warning signs for use on approaches to circular intersections. (3)

Chapter 3C contains the MN MUTCD’s standards and guidance on pavement markings at roundabouts. The Manual’s general guidance to open that chapter states that “pavement markings and signing for a roundabout should be integrally designed to correspond to the geometric design and intended lane use of a roundabout. Markings on the approaches to a roundabout and on the circular roadway should be compatible with each other to provide a consistent message to road users and should facilitate movement through the roundabout such that vehicles do not have to change lanes within the circulatory roadway in order to exit the roundabout in a given direction.” (3) The Manual provides multiple examples of markings for different configurations of roundabouts and roundabout approaches; representative examples are reproduced here as Figure 2.5 and Figure 2.6.

Section 3C.6 provides the option that lane-use arrows may be used on any approach to and within the circulatory roadway of any roundabout. YIELD (word) and YIELD AHEAD (symbol or word) pavement markings (see Figure 2.5) may be used on approaches to roundabouts.

Word and/or route shield pavement markings may be used on an approach to or within the circulatory roadway of a roundabout to provide route and/or destination guidance information to road users.

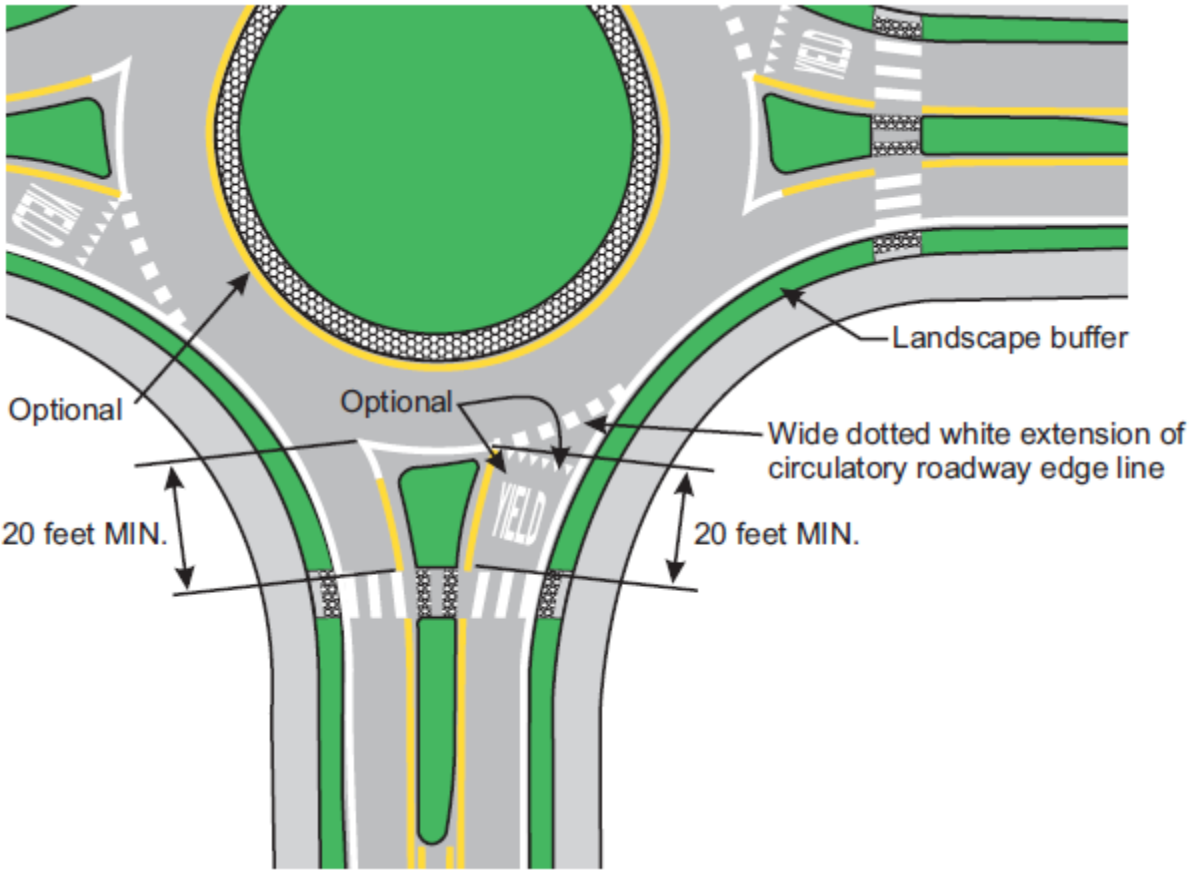


Figure 2.5 Example of markings for approach and circulatory roadways at a roundabout. (3)

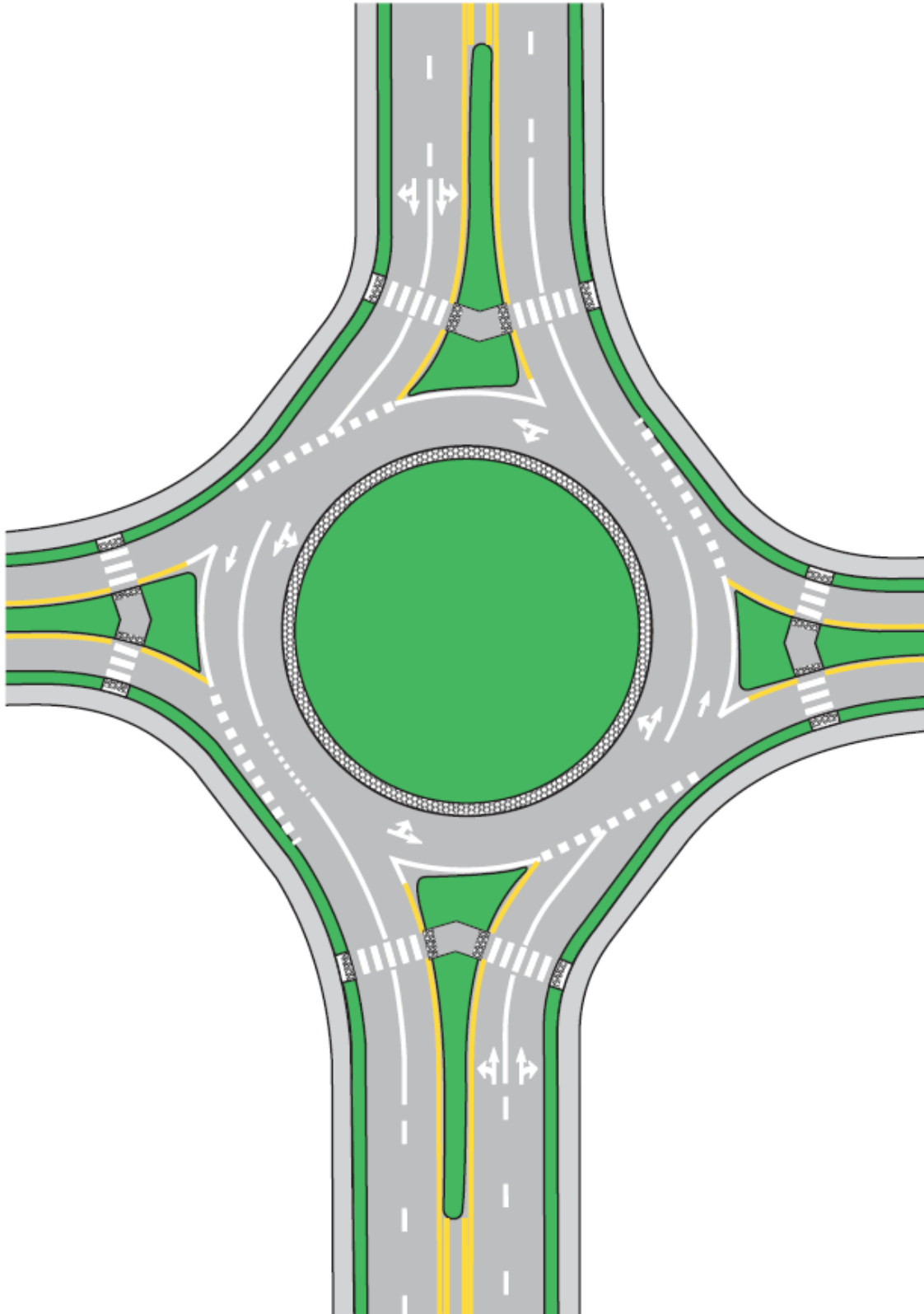


Figure 2.6 Example of markings for a two-lane roundabout with one- and two-lane approaches. (3)

2.3 REQUEST FOR PRACTITIONER INFORMATION

To better understand the current practices of practitioners in Minnesota and elsewhere in the United States, relative to the guidance described in the previous sections, the research team requested information on the experiences of practitioners who have designed and/or installed roundabouts with high-speed approaches. The intent of this task was to request information on the documented experiences that these practitioners have had on treatments they have considered or used on high-speed approaches and the results they have observed.

The research team began with a draft set of questions to share with the project's Technical Assistance Panel (TAP) at the kickoff meeting. The panel members were asked to provide their feedback on the questions at that meeting and a revised draft set of questions was developed based on the panel's comments. The panel reviewed the revised draft and, after making some additional changes, the final list of questions was approved by the panel for use. The questions were also submitted to the Institutional Review Board (IRB) at Texas A&M University for their approval to ensure compliance with requirements and guidelines for research involving human subjects; IRB determined that the question list was appropriate and deemed it exempt from further review.

The final list contained 10 questions, the text of which is reproduced here:

1. Within your jurisdiction, do you have any roundabouts with high-speed (i.e., > 40 mph) approaches, or do you have experience installing such roundabouts in other locations? (*Skip remaining questions if answer to Question 1 is "no"*)
2. What are the locations of the roundabouts referred to in your answer to Question 1?
3. What kind of geometric treatments (e.g., horizontal curvature, channelizing island, etc.) were used on the high-speed approaches that are not typically used on low-speed approaches?
4. What kind of traffic control device treatments (e.g., advance signs, beacons, pavement markings, pylons, etc.) were used on the high-speed approaches that are not typically used on low-speed approaches?
5. What kind of geometric or traffic control device treatments were used on the high-speed roundabout approaches that are not typically used on high-speed approaches for other intersection types (e.g. two-way or all-way stop-controlled, signalized, T intersections, etc.)?
6. Thinking about the treatments described in Questions 3 and 4, what changes in maintenance have you experienced at the treated sites (e.g., replacement of signs, snow removal, etc.)?
7. How have you identified and documented crashes and safety issues at roundabouts with high-speed approaches? This could include formal crash reports, or it could include indicators of incidents such as tire marks, damaged signs, or roadside intrusions observed in the field indicating unreported crashes. What indicators do you use to determine that speed was a factor in a crash?
8. Do you have locations of roundabouts with high-speed approaches with no documented crashes or indicators?
9. What countermeasures were considered and/or implemented to prevent or reduce crashes or indicators of incidents on high-speed approaches?

10. What effects on crash frequency or severity were documented after the treatments in Question 9 were installed? Was there a reduction in treatable crashes or indicators of incidents?

With the question list finalized, researchers contacted three groups of practitioners, based on input and guidance from the TAP: the Transportation Research Board (TRB) Roundabout Committee and listserv used heavily by more than 400 practitioners, the technical consultants on MnDOT list of pre-qualified contractors for roundabout work types, and the city and county staff who are on MnDOT's state-aid contact list. The question list was sent to the state-aid contact list through the TAP; researchers contacted the TRB listserv directly, and with help from TAP members, obtained the contact information for the 12 consultants on the pre-qualification list to contact them directly by e-mail as well. The 12 firms on the pre-qualification list were:

- Bolton & Menk, Inc.
- DLZ National, Inc.
- GHD INC
- HDR Engineering, Inc.
- Kimley-Horn and Associates, Inc.
- MTJ ENGINEERING, INC.
- Short Elliott Hendrickson, Inc.
- SRF Consulting Group, Inc.
- Stantec Consulting Services Inc.
- Stonebrooke Engineering, Inc.
- Toltz, King, Duvall, Anderson and Associates, Inc.
- WSB & Associates, Inc.

2.4 PRACTITIONER RESPONSES

During the first week after the requests were sent to the various practitioner groups, the research team received six responses from TRB listserv participants, one of which was a completed survey and one of which was a request to contact by telephone to complete the questionnaire through an interview. Researchers conducted the phone interview with that respondent within the same week. Remaining responses from the TRB listserv were either suggestions for additional practitioners for researchers to contact or suggestions on additional literature to review. There were no responses from the MnDOT prequalified list or the state-aid list.

During the following two weeks, researchers sent reminders to the three groups and received two additional completed surveys from the TRB listserv, as well as one response with no high-speed roundabouts in his jurisdiction. One response was received from the MnDOT prequalified list, providing the name of the most appropriate contact person within that firm; a follow-up e-mail was sent to that contact person, but no response was ever provided. No responses were received from the state-aid list.

In total, during the month in which the practitioner request was conducted, researchers received nine responses from the TRB listserv and one updated contact person from the MnDOT prequalified list. Of these responses, four completed questionnaires were received, representing respondents from four states (Minnesota, Arizona, Kansas, and Wisconsin) and were employed by two state DOTs, a city, and a consultant. The remainder of this section will describe the responses from those four completed questionnaires.

2.4.1 Responses to Question 1

Question 1 asked practitioners: *“Within your jurisdiction, do you have any roundabouts with high-speed (i.e., > 40 mph) approaches, or do you have experience installing such roundabouts in other locations? (Skip remaining questions if answer to Question 1 is “no”)”*

As could be expected, each of the four respondents answered “yes” to this question. An additional questionnaire was returned with an answer of “no”, leaving the answers to the remaining questions blank. The research team had intended to gain an appreciation for how many practitioners had no previous experience with high-speed approaches by counting the number of “no” answers to this question, but the lack of response provided no meaningful information to that effect.

2.4.2 Responses to Question 2

Question 2 asked practitioners: *“What are the locations of the roundabouts referred to in your answer to Question 1?”*

The respondent from Wisconsin provided a general answer: “Facilities include two-lane rural roadways, multi-lane expressways (with at-grade intersections) and interchange exit ramps.” The remaining respondents provided specific locations for their answers. Scottsdale, Arizona, has one intersection of interest, at Hayden Road and Northsight Boulevard. The state of Kansas has nine such intersections on their state highway system, and the respondent from Minnesota described 12 intersections, including Trunk Highways (THs), County State Aid Highways (CSAHs), county roads, and city streets. The Minnesota respondent provided a Google Earth file containing pushpins noting each of the locations, and the research team created similar files for the other sites.

2.4.3 Responses to Question 3

Question 3 asked practitioners: *“What kind of geometric treatments (e.g., horizontal curvature, channelizing island, etc.) were used on the high-speed approaches that are not typically used on low-speed approaches?”*

Common treatments among the practitioners included introducing horizontal curvature and curbing (typically on the splitter island but perhaps also on the right edge of traveled way instead of shoulder) at a greater distance from the intersection than usually found on low-speed approaches. One respondent specified that reconstruction limits with the introduction of first horizontal curve may be 1000 feet or

more in advance of the roundabout. References were made to the Wisconsin DOT (WisDOT) *Facilities Development Manual* (FDM) [Figure 30.19 High-Speed Roundabout Approach](#) and to AASHTO *Green Book Exhibit 10-73 Minimum Deceleration Lengths for Exit Terminals with Flat Grades of Two Percent or Less* (NOTE: this exhibit is Table 10-5 in the current 2011 edition of the *Green Book*).

The AASHTO table was described in the context of designing to assume comfortable deceleration from the point drivers first encounter the curb and then slowing down to a comfortable speed to negotiate the roundabout, usually using a target speed of 15 mph (the speed figured to obtain at the yield line). Another respondent indicated that their roundabouts are generally designed for less than 30 mph, with a fastest path around 25 mph.

Additional treatments mentioned by the respondents included:

- An increased offset left to provide wider entry throat for oversize/overweight vehicles.
- Minimal landscaping in the central island, to keep maintenance at a minimum, but often small domes or a raised surface level to provide a visual cue that approaching drivers would need to drive around the island.

2.4.4 Responses to Question 4

Question 4 asked practitioners: *“What kind of traffic control device treatments (e.g., advance signs, beacons, pavement markings, pylons, etc.) were used on the high-speed approaches that are not typically used on low-speed approaches?”*

All of the respondents listed advance diagrammatic signs as a treatment they have used to provide drivers additional information, not only to inform them of an approaching roundabout, but also to indicate to drivers how to prepare for turns to their intended destination, especially on multilane roundabouts. One state installs yellow flashing beacons at selected roundabouts as an additional notice to the driver, particularly when a roundabout is new. Spacing of signs is adjusted for speed-appropriate distances, roadway lighting is commonly used to provide added illumination on the splitter island and central island, and one state installs rumble strips on approaches with posted speed limits at or above 55 mph.

