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16. Abstract

Although roundabouts have now been implemented in many parts of the U.S., very few have been built in Texas. This report contains best practices for choosing appropriate locations and design concepts for Texas roundabouts. This research effort is comprised of the following components: synthesis of available literature and analysis methods, development of capacity analysis methods, validation and enhancement of existing tools, and a spreadsheet tool to aid in roundabout planning and implementation.

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TEXAS ROUNDABOUT GUIDELINES: FINAL REPORT

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1. Introduction

1.1. What is a Roundabout

Circular intersection forms have been part of the transportation system in the United States since at least 1905. Their widespread usage decreased after the mid-1950s due to high crash experience and problems with congestion. Therefore, the modern roundabout was developed to improve the safety and operations of the early circular intersection forms.

1.1.1. Roundabout Elements

A roundabout is a form of circular intersection with the following characteristics and design features:

- Yield control on entering traffic to circulating traffic;
- Counterclockwise circulation of traffic around a central island; and
- Appropriate geometric curvature to induce slow and consistent speeds through the intersection.

Requiring entering traffic to wait for gaps in the circulating traffic flow prevents the intersection from locking up. Adequate horizontal curvature of entering and exiting vehicle paths reduces the entry and circulating speeds, which improves safety by reducing the severity of crashes. Figure 1-1 illustrates a typical multi-lane roundabout and identifies the major characteristics. Figure 1-2 identifies the predominant design features of a roundabout.

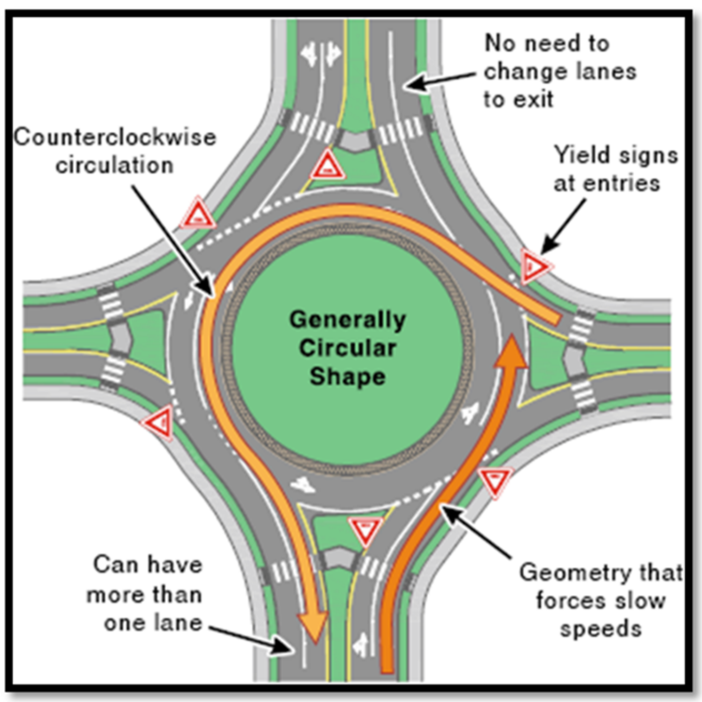


Figure 1-1: Key roundabout characteristics (Source: NCHRP 672)

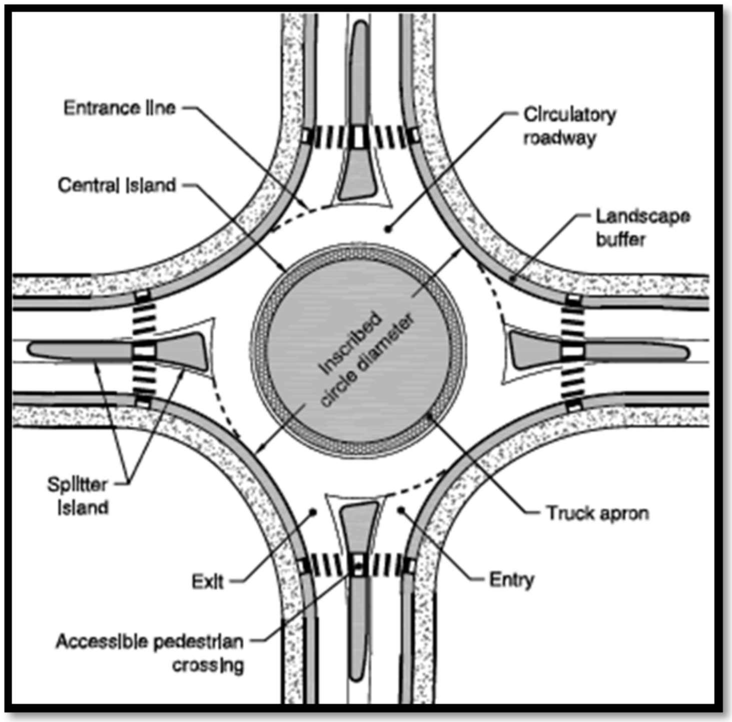


Figure 1-2: Roundabout design features (Source: FHWA Roundabouts Technical Summary)

In a modern roundabout, the curvature of the splitter islands, the location of the splitter islands in relation to the central island, and the width of the circulatory roadway create an environment for low and consistent operating vehicle speeds. Small and medium roundabouts use truck aprons around the central island to accommodate larger vehicles such as tractor-trailers and emergency vehicles. Larger vehicles are able to track on the truck apron without running over the central island. Table 1-1 provides a description of each of the design features.

Table 1-1: Description of key roundabout features (Source: NCHRP 672)

Feature	Description
Central Island	The central island is the raised area in the center of a roundabout around which traffic circulates. The central island does not necessarily need to be circular in shape. In the case of mini-roundabouts the central island is traversable.
Splitter Island	The splitter island is the raised or painted area on an approach used to separate entering from exiting traffic, deflect and slow entering traffic, and allow pedestrians to cross the road in two stages.
Circulatory Roadway	The circulatory roadway is the curved path used by vehicles to travel in a counterclockwise fashion around the central island.
Truck Apron	The truck apron is the traversable portion of the central island adjacent to the circulatory roadway that may be needed to accommodate the wheel tracking of large vehicles. An apron is sometimes provided on the outside of the circulatory roadway.
Entrance Line	The entrance line marks the point of entry into the circulatory roadway. This line is physically an extension of the circulatory roadway edge line but functions as a yield or give-way line in the absence of a separate yield line. Entering vehicles must yield to any circulating traffic coming from the left before crossing this line into the circulatory roadway.
Accessible Pedestrian Crossings	For roundabouts designed with pedestrian pathways, the crossing location is typically set back from the entrance line, and the splitter island is typically cut to allow pedestrians, wheelchairs, strollers, and bicycles to pass through. The pedestrian crossings must be accessible with detectable warnings and appropriate slopes in accordance with ADA requirements.
Landscape Strip	Landscape strips separate vehicular and pedestrian traffic and assist with guiding pedestrians to the designated crossing locations. This feature is particularly important as a way-finding cue for individuals who are visually impaired. Landscape strips can also significantly improve the aesthetics of the intersection.

1.1.2. Categories of Roundabouts

Roundabouts are categorized according to size and number of lanes to facilitate discussion of specific performance or design issues. Following are the categories:

- mini-roundabouts,
- single-lane roundabouts, and
- multi-lane roundabouts.

The three main roundabout categories can be further subdivided by their location (e.g., rural, urban, and suburban). For a roundabout in an urban environment, the inscribed circle diameter tends to be smaller due to smaller design vehicles and existing right-of-way restrictions. Urban areas also have more extensive pedestrian and bicycle features. Roundabouts located in rural areas allow for higher approach speeds; therefore, more attention must be given to visibility, approach alignment, and cross-sectional details. Roundabouts in suburban areas incorporate features of both urban and rural roundabouts. Table 1-2 compares the different categories of roundabouts.

Table 1-2: Roundabout category comparison (Source: NCHRP 672)

Design Element	Mini-Roundabout	Single-Lane Roundabout	Multilane Roundabout
Desirable maximum entry design speed	15 to 20 mph (25 to 30 km/h)	20 to 25 mph (30 to 40 km/h)	25 to 30 mph (40 to 50 km/h)
Maximum number of entering lanes per approach	1	1	2+
Typical inscribed circle diameter	45 to 90 ft (13 to 27 m)	90 to 180 ft (27 to 55 m)	150 to 300 ft (46 to 91 m)
Central island treatment	Fully traversable	Raised (may have traversable apron)	Raised (may have traversable 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.

1.1.2.1. Mini-Roundabouts

Mini-roundabouts have relatively small inscribed circle diameters (typically 45 to 90 ft. [13 to 27 m]) and fully traversable central islands, allowing larger vehicles to cross over the central island when turning. However, they are designed to accommodate passenger vehicles without requiring them to drive over the central island. Mini-roundabouts are useful in locations with limited right-of-way or other restrictions. They are most commonly implemented in low-speed urban environments with average operating speeds of 30 mph (50km/h) or less. Typical entry speeds for a mini-roundabout are 15 to 20 mph (25 to 30 km/h). A mini-roundabout controls speed through the geometric design of the entry and exit legs and the design that requires most vehicles to travel around the central island.

Mini-roundabouts are moderately inexpensive, because they do not require extensive additional pavement at an intersection. They are perceived as pedestrian-friendly because they are small, have short crossing distances, and have very low vehicle speeds entering and exiting the intersection. Figure 1-3 is an example of a modern mini-roundabout.

The Federal Highway Authority (FHWA) provides a technical summary dedicated to mini-roundabouts that can be found at http://safety.fhwa.dot.gov/intersection/roundabouts/fhwasa10007/.

Figure 1-3: Example of a mini-roundabout in Dimondale, Michigan (Source: NCHRP 672)

1.1.2.2. Single-Lane Roundabouts

Single-lane roundabouts have one-lane entries at all legs and one circulatory lane. They are distinguished from mini-roundabouts by their larger inscribed circle diameters (typically 90 to 180ft [27 to 55 m]), more tangential entries and exits, and non-traversable central islands. Their design, focused on achieving consistent entering and circulating vehicle speeds, allows slightly higher speeds than a mini-roundabout at the entry, on the circulatory roadway, and at the exit. Typical entry speeds for a single-lane roundabout are 20 to 25 mph (30 to 40 km/h). The geometric design features of a single-lane roundabout include raised splitter islands, a non-traversable central island, cross walks, and a truck apron. Figure 1-4 shows the features of a typical single-lane roundabout, and Figure 1-5 is an example of a single-lane roundabout.

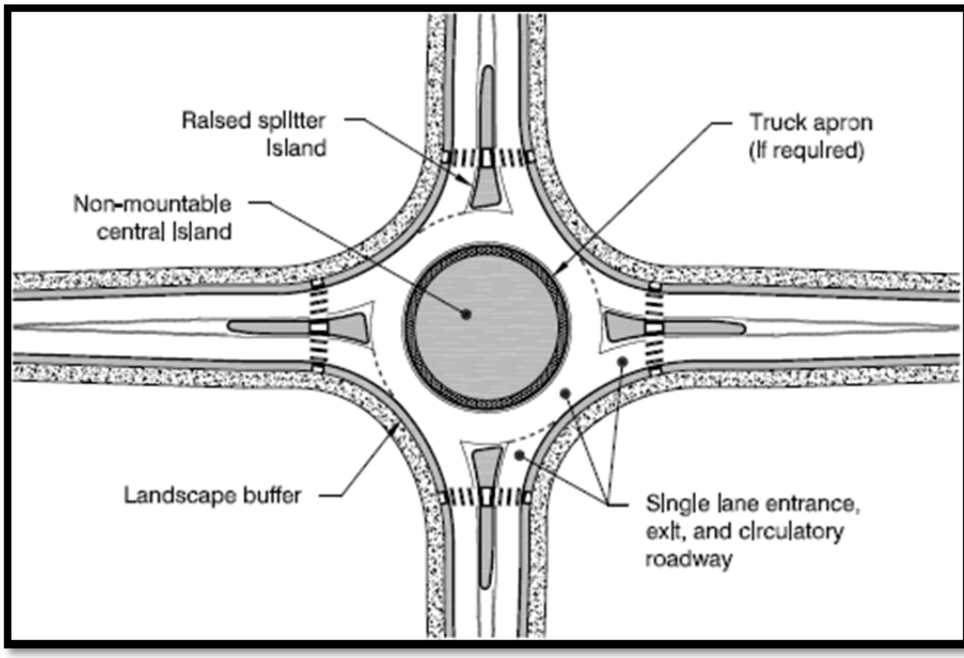


Figure 1-4: Features of a single-lane roundabout (Source: NCHRP 672)

Figure 1-5: Example of a single-lane roundabout in Dublin, Ohio (Source: NCHRP 672)

1.1.2.3. Multi-Lane Roundabouts

Multi-lane roundabouts have a minimum of one entry with more than one lane. Entry lanes can flare from a single-lane approach to two lanes to accommodate traffic patterns (e.g., heavy turn movement). The circulatory roadway is wider for a multi-lane roundabout to accommodate vehicles traveling side-by-side. The design allows speeds at the entry, on the circulatory roadway, and at the exit similar to or slightly higher than those for the single-lane roundabouts. Typical entry speeds for a multilane roundabout are 25 to 30 mph (40 to 50 km/h). The geometric design features of a multi-lane roundabout include raised splitter islands, a non-traversable central island, and possibly an apron. Figure 1-6 shows the features of a typical multi-lane roundabout, and Figure 1-7 provides an example of a multi-lane roundabout.

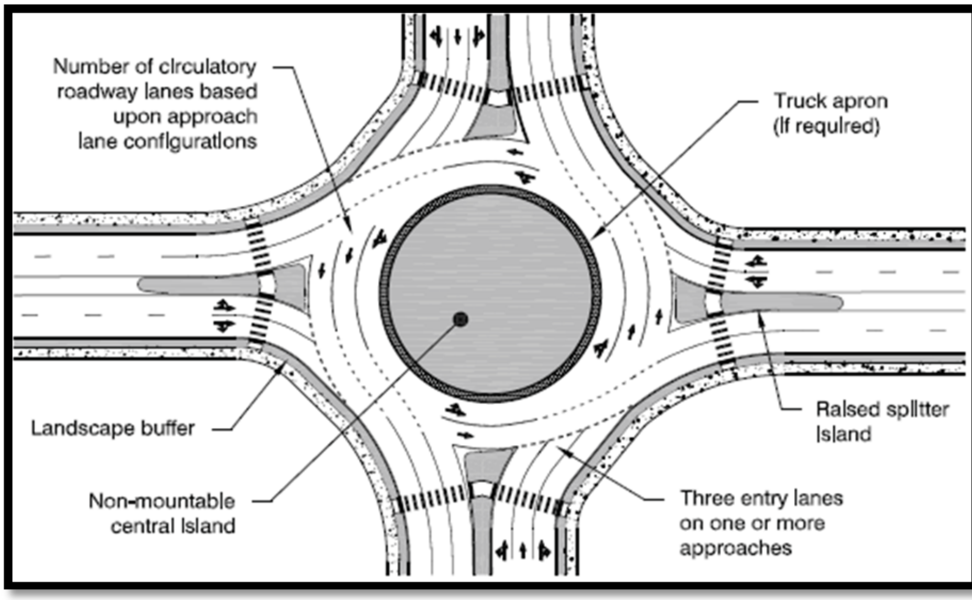


Figure 1-6: Features of a multi-lane roundabout (Source: NCHRP 672)

Figure 1-7: Example of a multi-lane roundabout in Carmel, Indiana (Source: NCHRP 672)

Table 1-3 compares fundamental design and operational elements for each of the three roundabout categories.

Table 1-3: Comparison of roundabout categories (Source: NCHRP 672)

Design Element	Mini Roundabout	Single-Lane Roundabout	Multi-Lane Roundabout
Desirable maximum entry design speed	15 to 20 mph (25 to 30 km/h)	20 to 25 mph (30 to 40 km/h)	25 to 30mph (40 to 50 km/h)
Maximum number of entering lanes per approach	1	1	2+
Typical inscribed circle diameter	45 to 90 ft. (13 to 27 m)	90 to 180 ft. (27 to 55 m)	150 to 300 ft. (46 to 91 m)
Central island treatment	Fully traversable	Raised (may have traversable apron)	Raised (may have traversable apron)
Typical daily service volumes on 4-leg roundabout* (detailed capacity analysis required for volumes above the level specified)	Up to approximately 15,000 veh/day	Up to approximately 25,000 veh/day	Up to approximately 45,000 veh/day for two-lane roundabout

*Operational analysis needed to verify upper limit for specific applications or for roundabouts with more than two lanes or more than four legs.

1.1.3.How Roundabouts Differ from Other Types of Circular Intersections

Roundabouts are only one type of circular intersection. Three other distinct types of circular intersections are rotaries, signalized traffic circles, and neighborhood traffic circles. Table 1-4 presents five key elements that distinguish roundabouts from other types of circular intersections, which are detailed later in this section.

Table 1-4: Key elements of roundabouts and traffic circles (Source: Kansas Roundabout Guide)

Key Element	Roundabout	Traffic Circle
Control on entry	YIELD control on entry.	Some use a signal, stop control, or no control on one or more entries.
Priority to circulating vehicles	Circulating vehicles have the right of way.	Some require circulating traffic to yield to entering traffic.
Pedestrian access & crossing	Allowed only across the approaches to the roundabout, behind the entrance line.	Some allow pedestrians to cross to the central island.
Parking	No parking allowed within the circulatory roadway or at the entries.	Some allow parking within the circulatory roadway.
Direction of circulation	Counterclockwise direction to the right of the central island.	Some allow left-turning vehicles to pass to the left of the central island.

1.1.3.1. Rotaries

Rotaries are old-style circular intersections characterized by a diameter that is greater than 300 ft. (100 m). The large diameter of a rotary is a result of the length of the weaving section required between intersection legs. Because of the large diameter, circulating speeds are high, making necessary maneuvers within the circle challenging. Unlike the roundabout, lane changes are necessary within a rotary for some movements. For some rotaries, circulating traffic yields to entering traffic. This practice can create congestion on the circulatory roadway. Figure 1-8 provides an example of a rotary.

Figure 1-8: Example of a rotary in Fort Worth, Texas (Source: NCHRP 672)

1.1.3.2. Signalized Traffic Circles

A signalized traffic circle is an older style circular intersection that uses traffic signals to control one or more entry legs into the circulatory road. Signalized traffic circles operate very differently from yield-controlled roundabouts. Vehicles on the circular roadway are required to queue and traffic can progress only at the appropriate traffic signal. Figure 1-9 provides an example of a signalized traffic circle.

Figure 1-9: Example of a signalized traffic circle in Hollywood, California (Source: NCHRP 672)

1.1.3.3. Neighborhood Traffic Circles

Neighborhood traffic circles are generally smaller than modern roundabouts. They are in areas with very low traffic volumes, such as in residential neighborhoods, to calm traffic and for aesthetics. The traffic island creates a physical impediment that requires vehicles to negotiate around it, slowing traffic. At some neighborhood traffic circles, left-turn movements for larger vehicles occur in front of the traffic island. The entry legs into the circulatory road are either uncontrolled or stop-controlled. The cost of implementing neighborhood traffic circles is low because no additional right-of-way is required. Figure 1-10 provides an example of a neighborhood traffic circle.

Figure 1-10: Example of a neighborhood traffic circle in Portland, Oregon (Source: NCHRP 672)

1.2. Resources

The Federal Highway Administration's (FHWA) Roundabouts*: An Informational Guide, Second Edition* (otherwise known as National Cooperative Highway Research Program [NCHRP] 672) is the current national guidance document regarding roundabouts. Several states, including Kansas, Maryland, Florida, Arizona, Iowa, Oregon, New York, Washington, and Wisconsin, have developed supplemental state guidance regarding roundabouts. The supplemental state guidance documents tend to build on the first edition of the FHWA's Roundabout Guide published in 2000. These existing guidance documents provide a valuable point of reference and foundation for developing the Texas Roundabout Guide. NCHRP 672 and existing state guidance documents are discussed in this section.

1.1.4. NCHRP 672

Published in late 2010, NCHRP 672 covers many critical pieces of information, including operations analysis, safety, geometric design, traffic design, and system considerations. The information presented in NCHRP 672 is largely based on past research and practices; it forms the basis for many of the state and local roundabout guides written since 2000. As noted above, while some of the information in the FHWA Roundabout Guide remains pertinent and accurate, key pieces of methodology are outdated relative to research conducted since 2000. These pieces of methodology will be discussed later. An update to the FHWA Roundabout Guide is set for publication sometime in 2010.A complete updated draft was submitted for review in August 2009.The updated version is anticipated to cover many of the topics discussed here. The research team will strive to incorporate the updated materials upon release of the next edition of the FHWA Roundabout Guide.

1.1.4.1. Safety

Roundabouts improve the safety of intersections by providing a slower speed environment and decreasing the number of conflict points. Key points in NCHRP 672 that remain pertinent and accurate discuss creating a slower speed environment in order to give drivers more time to react to potential conflicts on the roadway and to help reduce the severity of a collision. The reduced number of pedestrian-vehicle and vehicle-vehicle conflicts is also discussed. Using U.S. data from several studies, the NCHRP 672 reports the many settings in which roundabouts increase the safety level of an intersection. NCHRP 672 also presents crash reduction statistics, safety prediction models, and information regarding considerations for serving visually impaired pedestrians at roundabouts. This topic is discussed further in this document's Section 2, "Safety Assessment Techniques."

For additional context, NCHRP Report 572, *Roundabouts in the United States*, provides updated, U.S.-specific information regarding crash reduction statistics and crash prediction models. The NCHRP Report 572 found the previous crash prediction models based on non-U.S. data did not fit U.S. roundabout crash data well (Rodegerdts et al., 2007). Additional roundabout safety studies by Persaud et al. (2001), Eisenman et al. (2004), and others also provide more recent U.S.-specific roundabout safety information. The current NCHRP Project 3-78, *Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities*, addresses how to accommodate visually impaired pedestrians at roundabouts. Recent and past pertinent roundabout research is discussed further in Section 1.3, "Roundabout Research Findings."

1.1.4.2. Operations

Following are the primary traffic operations topics addressed in NCHRP 672:

- Principles of roundabout operations;
- Capacity methodology for various roundabout configurations;
- Measures of effectiveness used to determine the performance of a roundabout and estimation methods for such measures;
- Information on computer software packages to facilitate capacity and performance analysis procedures.

Results found by Rodegerdts et al. (2007), documented in NCHRP Report 572, indicated that capacity methodology in the first FHWA Roundabout Guide should be updated to reflect operations at U.S. roundabouts. The existing guidance regarding calculating delay and queues was found to be acceptable (Rodegerdts et al., 2007).

Rodegerdts et al. (2007) recommend two alternative U.S.-specific capacity models in NCHRP Report 572. These capacity models can also be found in NCHRP 672 and the 2010 Highway Capacity Model and are a major update of the information found in the first FHWA Roundabout Guidelines. The methodology is largely based on data collected at 31 U.S. roundabouts. Research by Polus et al. (2003), Pollatshek et al. (2002), Xie et al. (2007), and others also provides additional potential resources for updating the capacity methodology. In these guidelines the new capacity models will be presented as well as information on how to use them in conjunction with existing software packages. Recent and past pertinent roundabout research related to operations is discussed further in Section 1.3, "Roundabout Research Findings." Additional detail on this topic can be found later in this document.

1.1.4.3. Geometry

Guidance regarding geometric design of roundabouts in NCHRP 672 is largely consistent with the information found in the 2000 FHWA Roundabout Guidelines. The geometric design guidelines are now more user-friendly, provide information on initial operations analysis, and emphasize the idea that there is no one optimal roundabout design. New information in NCHRP 672 includes a section on managing conflict areas and more information on mini-roundabouts. NCHRP 672 provides a solid base for developing new design guidelines specific to Texas conditions. The topics addressed include the following:

- The design process;
- Managing speeds at the roundabout and on the approaching roadway;
- Lane arrangement to ensure lane continuity;
- Accommodating design vehicles;
- Approach and entry alignment;
- Specific considerations for multilane roundabouts;
- Considerations for right-turn bypasses;
- Pedestrian and bicycle accommodations;
- Sight distance;
- Vertical alignment; and
- Parking and bus stop locations.

These topics are discussed in further detail later in these guidelines.

Information related to managing speeds into, through, and out of the roundabout, specific considerations for multilane roundabouts, and pedestrian and bicyclist issues are the primary topics identified as those needing to be refreshed or expanded. The research by Rodegerdts et al. (2007) indicates the speed analysis techniques in the FHWA Roundabout Guide used to estimate the 85th Percentile vehicle speeds are reasonably reliable for circulating speeds but overestimate entering and exiting speeds. Additional research findings found by Rodegerts et al. (2007) as well as Easa and Mehmood (2004), Knotsman (2008), and others are discussed in Section 1.3, "Roundabout Research Findings."

1.1.5. Supplemental State Roundabout Design and Implementation Guides

The first edition of the FHWA Roundabout Guide was meant to be a transferable document, applicable across the United States. Different states have developed their own supplemental roundabout guides or roundabout material. The supplemental material tends to be based on the first edition of the FHWA Roundabout Guide with additional state-specific information related to planning considerations, design attributes, or signing and pavement markings.

State Departments of Transportation with supplemental roundabout guides or guidelines include New York (NYSDOT), Wisconsin (WisDOT), Missouri (MoDOT), Kansas (KDOT), and Washington (WSDOT). NYSDOT's Highway Design manual includes a chapter on roundabouts, based largely on the FHWA Roundabout Guide, but also influenced by British practice, which generates some significant differences in operations analysis and design techniques. The manual specifies that the regression-based model, RODEL, is to be used for all capacity analysis, and it includes discussion and values for entry angles and effective flare length. Similar to NYSDOT, Wisconsin's supplemental roundabout material is also more heavily influenced by British practice than the FHWA Roundabout Guide. MoDOT's Project Development Manual specifies capacity models (SIDRA and capacity models in the Highway Capacity Manual [HCM]) and simulation software (VISSIM) to be used. It also specifies roundabout justification procedures, which include three stages: appropriateness, operational feasibility, and comparative performance. Washington's manual includes design parameters meant to conform to WSDOT's broader roadway design standards. KDOT's guide provides system considerations, including the design of roundabouts in series, and considers the proximity of other control devices.

States that have directly adopted the FHWA Roundabout Guide and generated supplemental supporting materials include California (Caltrans), Pennsylvania (PennDOT), and Maryland. Caltrans provides changes in certain design parameters in its Appendix A. PennDOT's guide is meant to assist transportation professionals in the planning and early phases of the project development process. It includes a questionnaire aimed at determining whether a roundabout is warranted or beneficial. The Maryland State Highway Administration has created supplements with regard to signing and pavement markings.

1.2. Roundabout Research Findings

Roundabout research has informed and continues to influence the guidelines developed for analysis, design, and implementation considerations regarding roundabouts. Due to the small number of roundabouts in the U.S., many of the guides discussed earlier are based on research and information obtained from studies conducted outside the U.S. However, over the last few years the number of roundabouts and corresponding U.S. data has become sufficient to enable research specific to the safety, operations, geometric performance, and characteristics of U.S. roundabouts. The recent research focused on U.S. roundabout experience coupled with knowledge gained from past research is now capable of informing new editions and/or first editions of roundabout guidance documents produced in the U.S. The most recent U.S. research related to roundabout safety, operations, and geometry is discussed here along with highlights of research findings from abroad.

1.2.1.Safety

Safety-related research is useful in developing effective design and implementation guidelines; safety research aims to predict and quantify the relationships between roundabout geometric and operational characteristics and safety performance. Ideally, the results provide information indicating the expected safety performance of a given roundabout (i.e., crash prediction models) and the expected difference in crashes due to converting a traditional intersection to a roundabout (i.e., before/after studies). These safety considerations can impact geometric design as well as implementation decisions. An overview of the studies conducted abroad and in the U.S. is provided here.

1.2.1.1. Crash Prediction Models

Crash prediction models are developed to identify critical geometric and traffic flow characteristics influencing crash occurrence and severity. The literature regarding crash prediction models for roundabouts is dominated by research using data sets from roundabouts outside the U.S. It was not until 2007, in the NCHRP Report 572, that crash prediction models based on U.S. data were published. This section discusses key research conducted abroad and recent U.S. research regarding crash prediction models.

Maycock and Hall (1984) considered the crash, operational, and geometric characteristics of 84 roundabouts in the United Kingdom. They found the average annual daily traffic (AADT) on the major and minor approaches to be significant variables for all crash types and the influence of geometry to vary by crash type (Maycock and Hall, 1984). Research in Australia by Arndt (1998) developed a procedure for estimating vehicle paths and speed through the roundabout based on the geometry; Arndt (1998) used these as inputs for crash prediction models. Crash prediction models produced by Brude and Larsson (2000) were based on data from 650 roundabouts in Sweden. Findings from Brude and Larsson (2000) indicate that lower travel speeds tend to occur when the central island of the roundabout is 33 to 66 ft. in radius and that a perpendicular approach to the roundabout is significantly beneficial to slowing vehicle speeds. The study also found single-lane roundabouts to be safer for cyclists compared to multilane roundabouts and found pedestrians to be no less safe at roundabouts compared to conventional intersections (Brude and Larsson, 2000).

NCHRP Project 3-65, *Applying Roundabouts in the United States*, is the first published research with roundabout crash prediction models based on U.S. roundabout data. The researchers first assessed the ability of the non-U.S. crash prediction models to estimate U.S. crash data at roundabouts and found none of the non-U.S. models fit U.S. data well (Rodegerdts et al., 2007). Rodegerdts et al. (2007) developed intersection and approach level crash prediction models using data collected from 90 roundabouts for intersection level models and 139 roundabout approaches for approach-level models; all data were from roundabouts in the U.S. The intersection-level models predict crashes for total as well as injury crashes based on AADT on the major and minor approaches, the number of approaches, and number of lanes (Rodegerdts et al., 2007). Both the intersection- and approach-level models need to be calibrated prior to local application.

1.2.1.2. Before/After Studies

The before/after studies conducted at intersections where roundabouts replaced traditional intersection forms consistently indicate a relatively large decrease in injury and/or fatal crashes as well as a tendency to decrease total crashes. A meta-analysis of 28 before/after roundabout non-U.S. studies performed by Elvik (2003) indicates converting an intersection to a roundabout produces a 30% to 50%

reduction in injury crashes and a 50% to 70% reduction in fatal crashes. Specific examples from abroad include a study conducted by Tudge (1990), which considered 230 roundabouts and found a 41% reduction in total crashes and a 45% reduction in injury crashes. Similarly, Schoon and Minnen (1993) considered 201 single-lane roundabouts and found a 47% reduction in total crashes and a 71% reduction in injury crashes. A study by Ourston (1996) in the Netherlands found a 27% reduction in crashes and 33% reduction in fatalities when nine traffic signal control intersections were converted to roundabouts.

The first definitive before/after study conducted with sites in the U.S. was by Persaud et al. (2001), which considered 23 intersections converted from a stop-controlled or signal-controlled intersection to a roundabout. Considering the entire data set, a 40% reduction in total crashes and an 80% reduction in injury crashes were found (Persaud et al., 2001). A subsequent study in 2004 adding additional data to the original data set produced similar results (Eisenman et al., 2004). The before/after analysis conducted by Rodegerdts et al. (2007) built on the foundation laid by the previous studies. General conclusions drawn from the research include the following: 1) the safety benefits of converting a signal or two-way stop-control intersection to a roundabout are significant, 2) larger safety benefits tend to be associated with single-lane roundabouts compared to multilane roundabouts, and 3) safety benefits reduce as AADT increases (Rodegerdts et al., 2007).

1.2.2. Operations

Operational research regarding roundabouts has focused on capacity, delay, and queuing models. Operations analysis is a critical piece to planning and designing appropriately sized roundabouts. Related research is discussed in this section; the studies discussed, as well as similar work, will contribute to forming operations methodology recommendations for the Texas Roundabout Guide.

1.2.2.1. Capacity

Capacity models used to analyze roundabouts can be categorized into gap acceptance models or linear regression models.

1.2.2.1.1. Gap acceptance models

These models assume traffic entering a roundabout will do so only when an acceptable gap (defined as the headway between two adjacent cars) is found in the conflicting lane. To develop a gap acceptance model, additional assumptions must be made, namely the values for minimum acceptable gap (t_c) and follow-on time (t_f), the distribution of priority gaps in the flow stream, and behavior of flow on each stream.

Australia's current capacity model is based on a gap acceptance method and assumes t_c, t_f, and the conflicting flow to be constant. These assumptions tend to limit the performance of the model in predicting capacities (Taekratok, 1998). The HCM method, introduced in 1997, is based on the Australian method. SIDRA, a computer program based on the Australian method, uses gap acceptance models and is widely used in practice. More detailed information on

SIDRA is presented in Section 3.6, “Capacity Analysis of Texas Roundabouts Using SIDRA and VISSIM.”

More recent research in the area of gap acceptance models has been aimed at relaxing certain model assumptions, namely the constant value of t_c and t_f, and the distribution of gaps in the flow stream. Polus et al. (2003) looked at the critical gap as a function of waiting time, which was found to follow an S-shaped curve, and also looked at the entry capacity of the roundabout. Pollatshek et al. (2002) developed a decision model for gap acceptance and capacity at intersections, based on the risk associated with not accepting small gaps. By comparing different driver populations, the authors show how this decision model affects capacity.

The research conducted in modeling priority gaps in a flow stream has mostly focused on the choice of probability distribution. The Australian model and models based on it make use of bunched exponential distributions, while other authors have suggested the use of negative binomial and shifted negative binomial distributions as well. A review of gap acceptance models based on bunched exponential, negative binomial, and shifted negative binomial distributions was conducted by Akcelik (2007). Xie et al. (2007) looked at a gap acceptance model assuming the Erlang distribution and found positive results.

1.2.2.1.2. Linear Regression Models

In these models, different explanatory variables are considered predictors of roundabout capacity. Coefficients for these parameters are determined to develop a functional equation that relates roundabout capacity to the different explanatory variables. The quality of the regression model is highly dependent on the availability of data.

The UK model is a linear regression model based on empirical data. The UK model not only takes into consideration the flow characteristics but also includes the geometric parameters of the roundabout. The UK model requires a large amount of data over a wide variety of roundabout types to accurately calculate capacity, which can be challenging. RODEL is a computer program based on the UK linear regression model (Taekratok, 1998). The FHWA Roundabout Guide mainly uses a simplified British regression relationship.

NHCRP Report 572 performs a thorough analysis of how different capacity methods, including the HCM and FHWA, recreate real U.S. roundabout operations and proposes its own capacity equation for the entire U.S. The report stresses the need for the capacity equation to be calibrated for local drivers. The driver’s behavior contributes greatly to roundabout capacity and driver behavior is greatly dependent on the driver’s local environment. The constants in the equation (1130 and -0.0010) should be recalibrated for specific locations to better predict capacity. Other states have started creating their own roundabout guidelines and as a result have created their own capacity calculation methods. It appears that a state will either side with the HCM or the FHWA Roundabout Guide. Florida uses the HCM guidelines (Florida, 1996), while Kansas (2003), New York (2009), Wisconsin (2009), and Alaska (2005) prefer the FHWA standards.

1.2.2.2. Delay

Delay equations for under-saturated conditions have usually been calculated using basic queuing equations (Kremser, 1964; Brilon, 1988; Yeo, 1962). Time-dependent delay solutions (those that consider oversaturated conditions) were developed by Kimber and Hollis (1979) and later simplified by Akçelik and Troutbeck (1991) and are presented in the HCM. The delay calculation in the NCHRP 672 is based on the HCM's control delay equation. The NCHRP 572 equation differs from the HCM equation by a constant value of 5, attributed to different acceleration patterns of roundabouts (Rodegerdts et al., 2007).

1.2.2.3. Queue Length

Queue length is useful when comparing roundabouts to other intersection treatments. While average queue length is good to know, the 95th percentile queue length is the length useful for design. The HCM uses graphs to associate 95th percentile queue lengths with volume-to-capacity ratios. NCHRP 672 presents the HCM methodology for 95th percentile queue lengths.

Several recent research studies consider queuing. Flannery et al. (2005) presents an analytical model, obtains renewal-based analytical expressions for summary statistics of the time required for entry into the circulation stream for an arbitrary vehicle, and applies the models in an M/G/1 queuing model to compute steady-state average delay and length of the queue. Ross (2009) analyzes the sensitivity of a queue to traffic incidents. Heidemann and Wegmann (1996) developed a general queuing theory model for unsignalized intersections that has most mathematical models in the literature as special cases. Critical gaps and follow-up times are allowed to be stochastically dependent.

1.2.3.Geometry

As discussed earlier, a roundabout's geometry tends to be a significant contributing factor to its successful safety and operations performance. As such, research related to roundabout geometry tends to focus on the effects geometric elements have on safety and operations. As such, the previous two sections incorporated studies relating safety and operations to geometry. An overview of several additional geometry-oriented studies is presented here.

Easa and Mehmood (2004) and Mehmood and Easa (2006) proposed a speed consistency and a multi-objective optimization model, respectively, that determine optimal design parameters, including central island radius, flaring length, and entry angle. Kent et al. (2008) proposes a design approach that allows for expandable roundabouts (i.e., single lane roundabouts that can be expanded to multilane roundabouts, if needed). Two alternatives are introduced, based on the concept of expanding inwards or outwards, and advantages and disadvantages are listed for both alternatives.

Arndt and Troutbeck (1991) determine the impact of geometric parameters on safety. Hels and Orozova-Bekkevold (2007) use regression models to determine the impact design parameters have on the safety of bicycles and found cyclist and driver volumes, potential vehicle speed, and age of the roundabout to be strong predictors. It is important to note, however, that roundabout age is a variable that can be representative of a large number of era-dependent parameters.

NCHRP Report 572 incorporated acceleration and deceleration into speed prediction models used in the FHWA set of guidelines to provide a better fit between predicted and observed entry and exit speeds. The improved models incorporate acceleration and deceleration effects relating to the circulating speeds (Rodegerdts et al., 2007). This finding is critical, as the current FHWA methodology would result in unnecessarily tight geometry, making it more difficult to accommodate a given design vehicle. Knostman (2008) contrasts the estimates obtained using the NCHRP Report 572 method and the UK method for estimating speeds with field conditions for three multilane roundabouts where significant discrepancies were found.

1.3. Evaluation Tools

At the intersection, corridor, or sub-network level, roundabout operations evaluation tools consist of analytical models and microsimulation models. Analytical models are used for individual intersection operations analysis; the intersection is analyzed in isolation from the surrounding network. Microsimulators model individual vehicle movements and can be used to model individual intersections as well as corridors or sub-networks limited in size. Both families of evaluation tools are discussed in this section.

1.3.1. Analytical Models

Several software packages make use of analytical models to predict the performance of intersections in general, including roundabouts. Two of the more widely used programs for analyzing roundabouts are SIDRA and RODEL.

SIDRA, an analytical model developed by the Australian R&D company Akcelik& Associates Pty Ltd, is “an advanced micro-analytical traffic evaluation tool that employs lane-by-lane and vehicle drive cycle models” (SIDRA website, 2009). RODEL is a regression-based model that takes turning flows, lane geometry, and circle diameter as inputs in order to determine the design parameters of a roundabout (RODEL, 2000).

A survey of Australian traffic and transport professionals found the majority of them use SIDRA for their intersection analysis of roundabouts (Akcelic, 2008). Sisiopiku and Oh (2001) analyzed different types of roundabouts using SIDRA and compared them to regular signalized intersections. The authors did not, however, address issues of calibration. Akcelik (2003) compared the performance of SIDRA to other analytical models, and addressed SIDRA’s calibration issues, presenting two different calibration methods and a case study making use of these calibration methods (Akcelik, 2005).

1.3.2. Microsimulation

Microsimulators attempt to model individual vehicles with a high degree of realism. Microscopic simulators enable researchers to model the impact of roundabout geometry on lane change maneuvers and weaving, and the resulting travel times on roadway sections. They assume driver responses to different stimuli to determine specific trajectories followed by vehicles. Although micro simulators can model traffic realistically, the computational effort required to simulate large networks limits their use to specific corridors or sub-networks.

Because microsimulation models explicitly account for individual driver behavior, they are well suited for modeling the operational performance of different transportation facilities. Measures of efficiency such as travel time, delay, and queue length can be calculated from the model. TxDOT project 0-5422 on Ramp Closure for Incident Management made use of the microsimulation software suite VISSIM to evaluate the performance of ramp closure strategies on specific corridors. Microsimulation can also be used to evaluate the safety of freeway sections and intersections by extracting surrogate measures of safety from a microsimulator's output (Dazentas et al., 1980; Archer et al., 2000). Different measures, such as simulation environment, include time to collision (TTC), time exposed TTC (Te-TTC), and time-integrated TTC (TInT), and relate traffic conflicts to the likelihood of a crash (Minderhoud et al., 2001; Al-Mudhaffar et al., 2004, Eisel et al., 2003, 2004).

Use of microsimulators to evaluate transportation facilities, especially intersections, has been extensive; however, modeling roundabouts has been a more recent development. Gagnon et al. (2008) compared the calibration potential of two analytical models (SIDRA and RODEL) as well as three microsimulators (PARAMICS, SimTraffic and VISSIM) in their ability to replicate traffic conditions at two New England roundabouts. Kinzel et al. (2009) compared three analytical models (SIDRA, HCM, and RODEL) as well as two microsimulators (SimTraffic and VISSIM) in a case study consisting of three different flow scenarios in a hypothetical roundabout. Oketc et al. (2004) implemented a roundabout model in PARAMICs, although the authors did not address calibration issues. It is important to note that most of the work related to microscopic modeling of roundabouts has focused on operational issues, and has not addressed safety issues.

1.4. Experience from Other Agencies

We assembled and distributed a set of survey questions regarding roundabouts to public agencies with experience evaluating, designing, and implementing roundabouts. The 20-question survey was distributed on November 6, 2009, to these entities:

- City of Kenewick, Washington,
- Alaska Department of Transportation & Public Facilities (Alaska DOT & PF),
- Virginia Department of Transportation (VDOT),
- City of Bend, Oregon,
- City of Davis, California,
- Maryland State Highway Administration (SHA),
- Arizona Department of Transportation (ADOT),
- Kentucky Transportation Cabinet (KYTC),
- Washington Department of Transportation (WsDOT), and
- City of Lawrence, Kansas.

The questionnaire covered topics including the number of roundabouts in the jurisdiction, the processes used to screen sites for roundabouts, safety analysis techniques used, preferred software for conducting roundabout traffic operations analysis, challenges faced in implementing roundabouts, and lessons learned in planning for, designing, and operating roundabouts. We received responses from Alaska DOT&PF, VDOT, WsDOT, KYTC, City of Kennewick, and City of Davis.

Agencies responding to the survey reported installing and operating as few as 6 roundabouts to more than 150 roundabouts. The survey responses are summarized in the following sections.

1.4.1.Planning Process, Review Process, Work Allocation

Improving safety and mobility are the primary potential benefits motivating the roundabout planning and review processes used by the responding jurisdictions. Alaska DOT, City of Kennewick, City of Davis, and VDOT have a *roundabout first policy* or a policy requiring a roundabout to be considered as an alternative to a traffic signal for new or upgraded intersections. A roundabout first policy requires designers to provide justification for not installing a single-lane roundabout.