2.4.5 Responses to Question 5

Question 5 asked practitioners: *“What kind of geometric or traffic control device treatments were used on the high-speed roundabout approaches that are not typically used on high-speed approaches for other intersection types (e.g. two-way or all-way stop-controlled, signalized, T intersections, etc.)?”*

Splitter islands and approach curves to transition to the appropriate entry speed were the most obvious geometric differences between roundabouts and other intersection types; while they could have applications for certain intersections with specific characteristics, those two treatments would not be automatically used at other intersection types as they would be for roundabouts. Guide signs were also commonly mentioned, as there are signs specifically intended for roundabouts in the MUTCD (e.g.,

Circular Intersection signs, ROUNDABOUT plaques, chevrons in the central island, etc.) that would not be used at other intersections. The application of lighting and rumble strips could be different for roundabouts than for other high-speed approaches. One state described additional treatments for multilane roundabouts: overhead signing to supplement the arrow pavement marking, ground-mounted signing for advance lane designation declaration, and pavement marking arrows within the roundabout.

2.4.6 Responses to Question 6

Question 6 asked practitioners: *“Thinking about the treatments described in Questions 3 and 4, what changes in maintenance have you experienced at the treated sites (e.g., replacement of signs, snow removal, etc.)?”*

Respondents indicated very little change in routine maintenance. Some accommodations have been made for roundabouts that serve oversized/overweight vehicles, by installing sign assemblies with pinned sleeves that are more easily removed and replaced. One respondent mentioned that they now recommend light poles be placed about 10 ft from the curb around the circle, rather than the 3 ft distance previously used, because some vehicles have lost control in snowy weather and hit the poles. In general, snow removal was not considered an issue for the states that commonly have snow; one specifically stated that maintenance groups have adapted very well by clearing the circulatory roadways into the truck apron and collecting the snow. Another state indicated that, for crashes that have needed to replace signs, the sign replacements have been less than would have been expected for another type of intersection.

2.4.7 Responses to Question 7

Question 7 asked practitioners: *“How have you identified and documented crashes and safety issues at roundabouts with high-speed approaches? This could include formal crash reports, or it could include indicators of incidents such as tire marks, damaged signs, or roadside intrusions observed in the field indicating unreported crashes. What indicators do you use to determine that speed was a factor in a crash?”*

Two of the four respondents stated that their agency has conducted a formal review of crash reports and safety performance. One review included several phased studies to evaluate crashes at roundabouts, and they started a road safety audit/assessment with select roundabouts, including ones with high-speed approaches. The other respondent said that they review crash records and collect traffic counts; their reported crash rate was the same, but injuries/severity were down 80 percent.

Multiple respondents confirmed that formal crash reports were not the only method of identifying potential safety problems; in one state, maintenance crews may report broken curbs, missing signs, and other items, and those logs can be requested by HQ, but they may not voluntarily report those items without asking. The state conducting the road safety audit offered that skid marks, debris, and near-misses are helpful in documenting the risk and can point to deficiencies that aren't evident from reviewing crash reports. They added that they are also looking into the human behavior aspects of

driving roundabouts, anticipating that they could learn more anecdotal information after discussions with the region safety engineers and stakeholders such as the drivers and representatives from the maintaining units of government.

Even for the agencies without a formal review of crash records, all of them indicated that the number of crashes and/or the severity of such crashes had declined since installing roundabouts. One state added that speed-related crashes tended to be single-vehicle crashes involving passenger vehicles.

2.4.8 Responses to Question 8

Question 8 asked practitioners: *“Do you have locations of roundabouts with high-speed approaches with no documented crashes or indicators?”*

All four responses to this question answered in the negative. The following response is representative of all four: *“Most everything has some sort of history of crashes or indicators. But all of the locations have had greatly reduced injuries and fatalities, despite the occurrence of crashes from time to time, and they have addressed the concerns for which they were installed. Many of them were locations at which there was a long-term documented trend of many crashes and/or injuries prior to installation of roundabouts and those concerns have essentially been eliminated.”*

2.4.9 Responses to Question 9

Question 9 asked practitioners: *“What countermeasures were considered and/or implemented to prevent or reduce crashes or indicators of incidents on high-speed approaches?”*

The two state DOTs mentioned a specific roundabout that received special review and treatment to reduce crashes. At one location, the DOT implemented countermeasures this summer at a problematic high-speed roundabout approach to improve safety. The countermeasures included mounding the central island, adding one-way chevron panels in the central island, installing transverse rumble strips at the approaches, adding a diagrammatic sign and altering signing locations closer to the roundabout. The roundabout is downstream from a partial cloverleaf interchange ramp, so further signing separation from the ramp was being sought.

The other DOT site was a multilane roundabout that had a particular problem with trucks that did not have an appropriate angle of approach and ran into the central island. Truck crashes occurred with regularity. The solution was to convert the intersection to a one-lane roundabout, which was accomplished through striping and realignment. The crash problem dropped significantly after the change was made.

Other than these two locations, in general, the respondents did not indicate that there have been any noteworthy crash problems at roundabouts. At some locations there were reports of problems with rear-end crashes because drivers stop in the circulatory roadway, as well as rear-end crashes at the yield line on entry due to trailing vehicles being more aggressive than lead vehicles. Those can sometimes be countered by additional signing or marking, though they do not want to lead to sign clutter, so spacing

of signs and content of signs is important. Generally, however, suitable geometric design and appropriate signing and marking have been sufficient. One respondent stated that roundabouts have frequently been the treatment for intersections, rather than the roundabouts needing subsequent treatments.

2.4.10 Responses to Question 10

Question 10 asked practitioners: *“What effects on crash frequency or severity were documented after the treatments in Question 9 were installed? Was there a reduction in treatable crashes or indicators of incidents?”*

For the first location described in the responses to Question 9, the DOT will conduct a formal review of the crash history after sufficient time has passed following the treatments. For the remaining locations, the general indication was that the crash rates have tended to be at or below the rates found prior to treatment, and severity has declined with the installation of roundabouts. One respondent mentioned that they regularly hire consultants with robust experience in high-speed roundabouts, so that the designs are thoroughly reviewed and anticipated problems dealt with prior to construction.

2.5 CONCLUSION

There is existing guidance, both within Minnesota and nationally, on geometric design and traffic control devices for roundabouts, though not much is provided specifically for high-speed approaches. However, the low level of response to the practitioners’ request for information suggests that either there are not many jurisdictions with high-speed roundabout approaches being constructed, or they have not experienced many concerns with them. In general, the responses received through this request have indicated that speed-appropriate geometric design principles can provide a good operating environment that can be supplemented with commonly used signs and markings. Any horizontal alignment features, whether they be curvature in the vicinity of the yield line (cf. Subsection 12-4.06.03.2 of the *MnDOT Road Design Manual*) or curvature added to the approach near the upstream end of the splitter island (as used by some practitioners in their responses), need to provide a proper transition into the target speed or fastest path speed for the circulating roadway, and approach curbing and visual treatments (e.g., mounding) on the central island provide advance cues to the driver that they will need to slow down to prepare to drive around the roundabout. Roadway lighting to illuminate the boundaries of the splitter island and central island was particularly useful to supplement the geometric design. Roundabout-specific signing found in the MUTCD (e.g., advisory/warning signs, diagrammatic route signs, etc.) provides additional cues to reduce speed as well as inform the driver of an upcoming decision point; there was little evidence of any experimental or novel signing, markings, or beacons used to inform or caution the driver that was not able to be accomplished through conventional traffic control devices.

CHAPTER 3: ANALYSIS OF PREVIOUS RESEARCH ON SPEED REDUCTION TECHNIQUES

3.1 INTRODUCTION

Excessive speed is cited as a contributing cause in 28% of fatal crashes nationwide (4). Traffic safety experts have researched speed reduction techniques through education, enforcement, and engineering. The literature summary presented in this report includes a range of engineering countermeasures evaluated for applications on horizontal curves, intersections, and tangent sections. In addition, federal and state guidance on speed reduction techniques specific to roundabouts are summarized.

Drivers select their speed based on a number of conscious and unconscious factors of perception and motivation. The perception of speed is determined by sight, hearing, and touch. The visual sensation of both forward and peripheral vision affect one's estimate of speed. The rate of change of the size of objects in the forward view, referred to as a perceptual constant τ , contributes to speed perception and estimates of time to contact with objects. Roadside objects streaming by in peripheral vision, called optical flow, also affect speed perception. Eye height above the road can also affect speed perception – one reason why go-karts feel so fast (5). Hearing also contributes to speed perception both in perceiving road noise, but also engine noise. The touch sensation is important, especially in high-frequency vibration, to estimate one's speed. The vestibular system is also involved in the perception of speed and lateral and longitudinal acceleration. In rural areas, especially, another perceptual process called speed adaptation causes drivers to underestimate their speed after driving at high speed for a period of time. So that, after driving 60 mph for a period of time, a driver may feel that 45 mph is excessively slow (6).

Beyond the pure sensory experience, there are more conscious factors at work for the selection of speed. Driver's motivation and emotional state affect speed choice (7). These also affect the level of risk a driver is willing to tolerate – risk of getting a speeding ticket and risk of crashing. The prevailing view is that drivers are willing to trade off safety for a gain in time (8).

The research team conducted an online search on roundabout design guidance documents for all states. The online search found:

- 20 states do not have a roundabout design guidance available online,
- 13 states use the 2000 Federal Highway Administration's (FHWA) *Roundabouts: An Informational Guide* as their main source (9)
- 15 states documents use 2010's *NCHRP Report 672, Roundabouts: An Informational Guide* (10) as their main source,
- Two states have design manuals that reference other documents

As a result, *NCHRP Report 672 Roundabouts: An Informational Guide*, and *FHWA Roundabouts: An Informational Guide* and other documents are summarized in the following sections. Because the scope of the project is speed calming and speed countermeasures the summary focuses on the guidance these documents give concerning speed at roundabouts. In addition, the research team focused on the design guidance from Iowa, Kansas, Wisconsin, and Washington State. The sections below provide a summary.

3.2 NATIONAL GUIDANCE DOCUMENTS

3.2.1 Federal Highway Administration (FHWA) Roundabouts: An Informational Guide

In the roundabout informational guide, the FHWA points out that roundabouts operate safely when the geometry forces drivers to enter and circulate at slow speeds. Narrow pavement widths and horizontal curves are used to reduce speed, however if widths and radii are reduced, then capacity is reduced. The following figure shows the approach speed profiles. Distances are measured from the center of the circle.

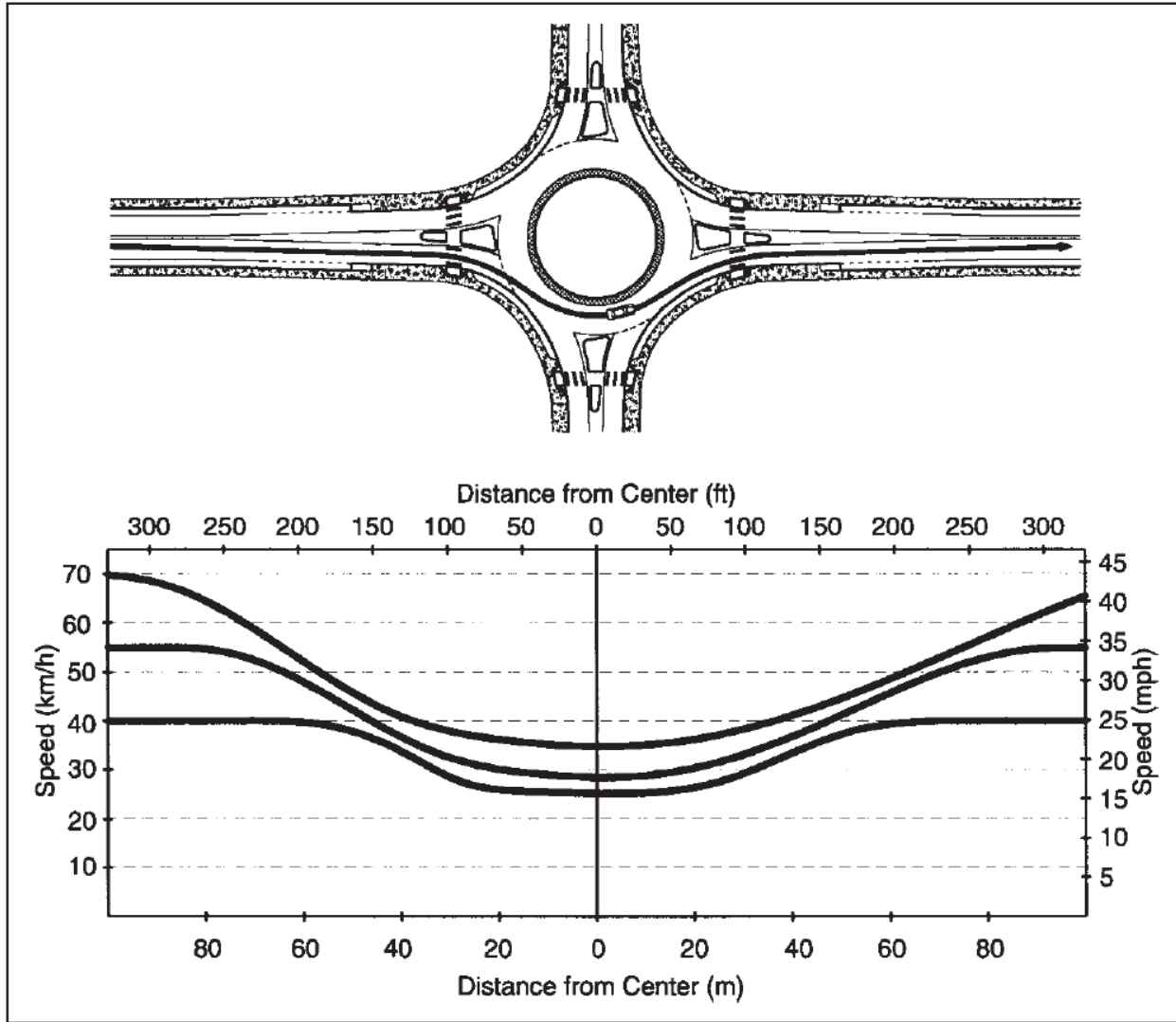


Figure 3.1 Sample of theoretical speed profile (9).

The greatest distance from the center in the exhibit is 325 feet. However, deceleration should begin before that. According to the Guide, increasing the vehicle path curvature decreases the speed (9).

3.2.2 NCHRP Report 672 Roundabouts: An Informational Guide

The second edition of *NCHRP Report 672: An Informational Guide* is meant as a useful tool for anyone interested in building or evaluating roundabouts (10). The report gives guidance on trade-offs of installing a roundabout, identifying whether implementation of a roundabout is appropriate, operational analysis, safety performance and analysis, geometric design, traffic control devices, illumination, landscaping, and maintenance of roundabouts.

In chapter 6 basic geometric elements are outlined (Figure 3.2). The maximum recommended design speeds at the entry of the roundabout are 20 to 25 mph for single-lane roundabouts, and 25 to 30 mph for multilane roundabouts. The report highlights that splitter islands should be provided at all single-lane roundabouts, and one of the purposes of islands is to assist on controlling speeds. The recommended minimum length is 50 ft, but the desirable length is 100 ft. For roundabouts on high speed roadways the report recommends a splitter island length of 150 ft or more.

Speed consistency between traffic streams of various movements within the intersection help minimize crash rates. Using the design of the fastest path can help in obtaining the theoretical entry speeds from the designed roundabout. Speed differential between entering vehicles and those already in the circulatory roadway should be minimized to be no more than 10 to 15 mph. In section 6.7.1.4 the guidance recommends that when attempting to achieve adequate vehicle speeds at single lane roundabouts it may be simple to reduce the entry path radius but this may impact safety. Other options include:

- Offsetting the alignment of the approach to the left.
- Increasing the size of the ICD that provides better approach geometry and deflection.
- Adjust the entry width or radii.

In chapter 6 the report gives the diameter range of the Inscribed Circle Diameter (ICD) range according to design vehicle. The ranges are shown in Figure 3.3.