In general, these jurisdictions consider single-lane roundabouts to be a superior alternative to a traffic signal or four-way stop with regard to safety, capacity, and air quality. Multilane roundabouts are more complex and require more detailed, site-specific analyses. Key characteristics considered when comparing a roundabout alternative to another intersection form tend to be expected delay, queue length, and safety. Formal cost-benefit analyses and peer review are conducted on a case-by-case basis.

The responding agencies reported performing the majority of the planning, evaluating, and design work for roundabouts in-house. The agencies use consultants for design review and for specialized expertise at unique locations. However, the agencies reported that roundabout design was originally performed by consultants. It was not until agency staff gained experience with roundabout analysis and design that agency engineers took on the majority of roundabout related tasks.

1.4.2. Preferred Guidance Documents and Software

The FHWA Roundabout Guide was the most commonly used guide among the respondents; each noted using the FHWA Roundabout Guide and in some instances a state-specific guide to supplement the federal guide. Alaska DOT&PF also noted they are using the Draft 2009 MUTCD guidance for their roundabout signing and striping plans. The Kentucky Transportation Cabinet is currently in the process of creating its own state supplemental guide. The guide will draw upon state guides from Wisconsin, Florida, and Kansas as well as the FHWA Roundabout Guide and NCHRP Report 572.

SIDRA, AutoTURN, and VISSIM are the most commonly used software packages for conducting roundabout analysis and design activities. SIDRA is used to assess expected roundabout traffic operations performance (e.g., delay, volume-to-capacity per approach).Alaska DOT&PF was the only respondent that cited using RODEL for operations analyses. AutoTURN and AutoCAD were cited for use in design and particularly critical to ensure the roundabout is large enough to accommodate the appropriate design vehicle (e.g., WB-50 truck). WsDOT and VDOT noted that VISSIM can be a useful tool to create illustrative simulations for public display and to assist in educating the public on how to properly navigate a roundabout.

1.4.3. Public Education Efforts

Public education efforts tended to be through

- public meetings;
- newspaper articles;
- informational websites;
- brochures;
- videos; and
- radio announcements.

Each of the respondents reported that public education efforts are worthwhile, particularly when planning to install the first roundabout in an area. Jurisdictions also found public education and outreach key in addressing community opposition and concerns. Education focused on the benefits of roundabouts as well as how to use them as a motorist, bicyclist, and pedestrian.

1.4.4. Words of Wisdom

The words of wisdom shared by respondents covered a full range of topics from design to the need for technical expertise. A frequent recommendation is to perform a thorough truck-turning analysis to ensure the roundabout is sufficiently large to accommodate the design vehicle. With regard to roundabout design, the agencies strongly recommended against striping a bike lane through a roundabout as it can create negative safety implications for bicyclists. The responding jurisdictions also stressed the importance of having a solid understanding of existing roundabout guides, the pros and cons of roundabouts for various contexts, a strong technical team when moving forward with a roundabout concept, and political support prior to constructing a roundabout. Lastly, each agency strongly recommended educating the public on the benefits of roundabouts as well as how to use them.

2. Safety Assessment Techniques

2.1. Safety and Prediction Evaluation

Survey responses from the research study questionnaire indicate a majority of agencies planning for, designing, and implementing roundabouts are using a straightforward method for predicting and evaluating safety performance. Jurisdictions typically use traditional measures such as overall crash rates or crash rates by severity to identify candidate intersections that may benefit from implementing a roundabout. Similar measures are used to gage the safety benefit of implementing a roundabout or converting a conventional intersection to a roundabout. In some instances, findings from before and after studies at other, similar locations are used to gage the potential safety benefit of building a roundabout. While such approaches can be useful at the broadest planning level to gain a sense of safety performance and the potential benefit of implementing a roundabout, more robust, reliable methods are available and their use is being encouraged.

The more robust and reliable methods influence the way in which analysts quantify expected safety improvements due to changes in geometry or intersection control and the way in which analysts evaluate current safety performance. In both of these instances, safety prediction models (i.e., equations) and the Empirical Bayes (EB) method are key components in conducting more scientifically sound and reliable safety analyses.

2.1.1. Safety Prediction Models

Safety prediction models are equations used to calculate the expected number of crashes for a given intersection type or roadway link. They are considered improvements over measures such as crash rates because the models capture geometric design elements and local driving conditions as well as traffic volumes at the site being considered. The models are developed using existing data sets that combine crash history, geometric design elements, and traffic volume to identify significant features that influence safety and determine the extent of their influence. Safety prediction models are used in planning for, designing, revising, and evaluating new or existing intersections or roadways.

2.1.2. Empirical Bayes (EB) Method

The EB method is a procedure for combining model predictions and observed crash frequencies at an existing site into a single expected crash estimate (Rodegerdts et al., 2007).This method is advantageous because observed crash counts on their own can be misleading due to the randomness of crash occurrences; model predictions divorced from actual experience at a site can also be misleading.

Prior to delving into the discussion in subsequent sections regarding safety prediction models and safety analysis for roundabouts, it is worth taking the time to understand the concept of how and when to use safety prediction models and how and when to use the EB method. Table 2-1 summarizes when (i.e., the type of analysis) to use safety prediction models and the EB method.

Table 2-1: When to use safety prediction models and the EB Method

Analysis Type	Use a Safety Prediction Model?	Use the EB Method?
Planning for a New Intersection and/or Roadway	Yes	No
Planning to Change or Modify an Existing Intersection and/or Roadway	Yes	Yes
Designing a New Intersection and/or Roadway	Yes	No
Designing Changes or Modifications for an Existing Intersection and/or Roadway	Yes	Yes
Evaluating Existing Intersections and/or Roadways	Yes	Yes

As Table 2-1 indicates, applying a safety prediction model is valuable in most types of safety analysis—assuming that a safety prediction model fits the type of intersection and/or roadway being evaluated and that the model is calibrated to local conditions. Model calibration as it relates to roundabouts is discussed in the following sections. The EB method applies when evaluating the safety performance of an existing intersection or predicting the expected safety performance in a do-nothing (i.e., no-build) scenario.

Once the analyst selects the appropriate safety prediction model (i.e., matches the model to the intersection or roadway type under consideration and calibrates the model to local conditions), using the model (i.e., equation) is relatively straightforward. Most equations, including those that follow, predict the expected annual number of total crashes or injury crashes. The variables in the equations are often AADT and geometric design parameters. Therefore, the analyst would plug-in the corresponding values for the AADT and intersection (or roadway) geometry into the equation and the resulting value would be the expected annual number of crashes, denoted below as *P*. The discussion in subsequent sections will help clarify the use of safety prediction models.

As noted earlier, the EB method is used when calculating the expected annual number of crashes for existing sites (either their current performance or their anticipated future performance, assuming no changes to the site's geometry).The following three steps present the use of the EB method and are based on guidance provided in NCHRP Report 572.

1) Assemble Data: Gather geometric design data for the site based on the variables in the safety prediction model (e.g., if the model has a variable for number of lanes, know the number of lanes at the site). Also, obtain crash history data for a period of *n* years (up to 10 years); know the total number of crashes and total injury crashes over the selected period. For the same time period, obtain or estimate the AADT at the site.

2) Use Safety Prediction Model: Calculate the expected annual number of crashes, *P*, using the appropriate safety prediction model.

3) Integrate Site's Crash History: Combine the crash estimate, P, with the count of observed crashes (either total or injury crashes depending on the analyst's interest), x, using EB weights, z_1 and z_2.The weights are estimated from the mean and variance of the safety prediction model used in Step 2.The weights are calculated using these equations.

$$z_1 = P/[(1/k) + nP] \quad \text{(Equation 2-1)}$$

$$z_2 = (1/k)/[(1/k) + nP] \quad \text{(Equation 2-2)}$$

Where, z_1 and z_2 are the EB weights, P is the expected annual number of crashes from the prediction model, k is the dispersion factor associated with the prediction model, and n is the number of years in the analysis period.

The EB expected annual number of crashes, m, can then be calculated using Equation 2-3.

$$m = z_1x + z_2P \quad \text{(Equation 2-3)}$$

Where, m is the EB expected annual number of crashes, z_1 and z_2 are the EB weights, x is the number of observed crashes, and P is the number of predicted crashes from the safety prediction model.

The EB expected annual number of crashes, m, can then be compared to the calculated expected annual number of crashes for the alternative scenario(s) (if the analyst is considering changes to an existing site) or to the EB expected annual number of crashes at other sites in the network (if the analyst is screening the network to identify sites needing safety improvements).

The safety prediction models for roundabouts presented in the following sections were developed using U.S. data; however, to be directly applicable to Texas, each model should be calibrated to Texas conditions. In the interim, the information presented will serve as a base reference for the types of models to be used to assess roundabout safety performance as well as use of the models. The methods discussed here are presented in more detail in NCHRP Report 672.The first edition of the Highway Safety Manual (HSM), published in April 2010, also provides more detailed information on safety prediction models and the EB method. Furthermore, it contains a comprehensive discussion as to why safety prediction and evaluation methods are evolving to more robust, reliable methods than strictly the use of crash rates or crash counts.

2.2. Intersection-Level Safety Prediction Model

Intersection-level safety prediction models are used in planning level analysis to compare the anticipated roundabout safety performance to other intersection forms. Variables in these models are intentionally kept as basic information so they can be used in planning level analysis. The variables in these models tend to be AADT, number of intersection approaches (i.e., legs to the roundabout), and number of circulating lanes in the roundabout.

Research findings presented in NCHRP Report 572 indicate that previous intersection-level safety prediction models developed from non-U.S. data tend to underpredict crashes at U.S.

roundabouts and, in general, do not fit U.S. data well (Rodegerdts et al., 2007).Therefore, the researchers conducting the research for NCHRP Report 572 (i.e., Rodegerdts et al., 2007) developed intersection-level safety prediction models using data from U.S. roundabouts.

2.2.1.Recommended Intersection-Level Safety Prediction Models for U.S. Roundabouts

Intersection-level safety prediction models were developed to predict total crashes and injury crashes at roundabouts. Injury crashes consist of fatal and definite injury crashes (possible injury and property damage only are not included in this measure). Refer to NCHRP Report 572 for more detailed information on how these models were developed. The recommended intersection-level models, based on number of circulating lanes and approaches, from NCHRP 672 are given in this section.

2.2.1.1. Models for Predicting Total Crashes at Roundabouts

Table 2-2 shows the intersection-level safety performance models for total crashes at a roundabout. The dispersion factor for each model is 0.9.

Table 2-2: Intersection-level safety performance models for total crashes

Number of Circulating Lanes	Number of Legs	Total Crash Frequency per Year	Valid Total Entering AADT Range
1	3	$0.0011(AADT)^{0.7490}$	4,000 to 31,000
	4	$0.0023(AADT)^{0.7490}$	4,000 to 37,000
	5	$0.0049(AADT)^{0.7490}$	4,000 to 18,000
2	3	$0.0018(AADT)^{0.7490}$	3,000 to 20,000
	4	$0.0038(AADT)^{0.7490}$	2,000 to 35,000
	5	$0.0073(AADT)^{0.7490}$	2,000 to 52,000
3 or 4	4	$0.0126(AADT)^{0.7490}$	25,000 to 59,000

2.2.1.2. Models for Predicting Injury Crashes at Roundabouts

Table 2-3 shows the intersection-level safety performance models for injury crashes at a roundabout. The dispersion factor for each model is 0.946.

Table 2-3: Intersection-level safety performance models for injury crashes

Number of Circulating Lanes	Number of Legs	Injury Crash Frequency per Year	Valid Total Entering AADT Range
1 or 2	3	$0.0008(AADT)^{0.5923}$	3,000 to 31,000
	4	$0.0013(AADT)^{0.5923}$	2,000 to 37,000
	5	$0.0029(AADT)^{0.5923}$	2,000 to 52,000
3 or 4	4	$0.0119(AADT)^{0.5923}$	25,000 to 59,000

To apply the intersection-level safety performance models in practice, each should be calibrated to jurisdiction-specific conditions; the calibration should use data from roundabouts within the jurisdiction (Rodegerdts et al., 2007). Therefore, to make these equations applicable to Texas, data from roundabouts in Texas should be collected and used to calculate a calibration factor for each equation. The calibration factor is the ratio of the sum of crashes recorded in the data to the sum of crashes predicted by the general model for the roundabouts in the data sample (Rodegerdts et al., 2007).

The minimum data needed to calculate a calibration factor is 10 roundabouts of the specified type (e.g., single-lane with four approaches) with at least 60 crashes across the set of roundabouts in the data (either total crashes or injury crashes depending on the model being calibrated) (Rodegerdts et al., 2007).The number of crashes across the Texas roundabouts considered for this literature did not have enough crashes, so a local calibration factor could not be calculated. As roundabouts in Texas become increasingly common, the calibration ratios for each equation should be updated to reflect local conditions (e.g., city-specific or county-specific calibration ratios).

2.2.2.Applying Intersection-Level Safety Prediction Models

The intersection-level safety prediction models can be applied in two ways. The first is to estimate expected changes in safety if a conventional intersection is converted to a roundabout. The second is to evaluate the safety performance of existing roundabouts. The following sections discuss these two applications. A more detailed discussion of these applications is in NCHRP 672.

2.2.2.1. Estimating Expected Changes in Safety from Converting a Conventional Intersection to a Roundabout

Two methods can be used to estimate the expected changes in safety from converting a conventional intersection to a roundabout. The preferred approach, recommended in NCHPR 672, is presented here.

2.2.2.1.1. The Preferred Method

The preferred method for estimating the expected safety changes from converting a conventional intersection to a roundabout is organized into the following three steps.

1) Calculate EB Expected Annual Number of Crashes: Calculate the EB expected annual crash frequency assuming the current intersection remains in place. Use a safety performance function specific to the existing intersection type (e.g., two-way stop controlled) and calibrated to local conditions. Also incorporate the site’s crash history using the EB method (see Section 2.1, “Safety Prediction and Evaluation” for more details).

2) Calculate Expected Annual Number of Crashes for the Roundabout Option: Calculate the expected annual crash frequency assuming a roundabout is constructed. Use the appropriate intersection-level model (e.g., two circulating lanes with four approaches) calibrated for local conditions and the same total entering AADT used in Step 1.

3) Compare Expected Annual Crash Estimates: Compare the EB expected annual crash frequency for the current intersection form to the expected annual crash frequency of the roundabout.

To apply this approach, the following information is necessary:

- a safety performance function for the existing intersection form (or a pre-existing safety performance function calibrated to local conditions);
- intersection crash history (up to 10 years' worth);
- an applicable intersection model for the roundabout being considered; and
- necessary variable inputs to use the safety performance function for the existing intersection and the roundabout intersection model (e.g., AADT).

2.2.2.1.2. The Alternative Method

In the event that the roundabout being considered for implementation is not represented by one of the intersection-level models described, the alternative approach can be used. The alternative approach differs from the preferred approach in its second step. NCHRP 672 provides more information on the alternative method.

2.2.2.2. Evaluating Safety Performance of Existing Roundabouts

Evaluating the safety performance of existing roundabouts is a valuable means for comparing the safety performance of intersections across a road network. The first edition of the HSM refers to this basic activity as network screening: screening the network to identify intersections (or roadway links) with the most potential to improve their respective safety performance. The HSM presents a variety of potential methods that can be used to identify candidate intersections for safety improvement.

In terms of roundabouts, the intersection-level models (calibrated to local conditions) can be used to calculate EB estimates for their respective expected annual crash frequencies and then compared to other intersections within the network. Network screening techniques tend to rank sites in descending order based on their EB expected annual crash frequency (or some variation of this estimate) to identify candidate sites and set a general priority for improving safety at those locations. More information regarding network screening can be found in the first edition of the HSM.

2.3. Approach-Level Safety Prediction Model

The primary purpose of approach-level safety prediction models is to understand the impacts of geometric design decisions on crash types and crash occurrence. These models require more detailed input and are for use when designing a roundabout. The crash estimates produced with these models are intended to indicate whether changing a geometric design parameter increases or decreases crashes (or a certain crash type) and the relative magnitude of the change (Rodegerdts et al., 2007).The approach-level models do not predict precise expected crash frequencies—only relative changes in expected crash frequency given a change in a design feature.

As with intersection-level safety prediction models, research in the NCHRP Report 572 found approach-level safety prediction models based on international data do not represent U.S. conditions accurately (Rodegerdts et al., 2007). Therefore, NCHRP Report 572researchers developed approach-level safety prediction models using data from U.S. roundabouts. The approach-level models developed within the NCHRP Report 572 research were designed to estimate these specific crash types: entering-circulating, exiting-circulating, and approaching crashes. Please refer to NCHRP Report 572 for information on how the models were developed.

Equations 2-4 through 2-6 are the approach-level safety prediction models recommended in NCHRP Report 572 for roundabouts in the U.S.

Equation 2-4 is the recommended approach-level model for predicting total entering-circulating crashes at a roundabout approach. The dispersion factor for this model is 1.080.

$$P = \exp(-7.2158) * AADT_E^{0.7018} * AADT_C^{0.1321} * \exp(0.0511e - 0.0276\theta) \quad \text{(Equation 2-4)}$$

Where, P is the expected annual number of entering-circulating crashes, $AADT_E$ is entering AADT on the approach, $AADT_C$ is circulating AADT in front of the approach entry, e is entry width, and ϑ is the angle (measured in degrees) to the next adjacent approach leg (to the right of the approach under consideration).

Equation 2-5 is the recommended approach-level model for predicting exiting-circulating crashes at a roundabout approach. The dispersion factor for this model is 2.769.

$$P = \exp(-11.6805) * AADT_X^{0.2801} * AADT_C^{0.2530} * \exp(0.0222d + 0.1107w) \quad \text{(Equation 2-5)}$$

Where, P is the expected annual number of exiting-circulating crashes, $AADT_X$ is the exiting AADT for the approach, $AADT_C$ is the AADT circulating in front of the approach exit, d is the inscribed circle diameter measured in feet, and w is the circulating width measured in feet.

Equation 2-6 is the recommended approach-level model for predicting crashes on the approach to a roundabout. The dispersion factor for this model is 1.289.

$$P = \exp(-5.1527) * AADT_E^{0.4613} * \exp(0.0301h) \quad \text{(Equation 2-6)}$$

Where, P is the expected annual number of crashes on a given approach to a roundabout, $AADT_E$ is the entering AADT for the approach, and h is the approach half-width measured in feet.

As long as the approach-level models are used to gage the relative differences in the expected number of crashes due to a design feature change, they can be used without recalibrating them to local conditions. As a result, NCHRP Report 572 recommends analysts do NOT use the approach-level models to estimate intersection-level safety performance. The intersection-level safety prediction models should be used to estimate the expected annual crash frequency for the roundabout intersection as a whole (Rodegerdts et al., 2007).

2.3.1. Applying Approach-Level Safety Prediction Models

There are two methods for applying the approach-level safety prediction models. The first is to apply them within the design process. The second way is to apply them to evaluate the performance of existing roundabout approaches. Both of these uses are discussed in the following sections.

2.3.1.1. Estimating Changes in Safety at or on Approaches due to Changes in Design Parameters

Approach-level safety prediction models can be applied to estimate expected changes in safety performance given changes in certain design parameters. For example, an analyst could calculate the expected annual number of entering-circulating crashes, P_1, at a specific roundabout approach for a given entry width, e, and angle to the adjacent approach, ϑ, using Equation 2-4. The analyst or designer could then consider a different alignment for that approach (thereby changing the value of ϑ) and calculate the corresponding expected number of crashes, P_2, given that design change. The expected number of crashes for both design options could be compared (i.e., P_1-P_2) to determine if the change in alignment is expected to increase, decrease, or not change the expected number of entering-circulating crashes at that approach. Similar calculations can be done using Equation 2-5 and Equation2-6 to assess the influence the inscribed circle diameter, circulating lane width, and approach half width would each have on crash occurrences at or approaching the roundabout being designed.

2.3.1.2. Evaluating Safety Performance of Existing Roundabout Approaches

Approach-level safety models can also be used to evaluate the safety performance of existing roundabout approaches. The purpose of this analysis is to compare roundabout approaches' actual safety performance across a set of existing roundabouts. To conduct an analysis, the first step is to calibrate Equations 2-4 through 2-6 to local conditions. However, as mentioned earlier the data from Texas roundabouts was insufficient. The next step is to use the calibrated equations and the EB procedure (discussed in the Section 2.1, "Safety and Prediction Evaluation") to calculate the EB expected annual number of crashes (of each crash type or summed across the crash types) for a set of approaches. The approaches in the set are then ranked in descending order as a means to identify the roundabout approaches with subpar safety performance and investigate possible improvements.

3. Traffic Operations Assessment Technique

3.1. Introduction

Traffic operations analysis plays a critical role in determining the approximate size and geometric characteristics of most intersection forms, including roundabouts. In roundabout design, traffic operations analysis influences some of the most basic roundabout attributes, including the number of circulating and entering lanes. Three key pieces of traffic operations analysis are capacity, delay, and queue analysis. Results from those analyses influence the desired number of entry lanes, circulating lanes, and storage distance on the approaches to the roundabout. As such, the purpose of this section is to present the recommended traffic analysis methods from the most comprehensive and recent research on traffic operations analysis for roundabouts in the U.S. The information presented in this section is primarily based on Rodegerdts et al. (2007) research published in NCHRP Report 672.

NCHRP Report 672 is the most current, comprehensive research focused on U.S. roundabouts. Findings presented in NCHRP Report 672 regarding roundabout traffic operations analyses also form the basis for the related roundabout capacity, delay and queue analyses in the updated HCM 2010 (HCM 2010). NCHRP 672 offers a planning level method for analyzing the performance of roundabouts, introduces the principles of roundabout operations, describes a methodology for estimating capacity of five (of six) configurations, presents performance measures for evaluating the performance of a roundabout, and goes over the computer software packages capable of carrying out capacity and performance analysis procedures. This section of the document:

- Discusses the information that can be found in NCHRP 672;
- Briefly describes capacity analysis conducted by the researchers of this document; and
- Introduces a spreadsheet evaluation tool for comparing roundabout and non-roundabout intersections.

This section adheres to the idea of using the appropriate traffic analysis tool for the level of analysis needed.

3.2. Analysis Techniques

NCHRP Report 672 identifies four basic analysis tools to analyze the performance of roundabouts:

- The planning method;
- The HCM method;
- Deterministic software; and
- Simulation.

Additional details of these methods are provided in Sections 3.3 through 3.6. The appropriate roundabout analysis tool is based on the available data for the roundabout and the output requirements of the method. Analysis tools that can be used for six different applications are discussed in NCHRP Report 672. Table3-1 from NCHRP 672 gives information on common applications of operational analysis tools with desired outcomes and input data that is typically available.

Table 3-1: Selection of analysis tool (Source: NCHRP 672)

Application	Typical Outcome Desired	Input Data Available	Potential Analysis Tool
Planning-level sizing	Number of lanes	Traffic volumes	Section 3.3 of this guide, HCM, deterministic software
Preliminary design of roundabouts with up to two lanes	Detailed lane configuration	Traffic volumes, geometry	HCM, deterministic software
Preliminary design of roundabouts with three lanes and/or with short lanes/flared designs	Detailed lane configuration	Traffic volumes, geometry	Deterministic software
Analysis of pedestrian treatments	Vehicular delay, vehicular queuing pedestrian delay	Vehicular traffic and pedestrian volumes, crosswalk design	HCM, deterministic software, simulation
System analysis	Travel time, delays and queues between intersections	Traffic volumes, geometry	HCM, simulation
Public involvement	Animation of no-build conditions and proposed alternatives	Traffic volumes, geometry	Simulation

3.3. Planning Method

Planning-level techniques are used to determine the appropriate type of roundabout. The number of lanes required to accommodate forecasted traffic volumes dictates the capacity and size of a roundabout. This section presents a methodology from NCHRP 672 for determining the necessary lanes using AADT volume data as well as a more "refined" method involving the use of turning-movement volumes. The number of lanes determined from this method can then be used to estimate the size and general footprint for the roundabout. Section 3.5.2 of NCHRP 672 provides planning-level capacity information for mini-roundabouts and Section 3.5.4 presents more design considerations for various sizes of roundabouts.

3.3.1. Lane Requirement Estimates at a Planning Level

An important aspect of a well-functioning roundabout is the number of lanes required to handle the expected traffic demand. Capacity and the size of a roundabout are directly impacted by the number of lanes. The information (taken from NCHRP 672) in this section is meant to provide an initial screening process of roundabout feasibility and is appropriate for planning-level considerations. Assumptions have been made to produce this approach. Section 1.3.2, "Operations," describes more detailed approaches to operational analysis.

An initial screening is an important first step in a high-level planning process. Figure 3-1 is provided in NCHRP 672 and gives ranges of AADT and left-turn percentages where single- and two-lane roundabouts have the potential to function sufficiently. Because the percentage of left turns on one approach contributes to the conflicting traffic facing other entries, capacity decreases as the percentage of left turns increases.

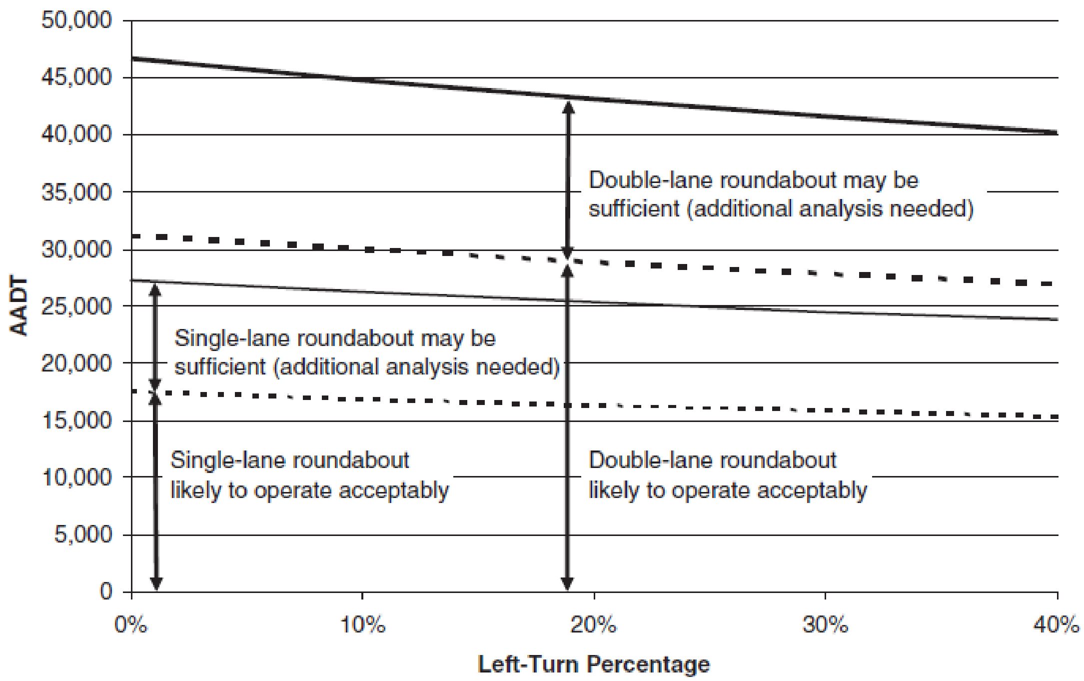


Figure 3-1: Planning-level daily intersection volumes (Source: NCHRP 672)

NCHRP 672 intends this graph to act as a "simple, conservative method for estimating roundabout lane requirements." Traffic conditions should meet the following requirements for this method to be used:

- Ratio of peak-hour to daily traffic (K) of 0.09 to 0.10;
- Direction distribution of traffic (D) of 0.52 to 0.58;
- Ratio of minor street to total entering traffic of 0.33 to 0.50;
- Volume-to-capacity ratio of 0.85 to 1.00.

More detailed analysis (discussed later in this section) is required for conditions outside the boundaries listed. The thresholds in Figure 3-1 were determined using various combinations of these values. Note that even though a particular scenario falls into the range where "additional analysis is needed," that does not necessarily mean a roundabout would not function well but that it is important to look closer at the actual designed turning-movement volumes.

If existing and/or projected turning-movement data is known, a better estimate of the necessary lane configuration can be made. In the event that future projections of turning movements are not available, an estimation of future turning movements using the current turning movements is potentially sufficient for appropriate use of this planning method.

The amount of vehicles on the circulatory roadway (conflicting traffic) directly affects capacity. The more traffic that crosses the path of a vehicle waiting to enter a roundabout, the less the opportunity for that vehicle to enter the circulatory roadway, which results in a reduction in entry-lane capacity. When little conflicting traffic exists, capacity increases because vehicles can easily enter the circulatory roadway. Evaluating each entry leg of a roundabout separately is important because different entries may require a different number of lanes. The number of lanes on the circulatory roadway should be able to facilitate lane continuity through the intersection. Lane configuration and assignments are determined in a more detailed manor.

The number of lanes needed on an entry can be estimated by using the sum of entering traffic and conflicting traffic at an entry leg. Table 3-2 gives the number of lanes required based on volume ranges. An example of planning-level calculations is in Section 3.5.1 of NCHRP 672.

Table 3-2: Relationship between vehicle volume and required number of lanes

Volume range (sum of entering and conflicting volumes	Number of Lanes Required
0 to 1,000 veh/h	• Single-lane entry likely to be sufficient
1,000 to 1300 veh/h	• Two-lane entry may be needed • Single-lane entry may be sufficient based upon more detailed analysis.
1,300 to 1,800 veh/h	• Two-lane entry likely to be sufficient
Above 1,800 veh/h	• More than two entering lanes may be required • A more detailed capacity evaluation should be conducted to verify lane numbers and arrangements

3.3.2.Space Requirements

The amount of space (footprint) a roundabout will take up is a crucial determining factor when evaluating feasibility at a particular location. Several questions should be asked regarding the sufficiency of space available, property impacts, acquisition of right-of-way, and existing physical constraints that could affect location and design. Roundabouts often require more space than other intersection forms because of the need to accommodate large trucks. The inscribed circle diameter has the greatest emphasis on the amount of space required for a roundabout. Each roundabout site requires a detailed design process to develop space requirements. This requirement becomes particularly important for multi-lane roundabouts. More information is available regarding geometric design in Section 4, “Geometric Design.”

As mentioned previously, it is important to determine if there is sufficient space for a roundabout or if additional right-of-way is needed. Figure 3-2 illustrates the different space requirements of a roundabout and a conventional intersection.

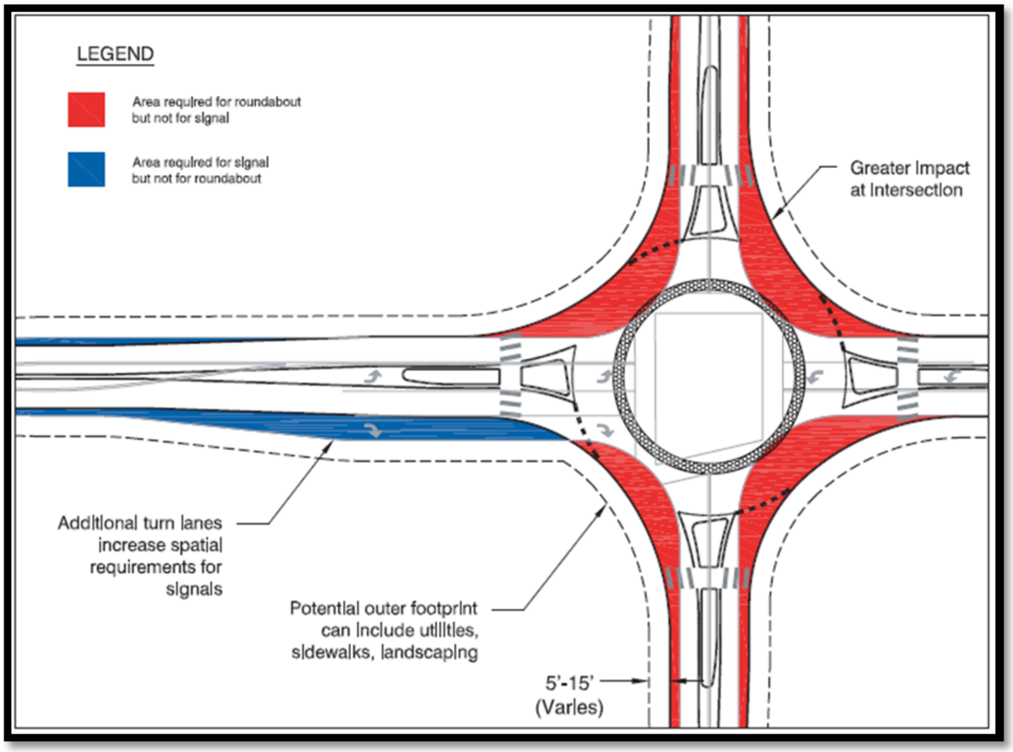


Figure 3-2: Single-lane roundabout versus signalized intersection spatial requirements (Source: NCHRP 672)

As capacity needs increase, the difference is minimized as the approaches on a conventional intersection become wider. A roundabout requires a shorter distance to achieve the widening and flaring necessary for left-turn lanes and transition tapers than does a conventional intersection. More information regarding spatial requirements of roundabouts is available in Chapter 2 of NCHRP 672. Roundabout design considerations can be found in Section 3.5.4 of NCHRP 672.

3.4. Highway Capacity Manual Methods

3.4.1.Capacity

Prior to NCHRP Report 672, the majority of roundabout capacity analysis was conducted using models developed from non-U.S. data or limited U.S. data. Rodegerdts et al. (2007) assessed how well these pre-existing capacity models captured the actual capacity at a variety of single-lane and multi-lane roundabouts in the U.S. Findings from this assessment revealed the pre-existing capacity models for single-lane and multi-lane roundabouts tend to overestimate capacity; the capacities predicted by the models were higher than what was observed at the sites (Rodegerdts et al., 2007). The lower capacities measured in the U.S. are attributed to drivers being unfamiliar with the operation of the roundabout. As a result, Rodegerdts et al. (2007) developed capacity models for single-lane roundabouts and multi-lane roundabouts in the U.S. using a robust data set assembled as part of the research effort for NCHRP Report 672. Please see the 2010 HCM for detailed information on how these models were developed.

Capacity is a means to measure optimal performance and determine optimal design characteristics. Capacity refers to the maximum hourly rate at which vehicles traverse a uniform section of a roadway during a given time period. The recommended capacity model for single-lane and multi-lane roundabouts are empirical models based on gap acceptance theory. The capacity models estimate the entry capacity, *c*, in passenger car units per hour, for a given approach entry. The input parameters to the equations are conflicting vehicle flow, v_c, in passenger car units per hour, follow-up headway, t_f, in seconds, and critical headway, t_c, in seconds. Critical headway, t_c, is the minimum headway (i.e., opening in conflicting traffic stream) a motorist would find acceptable for entering the intersection (Rodegerdts et al., 2007). Follow-up headway, t_f, is the headway maintained by two consecutive entering vehicles using the same gap to enter the intersection (Rodegerdts et al., 2007).

The general form presented in NCHRP Report 572 for both of the recommended capacity models is given in Equation3-1.

$$c = \left(\frac{3600}{t_f}\right) * \exp\left[-\left(\frac{t_c - \frac{t_f}{2}}{3600}\right) * v_c\right] \qquad \text{(Equation 3-1)}$$

Where, *c* is the entry capacity in passenger car units per hour for a given entry, t_f is the follow-up headway in seconds, t_c is the critical headway in seconds, and v_c is the conflicting flow (i.e., circulating flow in front of the entry) in passenger car units per hour.

Capacity of a roundabout entry increases as the circulating flow of vehicles on the circulatory roadway decreases. As the circulating flow approaches zero, the maximum entry flow is given by 3,600 seconds per hour divided by the follow-up headway.

Equation 3-2 is the recommended entry capacity model presented in NCHRP Report 672 for a one-lane or two-lane entry opposed by a single conflicting circulating lane. This equation is a simplified form of Equation 3-1 based on U.S. roundabout data.

$$c = 1130 * \exp(-0.0010 * v_c) \qquad \text{(Equation 3-2)}$$

Where *c* is entry capacity in passenger car units per hour for a given entry and v_c is the conflicting flow (i.e., circulating flow in front of the entry) in passenger car units per hour.

Equations beyond 3-1 were developed as part of the research for NCHRP Report 572. Through this research the coefficients for each roundabout scenario were determined (i.e., 1130 and 0.0010 in Equation 3-2).

Equation 3-3 is the recommended entry capacity model presented in NCHRP Report 672 for a one-lane entry opposed by two conflicting circulating lanes.

$$c = 1130 * \exp(-0.0007 * v_c) \qquad \text{(Equation 3-3)}$$

Equation 3-4 is the recommended entry capacity model presented in NCHRP Report 672 for estimating the capacity of the left entry lane of a two-lane entry into a two-lane circulatory roadway.

$$c_{crit} = 1130 * \exp(-0.0005 * v_c) \qquad \text{(Equation 3-4)}$$

Equations 3-5 is the recommended entry capacity model presented in NCHRP Report 672 for estimating the capacity of the critical lane (i.e., approach lane with highest traffic volume which is the right entry lane) of a two-lane entry into a two-lane circulatory roadway.

$$c_{crit} = 1130 * \exp(-0.0007 * v_c) \qquad \text{(Equation 3-5)}$$

Where, c_{crit} is the entry capacity of the critical lane in passenger car units per hour and v_c is conflicting flow (i.e., circulating flow in front of the entry) in passenger car units per hour.

The capacity models given are calibrated to local conditions by using the general form of the entry capacity model, shown in Equation 3-1, assuming the expected follow-up headway and critical headway at roundabout entries (both single-lane and two-lane) can be quantified. This calibration requires a sufficient number of existing roundabouts with adequate traffic demand to observe and then measure critical headways and follow-up headways. As roundabout use increases in Texas, the capacity models can be better calibrated to reflect local driving conditions and driver adaptation (e.g., city-specific, county-specific).

Equations 3-2 through 3-5 are represented in Figure 3-3 from NCHRP 672.

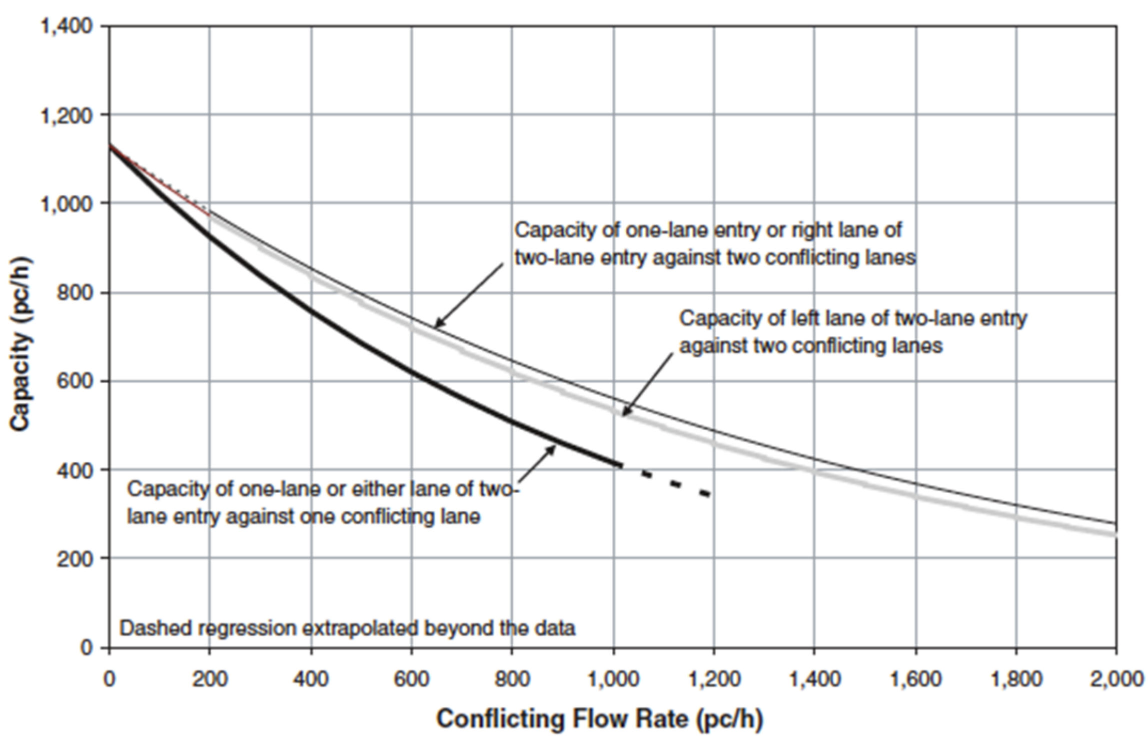


Figure 3-3: Entry lane capacity curve (Source: NCHRP 672)

3.4.2. Effect of Pedestrians on Vehicular Operations at the Entry

The capacity of vehicles entering a roundabout is affected by the presence of pedestrian traffic. When a high volume of conflicting traffic is on the circulating roadway, pedestrians typically pass between queued vehicles on entry, which has a negligible impact on vehicular entry capacity. However, when the circulating roadway has a low volume of conflicting traffic, pedestrian crossings reduce the vehicular entry capacity. An increase in pedestrian traffic volume increases the effect on vehicle entry capacity.

NCHRP Report 672 provides models to approximate the entry capacity adjustment factor for pedestrians crossing a one-lane entry and a two-lane entry. These models assume that pedestrians have priority. The 2010 HCM contains the equations used in the models.

3.4.3. Delay Model and Queue Length Model

Research findings from NCHRP Report 672 found the existing delay and queue length models used for roundabout analysis in the U.S. are reasonable methods for estimating control delay and queue length at roundabout approaches (Rodegerdts et al., 2007). The delay model and queue length model used for U.S. roundabouts are consistent with similar analysis at unsignalized U.S. intersections.

3.4.3.1. Control Delay

Control delay is the time it takes for a driver to decelerate to a queue, wait for an acceptable gap in the circulating flow, and accelerate into the roundabout. Control delay measures the performance of an intersection. Equation 3-6 presents the recommended control delay model presented in NCHRP Report 672.

$$d = \frac{3600}{c} + 900T * \left[\frac{v}{c} - 1 + \sqrt{\left(\frac{v}{c} - 1\right)^2 + \frac{\left(\frac{3600}{c}\right)\frac{v}{c}}{450T}} \right] + 5 * \min\left[\frac{v}{c}, 1\right] \qquad \text{(Equation 3-6)}$$

Where, *d* is average control delay in seconds per vehicle, *c* is entry capacity of the subject lane in vehicles per hour, *T* is time period (*T* = 1 is for 1 hour of analysis, *T* = 0.25 for 15-minute analysis), and *v* is vehicle flow in the subject lane in vehicles per hour.

3.4.3.2. Geometric Delay

Geometric delay is the time it takes for a single vehicle to slow down to the designed speed, proceed through the intersection, and accelerate back to the original operating speed. It is important to consider geometric delay in network planning and in comparing the operation of alternative intersection types. Geometric delay is important for turning movements at stop-controlled and signalized intersections and for all movements through a roundabout. The Australian Design Guide provides detailed procedures in calculating geometric delay given the geometry of a roundabout.

3.4.3.3. Queue Length

Equation 3-7 presents the 95th percentile queue length model from NCHRP Report 672.

$$Q_{95} \approx 900T * \left[\frac{v}{c} - 1 + \sqrt{\left(1 - \frac{v}{c}\right)^2 + \frac{\left(\frac{3600}{c}\right)\frac{v}{c}}{150T}} \right] * \left(\frac{c}{3600}\right) \qquad \text{(Equation 3-7)}$$

Where, Q_{95} is the 95th percentile queue length in number of vehicles, *c* is entry capacity of the subject lane in vehicles per hour, *T* is time period (*T* = 1 is for 1 hour of analysis, *T* = 0.25 for 15-minute analysis), and *v* is vehicle flow in the subject lane in vehicles per hour.