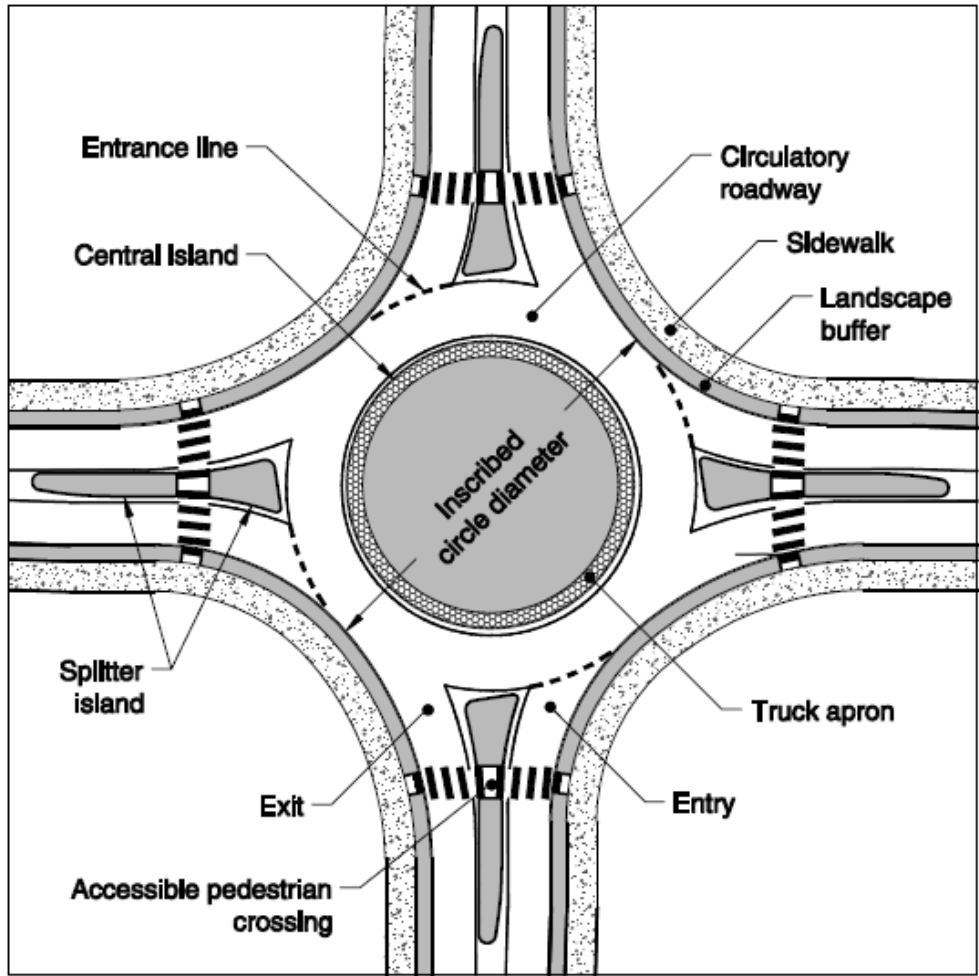


Figure 3.2 Exhibit 6-2 in NCHRP Report 672 Roundabouts: An Informational Guide (10)

Roundabout Configuration	Typical Design Vehicle	Common Inscribed Circle Diameter Range*	
Mini-Roundabout	SU-30 (SU-9)	45 to 90 ft	(14 to 27 m)
Single-Lane Roundabout	B-40 (B-12)	90 to 150 ft	(27 to 46 m)
	WB-50 (WB-15)	105 to 150 ft	(32 to 46 m)
	WB-67 (WB-20)	130 to 180 ft	(40 to 55 m)
Multilane Roundabout (2 lanes)	WB-50 (WB-15)	150 to 220 ft	(46 to 67 m)
	WB-67 (WB-20)	165 to 220 ft	(50 to 67 m)
Multilane Roundabout (3 lanes)	WB-50 (WB-15)	200 to 250 ft	(61 to 76 m)
	WB-67 (WB-20)	220 to 300 ft	(67 to 91 m)

* Assumes 90° angles between entries and no more than four legs. List of possible design vehicles is not all-inclusive.

Figure 3.3 Exhibit 6-9 in NCHRP Report 672 Roundabouts: An Informational Guide (10)

3.2.2.1 Traffic Control Devices

The report encourages engineers to use the Manual for Uniform Traffic Control Devices (MUTCD) as a guide. The document discusses the use of roundabout directional arrow signs, roundabout circulation plaque, and yield signs. The guide maintains that the Circular Intersection sign (W2-6) should be installed on each approach of a roundabout, especially if the roundabout is not clearly visible. When it comes to the plaque with the advisory speed that supplements sign W2-6 it can be difficult to define the advisory speed for a roundabout. The question is whether the advisory speed should be related to the slowest speed for through traffic, the slowest speed for all movements or another speed. The report concludes that the MUTCD is silent about advisory speed plaques for roundabouts. Though not expressly prohibited in the MUTCD, the report states “In practice it is difficult to define an appropriate advisory speed: Should it be related to the slowest speed for through traffic (V2), the slowest speed of all movements (typically V4), or another speed (such as zero for potentially coming to a stop at the yield sign)? In addition, advisory speed plaques are usually only used for turns and curves, not intersections” (10).

3.2.2.2 Lighting

Illumination can improve a driver’s understanding of roundabout operations. Roundabout lighting should create a break in the linear path of the approaching roadway in order to emphasize the circular aspect. The recommendations given to achieve this are:

- Ensure lighting is consistent between the roundabout and intersecting roadways
- If roadway lighting is not continuous then transition lighting should be provided
- Adequate lighting should be provided at the approach nose of the splitter islands, conflict areas, and all places where the traffic streams separate to exit roundabout
- Provide adequate lighting at pedestrian crossings

The primary source for lighting levels should be the Design Guide for Roundabout Lighting published by the Illuminating Engineering Society (IES). Recommendations for lighting levels are shown in Figure 3.4.

Functional Classification	Maintained Average Horizontal Illuminance on the Pavement Based on Pedestrian Area Classification			E_{avg}/E_{min}
	High	Medium	Low	
Major/Major	3.4 fc (34.0 lux)	2.6 fc (26.0 lux)	1.8 fc (18.0 lux)	3:1
Major/Collector	2.9 fc (29.0 lux)	2.2 fc (22.0 lux)	1.5 fc (15.0 lux)	3:1
Major/Local	2.6 fc (26.0 lux)	2.0 fc (20.0 lux)	1.3 fc (13.0 lux)	3:1
Collector/Collector	2.4 fc (24.0 lux)	1.8 fc (18.0 lux)	1.2 fc (12.0 lux)	4:1
Collector/Local	2.1 fc (21.0 lux)	1.6 fc (16.0 lux)	1.0 fc (10.0 lux)	4:1
Local/Local*	1.8 fc (18.0 lux)	1.4 fc (14.0 lux)	0.8 fc (8.0 lux)	6:1

Major = Roadway system that serves as the principal network for through traffic flow.

Collector = Roadway servicing traffic between major and local streets.

Local = Streets primarily for direct access to residential, commercial, industrial, and other abutting property.

High = Areas with significant numbers of pedestrians expected to be on the sidewalks or crossing the streets during the hours of darkness. Over 100 pedestrians during the average annual peak hour of darkness, typically 18:00 to 19:00 hours.

Medium = Areas where lesser numbers of pedestrians use the streets at night. Between 11 and 100 pedestrians during the average annual peak hour of darkness, typically 18:00 to 19:00 hours.

Low = Areas with low volumes of nighttime pedestrian usage. Less than 11 pedestrians during the average annual peak hour of darkness, typically 18:00 to 19:00 hours.

*Note: Use values for local/local functional classification if roundabout is located on roadway without continuous lighting.

Figure 3.4 Recommended levels for illuminance at roundabouts (10).

3.2.2.3 Landscaping

The report states that improving safety by making the central island more conspicuous and indicating to drivers that they cannot drive straight through the intersection are among the primary reasons to incorporate landscaping at roundabouts. Considerations should be given to avoid obscuring the roundabout or signing to the driver, and speed appropriate for the roadside environment of the location of the roundabout. In environments with higher approach speeds, fixed objects can introduce a potential safety risk. The report gives recommendations on objects that could be used, but does not provide specific instructions on which ones should be used and which ones should be avoided. If plants are being used in splitter islands and on the right side they might slow drivers down by creating a funneling effect. However, splitter islands should use low-growth plants and not have trees, planter boxes or light poles.

3.3 STATE GUIDANCE MANUALS

3.3.1 Iowa

The general guidance of the Iowa Department of Transportation (Iowa DOT) describes the difference between a modern roundabout, rotaries, and neighborhood traffic circles. Modern roundabouts slow all the vehicles to speeds between 10 and 25 mph. Roundabout geometry, splitter islands, and outside curbs deflect vehicles entering the circulating roadway, which can control speeds. The inscribed circle diameter for single-lane roundabouts is 100 to 130 feet, but the diameter may depend on design vehicle and intersection layout. Approach lane width is typically 12 ft per lane, entry width 14 to 18 ft. The recommended maximum entry design speed is 25 mph for rural and 20 mph for urban roundabouts (11).

3.3.1.1 Traffic Control Devices

The guidance document does not provide any specific guidance on signing at roundabouts.

3.3.1.2 Lighting

Illumination should be provided at all conflict areas, the beginning of splitter islands, crosswalks, entries and exits to the circular roadway.

3.3.1.3 Landscape

Chapter 6A-3 Modern Roundabouts – General Guidance does not provide specific guidance on landscaping at the central island. Grass and small plantings may be used between the roadway and the sidewalk.

3.3.1.4 Curbing

The manual lists truck aprons and outside curbing as key features of a roundabout. The truck apron between the central island and circulatory roadway should be between 2 and 4 inches in height. Outside curbs ideally should begin at the deceleration point on each approach.

3.3.2 Kansas

Figure 3.5 shows the guidance given in the Kansas Roundabout Guide for entry speeds at roundabouts.

Design Element	Mini Roundabout	Single-Lane Roundabout	Multilane Roundabout
Desirable maximum entry speed	15 to 20 mph	20 to 25 mph	25 to 30 mph
Maximum number of entering lanes per approach	1	1	2+
Typical inscribed circle diameter	45 to 90 feet	90 to 180 feet	150 to 300 feet
Central Island Treatment	Full traversable	Raised with traversable truck apron	Raised with traversable truck apron
Typical daily service volumes on 4-leg roundabout below which may be expected to operate without requiring a detailed capacity analysis (veh/day)*	Up to approximately 15,000	Up to approximately 25,000	Up to approximately 45,000 for two-lane roundabout

*Operational analysis needed to verify upper limit for specific applications or for roundabouts with more than two lanes or four legs.
NCHRP 672, Exhibit 1-9 (1)

Figure 3.5 Exhibit 1-6 from the Kansas Roundabout Guide (12).

The guide recommends entry speeds between 20 and 25 mph for single-lane roundabouts. The manual also counsels to exercise caution when considering placement of a roundabout at intersections with heavy flow of through traffic on the main street opposed by light traffic on the minor street, and intersections that regularly service oversized-vehicle traffic. The guide points out that an advantage to roundabouts is that they reduce vehicle speeds and that they are “beneficial in transition areas by reinforcing the notion of a significant change in the driving environment” (12). The guide also points out that roundabouts may be advantageous to older drivers because they slow traffic speeds. In Chapter 5 of the guide it further adds about speed:

- “Roundabouts slow vehicular speeds, which provides drivers more time to react to potential conflicts and reduces crash severities.
- Roundabouts generally reduce the speed differential between vehicles traveling through the intersection, which reduces crash severity.”

For reducing vehicle speeds the guide points out some of the recommendations outlined in section 6.7.1.4 of *NCHRP Report 672, Roundabouts: An Informational Guide* referenced earlier in the previous section of the document. Some additional strategies this guide points out are:

- Provide a more perpendicular approach
- Adjust curvature of the approach upstream of the entry

For roundabouts in high-speed rural environments the guide recommends:

- Larger inscribed circle diameters: a larger ICD accommodates large trucks and provides an increased visibility and speed control
- Extend the splitter islands: length of splitter island should equal the length it takes a vehicle to comfortably decelerate from the approach speed to the entry design speed. For high-speed approaches, the raised median of the splitter island should extend several hundred feet, and curbing and pavement markings should provide further channelization.
- Offsetting the approach alignment left of center: this can increase deflection and slow entry speeds. This could be done when increasing the ICD is not feasible.
- Use curbs: curbing can alert drivers that they are entering a more controlled environment, therefore encouraging them to slow down. Curbing can be extended the length of the required deceleration and beyond the splitter island.
- Approach curves: curves that are successively smaller in radii may reduce speeds.

3.3.2.1 Traffic Control Devices

Among the recommendations and standards in the guide, there is guidance for signs that warn drivers about a roundabout intersection. Figure 3.6 shows the assembly for the roundabout ahead sign



Kansas Department of Transportation

Figure 3.6 Exhibit 7-5 in the Kansas Roundabout Guide (12).

The sign assembly in Figure 3.6 recommends the use of plaque W13-1 which recommends the speed of approach to drivers. The manual recommends that all plaques should be installed on approaches with a speed limit of 40 mph or higher. Note that this diagram includes the advisory speed plaque as part of the recommended sign assembly which is different than the 2009 MUTCD guidance for the use of advisory speeds. The MUTCD states that advisory speed plaques may be used with any warning sign but does not illustrate any roundabout warning signs with the plaques, but does not expressly prohibit the practice.

3.3.2.2 Lighting

The guidelines state that proper lighting should be provided to help users identify the layout and operations of the roundabout so that motorists can safely traverse the intersection. Kansas does not have its own illuminance levels guide, but recommends the Illuminating Engineering Society (IES) guide shown in NCHRP Report 672 *Roundabouts: An Informational Guide*. Kansas adds guidance for illuminance at insulated rural intersections as shown in Figure 3.7.

Pavement Classification	Average Maintained Illuminance at Pavement	Uniformity Ratio (Eavg/Emin)	Veiling Luminance Ratio (Lvmax/Lavg)
R1	0.6 fc (6.0 lux)	4.0	0.3
R2/R3	0.9 fc (9.0 lux)	4.0	0.3

IES American National Standard Practice for Roadway Lighting

Figure 3.7 Exhibit 8-2 in the Kansas Roundabout Guide, IES lighting guide for rural intersections (12).

3.3.2.3 Landscaping

The Kansas Roundabout guide suggest that trees, bushes and other large items that would make the central island more conspicuous be placed in the central island. This would indicate to the drivers that they cannot travel through the intersection. Furthermore the central island should discourage pedestrian traffic. The manual says that trees with large canopies should be avoided in the central island. Spatial art should be located where it will not be struck by errant vehicles and should be outside of the sight triangles.

3.3.2.4 Curbing

For the curbs on the outside edge of the roundabout and approach legs, they should be KDOT's 6-inch standard curb. The truck apron should be a 3-inch curb and the central island may be 6- or 8-inch curb.

3.3.3 Wisconsin

The Wisconsin Design Manual uses *NCHRP Report 672 Roundabouts: An Informational Guide* as a main reference. The manual suggests that entry curvature is essential in reducing speeds. Excessive sight distance can lead to higher vehicle speeds, landscaping within the central island can reduce the sight distance to a minimum and reduce speeds. The manual provides the following trade-offs table shown in Figure 3.8.

Element	Safety	Capacity	Speed
Wider entry (gore area)	Less safe	Increase	Increase
Wider Circulatory lanes	Less safe	Better	Increase
Larger entry radius	Less safe	Better	Increase
Larger inscriber circle diameter	Less safe	Better	Increase
Larger angle between approach legs	Safer	Decrease	Neutral
Smaller entry angle (phi)	Poorer sight	Better	Increase
Longer flare length	Neutral	Better	Neutral

Figure 3.8 Table 30.1 in the Wisconsin Facilities Manual about effects on design elements on safety and operations of roundabouts (14).

For typical ICD values the guide gives the table shown in Figure 3.9.

Roundabout Type	Typical Inscribed Circle Diameter ¹	Typical Daily Service Volume ^{2,3} (vpd) 4-leg roundabouts
Single-Lane	120 -160 ft (35 – 50 m)	less than 25,000
Multilane (2-lane entry)	160 - 215 ft (50 – 65 m)	25,000 to 45,000
Multilane (3 lane entry)	215 - 275 ft (65 – 85 m)	45,000 or more

¹ For additional guidance based on design vehicle see Exhibit 6-9 Inscribed Circle Diameter Ranges in NCHRP Report 672

² Capacities vary substantially depending on entering traffic volumes and turning movements.

³ Consult with Exhibit 3-12, “NCHRP Report 672, Roundabouts: An Informational Guide, Second Edition” to estimate the ADT for a specific left-turn percentage.

Figure 3.9 ICD guidance in the WisDOT Facilities Manual (14).

According to the manual, rural single lane roundabouts may require supplementary treatments such as raised and extended splitter islands, non-traversable central islands, and horizontal deflection (14). The

Facilities Manual further advises that rural roundabouts may have a larger diameter than urban roundabouts, however rural roundabouts that may become part of an urban area should be designed as urban roundabouts (14).

3.3.3.1 Traffic Control Devices

For advance warning signing Figure 3.10 shows what signs can be used.