Rodegerdts et al. (2007) acknowledge in NCHRP Report 572 that further research is needed on U.S. roundabouts with high delays to confirm that these above predict control delay and queue length reliably at higher magnitudes of delay. However, currently an insufficient number of U.S. roundabouts are operating with high delays; future research is anticipated to revisit the control delay and queue length model when sufficient U.S. data is available.

3.5. Traffic Operations Software Tools

A number of existing software packages includes roundabout traffic operations analysis. Two of the most commonly used software programs for roundabout traffic operations analysis in the U.S. are RODEL and SIDRA. The prevalence of these two software programs was reflected in NCHRP Report 572 and the survey responses from the questionnaire distributed to U.S. agencies in Section 1.5, “Experience from Other Agencies. ” A third software program similar to RODEL but more recently updated is ARCADY 7. Of these software programs, the research team’s preliminary recommendation for roundabout traffic operations analysis in Texas is SIDRA, as is discussed below.

The ARCADY 7 and RODEL software programs model roundabout capacity, delay, and queue length. These models are empirical equations developed from British roundabout data; they link roundabout capacity to roundabout geometry including precise geometric details (e.g., entry angle, entry radius) without directly incorporating gap acceptance theory (Ourston, 2010; Akcelik, 2007). These two software programs require relatively detailed input regarding geometric design parameters, which notably influence capacity at British roundabouts; however, these parameters are less significant at U.S. roundabouts (Rodegerdts et al., 2007). ARCADY 7 does provide a calibration process to incorporate findings presented in NCHRP Report 572 (Ourston, 2010). However, it is not clear how well the calibration process in ARCADY 7 captures the findings from NCHRP Report 572. RODEL does not appear to have a calibration process to integrate NCHRP Report 572 findings. None of the agencies surveyed in Section 1.5, “Experience from Other Agencies,” mentioned the use of ARCADY 7 when asked to list the software programs used for roundabout traffic operations analysis.

SIDRA also models roundabout capacity, delay, and queue length; these models integrate gap acceptance theory as well as basic geometric features (e.g., number of entry lanes, number of circulating lanes) (Akcelik, 2007). SIDRA's incorporation of gap acceptance theory is attractive for modeling U.S. roundabouts because key parameters such as critical headway and follow-up headway are common between the two approaches. The models within SIDRA are also consistent with findings in NCHRP Report 572 that variations in driver behavior (e.g., critical headway) and aggregate geometry (e.g., number of lanes) have a more significant influence on capacity than details of geometric design (Rodegerdts et al., 2007). Furthermore, analysts can modify the parameters in SIDRA relatively easily to reflect local driving conditions. A practice that has become relatively common among agencies and consulting firms since NCHRP Report 572 was published has been to input an "environmental factor" of 1.2 into SIDRA. Inputting this value for the SIDRA program's environmental factor parameter is intended to reflect the tentative nature of U.S. drivers (compared to drivers abroad). This approach appears to reasonably approximate the capacity calculations achieved with the capacity, delay, and queue models recommended in NCHRP Report 572. The analyst can also modify the follow-up headway and critical headway parameters in SIDRA to reflect local driver behavior at roundabouts.

Based on the modeling structure of the SIDRA, ARCADY 7, and RODEL software programs, the research team's preliminary recommendation is to use SIDRA software for conducting roundabout traffic operations analysis (i.e., estimating capacity, delay, and queue length).

3.5.1. Deterministic Method

Deterministic software programs model vehicle flows as flow rates and are sensitive to various flow and geometric features of a roundabout (e.g., number of lanes, arrangement of lanes, entry width, and inscribed circle diameter). Although roundabout research in the U.S. has not confirmed which factors have a more significant effect on capacity, the most common deterministic model used in the U.S. is based on British and Australian research and practice. British research correlates capacity to the geometry (e.g., approach width, entry width, effective flare length, entry angle, and entry radius) of the roundabout. Conversely, Australian research correlates capacity to traffic flow (e.g., lane-by-lane assessments and origin-destination patterns). NCHRP 672 discusses the necessary driver behavior, geometry, and lane use calibrations that are applied when using any of the deterministic software models.

3.5.2. Simulation Method

Simulation software programs model transportation networks and are sensitive to individual vehicle behaviors (e.g., car-following behavior, lane-changing behavior, and decision-making behavior). The most commonly used simulation method in the U.S. is based on U.S., British, and German research and practice. NCHRP 672 discusses the necessary driver behavior and traffic volume calibrations that are applied when using the simulation model. Additional information on simulation models is in the FHWA Traffic Analysis Toolbox, which can be found at http://ops.fhwa.dot.gov/trafficanalysistools/index.htm.

4. Entry lane Capacity Analysis of Roundabouts in Texas Using VISSIM, SIDRA, and the Highway Capacity Manual

4.1. Introduction

The objective of this study is to use microsimulation results from VISSIM and the relatively common roundabout analysis software SIDRA to enhance the current guidelines for evaluating roundabout operations. VISSIM is used to conduct the analysis of capacity and results are compared to capacity values found using SIDRA and the current Highway Capacity Manual (HCM) entry lane capacity curve. This study uses two roundabouts located in Texas for analysis in VISSIM and SIDRA. One is located in Southlake, Texas and then other is a considerably smaller roundabout located in San Antonio, Texas. The primary contribution of this work is to provide new insight into estimating entry-lane capacity. The effects of exiting flow, origin-destination patterns, and mean speed on roundabout capacity will be evaluated separately in hopes of improving current guidelines for evaluating roundabout operations by offering recommendations for how the current methodology should be expanded. This work offers a secondary contribution by showing that VISSIM can reasonably validate for roundabouts and offering a methodology for calibration and validation. Literature review in these areas will be explained throughout the work.

Assuming that VISSIM provides the most behaviorally consistent approach to capacity analysis, researchers are also asking the questions: Can the HCM predict roundabout capacity? Can SIDRA?

4.2. Site Description

4.2.1. SOUTHLAKE, TEXAS ROUNDABOUT

A single lane roundabout located in Southlake, Texas provides the intersection of East Continental Boulevard and South Carroll Avenue. Since this example intersection includes the essential characteristics of a modern roundabout, it was selected for field monitoring and analysis. The northwest and southeast corners of the roundabout are open green space. There is a commercial structure on the northeast corner of the roundabout and a residential neighborhood on the southwest corner. The surrounding area is mostly residential and commercial. The inscribed circle diameter is approximately 130 feet and the angles between approach centerlines are all approximately 90 degrees. Average traffic volume during the morning peak hours is about 1200 vph versus about 1150 vph during the afternoon peak hours. Heavy vehicle percentage for the morning and afternoon are 2.6% and 5.2% respectively. Although both morning and afternoon video footage was used during the model validation process only data from the afternoon video footage was used during in-depth capacity analysis.

Figure 4-1: East Continental Boulevard and South Carroll Avenue, Southlake, Texas (Source: Google Maps)

4.2.2. SAN ANTONIO, TEXAS ROUNDABOUT

The Fulton Avenue & Blanco Road roundabout is a single lane roundabout in an urban area of San Antonio, Texas. With an inscribed circle diameter of about 90 feet it is on the low end of inscribed circle diameter for single-lane roundabouts. Average traffic volume during the morning peak hours is about 500 vph. Heavy vehicle percentage observed during the morning peak is 2.3%.

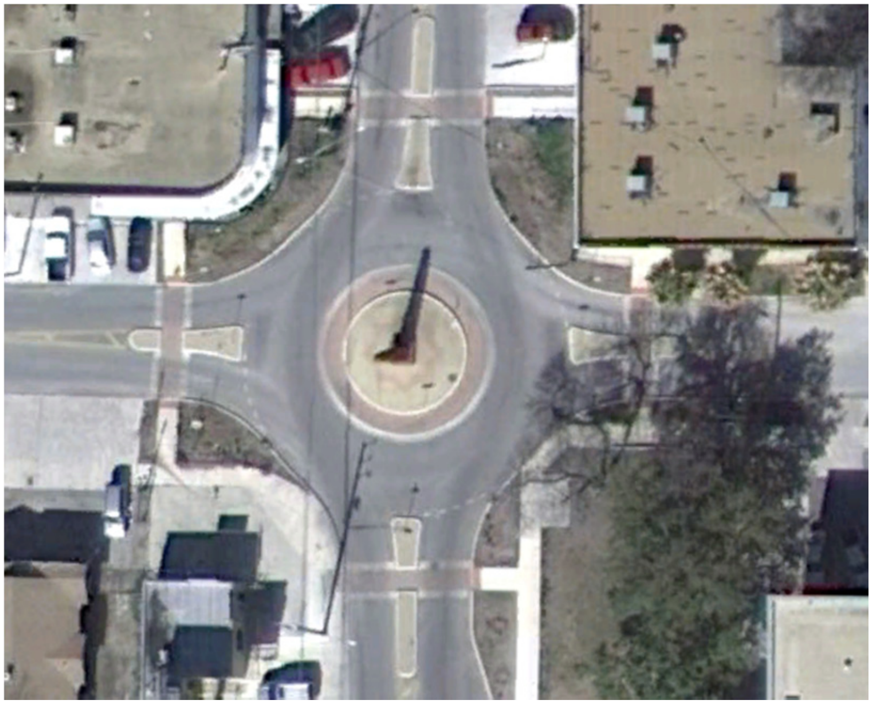


Figure 4-2: Fulton Avenue and Blanco Road, San Antonio, Texas (Source: Google Maps)

4.3. Software and Procedures

VISSIM 5.20 and SIDRA INTERSECTION are the software packages used during analysis for this work. VISSIM is a microsimulation software package used for modeling urban road and transit networks. Gagnon (2008) views VISSIM as the most "versatile" when compared to SIDRA and other roundabout analysis models.

SIDRA's primary function is to assist in design and evaluation of signalized intersections, signalized pedestrian crossings, single point interchanges, roundabouts, roundabout metering, two-way stop control, all-way stop control, and give-way/yield sign control. SIDRA is a micro-analytical traffic evaluation tool for isolated intersections that uses lane-by-lane and vehicle drive-cycle models in conjunction with an iterative approximations method for calculating capacity and performance statistics estimates. SIDRA predicts performance statistics including delay and queue length.

In this work, SIDRA is used for analysis of roundabout entry lane capacity. The results will be compared to those generated by VISSIM and the Highway Capacity Manual (HCM) 2010 roundabout entry lane capacity curve. The HCM roundabout entry lane capacity curve is available in NCHRP 672 and the 2010 Highway Capacity Manual. The SIDRA User Manual maintains that capacity estimations are sensitive to changes in approach and circulated lanes use, origin-destination traffic patterns, and the length of queues on roundabout approaches.

SIDRA can be calibrated for local conditions and is accepted by the U.S. Highway Capacity Manual, the current FHWA Roundabout Guide, NCHRP 572 (Rodergerdts, 2007), and many local roundabout guides. SIDRA comes equipped with various intersection configuration templates. Figure 4-3 shows the SIDRA interface and the template used for analysis.

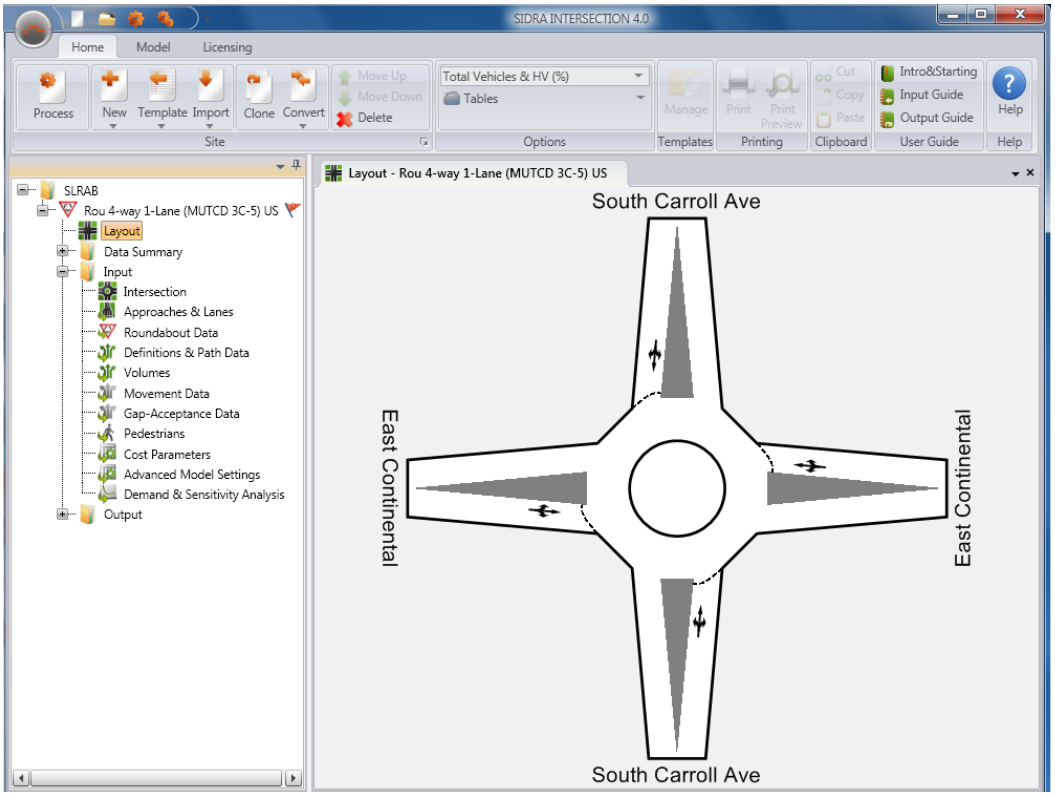


Figure 4-3: SIDRA interface

Once an appropriate template is selected the characteristics of the roundabout can be adjusted using the Input Dialogs. These are labeled in Figure 4-3. Input Dialogs include Intersection, Approaches and Lanes, Roundabout Data, Freeway, Roundabout Metering, FHWA Roundabout Data, Definitions and Path Data, Volumes, Movement Data, Priorities, Gap Acceptance Data, Phasing and Timing, Pedestrians, Cost Parameters, Advanced Model Settings, Demand & Sensitivity Analysis. When Input Dialogs are filled out and adjusted, SIDRA processes the input and provides a range of outputs. As mentioned previously, in SIDRA a template (such as the one shown in Figure 4-3) is chosen that best matches the roundabout in question. Other geometric features are specified in Input Dialogs including lane width, circulatory roadway width, and approach distance. The output of most interest during this analysis was Lane Capacity located in the Lane Summary section of the outputs. This is the value that can be compared most directly to VISSIM and HCM capacity results.

Few studies have been done that compare roundabout performance factors such as capacity from analysis models like SIDRA to field measurements (Gagnon, 2008). Akcelik (2003) used capacity data from a United States roundabout and compared it to four analytical models including SIDRA, the UK linear regression model, the HCM 2000 model, and the Australian National Association of Australian State Road Authorities 1986 model. NCHRP 3-65 was funded to improve safety estimations for roundabouts in the U.S., however, capacity estimates from RODEL and SIDRA were compared. RODEL, a roundabout design software based on empirical models, overestimated delay while SIDRA underestimated it.

For VISSIM, an aerial image of the intersection was imported and scaled, and links and connectors were organized over the image to match the geometry of the roundabout. This is depicted in Figure 4-4. Priority rules were designated at each entry leg so traffic in and around the roundabout functioned accurately. That is to say vehicles approaching the roundabout on the entry legs yield to vehicles traveling on the circulatory roadway before entering.

Figure 4-4: Screen shot of VISSIM model for Southlake roundabout

In VISSIM, capacity results are taken from the output. The entry lane capacity curve provided in NCHRP 672 supply the HCM values. Information on what parameters were adjusted in VISSIM and SIDRA can be found in the following section, Calibration and Validation. It is important to note that although VISSIM performs microscopic traffic simulation the software does not contain a capacity model (Wei, 2011).

For more information on SIDRA and VISSIM, see Akcelik and Associates (2009) and PTV (2007), respectively. Calibration of the SIDRA and VISSIM models is explained in detail in the following section.

4.4. Calibration and Validation

Gagnon (2008) found that calibration of VISSIM and SIDRA models “have a significant impact on improving results”. Calibrating models reduced average percent error by as much as 39% for SIDRA and 68% for VISSIM. However, Gagnon noted that the calibration process varies from site to site so there is no one set of calibration parameters for all roundabouts. It was recommended that future research be conducted on developing a classification of locations so parameters could be established for roundabouts with similar characteristics.

Very few studies discuss validation and calibration of microscopic simulation models such as VISSIM. Kinzel (2004) and Oketch (2004) have expressed a need for such research. Kinzel and Trueblood (2004) compared microscopic simulation and analytical-type deterministic models for operational parameters such as follow-up headway, speed and critical gap. They discuss how parameters vary but do not make any comparisons to field data. In their capacity analysis of roundabouts with flared entry and double lanes using SIDRA, VISSIM, RODEL, and PARAMICS (a microscopic traffic simulation software), Stanek and Milan (2005) did not include any information on calibration techniques and did not compare results to field data. When considering high-capacity roundabouts and their use in smart signalized streams, Bared and Edara (2005) based calibration on smooth simulation flow. Capacity results were compared to field data from 15 roundabout sites.

In this work, VISSIM and SIDRA models were calibrated using data collected from roundabouts in Southlake and San Antonio, Texas. Parameters such as volume, speed, and heavy vehicle percentage were changed to match that of the roundabout in question. All parameters for which no data was collected were left at their default values.

One of the most important parameters for calibrating the models is vehicle speed. VISSIM requires a probability distribution of driver speeds as they enter the roundabout. Speed distributions were developed using 40 speed readings from vehicles that did not have to yield before entry and were traveling straight through the roundabout on recorded video footage. These readings were used to create a distribution of speed that was then input into VISSIM. Using this distribution, VISSIM can reflect the stochastic nature of traffic speeds realistically. An average speed value was input into SIDRA for each approach into the circulatory roadway.

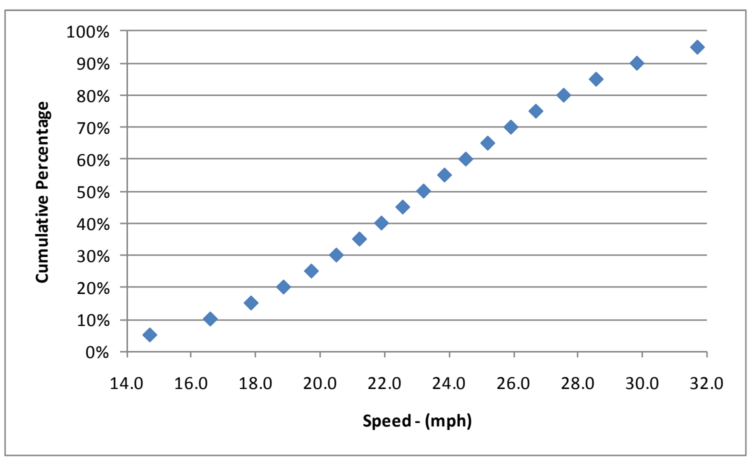


Figure 4-5: Speed distribution for morning peak period at Southlake roundabout

Heavy vehicle percentage was calculated from recorded video footage and used in VISSIM and SIDRA so vehicle composition approximately matched that of the actual roundabout.

Two methods of model validation were used to compare results from the VISSIM model to the video footage of the roundabout. This process was meant to ensure that the models were calibrated accurately and could simulate the roundabout realistically. These methods include an entry decision binary comparison and travel time comparison. For the entry decision comparison, the percentage of vehicles that chose to enter the roundabout while there was a vehicle on the approaching fourth of the circulatory roadway was calculated from VISSIM and the video footage. Figure 4-6 indicates the approaching fourth for the southern entry leg using red dotted lines. The difference between the two percentages could indicate if driver behavior is comparable between the model and the actual roundabout during peak periods. This validation method is important because driver behavior has been shown to affect roundabout performance significantly. This is explained in further detail in Section 4.5: Capacity Analysis.

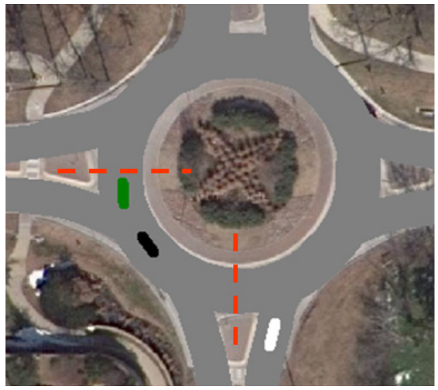


Figure 4-.6: Travel time comparison time stamp points.

Table 4-1 shows the entry decision percentages for Southlake during the morning and afternoon peak hours and San Antonio during the morning. The high p-values (corresponding to statistical tests of the differences between percentages) indicate that there is no significant difference between the video and VISSIM and therefore VISSIM is simulating driver entry decision accurately for all models.

Table 4-1: Entry decision percentages

Roundabout	VISSIM	Video	p-value
Southlake AM	35.9%	38.3%	**0.6707**
Southlake PM	46.9%	50.8%	**0.5008**
San Antonio	34.1%	30.6%	**0.7370**

The travel time comparison is meant to investigate how accurately VISSIM models the trajectory of vehicles through the curves of the roundabout and if the speed distribution used in VISSIM is appropriate. Figure 4-7 shows the points where time stamps were taken for each vehicle in VISSIM at the Southlake roundabout. Time stamps were taken at approximately the same points from the video footage. Forty sets of time stamps were retrieved from both VISSIM and the video and the average travel times between points were compared using a two-sided two-sample t-test. This comparison provides insight on how well the speed distributions compare for VISSIM and the video and how accurately VISSIM is modeling the speed of the vehicles navigating the roundabout.

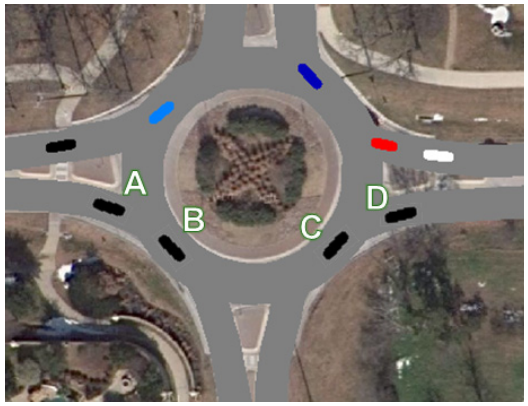


Figure 4-7: Travel time comparison time stamp points

Table 4-2 shows the travel time averages compared using a two-sided two-sample t-test with an assumed alpha-level of 0.05. The bolded values are those where the difference between the means is not significantly different from zero. Through this comparison Southlake PM (i.e. during the afternoon peak period) and San Antonio were concluded to be the best models since VISSIM was able to simulate trajectory and speed the most accurately. Where the differences were statistically significant, the actual difference in the average travel time is still relatively small. Further investigation is needed, however, to determine why such differences occurred.

Table 4-2: Average travel times

		Average Time [seconds]			
		A to B	B to C	C to D	A to D
Southlake AM	VISSIM	0.90	2.34	0.65	3.88
	Video	1.34	3.61	1.10	6.05
Southlake PM	VISSIM	**1.28**	3.66	**1.23**	6.17
	Video	**1.20**	5.03	**1.18**	7.40
San Antonio	VISSIM	**1.79**	**3.65**	**1.92**	**7.36**
	Video	**1.84**	**3.33**	**2.04**	**7.22**

***bold** values indicate that the difference between the means is not significantly different from zero (at the alpha=0.05 level)

The VISSIM models for Southlake PM and San Antonio model trajectory, speed, and entry decision accurately so they were concluded to be the best models overall. Both are used in the capacity analysis of this thesis. The calibration and validation methodology presented in this thesis shows that the results of VISSIM can be reasonably validated.

Since SIDRA is a simpler software package than VISSIM, the SIDRA models could not be validated in the same way. A comparison of approach leg capacity estimates from the HCM curve, SIDRA, and VISSIM, is undertaken in the following section.

4.5. Capacity Analysis

4.5.1.DRIVERBEHAVIOR AND CAPACITY

NCHRP 572 highlights driver behavior as the variable that affects roundabout performance the most. Variation in driver behavior between roundabout sites coincided with different levels of capacity. Second to driver behavior is the number of lanes in a roundabout. Varying other aspects of roundabout geometry such as lane width did not substantially change capacity.

Since driver behavior seems to have the greatest effect on roundabout performance, NCHRP 672 stresses the importance of taking into account local driver behavior when calibrating models to achieve accurate capacity estimates. More information on how this study accounts for local driver behavior in its models can be found in Section 4.4: Calibration and Validation.

4.5.2. ENTRY LANE CAPACITY ACCORDING TO THE 2010 HIGHWAY CAPACITY MANUAL

Capacity is a performance gauge and a very important design parameter. The 2010 Highway Capacity Manual dedicates an entire chapter to roundabout capacity methodology. The focus of the capacity methodology is on the operation of roundabouts. The methodology assumes that a roundabout is isolated. In other words, it does not take into account the effect of nearby traffic control devices. The chapter also discusses alternative tools capable of modeling situations that the analytical methodology they offer cannot.

The 2010 HCM methodology for roundabouts uses a combination of regression and analytical models. Regression models "use field data to develop statistically derived relationships between geometric features and performance measures such as capacity and delay". Analytical models are "based on traffic flow theory combined with the use of field measures of driver behavior, resulting in an analytic formulation of the relationship between those field measures and performance measures such as capacity and delay."

Gap-acceptance models are analytical and are often used for analyzing unsignalized intersections because of the ability to incorporate driver behavior directly. Parameters can be adjusted to make models site-specific. The limitation of gap acceptance models is that they don't always capture all of the behavior that is observed. Gap-acceptance models that incorporate limited and reverse priority are complex and hard to calibrate. In instances where driver behavior characteristics are not entirely known, regression models become useful.

The 2010 Highway Capacity Manual largely bases its entry capacity equations on data collected from U.S. roundabouts in 2003 for NCHRP Project 3-65. The methodology is comprised of several simple, empirical regression models and gap-acceptance models that are meant to predict capacity for roundabouts with up to two entry lanes and up to one bypass lane approach.

According to NCHRP 572, the models developed by the Highway Capacity Manual can be calibrated for local conditions by adjusting critical headway and follow-up headway. However, Wei maintains that results from calibrated models do not typically represent flow-rates observed in the field. Wei developed a streamlined process for developing new roundabout capacity models for local conditions. The model developed in the paper's case study produces capacity values higher than the HCM model. Wei explains that this is typically the case when comparing capacity estimates for roundabouts that have been in operation for a long time to the HCM model results.

4.5.3. Development of single-lane model

The capacity equation presented in the 2010 HCM is derived from a 2000 HCM model equation. The 2010 HCM shows how the HCM 2000 model can be changed into a regression-like form. The HCM 2000 offers the following equation:

$$q_{e,\max} = \frac{q_c \exp(-q_c t_c / 3600)}{1 - \exp(-q_c t_f / 3600)} \quad (1)$$

where,

$q_{e,max}$ = entry capacity (veh/h)

q_c = conflicting circulating traffic (veh/h)

t_c = critical headway (s)

t_f = follow-up headway (s)

The previous equation can be simplified into this form:

$$q_{e,\max_c} = \frac{3600}{t_f} \exp\left(- \frac{t_c - t_f / 2}{3600} q_c \right) \quad (2)$$

which is equivalent to this form:

$$q_{e,\max} = A \cdot \exp(-B \cdot q_c) \quad (3)$$

where,

A = $3600/t_f$

B = ($(t_c - t_f / 2)/3600$

t_c = critical headway (s)

t_f = follow-up headway (s)

Figure 4-8 shows the capacity estimate using the HCM 2000 model and average field values for the gap parameters, and the capacity estimate using the exponential regression of the data collected at U.S. roundabouts in 2003. The intercept and slope predicted by the exponential regression of 1129 and 0.0010 compare with the HCM intercept of (3600/tf = 3600/3.2=) 1125 and slope of [(tc-tf/2)/3600=(5.1-3.2/2)/3600=] 0.0010. These results make application of the exponential regression more practical. This process has the potential to be used to calibrate constants against local data.

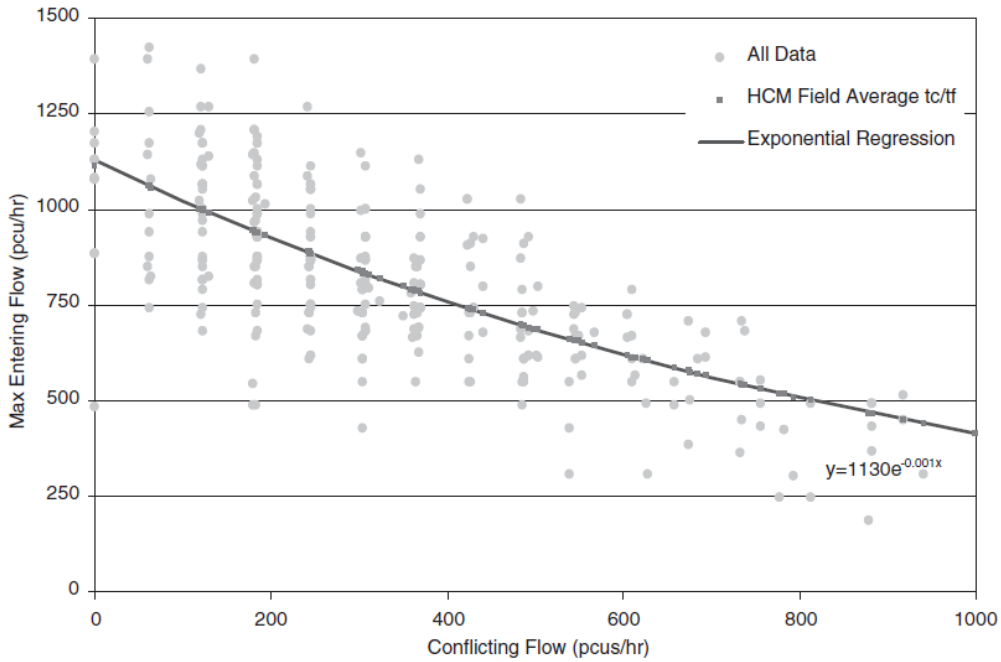


Figure 4-8: Capacity using HCM and exponential regression models (Source: NCHRP 572/2010 HCM)

The previous discussion is the basis for this equation which is recommended by the 2010 HCM for the entry lane capacity at single-lane roundabouts:

$c = 1130 \cdot \exp(-0.0010 \cdot v_c)$ (4)

where,

c = $q_{e,max}$ = entry capacity (veh/h)

v_c = q_c = conflicting circulating traffic (pcu/h)

The primary explanatory variable for this model is the conflicting flow measured in passenger cars per hour (pc/h). Primary conflicting flow is the conflicting flow that travels along the circulatory roadway in front of the entry leg in question. Generally speaking, as conflicting flow increases the capacity of a roundabout entry decreases.

Figure 4-9 is a plot of the capacity equations provided by the HCM. The bold line corresponds to Equation 4.

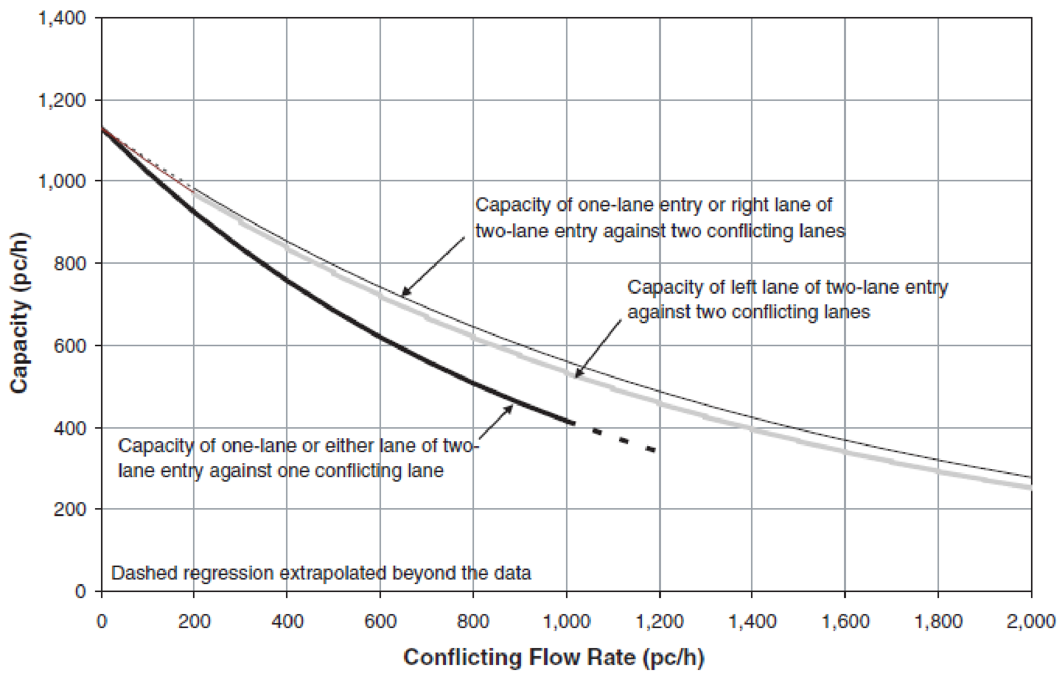


Figure 4-9: Entry Lane Capacity (Source: NCHRP 672)

4.5.4. EXTENDING THE HIGHWAY CAPACITY MANUAL EQUATIONS

The HCM points out the capacities of United States roundabouts are lower than that of roundabouts in other countries. This is attributed to the lack of familiarity of drivers in the United States with roundabouts since they are largely uncommon. It is predicted that the capacity of roundabouts in the United States will improve over time as drivers get used to roundabouts and they are forced to use them more efficiently due to increasing demand.

The 2010 HCM states that the “capacity of a roundabout approach is directly influenced by flow patterns.” They identify the flows of interest as entering, exiting, and circulating flow. Figure 4-10 shows the different flows associated with a roundabout. Total flow is comprised of the flow of vehicles that conflicts with the entry-lane in question (conflicting flow) and the flow of vehicles that exits the circulatory before crossing the path of the entry (exiting flow).

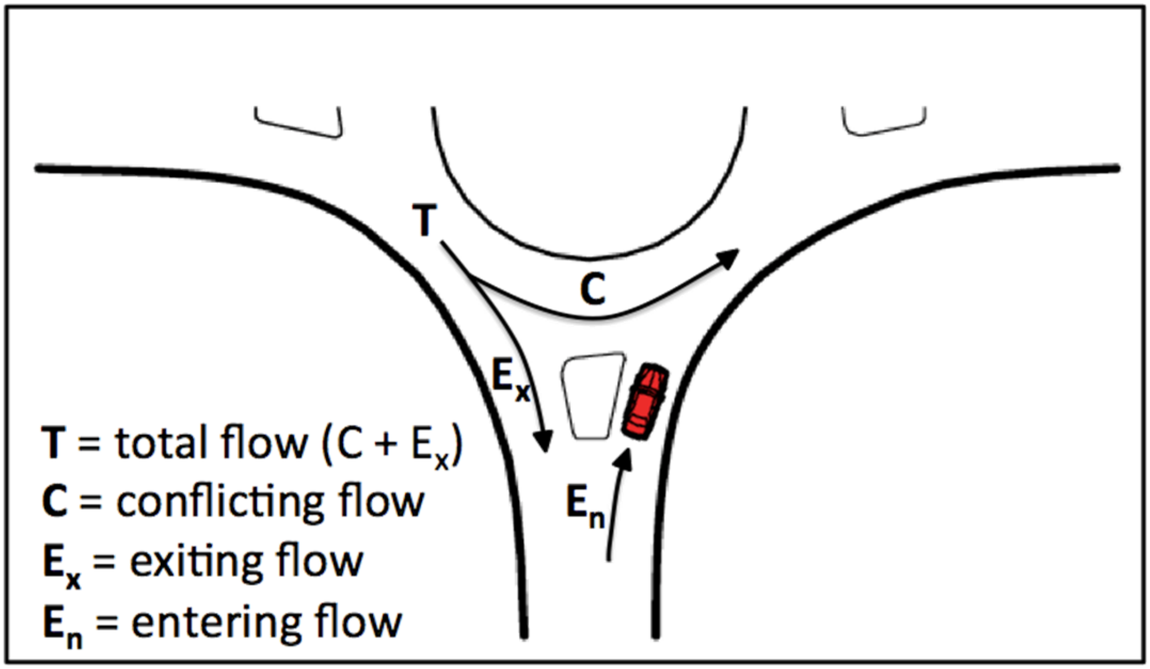


Figure 4-10: Roundabout vehicle flows

NCHRP 672 recognizes that the effect of exiting flow has the potential to affect the capacity prediction accuracy. It is often unclear to drivers attempting to enter a roundabout if cars approaching on the circulatory roadways will exit the roundabout before crossing their path or not. This uncertainty can affect a driver's decision to enter or not enter the circulatory roadway. The manual explains that including the effect in its capacity models did not significantly improve the overall fit to their data and so it was not included in the methodology. However, since the behavior is observed in the field "refinements to assumptions may suggest otherwise". They assert that "in practice the exiting flow does not impact all entering vehicles, and the exact extent of the influence of exiting vehicles has not been determined."

Hagring (2001) was able to show that the share of exiting vehicles "could have a large effect on the entry capacity depending on entry drivers' abilities to detect exiting vehicles." Through simulation, Hagring (2001) found that entry capacity increased as the proportion of exiting vehicles increase when the major flow of a roundabout is constant. Hagring (2001) (as well as Troutbeck (1990)) attributed the effect of exiting vehicles on entry capacity to the geometry of the approach, major stream vehicle speeds, and the percentage of major stream exiting vehicles.

Troutbeck (1990) collected data at roundabouts in Australia and concluded that exiting vehicles had very little effect on entry capacity. He recommended that exiting traffic be considered when circulating speeds are high and also when differences between circulating and exiting travel paths are difficult to recognize based on roundabout geometry.

Mereszczak (2006) expanded on Hagring's (2001) study by comparing capacity estimates with and without exiting traffic with capacities measured in the field at U.S. roundabouts. They concluded that including exiting vehicles results in an improved estimate of capacity. Specifically, an overall reduction in capacity prediction error of almost 20% was observed. From this, they recommend that exiting vehicles be included in capacity estimation for U.S. roundabout approaches and further research be conducted to find the precise way exiting vehicles should be taken into account. Although, they do warn that despite the improved capacity estimation significant errors in capacity prediction are still prevalent as seen in Figure 4-11.

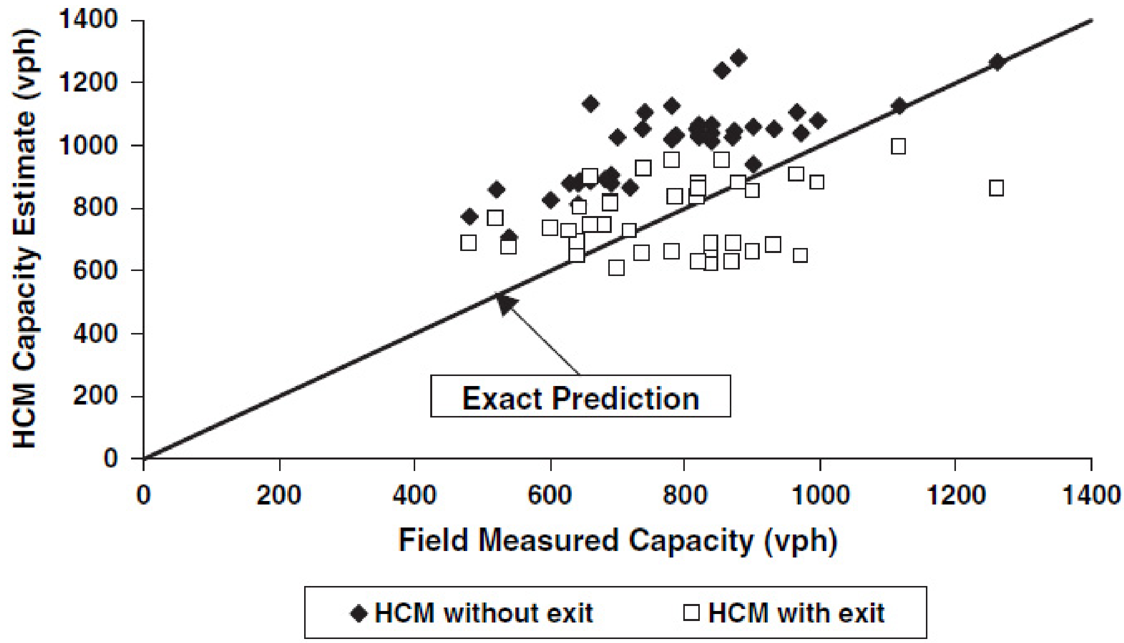


Figure 4-11: Merezcazak's capacity estimates compared with measured capacities (2006)

Entry decision is included in the model validation process to assure that VISSIM accurately models entry decision behavior. See Section 4.4: Calibration and Validation of this work for more information. When the term "exiting traffic" is used it is in reference to the traffic exiting at the leg where entry capacity is being measured. This work explores the effects of exiting vehicles on capacity predictions.

Along with exiting traffic, origin-destination patterns have also been identified as a variable that influences the capacity of a given entry. NCHRP 572 does not explore its effects and the 2010 HCM manual does not include it in capacity models. Akcelik (2004) found that although unbalanced flows did not prove to be an issue when total demand was low it did become problematic when traffic increased to toward medium demand levels. Case studies showed that not only does circulating flow rate affect capacity but the characteristics of approach flows that create the circulating flow do as well. They recommend that the amount of queuing on the approach road, circulating lane use, priority sharing, and priority estimates be taken into account when determining capacity. Part-time metering signals during peak travel times have been used as a solution to this issue.

Krogscheepers (2000) did a study using the simulation program TRACSIM and found that delay is responsive to the change in balance of the circulating flows. Specifically, if the majority of traffic is originating from the approach directly to the left of the approach being considered then delay is usually higher. But if the same traffic volume is coming from the approach directly across the roundabout from the approach being considered the average delay is lower. As a result, the origin and destination of traffic along with the amount of traffic at various approaches affects overall roundabout performance. Krogscheepers (2000) also notes that although SIDRA attempts to account for the effect of one approach volume overshadowing other approaches it is not sensitive to location.

Origin-destination pattern effects are investigated in this study to see if capacity is sensitive to where circulating and exiting traffic is originating. Note that the approach leg capacity analyses conducted in this research were conducted on a roundabout's southern-most leg. Several different origin distribution patterns are used including:

- Southbound (SB) – All conflicting and exiting traffic originates from the northern entry.
- Eastbound (EB) – All conflicting and exiting traffic originates from the western entry.
- EVEN – Conflicting and exiting traffic is evenly distributed between the three legs other than the leg whose entry capacity is being considered.
- 25/50/25 – Meant to simulate a roundabout with an obvious major and minor street, 25% of the conflicting and exiting flow originates from the western entry, 50% of the conflicting and exiting flow originates from the northern entry, and the remaining 25% of conflicting and exiting flow originates from the eastern entry.

This work also analyzes the effect of the speed distribution of a roundabout on entry capacity. The mean of the observed speed distribution from the Southlake roundabout during the PM peak is increased and decreased to explore this relationship. Comments are made regarding the relationship between mean speed and inscribed circle diameter using the characteristics of both the San Antonio and Southlake roundabouts.