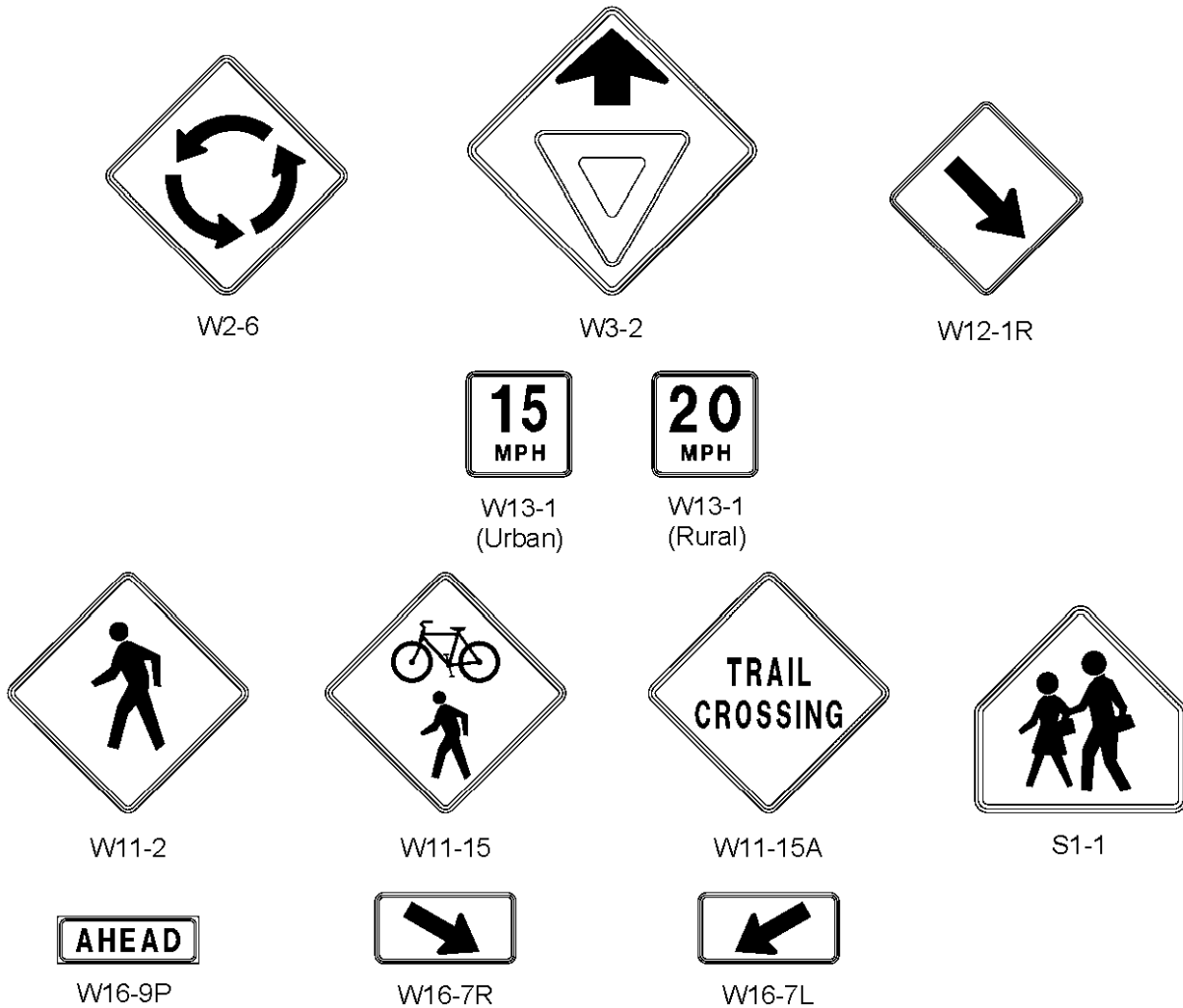


Figure 3.10 Warning signs recommended for use by the Wisconsin Department of Transportation (14).

The Wisconsin Facilities Development Manual dictates that the Yield Ahead (W3-2) sign must be used on an approach if the approach speed is 45 mph or higher, otherwise they can be used if the yield sign is not readily visible at minimum visibility distance. It is noteworthy that while Wisconsin recommends a Yield Ahead sign for roundabouts with higher speeds, this was not observed in other states' documents. The MUTCD recommends Yield Ahead only in cases that have limited visibility. Flashing beacons may

also be used above the warning signs on areas with an approach speed above 45 mph. Advisory speed plaques may also be used, and if used the typical values for urban areas are 15 mph, and for rural areas 20 mph.

3.3.3.2 Lighting

Chapter 11, section 4, subject 1 of the Traffic Guidelines Manual gives the policies for roundabout lighting for the state of Wisconsin (13). The policy states that all DOT maintained roundabouts shall be illuminated, all luminaries shall be LED, and all locally maintained roundabouts shall follow the requirements for permitted lighting. The manual outlines an illumination calculation method for the roundabout intersection area. The recommended illuminance level at the roundabout is the sum of the values for continuously illuminated approaching roadways. The recommended values are shown in Figure 3.11.

Table 1. Recommended Illuminance Levels at Roundabouts				
Roadway Classification	Average Maintained Illumination At Pavement by Pedestrian Area Classification in FC			E_{avg}/E_{min}
	High	Medium	Low	
Major/Major	3.16	2.42	1.67	3:1
Major/Minor	2.97	2.23	1.49	3:1
Major/Collector	2.70	2.04	1.39	3:1
Major/Local	2.42	1.86	1.21	3:1
Minor/Minor	2.79	2.04	1.30	4:1
Minor/Collector	2.51	1.86	1.21	4:1
Minor/Local	2.23	1.67	1.02	4:1
Collector/Collector	2.23	1.67	1.12	4:1
Collector/Local	1.95	1.49	0.93	4:1
Local/Local	1.67	1.30	0.74	6:1

Figure 3.11 Table 1 Chapter 11-4-1 of the Wisconsin DOT Traffic Guidelines Manual (13)

The manual notes that for roundabouts where roadways are not continuously illuminated, the values for Local/Local in Figure 3.11 should be used. These lighting values are to be calculated within the outer radius of the roundabout where crosswalks are not present. When crosswalks are present then the boundary of illumination calculation extends to the far side of the crosswalk.

For placement of lighting equipment, the manual calls for engineering judgement to determine the appropriate location. The manual also recognizes that it may be necessary to place a light pole on a larger splitter island in order to improve visibility of pedestrians.

Where approach roads are not illuminated transition lighting should be provided. Transition lighting allow a driver’s eyes to adjust as they approach the lighted roundabout. The manual provides a table with the minimum transition lighting distances, shown in Figure 3.12.

Table 2. Transition Lighting Lengths						
Posted Speed Limit (MPH)	30	35	40	45	50	55
Minimum Transition Lighting Distance (Feet)	-	175	200	250	275	325

Figure 3.12 Table 2 in Chapter 11-4-1 of the Wisconsin DOT Traffic Guidelines Manual (13).

3.3.3.3 Landscaping

For landscaping the document has the following list of items to **avoid in the central island**:

- Decorative statuettes
- Water fountains/features
- Artwork
- Decorative walls
- City logos or community welcome signs
- Commemorative plaques or monuments
- Banners and flags
- Roundabout sponsorship signing
- Street furniture (decorative and non-decorative)
- Combination of the above features

The guidance further emphasizes the importance of crashworthiness of items within the island. Decorative items in the island should be close to ground level and vegetative or natural looking. The following items are prohibited:

- Hazardous materials – i.e. concrete, stone, boulders or wood walls
- Fixed objects – i.e. trees having a mature diameter greater than 4 inches (14)

3.3.3.4 Curbing

According to the WisDOT Facilities Development Manual approaches with low speeds should incorporate 6 in vertical face curbs on both sides of the road. To accommodate oversize and overweight vehicles a 4 in mountable curb and gutter may be placed where tires may have to go over the curb or

splitter island. Since high-speed approaches are expected to take place in rural areas where there are no curbs present a transition area is proposed. At the splitter island nose a 4 in curb and gutter is offset 4 to 6 feet from the travel lane. As the shoulder narrows the curb transitions from a 4 in curb and gutter to a 6 in curb and gutter. At the truck apron the curb shall have an 18 in reverse-slope curb and gutter (14).

3.3.4 Washington

Chapter 1320 of the Washington Department of Transportation (WSDOT) Design Manual suggests that the outside diameter depends on design vehicle and speed. Figure 3.13 shows the ranges of the inscribed circle diameter.

Design Element	Mini ^[1]	Single-Lane	Multilane
Number of Lanes	1	1	2+
Inscribed Circle Diameter ^[2]	45'–80'	80'–150' ^[3]	135'
Circulating Roadway Width	N/A	14'–19'	29'
Entry Widths	N/A	16'–18'	25'

Notes:

[1] Reserved for urban/suburban intersections with a 25 mph or less posted speed.

[2] The given diameters assume a circular roundabout; adjust accordingly for other shapes.

[3] Inscribed circle diameters of less than 100 feet may not be appropriate on a state route.

Figure 3.13 Exhibit 1320-1 in the WSDOT design manual (15).

The manual further clarifies that the range of entry angle is between 20 and 40 degrees. The desired travel speeds range between 15 and 25 mph. The manual includes chicanes as a speed control strategy, shown in Figure 3.14.

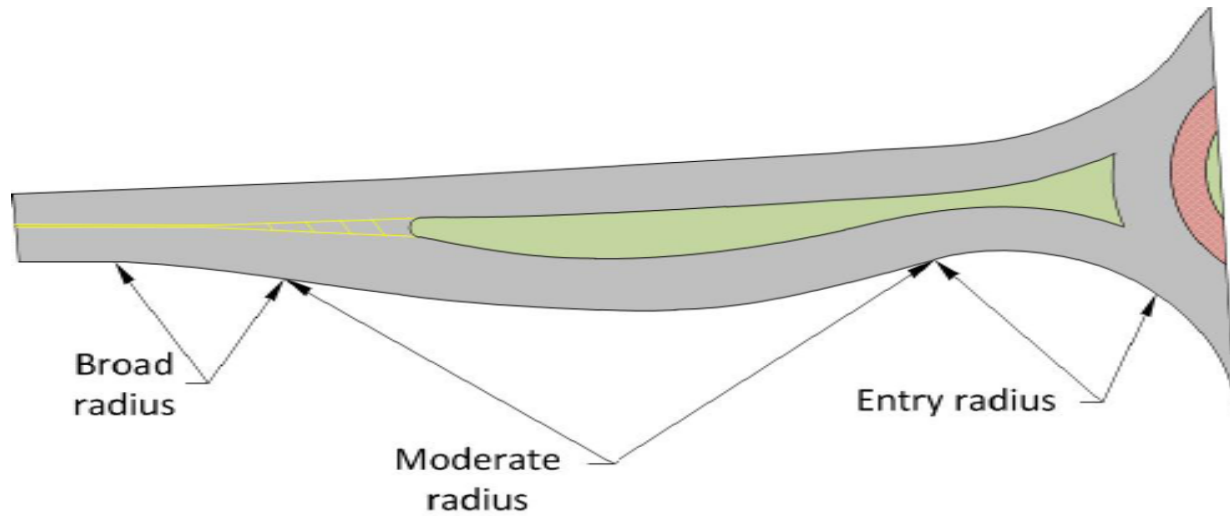


Figure 3.14 Example of chicanes at roundabout approach (15).

The manual suggests the use of chicanes at approaches of 45 mph or higher (15). All three curves should be designed to reduce the speed successively. The radii of the curves can be determined by using the radii-speed curve shown in Figure 3.15.

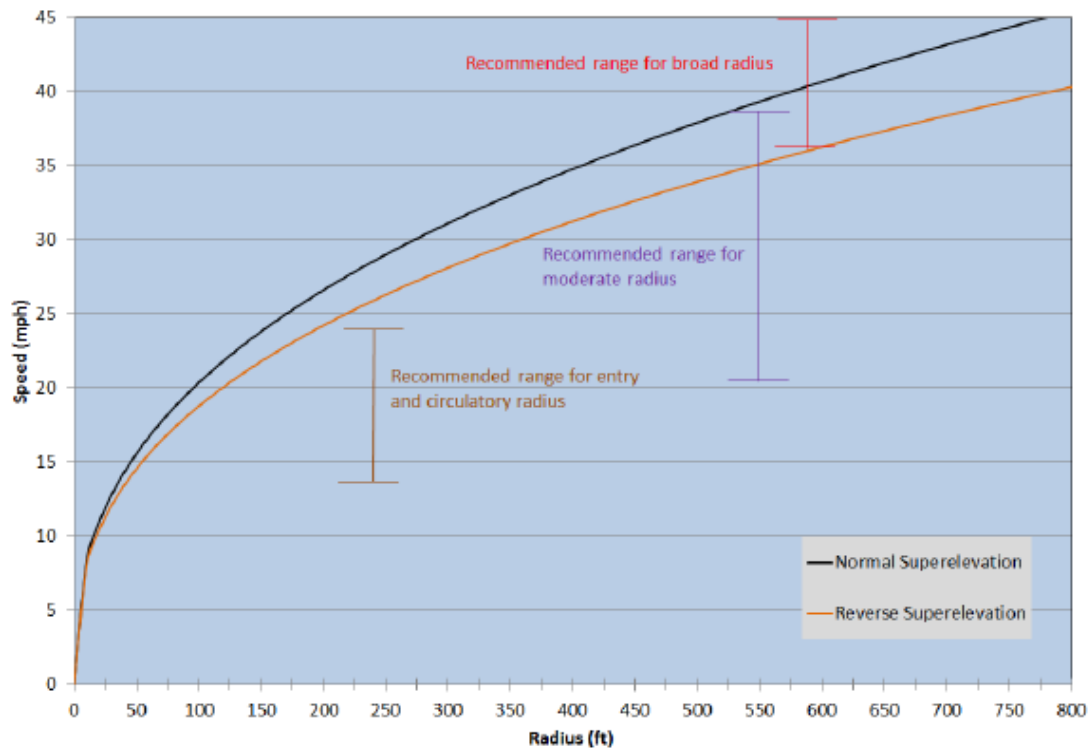


Figure 3.15 Radii-Speed relationship for chicane design (15).

3.3.4.1 Traffic Control Devices

The manual tells designers to refer to the MUTCD for signing and pavement marking details.

3.3.4.2 Lighting

The chapter does not provide luminance levels for roundabout illumination. The document does have similar guidelines to Iowa when it comes to what sections should be illuminated. The manual adds that roundabouts should be lighted from the outside in toward the center. Ground-level lighting within the central island shining upward also increases visibility. For higher-speed approaches, designers may consider internally illuminated bollards in lieu of other illumination (15).

3.3.4.3 Landscape

Chapter 1320 does not provide specific guidance on landscaping at roundabouts.

3.3.4.4 Curbing

Chapter 1320 does not provide specific guidance on curbs at roundabouts

3.3.5 Summary

Table 3.1 shows a summary of ICD ranges and splitter island lengths found in the guidance documents found.

Table 3.1 Summary of guidance for ICD and Splitter Island lengths.

Manual	Inscribed Circle Diameter for Single Lane Roundabouts (ft)	Splitter Island Length
NCHRP Report 672	90 – 180	200 ft or more for high-speed approaches
Iowa DOT Design Manual	100 – 130	No specific guidance given
Kansas Roundabout Guide	90 – 180	50 ft minimum, 100 ft desirable. For high-speed approaches the length of the raised splitter island should extend several hundred feet.

WisDOT Facilities Development Manual	120 – 160	Should extend upstream from the yield line to the point at which entering drivers are expected to start decelerating. Minimum of 200 ft.
WSDOT Design Manual	80 – 150	Length should vary between site operating speed and desired entry speed

When it comes to the range of ICD all states stay within the range given by *NCHRP Report 672 Roundabouts: An Informational Guide*. No specific guidance on length of the splitter island was found in the design manual for Iowa. Washington and Kansas don't give a specific minimum length for high-speed approaches, while Wisconsin specifies a splitter island length of at least 200 feet for approaches with 45 mph or higher.

3.4 COUNTERMEASURES

Traffic and safety engineers have used a variety of countermeasures to try to reduce speeds. Our literature review was focused on high-speed areas with special emphasis on intersections and curves as these are most applicable to roundabouts. *NCHRP Report 613 Guidelines for Selection of Speed Reduction Treatments at High-Speed Intersections*, published in 2008, reviewed and summarized many of the countermeasures used to reduce speeds at high-speed rural intersections (16). It is interesting to note that one of the treatments presented in this report is a roundabout. They point out that a roundabout uses the intersection geometry itself to reduce speeds.