In SIDRA, capacity is output based on empirical equations. In VISSIM, researchers estimated capacity by placing a high demand on the southern-most approach leg and measuring how much of that demand was able to enter the roundabout in a given period of time. All vehicles approaching from the southern-most leg were assumed to exit using the northern-most leg.

4.6. Analysis and Results

4.6.1. EFFECTS OF EXITING FLOW AND DISTRIBUTION OF THE ORIGIN OF CONFLICING TRAFFIC

4.6.1.1. Southlake - PM Peak

As seen in Figure 4-12, results from VISSIM show that the roundabout capacity does differ depending on the exiting flow. Therefore, depending on the exiting flow rate, the capacity estimate given by HCM may not be accurate. When exiting flow is low and conflicting flow is below approximately 800 vph the HCM underestimates capacity and then overestimates capacity beyond this threshold.

Exiting flow rates of approximately 760 and ~1100 vph were used because lower rates had no impact and higher rates were not able to enter the roundabout. Values of exiting flow are approximate because although this is the designated exiting flow the resulting flow does not turn out to be exactly this value due to the randomness inherent to the simulation. Table 4-3 shows the difference in capacity when exiting traffic was added compared to zero exiting traffic. Bolded values are differences greater than 100 vph, which the researchers considered to be significant. These scenarios were explored more thoroughly in capacity analysis.

Table 4-3: Comparison of entry lane capacity results for Southlake – PM Peak

Conflicting traffic (vph)	Exiting traffic (vph)	Entry Lane Capacity with exiting traffic (vph)	(Capacity without exiting) - (Capacity with exiting) (vph)
383	150	959	32
	300	920	71
	766	800	**191**
	1149	714	**277**
479	150	837	35
	300	794	78
	766	740	**132**
	1149	649	**223**
574.5	150	746	23
	300	720	49
	766	637	**132**
	1149	595	**174**
766	150	560	15
	300	548	27
	766	480	95
	1149	530	45
900	150	433	35
	300	428	40
	766	406	62
	1149	466	2
1000	150	368	23
	300	361	30
	766	376	15
	--	--	--

With the addition of ~760 vph exiting traffic at the entry leg, the HCM curve predicts the VISSIM results accurately below 600 vph of conflicting traffic. However, data points do not tend to fit the HCM curve beyond this range. The trend of the data points continues on a downward linear path as conflicting vph increases and the HCM curve overestimates capacity. When exiting traffic flow is increased to ~1100 vph the HCM overestimates capacity for the entire range of values. The differences become greater as conflicting traffic increases.

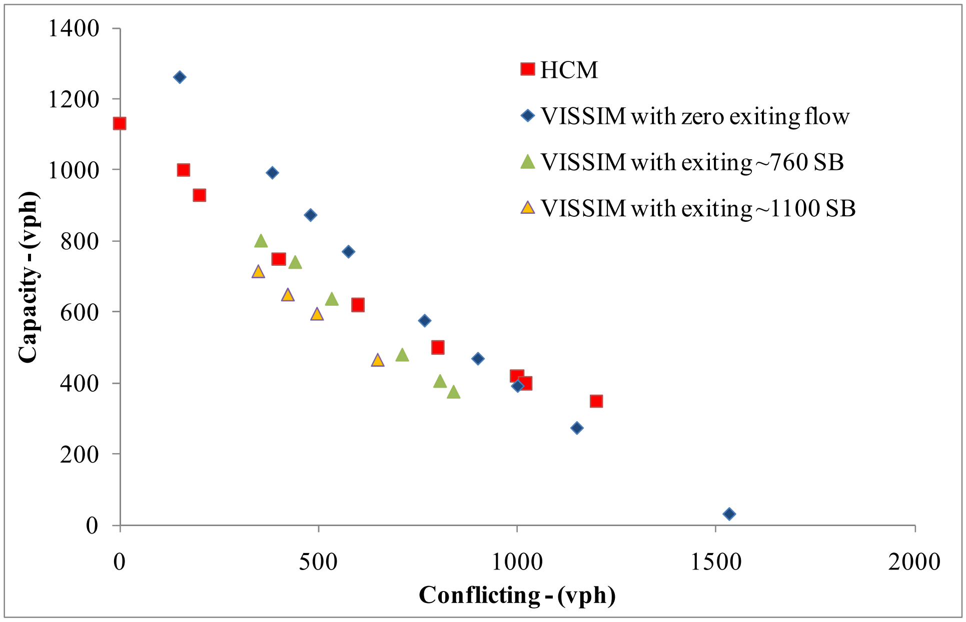


Figure 4-12: VISSIM results for entry lane capacity

As seen in Figure 4-13, VISSIM results did not show significant variation in capacity depending on the distribution of the origin of the conflicting traffic (i.e., SB, EVEN, and 25/50/25) when the exiting traffic flow rate was ~760 vph. All data points in the range provided tend to follow the HCM curve below 600 vph of conflicting traffic. However, when exiting traffic is increased to ~1100 vph capacity becomes more variable depending on the distribution of the traffic origin. In all cases besides EVEN, capacity is overestimated by the HCM curve. This could indicate that when exiting traffic volume is high the HCM curve is better suited to predict entry lane capacity for roundabouts when traffic is evenly distributed across the legs.

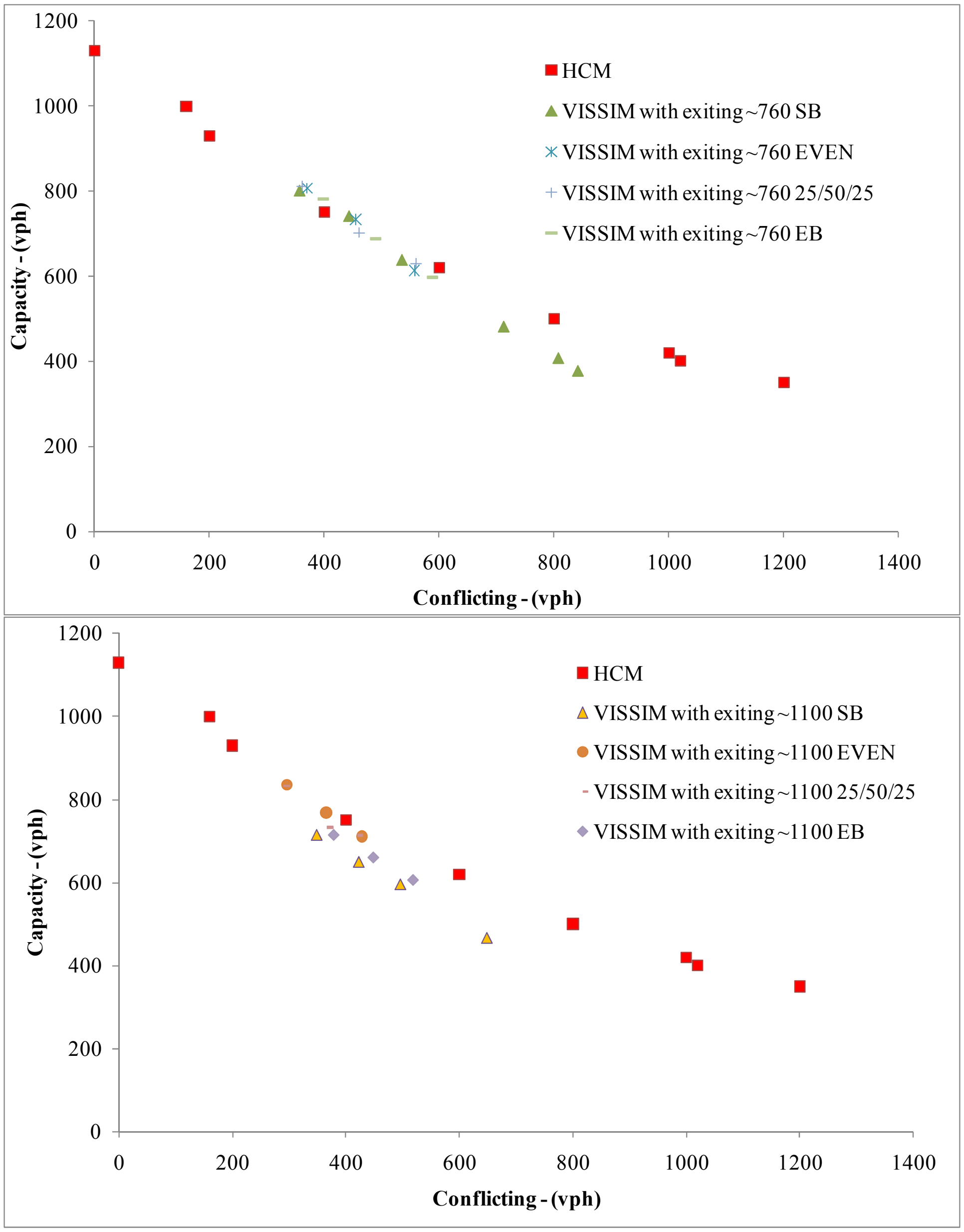


Figure 4-13: VISSIM entry lane capacity results with multiple distributions of the origin of traffic for ~760 vph and ~1100 vph exiting traffic

Results from SIDRA when exiting traffic is not taken into account predict capacity greater than that of the HCM curve as in Figure 4-14. It should be noted that results from SIDRA are largely based on the roundabout capacity equations from HCM 2010 and NCHRP 572.. When exiting flow is increased to ~1100 vph the capacity decreases and is comparable to that predicted by the HCM.

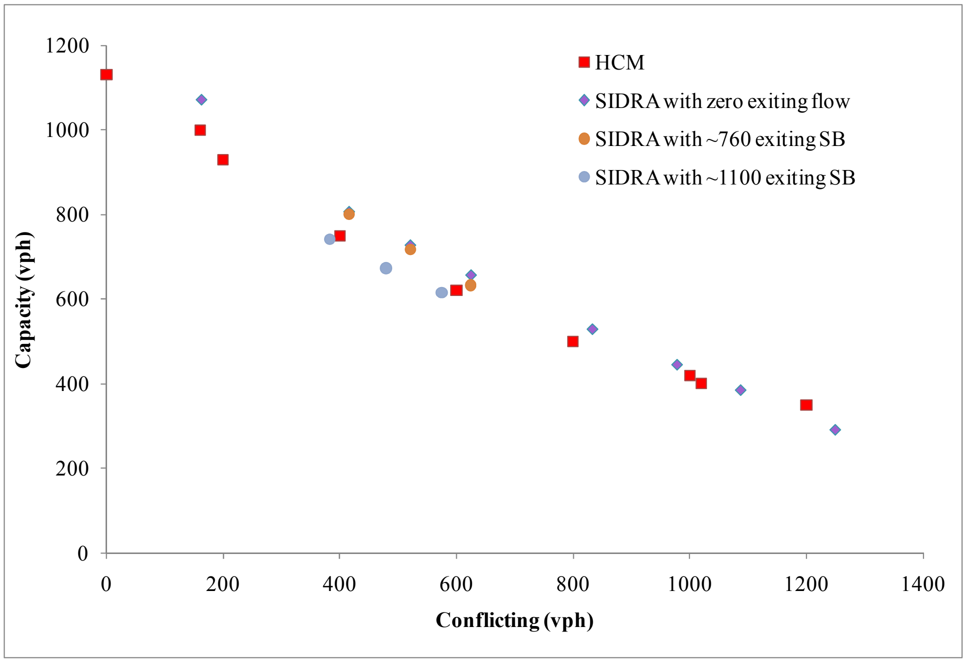


Figure 4-14: SIDRA results for entry lane capacity

As seen in Figure 4-15, capacity varies somewhat depending on the distribution origin of conflicting traffic when exiting traffic is ~760 vph. Capacity is lower and more similar to that predicted by the HCM curve when traffic is evenly distributed or distributed as in the 25/50/25 scenario. Variation in capacity appears to diminish when exiting traffic increases to ~1100 vph.

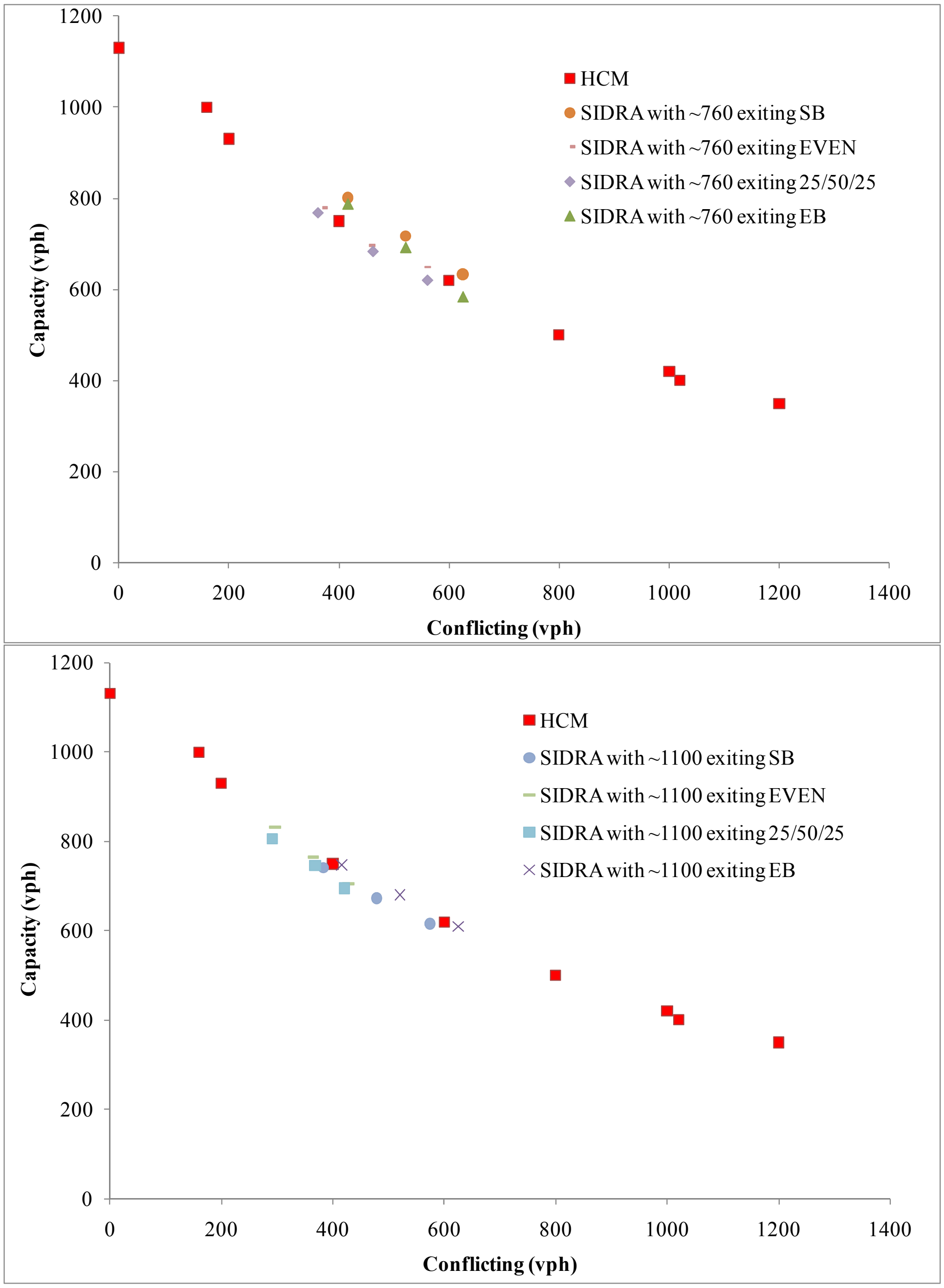


Figure 4-15: SIDRA entry lane capacity results with multiple distributions of the origin of traffic for ~760 vph and ~1100 vph of exiting traffic

For Southlake, the Highway Capacity Manual equation appears to give a reasonable estimate of capacity until conflicting flow goes above 600 vph when exiting flow is ~760 vph. However, beyond this threshold, and when exiting flow increases to ~1100 vph, the HCM overestimates capacity. Capacity results from SIDRA do not tend to be affected by exiting traffic to as great an extent as VISSIM. VISSIM predicts substantially lower capacity for exiting traffic of 1100 vph than SIDRA which tends to follow the trend of the HCM curve. Results from SIDRA and VISSIM are comparable for a roundabout of this nature so either software is recommended for use in entry lane capacity analysis.

4.6.1.2. San Antonio

Both values ~500 and ~700 vph exiting flow were used because lower rates had no impact and higher rates were not able to enter the roundabout. Table 7 shows the difference in capacity when exiting traffic was present compared to zero exiting traffic. Bolded values are those greater than 100 vph, which the researchers considered to be notably different. These scenarios were explored more thoroughly in capacity analysis.

Table 4-4: Comparison of entry lane capacity results for San Antonio

Conflicting traffic (vph)	Exiting traffic (vph)	Entry Lane Capacity with exiting traffic (vph)	(Capacity without exiting) - (Capacity with exiting) (vph)
329	150	594	51
	507	516	**129**
	761	458	**187**
	1014	505	**140**
507	150	441	48
	507	364	**125**
	761	395	94
	1014	423	66
634	150	323	37
	507	288	72
	761	339	21
	1014	352	8
761	150	161	80
	507	248	-7
	761	249	-8
	1014	--	--

As seen in Figure 4-16, capacity values from VISSIM where exiting traffic is not taken into account fall well below the HCM curve. Capacity continues to decrease when exiting flow is taken into account. VISSIM results indicate that the HCM roundabout capacity curve is not appropriate for roundabouts with such a small inscribed circle diameter. Based on the results from VISSIM, practitioners should be cautioned against using the HCM curve for smaller roundabouts as capacity will be largely overestimated.

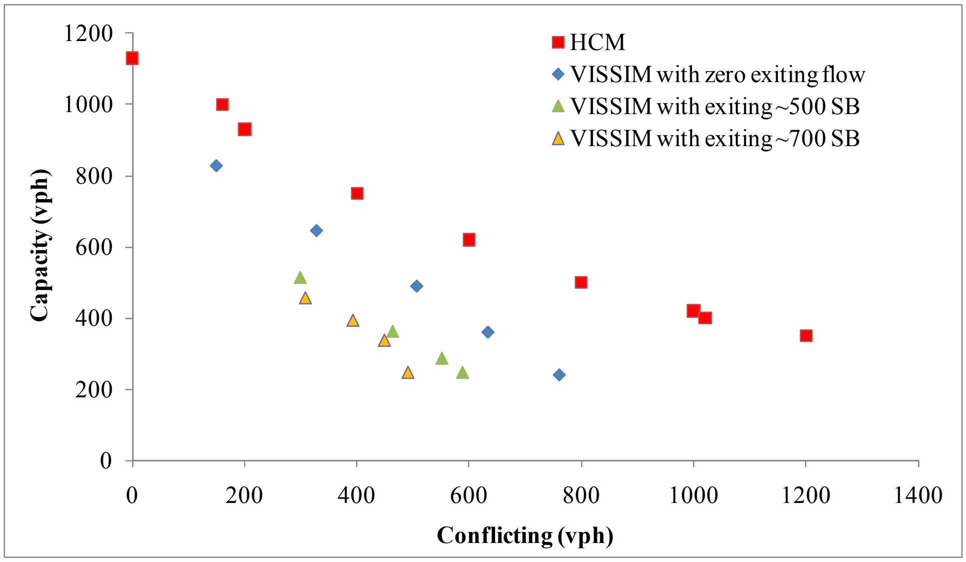


Figure 4-16: VISSIM results for entry lane capacity

It is also evident from Figure 4-17 that at the smaller San Antonio roundabout capacity varies slightly depending on the origin distribution of the conflicting traffic. For instance, capacity is at its lowest when all conflicting traffic enters from the northern leg. With the exception of the SB distribution, other distributions tend to vary little from one another. Variation seems to increase slightly as exiting traffic volume increases.