The research team compiled a list of key words to conduct a literature search. The search key words included among others:

- Dynamic speed message signs
- Optical speed bars
- Transverse pavement markings
- Transition zones (rural to urban)
- Gateway treatments
- Illumination

A 2015 FHWA study investigated factors influencing operating speeds and safety in rural and suburban roads (30). The study first conducted a literature review, and then conducted a field study on a few

countermeasures based on feedback. The literature review identified more than 40 traffic engineering countermeasures for speed in rural and suburban areas. The study identified the following treatments for possible field evaluations:

- Converging chevron markings
- Narrower lane and shoulder widths
- Speed tables
- Enhanced speed limit with colored surfacing
- Transverse markings or Optical Speed Bars (OSB)
- Red border speed limit sign
- High Friction Surface Treatment (HFST)
- Zigzag pavement markings
- Speed feedback signs

Based on feedback from study panel members the study evaluated HFST on rural two-lane horizontal curves, OSB on rural and suburban roads, and lane and shoulder reduction on rural two-lane highways.

3.4.1 High Friction Surface Treatment

The FHWA study treated four curves and four tangent sections in three different rural highways in West Virginia. The posted speed limit on the highways was 55 mph, and the advisory speed limit ranged from 25 to 50 mph. The study found that there were no consistent differences in operational and driver behavior before and after countermeasure was applied (30).

3.4.2 Dynamic Speed message signs

Dynamic speed display signs can be used to alert drivers that they are going over the speed limit. The effects of speed display signs have been investigated in work zones, horizontal curves, and transition zones to name a few examples. Researchers in South Carolina investigated the effects of an active speed display sign on motorists' speeds in work zones (17). The sign consisted of a standard warning sign with a flashing beacon and the read "YOU ARE SPEEDING IF FLASHING." For this study, data was collected at three different work zones. Speed data was collected at three different stations along each of the work zones. A two-sample t-test was used to evaluate the difference in mean speeds and a z-test was used to measure the difference in proportions. Overall their research study found a speed reduction of 3.29 mph on the average speed, and 3.22 mph reduction on the 85th percentile speed (a17). Sommers and McAvoy used a simulator to assess the effects of speed display signs, among other countermeasures, in a work zone environment. The study selected up to 20 speed countermeasures to input in a driving simulator. The message signs were used in combination with other countermeasures. The variable speed limit sign saw a reduction of 10.26 mph (18).

Hallmark et al. investigated the effects of Dynamic Speed Feedback Signs (DSFS) in transition zones at two lane rural highways. Four different types of signs were used on 4 different county roads in Iowa. Data were collected for periods of 48 hours under dry conditions. The study found that mean speed

reduction and 85th percentile speed reduction ranged between 3 and 9mph. The more significant decrease was observed in vehicle exceeding the posted speed limit (19). Another study by researchers in Pennsylvania found a mean speed reduction of 6.3 mph (range 0.8 to 11.9 mph) in transition zones (20). Researchers also looked at the effects of DSFS on rural horizontal curves. Data was collected at 22 sites on rural 2-lane roadways. Speed data was collected before and 12-months after installation. The study found that speeds ranged according to station along the curve. Significant decreases were observed in drivers exceeding the posted speed limit by 5 or more mph (21).

3.4.3 Pavement markings

Researchers have investigated the effects of different configurations of pavement markings on traveling speed. This section presents the findings from the literature search about different applications of pavement markings and speed reduction. One study conducted by FHWA explored the relationship between signing, marking, and erratic maneuvers that may lead to crashes (22). The study did this by observing erratic maneuvers through overhead cameras, and using in-vehicle eye tracker system. Table 3.2 shows the categories of erratic maneuvers in multilane roundabouts.

Table 3.2 Categories of erratic maneuvers (22).

Position	Erratic Maneuver Name	Description
Approach	Lane change	Driver enters the wrong lane of the circulatory roadway from the roundabout entry
Approach	Improper turn	Driver uses the left lane to make a right turn
Circulatory Roadway	Lane change	Driver changes lane within circulatory roadway
Circulatory Roadway	Improper turn	Driver exits from inside lane of circulatory roadway when not allowed by pavement markings
Circulatory Roadway	Lane straddle	Driver drives on lane lines

For erratic maneuvers the study identified the following contributing factors:

- Inconsistencies in lane use marking between the approach and circulatory roadway
- Inadequate channelization in the circulatory roadway
- Increased attention by drivers as volume increases

The study also looked at how many times participants looked at an object. When the gaze point from the eye-tracker data remained on a particular object for two video frames or more (approximately 69 milliseconds) this was defined as a glance. As far as glances were concerned the study reduced data from 1759 glances. Researchers measured the total amount of time a participant’s gaze was focused on an object (dwell time), the length of time between fixation points (fixation time), and the total glances. The research study found that:

- Out of the 1759 glances observed; 44 percent were towards traffic, 28 percent toward pedestrian related markings, 27 percent toward other markings and signs, and one percent at pedestrians.
- When looking at glances for only signs and pavement markings the majority of glances were towards lane use markings and center lane striping in the circulatory roadway
- Yield-ahead signs had the lowest mean dwell time of glances
- Lane control signs have the highest mean dwell time
- During their approach, participants glanced toward lane use markings in the circle more than any other sign or marking
- In the entrance, glances toward yield lines had a longer dwell time than other signs and markings (22)

3.4.3.1 Lane narrowing

Pavement markings may be used to give the driver the visual impression that the lane width is narrowing. The desired effect is that the driver will decrease their speed due to the constriction of space. This type of countermeasure has been deployed in residential streets. Hadayehi et al. investigated the effects of lane narrowing in suburban communities in Canada. The study collected data from a treated sites and control sites. The study looked at the reduction in 85th percentile speeds. Researchers found that the reduction in speeds ranged from 0.8 to 7.7 percent, which was not statistically significant (23). Ewing investigated the effects of lane narrowing, among other traffic calming countermeasures, by conducting a descriptive statistical analysis of reported before-and-after studies. Ewing found that the average speed reduction is 2.6 mph (4 percent) for lane narrowing (24). The FHWA's "Speed Management: A Manual for Local Rural Road Owners" reports that for rural roads speeds may decrease by as much as 3 mph for each foot that the roadway is narrowed down to 10 feet (25).

3.4.3.2 Optical pavement markings

Optical pavement markings are deployed in many different forms such as optical bars and transverse pavement markings. Overall the markings are installed with decreasing space between successive markings to give drivers the perception of high speed in order to make them slow down (26). Figure 3.16 shows some examples of optical pavement markings from a separate study (27).

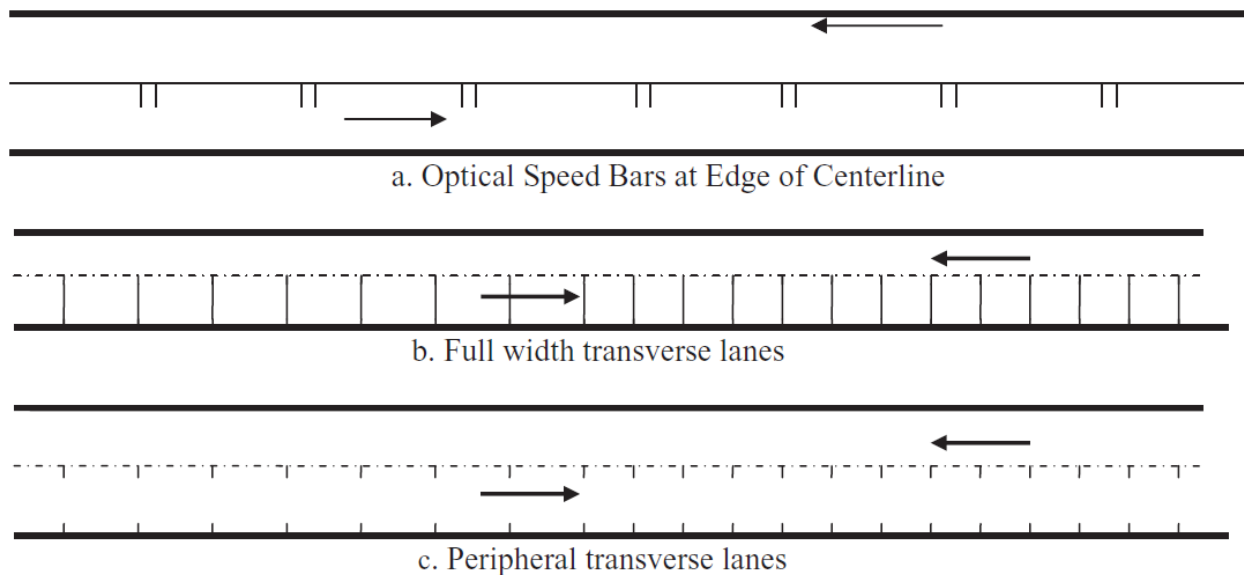


Figure 3.16 Example of optical pavement markings (27).

Researchers have done field and simulator studies to investigate the effects of optical pavement markings on motorists' speeds. Montella et al. used a driving simulator with nine scenarios consisting of a rural two lane road where two scenarios have no treatment and seven scenarios with different combinations of optical bars. The study found that speed reductions ranged between 1.86 and 9.32 mph (28).

Gates et al. investigated the effects of optical bars on a horizontal curve in a multilane interstate highway. For this study, speed data were taken at three locations along the curve (350 ft upstream, 600 ft downstream, 200 downstream). The study had a before, shortly-after (3 days after installation), and long-after periods (6 months after). An ANOVA analysis showed that speed was reduced between 1 to 5 mph in the short term. In the long-term there was an incremental decrease of 0.9 mph, which totaled a decrease of 3.7 mph between the before and long-after periods (26). A study conducted on two lane rural roads in Kansas showed an average speed reduction range of 0.9 to 4.5 mph for all vehicles. The study also observed that higher speed reductions were observed during weekdays and at daytime. Two-axle vehicles had a greater reduction in speed than other vehicle types (27). The FHWA reports that overall a speed reduction of 2 mph can be expected from optical speed bars (25), and Hallmark et al. report that, when applied on curves, transverse pavement markings decrease speeds between 0 and 5 mph (29).

The 2015 FHWA study looked at OSBs that were 18 inch long and 12 inch wide, white markings perpendicular to the centerline placed near the center and edgelines. The FHWA recommends that drivers be in the OSB segment for at least 4 seconds. The study placed OSBs in Arizona, Massachusetts, and Alabama. The optical bars in Alabama were different than the ones placed at sites in Arizona and Massachusetts. A total of 19 study sites were used. Overall the study found minor effects on speeds by the OSB, but they were too inconsistent between sites to draw any conclusions. The study did not consider the effects of lane and shoulder width at intersections (30). The results from several other

previous evaluations of optical speed bar treatments were also summarized in the report. The results have been mixed for this treatment and general conclusions are hard to draw because of the variety of shape, size, and placement of the bars.

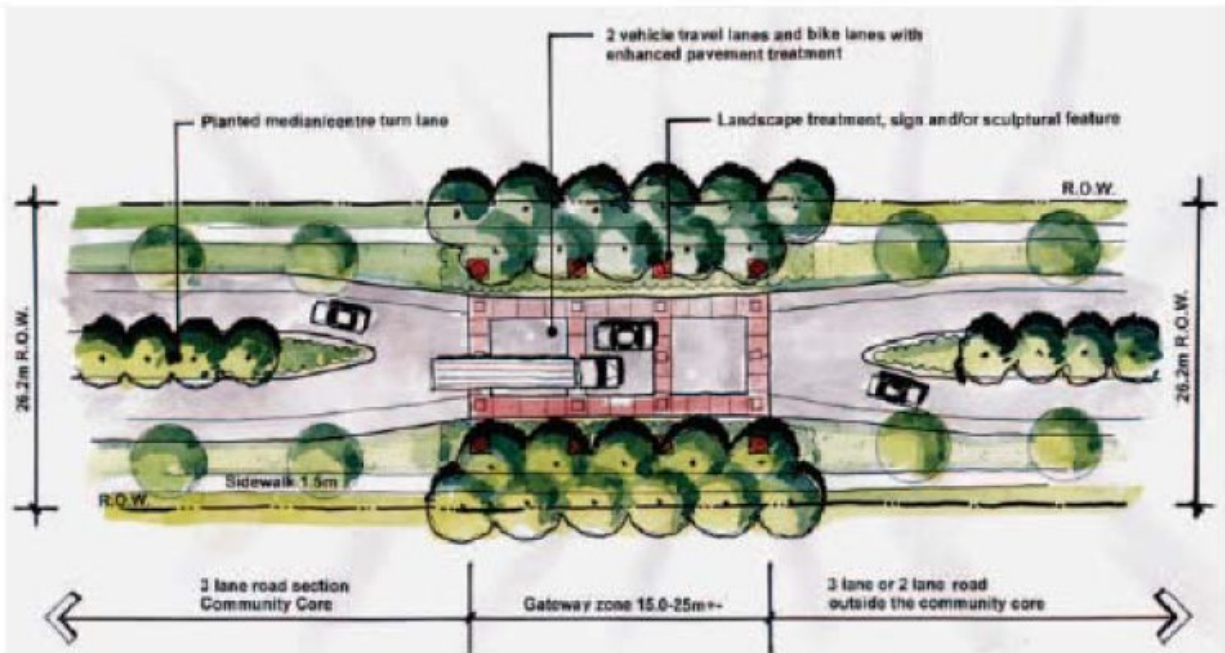
3.4.4 Illumination

Safety effects of illumination along corridors and at intersections have been researched nationally and internationally. Wanvik investigated the effects of roadway lighting in the Netherlands. The study analyzed a crash database that covered years 1987-2006. The database contained 763,000 injury accidents and 3.3 million property damage crashes. An odds ratio estimator analysis showed that road lighting has an effect of -50 percent on injury crashes during the dark hours. The effects of roadway during snow conditions were -26 percent, and -22 percent in ice covered surfaces (31). Assum et al. looked at the effects of roadway lighting on speed in Norway. Researchers collected speed and other data relating to driver behavior at a roadway segment before and after lights were installed. The study found that drivers generally do not increase their speed when lighting is present (32).

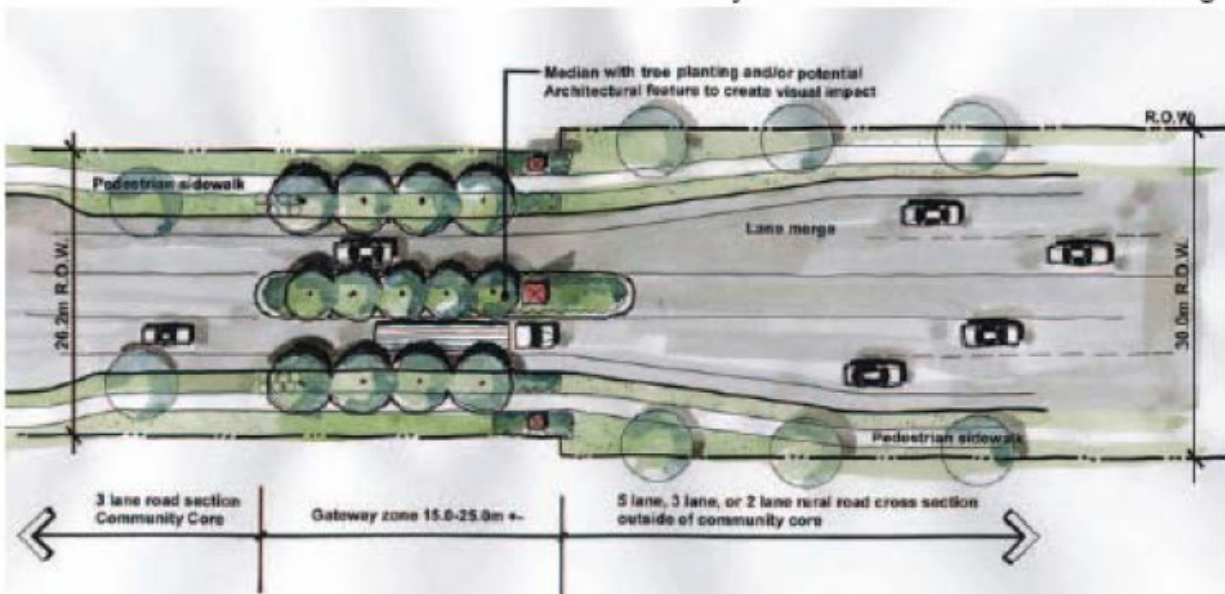
Researchers have also used crash data in the United States to investigate the effects of roadway lighting and safety. These studies showed that the severity of crashes increases at intersection without lights (33) and intersections with roadway lighting have fewer crashes in nighttime conditions, but more crashes during the daytime when compared to intersections without lights (34). Furthermore, research suggest that low-speed and high-speed intersections should be illuminated, and older drivers benefit from high illumination on high-speed highways (35).

3.4.5 Gateway Treatments

A gateway treatment is the deployment of a combination of signs, landscaping, monuments and other traffic calming devices at the entrance of a community or a neighborhood (36). An example of a gateway treatment is shown in Figure 3.17.



Gateway treatment with road narrowing



Gateway treatment with median

Figure 3.17 Example of gateway treatments (37).

Dixon et al. attempted to identify the effects of gateway treatments through a driving simulator study. This goal of the research project was to identify ways to calm operating speeds of vehicles as they enter suburban and urban areas or transition from rural to urban areas. The study investigated the following treatments: layered landscape, gateway with lane narrowing, median treatment only, median with gateway treatment, medians in series with no pedestrian crosswalks, medians in series with pedestrian crosswalks. For the simulation participants were divided into three groups, 17 to 25 year old drivers, 35

to 50 years old, and 65 and older. Lane narrowing yielded a mean speed reduction of 2 to 4 mph, and an 85th percentile speed reduction of 2 to 4 mph. Layered landscape yielded a mean speed reduction of 1 to 3 mph, and 85th percentile speed reduction of around 4 mph. Median only treatment reduced mean speed less than 1 mph, and 85th percentile speeds 0 to 3 mph. Medians in series reduced mean speeds by 4 mph, and 85th percentile speeds by 3 mph. All other treatments presented negligible results (37). The speed management toolkit by the FHWA reports that gateway treatments in rural transition areas produced a 5 percent reduction in 85th percentile speed, while a 7 percent 85th percentile speed reduction was observed in urban settings (36).

3.4.6 Transition Zones

Transition zones are areas where the posted speed limit is lowered as motorists traveling on rural roads approach more developed areas. Cruzado and Donnell investigated the factors affecting speed choice of drivers at two-lane rural highway transition zones. The study gathered operational speeds and volume data at 20 different transition zones using pavement sensors. The sensors were placed 500 ft upstream from the “REDUCED SPEED AHEAD” sign, at the “REDUCED SPEED AHEAD” sign, and at the speed limit sign at all transition zones observed. The data was analyzed using OLS linear regression to find common factors between sites and how they relate to speed. The study found that for each 1 ft reduction in lane width within the transition zone, speed was reduced by 2.4 mph. Each 1 ft reduction in shoulder width resulted in a 1.1 mph reduction in speed. The introduction of curbs is associated with 1.2 mph reduction when compared to sections with no curbs or gutters. Intersection Ahead signs are associated with a 2.5 mph reduction (38).

3.4.7 Horizontal Signing

A 2006 study conducted by TTI (39) evaluated various word and symbol pavement markings for speed reduction in advance of horizontal curves in urban and rural locations. The study found that the text CURVE AHEAD sign did not result in speed reduction, but a pavement message consisting of the word CURVE and an advisory speed did result in a 12-mph speed reduction compared to an 8-mph reduction with a warning sign alone in rural areas (Figure 3.18). On urban curves a curve arrow and advisory speed was evaluated (Figure 3.19) and resulted in a smaller percentage of vehicles exceeding the speed limit day and night for both trucks and cars (Table 3.3).



Figure 3.18 Text and advisory speed horizontal signing applications (39).



Figure 3.19 Urban freeway curve warning pavement markings (39).

Table 3.3 Percent of vehicles exceeding the posted speed limit. (39).

Vehicle Type	Time of Day	Before (%)	After (%)
Cars	Day	97.7	86.8
Trucks	Day	97.0	80.1
Cars	Night	93.2	77.6
Trucks	Night	88.9	69.0

3.4.8 Applications to Roundabouts with High-Speed Approaches

There is limited research in the application of the countermeasures mentioned in the previous sections to roundabouts. In 2005, Ritchie (40) conducted a study for the East West Partners, California Department of Transportation, and Transportation Research Board concerning high-speed approaches at roundabouts. The purpose of the study was to identify the concerns of placing a roundabout on roadways with 45 mph or greater speed limit. The report looked at five case studies of roundabouts in high-speed approaches in North America. The study documented design treatments for high-speed approach roundabouts and recommended non-geometric design measures.

For design treatments the report concludes that there is very little data to correlate geometric design and safety performance. However, the case studies have common elements that show early signs of positive performance. These elements are:

- Visible entries from a safe stopping sight distance
- Fastest entry paths that are designed to be consistently low
- Extending the splitter island to a distance equal to the appropriate deceleration length from approach speed to entry speed
- Landscaped central islands that prevent drivers to see through the roundabout
- Advance signage in combination with appropriate landscape and a well-illuminated intersection.

When taking into account the elements observed at the case studies and the design treatments used around the world, the study recommends:

- Only minimum stopping sight distance should be provided at the entry point based on approach operating speed,

- Make the central island conspicuous with landscaping, and sight blocking amenities,
- Extend splitter islands upstream from the yield line to the point drivers should begin to decelerate (minimum of 200 ft), and use landscaping on the extended island and on the roadside,
- Provide illumination on the transition to the roundabout, and use signs and markings to advise appropriate speed.

The main goal for non-geometric measures is to make the need to slow down clear to the driver. This goal can be accomplished by:

- Making the roundabout visible at both day and night,
- Adding side friction on single lane approaches,
- Creating a “tunnel effect” in combination with geometric measures, and
- Using larger chevrons.

The report highlights that in the U.K. an internally illuminated bollard that directs drivers to “KEEP RIGHT” has been attributed a 30 percent reduction in crash rates. Another countermeasure not used in North America are transverse yellow bar markings. There are no studies that quantify the effect of the yellow bar markings, however there are studies that they are an appropriate contribution to treating approaches with a history of speed related crashes. The author highlighted only these two countermeasures, since all other are currently deployed in North America.

3.5 CONCLUSION

The literature review identified many countermeasures that have been evaluated for reducing speed, especially at high-speed intersections. The relative effectiveness of the countermeasure depend on site characteristics such as geometric design and adjoining land use. The research team will take the findings from these studies and synthesize them into recommended practice in Task 3 by considering these site specific characteristics.

CHAPTER 4: RECOMMENDED PRACTICE AND EVALUATION METHODS

This chapter contains synthesis tables of the countermeasures discussed in the literature review, a summary of implementation considerations and expected benefits developed during this project. This chapter also contains recommendations for evaluation measures, including speed study procedures, that could be used for any future field evaluations of the countermeasures.

4.1 SYNTHESIS TABLES

Synthesis tables for the countermeasures researched during the literature review are provided in this section. The tables provide the name, category, brief description, picture or illustration, implementation and maintenance considerations, and key references for each countermeasure. Implementation is indicated in terms of broad categories of cost, which are provided to give the reader a sense of how the cost of the countermeasures compare to each other. The cost criteria for considerations of implementation efforts of each countermeasure are:

- Lower-cost (\$) – no new hardware or physical changes to the intersection. Work could be accomplished by a crew in less than two days.
- Moderate-cost (\$\$) – additions of hardware to infrastructure. Work could be accomplished by a crew between two and three days.
- Higher-cost (\$\$\$) – requires reconstruction, changes to existing infrastructure. Would require an extended period of time to construct.

Similarly, maintenance considerations are also presented in three broad categories, based on the maintenance effort relative to other countermeasures, using the following criteria:

- Lower-effort (🚧) – maintenance of countermeasure may require minimal crew and one day or less to repair/maintain device.
- Moderate-effort (🚧🚧) – maintenance may require longer than a day, or maintenance operations for countermeasure may be more frequent.
- Higher-effort (🚧🚧🚧) – maintenance operations may be frequent. Materials and equipment needed for repair may be costly and maintenance operations may take place for an extended period of time.

The estimates for implementation and maintenance are not meant to be used for a cost/benefit analysis; rather, the criteria are to serve as a comparison between the countermeasures. The synthesis tables are, in order of category, listed below:

- Infrastructure

- Gateway treatments
 - Lighting
- Pavement Markings
 - Optical speed bars
 - Transverse pavement markings
 - Narrow lanes
- Signing:
 - Transition zones
 - Speed feedback changeable message signs
 - Advance warning signs

Name	Gateway Treatment
Category	Infrastructure
Description	

A gateway treatment is the deployment of a combination of signs, landscaping, monuments and other traffic calming devices at the approach of the intersection. Research studies have reported a decrease of 5 to 7 percent in 85th percentile speeds.



Gateway treatment in Italy transitioning from rural road to village. Source: Lantieri, C., Lamperti, R., Simone, A., Costa, M., Vignali, V., Sangiorgi, C., & Dondi, G. (2015). Gateway design assessment in the transition from high to low speed areas. Transportation Research Part F: Traffic Psychology and Behaviour, 34, 41-53.

Implementation Considerations

\$\$\$

Cost may depend on the combination of countermeasures used.

Maintenance Considerations

Plowing and street sweeping may be impeded by certain gateway treatments such as raised islands. Landscape treatments may require seasonal maintenance.

References

Bagdade, J., Nabors, D., McGee, H., Miller, R., & Retting, R. (2012). *Speed Management: A Manual for Local Rural Road Owners*, Federal Highway Administration Publication No.FHWA-SA-12-027.

Xu, G. (2015). *Speed Management Toolkit* Federal Highway Administration Publication No. FHWA-SA-15-017.

Name	Illumination
Category	Infrastructure

Description

Lighting fixtures to make the intersection approach more noticeable during low visibility conditions. Research has shown that lighting decreases night-time crashes. No studies addressed speed reduction



Source: NCHRP Report 672: Roundabouts An Informational Guide

Implementation Considerations \$\$\$

Addition of new infrastructure including power source.

Maintenance Considerations 🚧🚧

Though maintenance operations may not be frequent, it may require additional equipment and crew for repair.

References

Anarkooli, A. J., and Hosseinlou, M. (2016). Analysis of the Injury Severity of Crashes by Considering Different Lighting Conditions on Two-Lane Rural Roads. *Journal of Safety Research* 56 (2016): 57-65.

Wanvik, P. E. (2009). Effects of Road Lighting: An Analysis Based on Dutch Accident Statistics 1987–2006. *Accident Analysis & Prevention* 41.1: 123-128.

Donnell, E. T., Porter, R. J., & Shankar, V. N. (2010). A Framework for Estimating the Safety Effects of Roadway Lighting at Intersections. *Safety Science*, 48(10), 1436-1444.

Rea, M. S., John D. Bullough, and Yingjie Zhou. (2010) A Method for Assessing the Visibility Benefits of Roadway Lighting. *Lighting Research and Technology*, Mar 31, 2010.

Assum, T., Bjørnskau, T., Fosser, S., & Sagberg, F. (1999). Risk Compensation—The Case of Road Lighting. *Accident Analysis & Prevention*, 31(5), 545-553.

Bullough, J. D., Donnell, E.T., & Rea, M.S. (2013) To illuminate or not to illuminate: Roadway lighting as it affects traffic safety at intersections. *Accident Analysis & Prevention* vol. 53, pp. 65-77.

Name	Optical Speed Bars
Category	Pavement Markings

Description

Optical speed bars are white markings that are 12 in long and 18 in wide. The markings may be placed perpendicular to the centerline or on the right and left edge of the travel lane. The spacing between bars may vary. Speeds may decrease from 0.2 to 4.5 mph.



Source: Hallmark, et al. Toolbox of Countermeasures for Rural Two-Lane Curves.

Implementation Considerations \$

Low-cost countermeasure that would require a minor effort to implement.

Maintenance Considerations



May require frequent maintenance to re-stripe the markings.

References

Balde, A.D. & Dissanayake, S. (2013) Effectiveness of Optical Speed Bars in Reducing Approach Speeds to Rural Communities, *Journal of Transportation Safety & Security*, 5:3, 240-256, DOI: 10.1080/19439962.2012.756090.

Bagdade, J., Nabors, D., McGee, H., Miller, R., & Retting, R. (2012). *Speed Management: A Manual for Local Rural Road Owners*, Federal Highway Administration Publication No.FHWA-SA-12-027.

Hallmark, S. L.; Hawkins, N. R.; & Smadi, O. G. (2013) Toolbox of Countermeasures for Rural Two-Lane Curves. *InTrans Project Reports*. Paper 114. http://lib.dr.iastate.edu/intrans_reports/114

Ray, B. (2008). *Guidelines for Selection of Speed Reduction Treatments at High-Speed Intersections*, NCHRP Report 613. Transportation Research Board.

Name	Transverse pavement markings
Category	Pavement markings

Description

Optical pavement markings include transverse pavement markings that are marked across the travel lane. The markings may have many patterns such as speed bars or converging chevrons. Research has reported a speed reduction ranging from 0 to 9 mph.



Source: Hallmark, et al. *Toolbox of Countermeasures for Rural Two-Lane Curves*.

Implementation Considerations \$

Low-cost countermeasure that would require a minor effort to implement.

Maintenance Considerations 

May require frequent maintenance to re-stripe the markings.

References

Montella, A., Aria, M., D’Ambrosio, A., Galante, F., Mauriello, F., & Perneti, M. (2011). Simulator evaluation of drivers’ speed, deceleration and lateral position at rural intersections in relation to different perceptual cues. *Accident Analysis & Prevention*, 43(6), 2072-2084.

Fitch, J., & Crum, N. (2007) *Dynamic Striping in Four Towns Along Vermont Route 30—Final Report*, No. 2007-14.

Gates, T., Qin, X, and Noyce, D. (2008). Effectiveness of Experimental Transverse-Bar Pavement Marking as Speed-Reduction Treatment on Freeway Curves. *Transportation Research Record: Journal of the Transportation Research Board* 2056: 95-103.

Ding, H., Zhao, X., Rong, J., & Ma, J. (2013). Experimental research on the effectiveness of speed reduction markings based on driving simulation: A case study. *Accident Analysis & Prevention*, 60, 211-218.

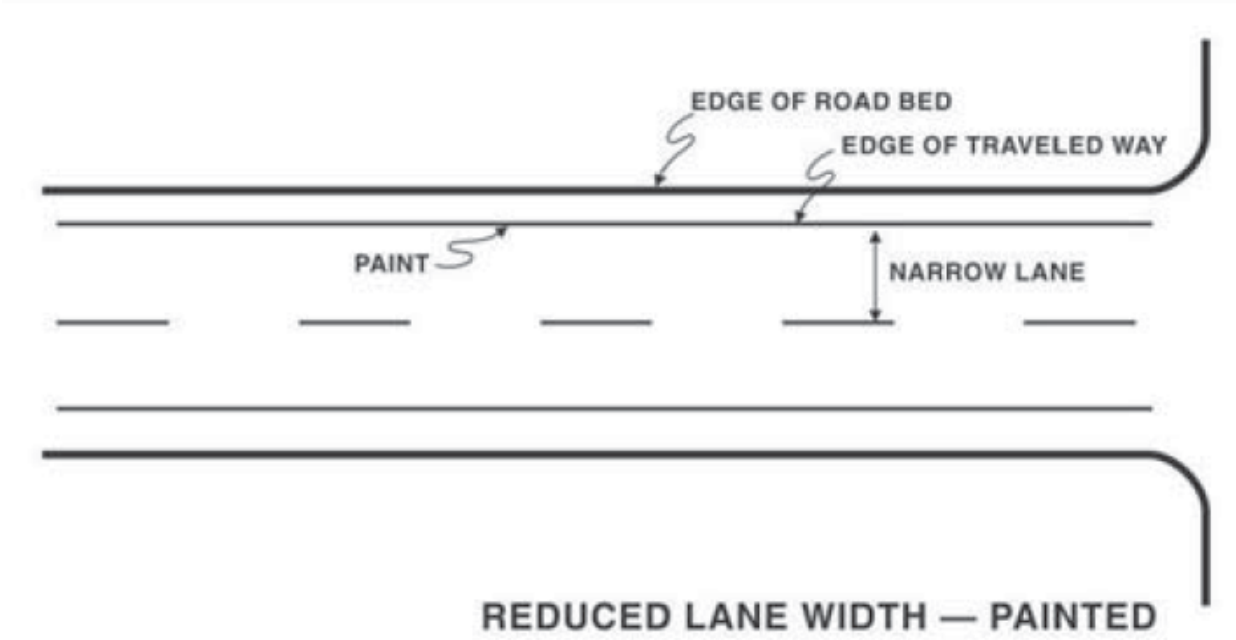
Hallmark, S. L., & Hawkins, N. (2011) Sustainable speed management in small rural communities. In *Integrated and Sustainable Transportation System (FISTS)*, 2011 IEEE Forum (pp. 215-220). IEEE.

Hallmark, S. L.; Hawkins, N. R.; & Smadi, O. G. (2013) Toolbox of Countermeasures for Rural Two-Lane Curves. *InTrans Project Reports*. Paper 114. http://lib.dr.iastate.edu/intrans_reports/114

Name	Lane narrowing
Category	Pavement Markings

Description

Lane narrowing may be done by using markings to narrow the lane width for approaching vehicles. At intersections speeds were reduced up to 3 mph.



Source: NCHRP Report 613: Guidelines for Selection of Speed Reduction Treatments at High-Speed Intersections.

Implementation Considerations \$

Low-cost countermeasure that would require a minor effort to implement.

Maintenance Considerations 🚧 🚧

May require frequent maintenance to re-stripe the markings.

References

Ray, B. (2008). *Guidelines for selection of speed reduction treatments at high-speed intersections*, NCHRP Report 613. Transportation Research Board.

Hadayeghi, A., Malone, B. and McIntyre, S. (2006). *Impact of Road Lane Narrowing Traffic Calming Treatments on Speed and Volume*. Annual Conference and Exhibition of the Transportation Association of Canada, Charlotte, Prince Edward Island.

Hallmark, S. L., & Hawkins, N. (2011) Sustainable speed management in small rural communities. In Integrated and Sustainable Transportation System (FISTS), 2011 IEEE Forum on (pp. 215-220). IEEE.

Ewing, R. (2001). Impacts of Traffic Calming. *Transportation Quarterly*, 55(1), 33-46.

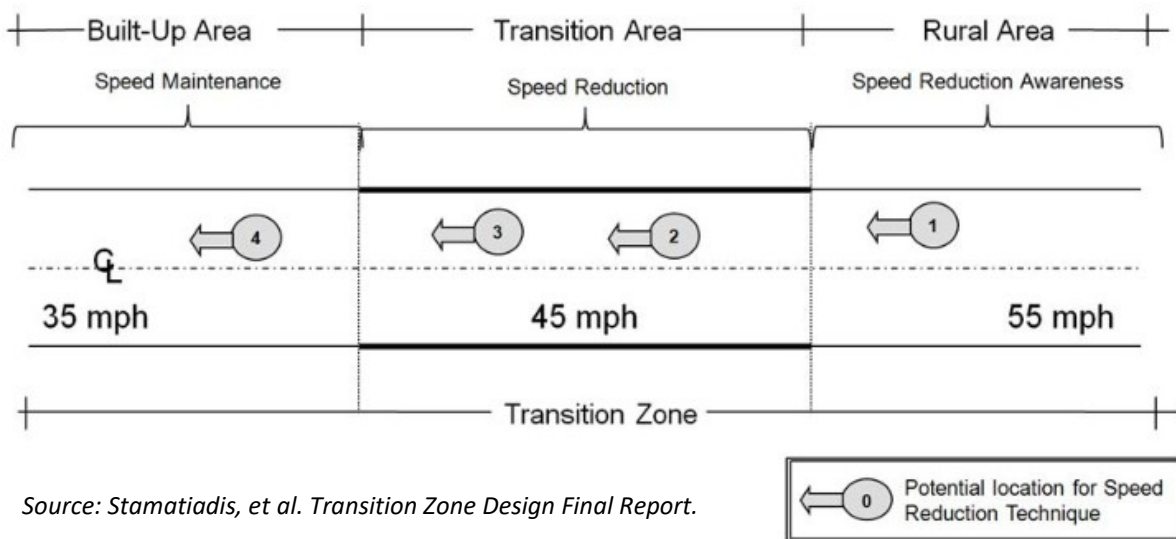
Turner, B. (2013). Engineering Based Measures to Manage Speeds on Rural Roads. In 16th International Conference Road Safety on Four Continents. Beijing, China (RS4C 2013). 15-17 May 2013. Statens väg-och transportforskningsinstitut.

Bagdade, J., Nabors, D., McGee, H., Miller, R., & Retting, R. (2012). *Speed Management: A Manual for Local Rural Road Owners*, Federal Highway Administration Publication No. FHWA-SA-12-027.

Transition zones have been used to encourage speed reductions at school zones and at urban/rural boundaries. Using the principles applied in those conditions, transition zones can also be used as treatments for approaches to roundabouts. When the regulatory speed limit on the approach to a roundabout is more than 20 miles per hour above the design speed or advisory speed of the roundabout, it may be appropriate to provide a buffer speed limit to encourage drivers to reduce their speed. For example, if the design speed of a roundabout is 15 miles per hour and the regulatory speed limit on the approach is 55 miles per hour, the road agency may consider posting a buffer speed limit of 35 miles per hour on the approach to reduce the speed in increments. At roundabouts where a buffer speed limit is used, signage indicating the highway's regulatory speed limit must be posted on each departure to inform drivers that they may return to the normal posted speed limit upon leaving the roundabout. The buffer speed limit should not be more than 20 miles per hour below the regulatory posted speed limit.

Name	Transition zones
Category	Signing
Description	

Transition zones are areas where the posted speed limit is lowered as motorists approach the intersection. Research reports speed reductions between 1 and 13 mph and compliance rates in school buffer zones of 82 to 88 percent.



Implementation Considerations

\$\$

Addition of signs and sign posts are required

Maintenance Considerations



Regular maintenance of signs will be needed

References

Cruzado, I., & Donnell, E. T. (2009). Factors Affecting Driver Speed Choice along Two-Lane Rural Highway Transition Zones. *Journal of Transportation Engineering*, 136(8), 755-764.

Stamatiadis, N., Kirk, A. J., Cull, A., & Dahlem, A. (2014). *Transition Zone Design Final Report*. KTC-13-14/SPR431-12-1F

Dixon, K. K., Zhu, H., Ogle, J. H., Brooks, J. O., Hein, C., Aklluir, P., & Crisler, M. C. (2008). *Determining Effective Roadway Design Treatments for Transitioning from Rural Areas to Urban Areas on State Highways*. Federal Highway Administration Publication No. FHWA-OR-RD-09-02.

Texas Department of Transportation (2015). *Procedures for Establishing Speed Zones*. p. 3-15.

Fitzpatrick, K., Brewer, M.A., Obeng-Boampong, K.O., Park, E., Trout, N.D. (2009). *Speeds in School Zones*. Texas Department of Transportation. Report No. FHWA/TX-09/0-5470-1

Name	Speed feedback changeable message signs
Category	Signing
Description	

A speed feedback changeable message sign may tell drivers when they are speeding by a flashing beacon, or by showing their traveling speed. They may be placed near the regulatory speed limit signs. Research studies report speed reductions between 3 and 8 mph.



Source: Walter, et al. effectiveness of speed indicator devices on reducing vehicle speeds in London.



Source: Hallmark, et al. Use of DSFS as a Speed Transition Zone Countermeasure in Small, Rural Communities.



Source: Mattox, et al. Development and evaluation of speed-activated sign to reduce speeds in work zones.



Source: Hallmark, et al. Toolbox of countermeasures for rural two-lane curves.

Implementation Considerations

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The signs may require installation of new infrastructure on the roadway segment, as well electrical equipment to power the sign.

Maintenance Considerations



Maintenance of equipment may depend on site and weather.

References

Hallmark, S. L.; Hawkins, N. R.; & Smadi, O. G. (2013) Toolbox of Countermeasures for Rural Two-Lane Curves. *InTrans Project Reports*. Paper 114. http://lib.dr.iastate.edu/intrans_reports/114

Cruzado, I., Donnell, E.T. Evaluating Effectiveness of Dynamic Speed Display Signs in Transition Zones of Two-lane, Rural Highways in Pennsylvania. (2009) *Transportation Research Record: Journal of the Transportation Research Board*, No. 2122, Transportation Research Board, Washington, D.C., pp. 1–8.

Sommers, N.M. McAvoy, D.S. (2013). *Improving work zone safety through speed management*. The Ohio Department of Transportation, Office of Statewide Planning & Research State Job Number 134625. Final Report.

Hallmark, S.L., Hawkins N., Knickerbocker S. (2015). *Use of DSFS as a speed transition zone countermeasure in small, rural communities*. IEEE 18th International Conference on Intelligent Transportation Systems.

Jomaa, D., Dougherty, M., Yella, S., & Edvardsson, K. (2016) Effectiveness of trigger speed of vehicle-activated signs on mean and standard deviation of speed. *Journal of Transportation Safety & Security*, Vol. 8, No. 4, pp. 293–309.

Sandberg, W., Schoenecker, T., Sebastian, K., & Soler, D. (2006). Long-Term Effectiveness of Dynamic Speed Monitoring Displays (DISMAYED) for Speed Management at Speed Limit Transitions. In *2006 ITE Annual Meeting and Exhibit Compendium of Technical Papers*.

Hallmark, S. L., & Hawkins, N. (2011) Sustainable speed management in small rural communities. In *Integrated and Sustainable Transportation System (FISTS)*, 2011 IEEE Forum on (pp. 215-220). IEEE.

Turner, B. (2013). Engineering Based Measures to Manage Speeds on Rural Roads. In *16th International Conference Road Safety on Four Continents*. Beijing, China (RS4C 2013). 15-17 May 2013. Statens väg-och transportforskningsinstitut.

Bagdade, J., Nabors, D., McGee, H., Miller, R., & Retting, R. (2012). *Speed Management: A Manual for Local Rural Road Owners*, Federal Highway Administration Publication No. FHWA-SA-12-027.

Name	Advance warning signs with beacon
Category	Signing

Description

Signs with flashing beacons that tell the drivers on the approach that there is an intersection ahead. Research has reported 0.2 to 1.8 mph speed reduction.



Source: Hallmark, et al. *Toolbox of countermeasures for rural two-lane curves*

Implementation Considerations

\$\$

Addition of crashworthy sign post and signs

Maintenance Considerations



Maintenance of equipment may depend on site and weather.

References

Xu, G. Speed Management Toolkit. FHWA-SA-15-017. FHWA, U.S. DOT, 2015.
http://safety.fhwa.dot.gov/speedmgt/ref_mats/docs/speedmanagementtoolkit_final.pdf

Turner, B. (2013). Engineering Based Measures to Manage Speeds on Rural Roads. In *16th International Conference Road Safety on Four Continents. Beijing, China (RS4C 2013). 15-17 May 2013*. Statens väg-och transportforskningsinstitut.

Hallmark, S. L.; Hawkins, N. R.; & Smadi, O. G. (2013) Toolbox of Countermeasures for Rural Two-Lane Curves. *InTrans Project Reports*. Paper 114. http://lib.dr.iastate.edu/intrans_reports/114

Name	Advance warning signs with advisory speeds, no beacons
Category	Signing
Description	

Signs without flashing beacons that tell the drivers of the change in the roadway ahead, and give an advisory speed. When applied on curves research has found a reduction of 1.3 mph at the point of curvature.



Source: Marcus Brewer, TTI

Implementation Considerations	\$
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Addition of crashworthy sign post and signs

Maintenance Considerations	
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Maintenance of equipment may depend on site and weather.

References

Hallmark, S. L.; Hawkins, N. R.; & Smadi, O. G. (2013) Toolbox of Countermeasures for Rural Two-Lane Curves. *InTrans Project Reports*. Paper 114. http://lib.dr.iastate.edu/intrans_reports/114

Xu, G. Speed Management Toolkit. FHWA-SA-15-017. FHWA, U.S. DOT, http://safety.fhwa.dot.gov/speedmgt/ref_mats/docs/speedmanagementtoolkit_final.pdf

Speed Management: A Manual for Local Rural Road Owners. FHWA-SZ-12-027. FHWA, U.S. DOT, 2012. http://safety.fhwa.dot.gov/local_rural/training/fhwasa010413spmgmt/

4.1.1 Placement of Traffic Control Devices

To provide approaching drivers sufficient time and distance to react to traffic control devices, their appropriate placement location must be calculated. Table 4.1 shows the calculations performed by the research team. From the literature search it was found that the desired speed at the approach of a roundabout is often 25 mph, though roundabouts may be designed for lower speeds such as 20 or 15 mph, and the desired speed may be zero at the yield sign, if drivers need to come to a stop to be able to yield at entry. Therefore, the research team used 0 mph as a conservative basis for the example shown in Table 4.1 and Figure 4.1.

Table 4.1 Advance sign placement calculation table.

Initial vehicle traveling speed (mph)	Desired speed at end of approach (mph)	Deceleration distance (feet)^a	Brake Reaction distance (feet)^b	Total distance (feet)	Rounded total distance (feet)	Sign Legibility distance (feet)^c	Sign Location (feet)
A	B	C	D	E	F	G	H
75	0	624	275.6	899.6	900	250	650
70	0	570	257.3	827.3	830	250	580
65	0	502	238.9	740.9	745	250	495
60	0	458	220.5	678.5	680	250	430
55	0	400	202.1	602.1	605	250	355
50	0	358	183.8	541.8	545	250	295
45	0	309	165.4	474.4	475	250	225

Sources:

- Figure 2-25 in the 2011 AASHTO *Policy on Geometric Design of Highways and Streets*
- Table 3-1 in the 2011 AASHTO *Policy on Geometric Design of Highways and Streets*
- Table 2C-4 in the 2009 *Manual on Uniform Traffic Control Devices*

Assumptions:

- Level roadway
- Perception Reaction Time (PRT) = 2.5 seconds
- Deceleration rate is 11.2 ft/s^2

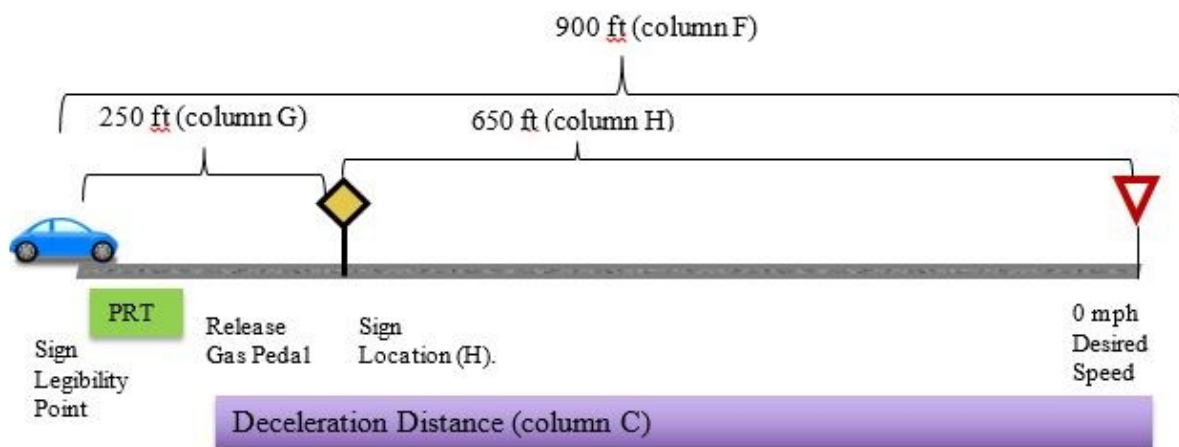











Figure 4.1 Example illustration for a vehicle with an initial speed of 75 mph

4.2 SUMMARY OF COUNTERMEASURES

A summary of the countermeasures is provided in this section. The expected speed reduction and the expected duration of the effect of the countermeasure is summarized from previous research.

Countermeasure	COSTS		BENEFITS	
	Installation cost	Maintenance effort	Expected speed reduction	Expected time duration of speed reduction
Gateway Treatments	\$\$\$		Two reports show a reduction of five to seven percent in 85 th percentile. Two studies reported average speed reductions of two to nine mph.	Two reports used a driving simulator or driving subjects. Other two reports were a synthesis of research results.
Illumination	\$\$\$		Six studies reported a positive effect on reducing crashes. None of the studies reported an effect on speed.	These studies were multi-year crash analysis studies.
Optical Speed Bars	\$		One study showed speed reduction in range of 0.9 to 4.5 mph on a two-lane rural road. One study showed a speed limit reduction of two mph. Another study showed varying effects	One study reported a decrease in speed 90 days after implementation. Another study analyzed data three, six, and seven months after installation, and showed a diminishing effect.

Countermeasure	COSTS		BENEFITS	
	Installation cost	Maintenance effort	Expected speed reduction	Expected time duration of speed reduction
Transverse Pavement Markings	\$		Three studies found a speed reduction ranging from one to nine mph. One study found a reduction of two mph on 85 th percentile speed. One study found an initial reduction of 0.1 mph, and later an increase of one mph in average speed was observed.	One study observed the effects of for one month and another study for six months after. Both studies reported speeds were lower on average than before.
Lane Narrowing	\$		Two studies found a speed reduction around three mph at intersections and suburban roads. Two studies showed a range of 0.8 to 7 percent reduction in speed on residential roads. One study found it was ineffective on rural roads.	One study reported an increase in speed one month after implementation, but a decrease four months after installation.
Transition Zones	\$\$		One study found a speed reduction of 1.1 to 2.5 mph. One study reported average speed reduction range from two to nine mph. Another report showed a five percent reduction in 85 th percentile speed.	These studies did not specify a before and after timeline, because the treatment was considered a permanent installation.
Speed Feedback Changeable Message Signs	\$\$-\$\$\$		Six studies found a speed reduction between 2 to 10 mph. Three studies found a	Five studies reported reductions in speeds four to 12 months after

Countermeasure	COSTS		BENEFITS	
	Installation cost	Maintenance effort	Expected speed reduction	Expected time duration of speed reduction
			reduction of three to nine mph in 85 th percentile speed.	installation. One study attempted to look at the effects 24 months after, however, the signs were damaged.
Advance Warning Signs with beacons	\$\$		Two studies found a decrease in average speed ranging from 0.2 to 2.3 mph.	One study analyzed the effects three months after implementation.
Advance Warning signs with advisory speeds, no beacons	\$		One study found the signs to be ineffective. One study found a reduction of 2 to 3 mph at the point of curvature. A summary report shows that results vary between applications and whether device was supplemented with flags.	The studies found did not report a time period of effectiveness.

4.3 EVALUATION MEASURES

Below are suggestions for measures of evaluation (MOEs) or evaluation methods, along with thoughts on how they can be used and what to use to measure them.

4.3.1 Spot Speed on the Approach

- Good for a “snapshot” of conditions at a specific point. Can tell you what the prevailing conditions are relative to the posted speed limit on the approach.
- One or more speed statistics (e.g., average, 85th percentile, posted speed limit +5, PSL + 10, PSL + 15, mode, pace, percent of vehicles exceeding a certain threshold speed, etc.)
- Use automated counter/classifier (or LIDAR) to collect spot speed at key location(s)

- 500 ft upstream of yield line or 100 ft upstream of splitter island for free-flow
- Beginning of splitter island
- Location of warning sign(s)
- Location of approach curve
- Comparison to data before roundabout installation could be insightful.
- Collect data no less than two weeks after installation, to allow time for drivers to adjust to the new configuration. Can measure multiple times after installation (e.g., one month, three months, and six months) to track results over time.

4.3.2 Location of Deceleration on the Approach

- Good for determining where drivers begin and end their deceleration, relative to the designer's intended location. Can be insightful to know where drivers either begin recognizing that there is an intersection to respond to or where they feel comfortable changing their speed.
- Use LIDAR (or maybe video) to track vehicles through the approach and collect speed-distance profiles along the approach
 - Depending on line of sight and capability of equipment, begin as far upstream as practical and track vehicles through the yield line.
- Collect data no less than two weeks after installation, to allow time for drivers to adjust to the new configuration. Can measure multiple times after installation (e.g., one month, three months, and six months) to track results over time.

4.3.3 Speed at Yield Line

- Good for determining whether drivers are predominantly driving at appropriate speeds at the decision/merge point of the approach.
- Use automated counter/classifier (or LIDAR) to collect spot speed (within 50 ft upstream of yield line).
- Collect data no less than two weeks after installation, to allow time for drivers to adjust to the new configuration. Can measure multiple times after installation (e.g., one month, three months, and six months) to track results over time.

4.3.4 Safety Surrogates

- Good for assessing whether speed patterns (or other characteristics) may be leading to specific problems and/or locations for treatment.
- Documented crash history
- Maintenance logs, particularly repeated repair/replacement of certain roadway/roadside features (e.g., signs, guardrails, delineators, etc.)
- Observed conditions on the approach (e.g., skid marks on the lane/shoulder, tire marks on curbs, evidence of frequent encroachments in the roadside off of the paved surface, etc.)
- Law enforcement/emergency personnel response logs

- Feedback from the driving public

4.3.5 Road Safety Audit/Assessment

- Good for developing a complete picture of conditions at the site. A more thorough evaluation than any of the aforementioned methods; in fact, an RSA may include any or all of the previous methods as a part of its evaluation.
- Besides the other evaluation methods mentioned previously, can include discussions with district/area/county engineers, discussions with stakeholders, a review by an outside design consultant, and other elements.
- The result of an RSA will describe not only speed-related safety issues, but also any other potential safety concerns identified at the intersection.

4.4 CONDUCTING A SPEED STUDY

The recommended MnDOT procedure for conducting a speed study can be found in the [Traffic Engineering Manual Chapter 14-7](#). Section 14-7.04 describes investigation procedures for collecting speed samples. In that section, the investigator is recommended to use calibrated radar or lidar tools in a spot-speed study to determine the 85th percentile speed. The Traffic Engineering Manual states that speed samples “should be collected during low-congestion periods in order to minimize the impact of these hazards. Intersections alone do not necessitate a reduction in speed, but the traffic congestion that occurs near intersections does affect speed. The 85th percentile speed will reflect the maximum safe speed for the roadway without measuring the impact of each factor.” The Manual recommends a minimum of 100 free-flowing vehicles to be sampled in studies with more than 1000 AADT; on roadways with less than 1000 AADT, the sample size should be at least 30 free-flowing vehicles. In either case, studies should be discontinued after two hours. Free-flow vehicles are defined as those with a headway of at least 6 seconds, and only the first vehicle in a platoon should be sampled. Additional recommendations on suitable study locations, separate consideration of trucks and buses, and factors to determine appropriate speed limits are also provided within Section 14-7.04, and a checklist of items submitted with a speed report is provided in Section 14-7.07. Practitioners should review this and other material in Chapter 14-7 for complete details.

According to information from the [“Speed Limits in Minnesota”](#) page and related resources on the MnDOT website, the ITE *Manual of Transportation Engineering Studies* (Schroeder, 2010) is also recommended for guidance on the appropriate methods for conducting a speed study. Following are selected guidelines from that manual; practitioners should consult the actual manual for full details.

4.4.1 General Speed Measurement Concepts

Spot-speed data are collected by one of two general approaches: direct and indirect measurements. Direct measurements of speed are made using permanent or handheld technology (e.g., radar or laser devices). Indirect measurements of spot speeds actually calculate speed from time measurements of a vehicle traveling a known, usually short, distance, such as the distance between two closely spaced magnetic inductance loops.

Two basic methods of data collection are the individual vehicle selection method and the all-vehicle sampling method. Both methods can use direct measurement or indirect measurement. Each is discussed separately below.

4.4.2 Individual Vehicle Selection Method

4.4.2.1 Study conditions

The location, analysis time period, and roadway, traffic, and weather conditions under which the study is conducted are generally determined by the study itself. The study’s objective and scope dictate the specific location, time and day, and conditions for which the data will be collected. If approach speeds

to an intersection are the sample of interest, speed measurements should be taken upstream on the approach just before the point that traffic begins to decelerate for a possible stop at the intersection. If the study team needs free-flow speeds, they should conduct the study during off-peak time periods.

4.4.2.2 Personnel/Equipment

The individual vehicle selection method may use a manual speed trap, but it is generally conducted using direct measurement with radar, laser, or infrared technologies that use the Doppler principle. A well-positioned overhead video camera can also be used to manually estimate speeds from known distances on the video.

The accuracy of laser and radar units is affected by two errors: round-off error and cosine angle error. Radar units typically display the measured speed in digital form rounded down to the nearest whole unit of speed (e.g., a display of 55 mph would mean this reading was actually between 55 and 56 mph). Laser units typically provide speeds to one decimal place, but differences may be found among different units and manufacturers.

The cosine angle error occurs because the angle of incidence of the beam to the travel direction of the target vehicle produces a reading on the unit that is less than the actual speed. The measurement is a function of the cosine of the incidence angle. In law enforcement, this error provides a margin in favor of the target driver, but for accurate speed measurement, this error may require a correction to the speed reading. The effect of the cosine angle error on true speed is shown in Table 4.2. Because of the absolute nature of these two error sources, the relative error decreases as speed increases.

Table 4.2 Radar and laser true speed and cosine error

Measured Speed (mph) at True Speed of:						
Angle (deg)	30 mph	40 mph	50 mph	55 mph	60 mph	70 mph
0	30	40	50	55	60	70
1	29.99	39.99	49.99	54.99	59.99	69.99
3	29.96	39.94	49.93	54.92	59.92	69.90
5	29.89	39.85	49.81	54.79	59.77	69.73
10	29.54	39.39	49.24	54.16	59.09	68.94

15	28.98	38.64	48.30	53.12	57.94	67.61
20	28.19	37.59	46.99	51.68	56.38	65.78
30	25.98	34.64	43.30	47.63	51.96	60.62
45	21.21	28.28	35.36	38.89	42.43	49.50
60	15.00	20.00	25.00	27.50	30.00	35.00
90	00.00	00.00	00.00	00.00	00.00	00.00

Source: Lunenfeld and McDade, 1983 via Schroeder, 2010.

4.4.2.3 Sample Size

A speed study must collect a sufficient number of spot-speed observations to allow statistical analysis of the study results. A minimum sample size can be determined for a desired degree of statistical accuracy by using the following equation:

$$N = \left(S \times \frac{K}{E} \right)^2$$

Where:

N = minimum number of measured speeds

S = estimated sample standard deviation, mph

K = constant corresponding to the desired confidence level

E = permitted error or tolerance in the average speed estimate, mph

The value of S for this equation can be estimated from previous speed studies under similar conditions or from Table 4.3 as a function of traffic area and highway type. The value of K for selected confidence levels is shown in Table 4.4. The permitted error, E, reflects the precision required in estimating the mean speed; it is an absolute tolerance and is expressed as plus-or-minus a specified value, typically ± 1.0 to ± 5.0 mph.

Table 4.3 Standard deviations of spot speeds for sample-size determination

Traffic Areas	Highway Type	Average Standard Deviation (mph)
Rural	Two-lane	5.3
	Four-lane	4.2
Intermediate	Two-lane	5.3
	Four-lane	5.3
Urban	Two-lane	4.8
	Four-lane	4.9
	Rounded value:	5.0

Source: Box and Oppenlander, 1976 via Schroeder, 2010.

Table 4.4 Constant corresponding to level of confidence

Constant, K	Confidence Level (%)
1.00	68.3
1.50	86.6
1.64	90.0
1.96	95.0

2.00	95.5
2.50	98.8
2.58	99.0
3.00	99.7

Source: Box and Oppenlander, 1976 via Schroeder, 2010.

4.4.2.4 Radar/Laser Procedures

Successful spot-speed data collection depends on the configuration of the site and how individual vehicles are selected. The positioning of the radar/laser unit at the site is constrained by the capabilities of the unit, the angle of incidence, and the ability to conceal the unit from approaching motorists. Capabilities and tolerances of current units vary, but they are often close to 1 mph, so it is important to have an angle of incidence that keeps the cosine error less than 1 mph, to match the tolerance of the unit. Concealing the unit is important to minimize distraction (a safety concern) and reaction (a potential source of bias) by drivers approaching the site.

The guiding principle is to randomly select target vehicles that represent the population of vehicles under study. Thus, analysts must clearly define the study population (e.g., free-flow vehicles, large trucks, platoon leaders, etc.). Once the population is defined, data collectors can use a strategy to provide a random sample of that population (e.g., every vehicle, every 3rd vehicle, every 5th vehicle, etc.).

4.4.2.5 Manual Speed Traps and Video Procedures

Analysts seldom use manual speed traps, and video is generally less efficient than direct speed measurement with radar or laser. However, spot speeds may be estimated in a speed trap by manually measuring with a stopwatch the time it takes a vehicle to travel a known distance. If video is to be used, it is necessary to establish known distances in the video field of view to use for reference in measurement, using pavement markings, roadside features, or other objects.

4.4.3 All-Vehicle Sampling Method

Analysts use this method when the purpose of the study requires or can be accommodated by measuring the spot speeds of all vehicles passing a point for a sample of time periods. Examples of such applications include monitoring speed trends, assessing highway safety, or establishing speed limits.

4.4.3.1 Study Conditions

As with the individual vehicle method, selection of study conditions is determined by the objective and scope of the study. These conditions include elements such as the location at which to take measurements, the time period over which to collect the data, and the condition of the roadway and weather during the study.

4.4.3.2 Personnel/Equipment

All-vehicle sampling uses automatic data collection equipment such as sensors placed in the travel lanes. An advantage of this method is that personnel are needed only during installation and removal of the equipment; once the equipment is installed, it can operate largely unattended for the duration of the study. A disadvantage of this method is that it typically requires the personnel to physically be in the travel lane. For this reason, activities in the travel lane should be completed by groups of two or more, with appropriate traffic control in place to divert, slow, or stop traffic.

4.4.3.3 Sample Size

With the all-vehicle method, sample size is typically not an issue because deployments are made for at least a 24-hour period. However, sample-size requirements can be calculated in the same manner as in the individual vehicle selection method.

4.4.3.4 Procedures

Successful studies using automatic data collection equipment depend on the operational reliability of the equipment, the physical installation of the equipment, and the calibration and quality control measures employed. External factors that can affect data collection include weather, traffic volumes, mix of vehicle types, and the immediate environment (e.g., dust or debris in the area). All data collection activities need to be coordinated with appropriate state and local officials (e.g., road agencies, law enforcement, etc.) to make sure that there are no conflicting activities in the area and that everyone involved is clear as to their expected duties. Safety in installing and removing equipment is paramount, so procedures must be established and followed to promote safety. The equipment used should be thoroughly checked and calibrated to avoid problems after installation or corrupted data during the study period.

4.4.4 Data Reduction and Analysis

The type of data analysis required depends on the nature of the study. For many of the studies used for approaches to roundabouts, a simple analysis will often suffice. Determining a particular percentile speed (e.g., 50th, 85th) at a specific spot-speed location or identifying where vehicles begin decelerating on an approach through inspection of speed-distance profiles is typically a straightforward process and does not require complex analysis procedures. However, it is important that the data collected be organized into a format suitable for the chosen analysis method. The *ITE Manual of Transportation Engineering Studies* provides guidelines and examples of basic data reduction and display methods, as

well as discussion of descriptive statistics and more detailed analyses. Additional information on data format is provided in MnDOT's summary of the methodology used in the Minnesota Speed Monitoring Program.

CHAPTER 5: FUTURE RESEARCH NEEDS

5.1 GENERAL RESEARCH NEEDS

The countermeasures identified in this research project have generally not been applied and evaluated at roundabouts. The research team believes that speed reduction techniques found effective for horizontal curves, urban-rural transition zones, and isolated rural intersections should be effective for rural roundabouts with high-speed approaches. So, the primary overarching research need is to establish that these countermeasures would achieve speed reductions on roundabout approaches.

A second need is to determine the effects of a combination of multiple countermeasures. While it is tempting to throw many solutions at the problem, there may be a point of driver information overload that is surpassed in doing so. This is true for any combination of speed reduction techniques, but especially to ones being applied to rural high-speed roundabouts because so little has been tested even in isolation.

The third area of research needs is to establish the comparative benefits of two or more countermeasures that fall within the same general cost and maintenance grouping. For instance, installing a sign can be a generally low-cost, low-maintenance countermeasure. This research project has demonstrated that certain kinds of signs may be more effective than others. But most of the research reviewed compared a single sign type to a condition where there was not a sign. More research is needed that compares Sign A to Sign B directly. This type of evaluation could be easily done by installing different sign types on different legs of the approach to a roundabout.

The research team has considered specific research needs for each of the general categories presented in the recommendations in Chapter 4.

5.2 INFRASTRUCTURE RESEARCH NEEDS

Gateway treatments have been used primarily at urban-rural transitions where after passing through the “gate” the roadside or land use changes. For a rural isolated roundabout, however, it is not clear what is on the other side of the gate that is different. Thus, this treatment may be more appropriate for a roundabout in an urban fringe area than in a rural area. Research is needed to compare speed reduction effects of gateway treatments in isolated rural areas to urban fringe areas.

Another research need identified regarding gateway treatments is the relative effectiveness of overhead signs to dual-posting signs warning drivers of the roundabout intersection ahead. Placing the warning signs on both sides of the road may provide enough visual gateway to achieve a speed reduction without the added cost of an overhead sign structure.

In the area of roadway lighting, most lighting studies have focused specifically on crash reduction by examining crash data, not speed at the site. A study of the effects of intersection lighting on approach speed is needed. Another study could examine how far upstream roadway lighting needs to be extended to achieve speed reduction effects.

5.3 PAVEMENT MARKINGS

Several of the pavement marking treatments recommended for consideration involve a transverse marking of some kind. These optical speed bars and transverse lines have been evaluated, but each study used a unique size, design, and placement making it difficult to draw general conclusions about their effectiveness. In addition, there are other approaches used in school and railroad crossing approaches where words are placed on the pavement – so-called “horizontal signing”. One research need is to compare the effectiveness of words or symbols to transverse lines on roundabout approaches. Transverse lines may have some maintenance and durability advantages in terms of wear in the wheel paths.

Lane narrowing achieved through pavement markings is another technique that has been successful in low-speed areas. Research is needed to evaluate lane narrowing in high-speed rural areas, especially for roundabout approaches.

5.4 SIGNING

Transition zones that step down a speed reduction can be achieved through signing. Research is needed to determine whether applying this to roundabout approaches would produce the same effects seen for rural school zones and urban fringe areas.

Research is needed on the long-term effects of signing treatments of all kinds. Several research projects reviewed, as well as practitioner experience, indicate a novelty effect of a new sign – especially for flashing beacons. Research is needed over an extended period of time to determine if any initial speed reduction observed is still present 2 to 5 years later, after motorists become accustomed to the signs.

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