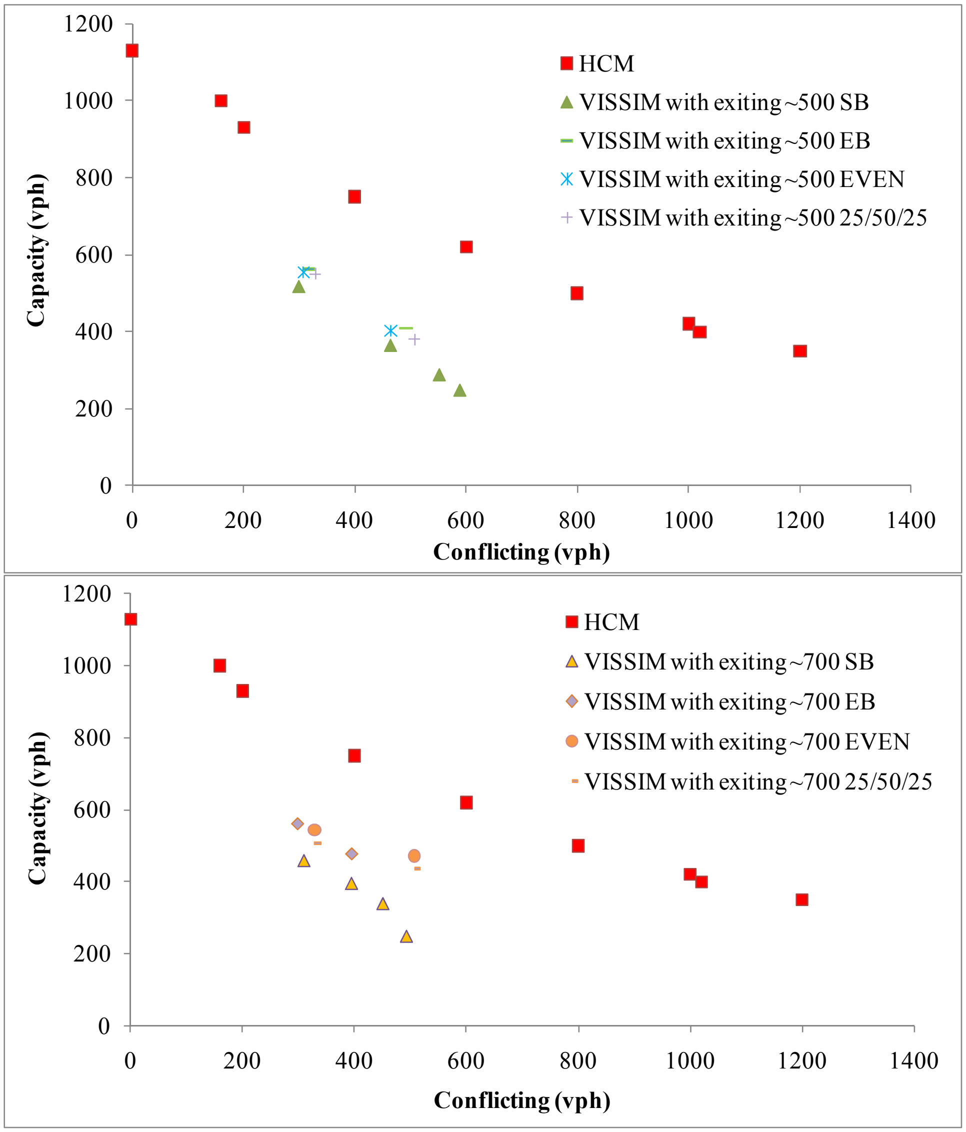


Figure 4-17:VISSIM entry lane capacity results with multiple distributions of the origin of traffic for ~500 vph and ~700 vph of exiting traffic

Vehicles coming from the northern entry (as in the SB scenario) traverse more of the roundabout quadrants as they exit at the leg in question and cross the path of vehicles waiting to enter. This provides vehicles with more opportunity to bunch according to the Wiedemann car following equations, which are used in VISSIM. Bunching can decrease gap sizes and therefore fewer cars may have the opportunity to enter the circulatory roadway. This could contribute to the fact that capacity is at its lowest when all traffic is coming from the northern entry.

Table 4-5 shows values of capacity from VISSIM for Southlake and San Antonio with approximately 500 vph conflicting traffic and approximately 700 vph exiting traffic.

Table 4-5: Entry lane capacity with ~500 vph conflicting traffic and ~700 vph exiting traffic

Distribution of the Origin of Traffic	Roundabout	Entry Lane Capacity (vph)	Percent Difference
SB	San Antonio	395	60.8
	Southlake	740	
EB	San Antonio	476	36.4
	Southlake	688	

The difference in capacities produced by VISSIM for the Southlake and San Antonio roundabouts could be explained by the difference in average speed of vehicles entering the roundabout and navigating the circulatory roadway. The average speeds for the Southlake and San Antonio roundabouts are approximately 20 mph and 12 mph, respectively. The speed-flow-density relationship says that flow (vehicles per hour) is a function of speed (miles/hour) and density (vehicles/mile). Therefore such a substantial difference in average speed likely contributed to the difference in entry lane flow.

The decrease in capacity could also be explained by the smaller diameter. As the inscribed circle diameter becomes smaller traffic entering from any side can sense approaching traffic more easily. At the San Antonio roundabout the diameter is small and obstructions are few so entering drivers can clearly see vehicle activity on the entire roundabout. The VISSIM model was calibrated to simulate this driver behavior. It is possible that drivers are more likely to yield to other drivers on the roundabout even though they may not necessarily conflict with their path. In the case of a larger inscribed circle diameter like Southlake, the driver cannot see activity on the entire roundabout so he considers the roundabout in terms of quadrants with the approaching fourth being the most crucial.

Results from SIDRA are shown in Figure 4-18. Unlike the results from VISSIM, results from SIDRA closely follow the HCM curve. This indicates that SIDRA relies heavily on equations from NHCRP 572 and HCM 2010 for calculating entry capacity even for smaller roundabouts. The speed-flow-density relationship appears to have no effect here. Capacity values from SIDRA seem to be affected minimally by the distribution of the origin of conflicting traffic unlike VISSIM as seen in Figure 4-19. The scenario 25/50/25 is not shown because capacity results were different from EVEN by less than 1 percent.

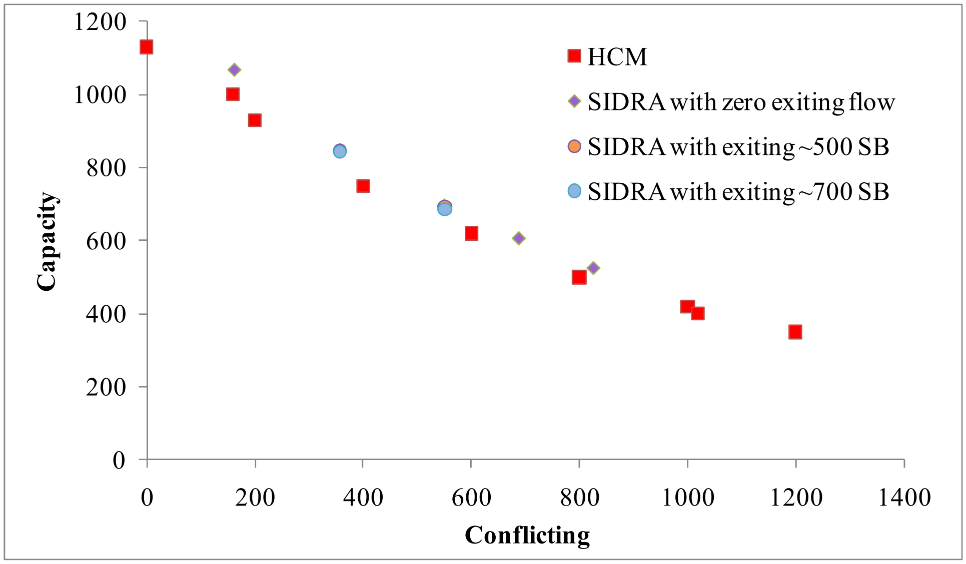


Figure 4-18: SIDRA results for entry lane capacity

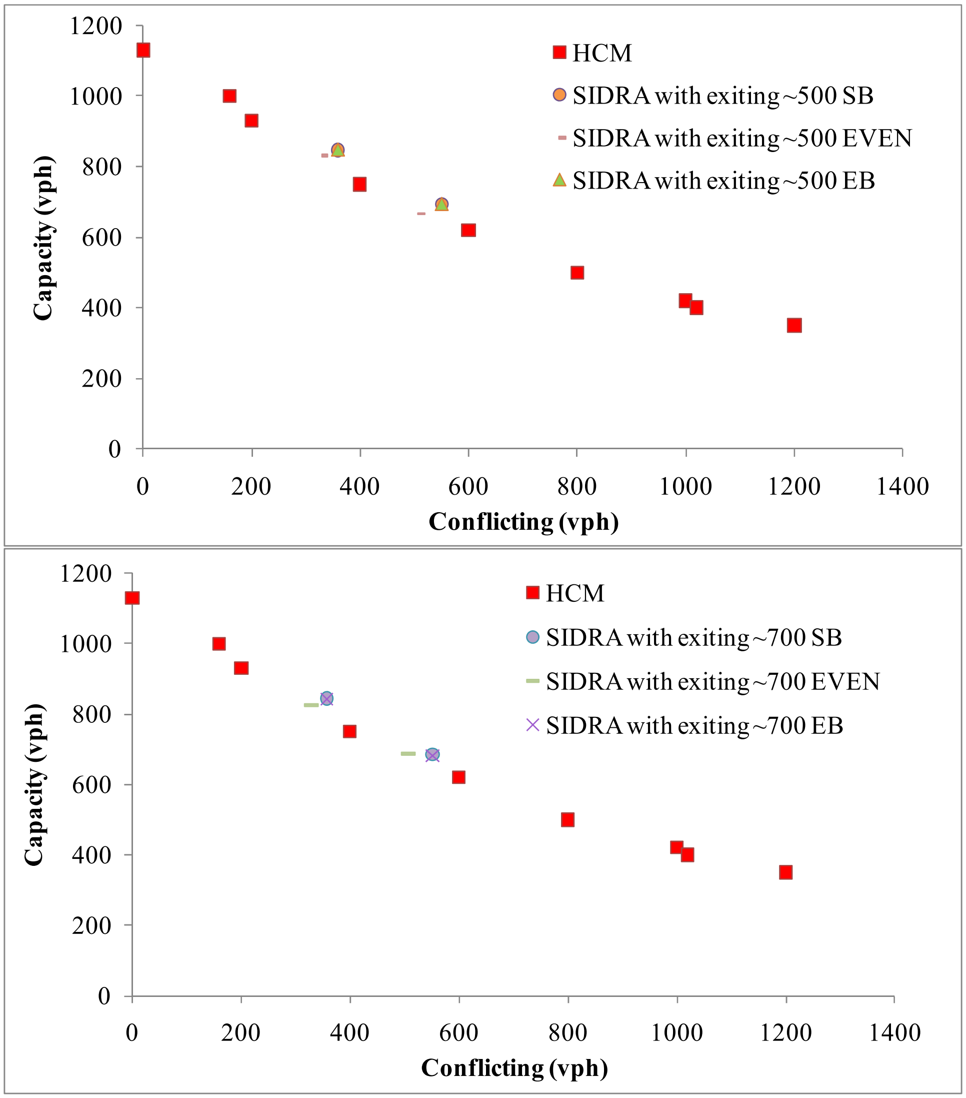


Figure 4-19: SIDRA entry lane capacity results with multiple distributions of the origin of traffic for ~500 vph and ~700 vph of exiting traffic

Overall, the San Antonio roundabout results from VISSIM are not comparable to SIDRA. Results from VISSIM indicate that inscribed diameter size substantially affects capacity while SIDRA does not. In some cases the difference from the HCM curve was as high as 200 vph for VISSIM results. Further research is needed to quantify the impacts of this effect and to assess the accuracy of the results from SIDRA and VISSIM for a roundabout with such a small diameter. This research indicates that SIDRA may not be accurate for a smaller roundabout that is approaching the size of a mini-roundabout and runs a great risk of overestimating entry leg capacity.

4.6.1.3. EFFECTS OF MEAN SPEED

This work investigates the difference in capacity between San Antonio and Southlake and attempts to determine the parameter that is responsible through simulation. Inscribed circle diameter and mean speed were identified as the two major differences between the roundabouts. The inscribed circle diameter of the Southlake roundabout is approximately 40 feet larger and the mean speed is 7.3 mph greater than San Antonio.

In order to gauge the effect of the inscribed circle diameter, the speed distribution of the Southlake roundabout was applied to the San Antonio roundabout and the resulting capacity values were compared to results from original San Antonio capacity values. All capacity values are with zero exiting flow. Figure 4-20 shows the capacity values in question.

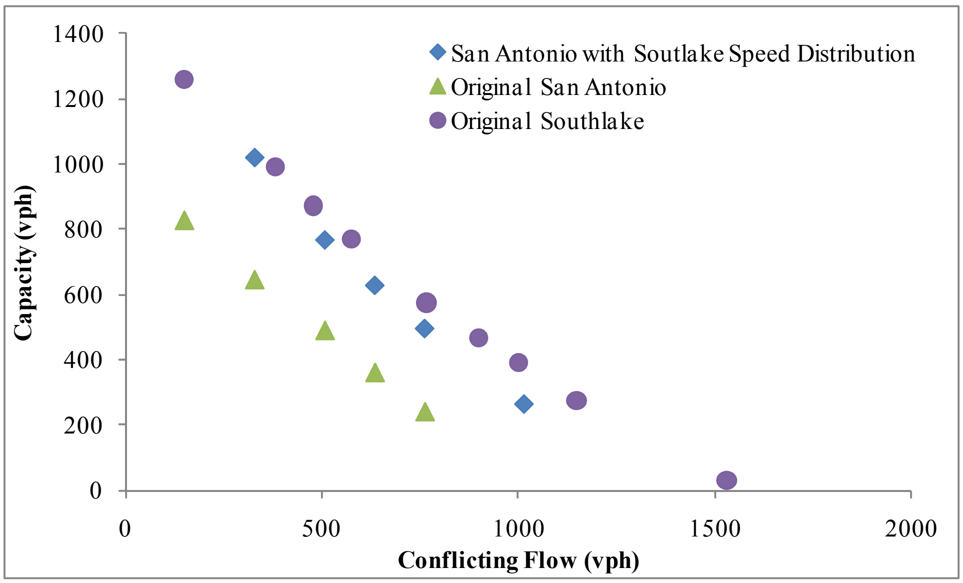


Figure 4.20: Comparison of capacity values for San Antonio with Southlake speed distribution, San Antonio with its original speed distribution, and Southlake with its original speed distribution.

By changing the speed distribution, the capacity values for the San Antonio roundabout are much closer to the capacity values for the Southlake roundabout despite the remaining difference in inscribed circle diameter. This suggests that the difference between the two roundabouts' speed distributions is primarily responsible for difference in entry lane capacity.

The VISSIM model for the Southlake roundabout was used to explore the effect of the mean speed of a roundabout on entry lane capacity further. The Southlake speed distribution was used as the base speed distribution. This base distribution was modified into four additional speed distributions by adding and subtracting a specified value from each point on the curve. For example, 5 mph was subtracted from each point on the original Southlake speed distribution to create a new speed distribution with a mean speed of 13.9 mph. Each distribution is represented with its resulting mean speed throughout this discussion. The distributions include 13.9 mph, 18.9 mph (the original distribution), 23.9 mph, 28.9 mph, and 38.9 mph. Figure 21 shows the capacity curve for the five speed distributions.

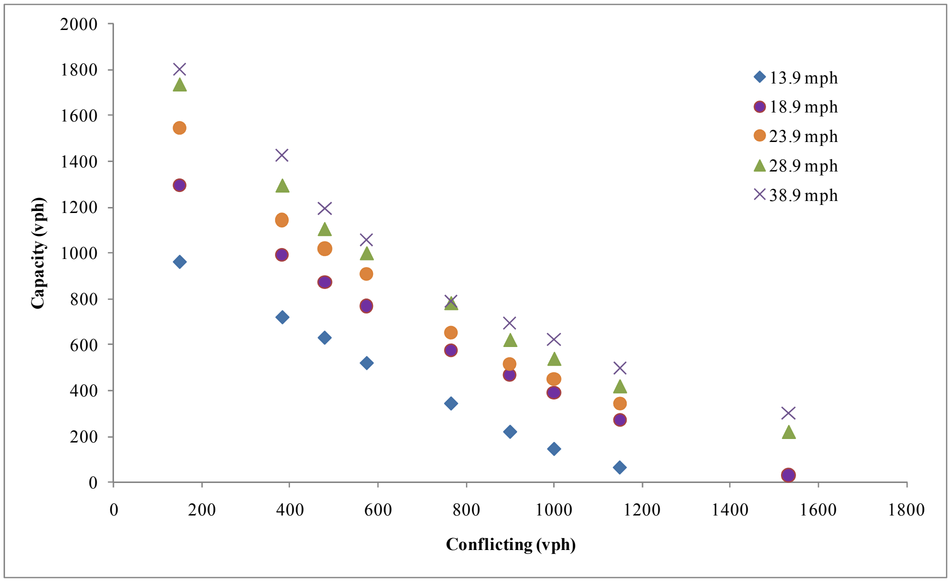


Figure 4-21: Capacity curve for varying speed distributions

At mean speeds of 18.9 mph and below, the data appears to be linear but beyond this range the curves are more exponential. Using these curves, equations were developed that may be useful in determining capacity depending on expected speed and conflicting traffic:

When mean speed is between 13.9 mph and 23.9 mph:

$$c = 666.641 - 1.045 v_c + 36.963 s$$

When mean speed is above 23.9 mph:

$$c = (1699.086 + 14.334 s) e^{-0.001 v_c}$$

where,

c = entry lane capacity (veh/hr)

s = speed (mi/hr)

v_c = conflicting traffic (veh/hr)

These equations are meant to act as a planning tool to give the user a general idea of the entry lane capacity they can expect given the expected mean speed of the roundabout and volume of conflicting traffic.

4.7. Summary of Results

The answer to one of the main objectives of this work – can the Highway Capacity Manual be used to predict capacity at Texas roundabouts? – the answer appears to be "it depends." Using VISSIM results as the baseline, the HCM provided reasonable approximations when (1) the roundabout diameter is "typical" for a single-lane roundabout (here, "typical" was 130 feet), (2) the conflicting flow rate is "low" or "medium" (here, less than ~ 760 vph) and (3) the exiting flow rate is “medium” (~ 760 vph). These conditions may appear strict, but it is likely that most roundabouts will experience conditions in these ranges. Further study is needed to provide guidelines on how the HCM results can be adjusted to provide better capacity estimates. However, the trends discussed in the bullet points below will provide a starting point to any potential adjustments.

Another objective of this work was to evaluate SIDRA INTERSECTION as software for evaluating roundabouts in Texas. SIDRA capacity results were shown to follow the HCM curve more closely than the results from VISSIM and in most cases SIDRA provides results that are between those of HCM and VISSIM. For this reason, this work recommends the use of SIDRA when (1) traffic analysis is needed that exceeds the capabilities of the planning method located in NCHRP 672 (2) the software is available and (3) using VISSIM is too time-consuming. Unlike VISSIM, which is a microsimulation model, SIDRA is a much simpler analytical tool. As described in the “Software and Procedures” section of this document, roundabout analysis is made very easy in SIDRA through the use of templates and it allows for some calibration based on local conditions, unlike using the HCM curve. While VISSIM gives the most behaviorally consistent results, building a model can be time-consuming and is unlikely to be used in practice unless the roundabout design is especially complex and does not fit any of the SIDRA templates.

A summary of results is below.

Southlake Roundabout (130-foot diameter, 20mph average entering speed)

Comparing HCM Capacity Curve Results to VISSIM Results

- When exiting flow is low and conflicting flow is below approximately 800 vph the HCM curve underestimates capacity and then overestimates capacity beyond this threshold.
- If exiting traffic is ~760 vph, and conflicting traffic is less than 600vph the HCM curve predicts accurately.
- If exiting traffic is increased to ~1100 vph the HCM curve overestimates capacity for all conflicting flows studied (~300 to ~720vph).
- As exiting traffic volumes increase, the effect of the distribution of entering traffic among intersection legs increases. In fact, distribution of traffic among roundabout entry points (origin of traffic) does not affect capacity when exiting traffic is ~760 vph, however, when exiting traffic increases to ~1100 vph, the distribution has a greater effect on approach leg capacity. The differences in capacity are small, but approach capacity is lowest when all conflicting and exiting traffic comes from the opposite side of the roundabout and is highest when this traffic is evenly distributed across the approach legs.

Comparing HCM Capacity Curve Results to SIDRA Results

- Compared to SIDRA, the HCM curve underestimates capacity when exiting traffic is ~760 vph or less but not when exiting traffic is increased to ~1100 vph
- Capacity estimates from SIDRA are variable depending on the distribution of the origin of traffic if exiting flow is ~760 vph. However, there is less variation when exiting traffic is increased to ~1100 vph. This is opposite to what was observed through VISSIM capacity results.
- Overall SIDRA values are comparable to HCM.

San Antonio (90-foot diameter, 12mph average entering speed)

Comparing the three capacity estimation methods:

- Compared to VISSIM results, the HCM curve highly overestimates capacity for all scenarios tested.
- VISSIM capacity estimates seem to be affected by the distribution of entering traffic among roundabout legs. If exiting traffic is ~760 vph, the distribution of the origin of traffic has a slight effect on VISSIM capacity results and this effect increases when exiting traffic volume increases.
- Overall SIDRA values are comparable to HCM.
- Exiting traffic volume and distribution of origin of traffic have little effect on SIDRA entry lane capacity.

Mean Speed

The mean speed of a roundabout appears to have an effect on roundabout capacity. A linear relationship between traffic speed and capacity was observed when mean speed is between 13.9 mph and 23.9 mph. The relationship becomes exponential as mean speed exceeds 23.9 mph. Equations are presented to predict entry-lane capacity based on expected mean speed and conflicting traffic. More research is needed to further explore the validity and usefulness of these equations.

5. Geometric Design

5.1. Introduction

This section presents the most up-to-date information available regarding geometric design guidelines. The majority of the information in this document is from two FHWA publications—*Roundabouts: An Informational Guide,* originally published in 2000, and *Roundabouts: Technical Summary,* published in February of 2010. The latter contains some information from the second edition of *Roundabouts: An Informational Guide*(otherwise known as NCHRP 672). This section summarizes this information and provides guidance on where more details can be found.

The geometric design of roundabouts is an iterative process between operational analysis, safety evaluation, and design vehicle accommodation. Minor alterations to the geometric design can result in substantial changes for the safety or operational performance of a roundabout. The geometric design features of a roundabout also depend on the unique attributes at its location (e.g., surrounding speed, design capacity, available space, amount and arrangement of lanes, design vehicle) and on the roundabout's size (e.g., single-lane or a multi-lane). Adjusting the preliminary design to alter capacity and improve safety while still complying with site-specific constraints is almost always necessary. For this reason, NCHRP 672 recommends that the initial layout of a roundabout is performed at a "sketch" level of detail. Figure 5-1 illustrates the iterative process of design and evaluation of roundabouts.

The specifications in NCHRP 672 are a starting point for designing roundabouts that comprehensively meet performance objectives. Roundabout design includes using deflection to dictate slow entry speeds and consistent speeds through the roundabout, employing the appropriate number of lanes and assignment, providing smooth channelization, accommodating the design vehicles, meeting the needs of pedestrians and bicyclists, and providing sight distance and visibility. The design process usually involves making tradeoffs. For instance, accommodating large trucks may increase the entry and circulatory speeds of passenger cars.

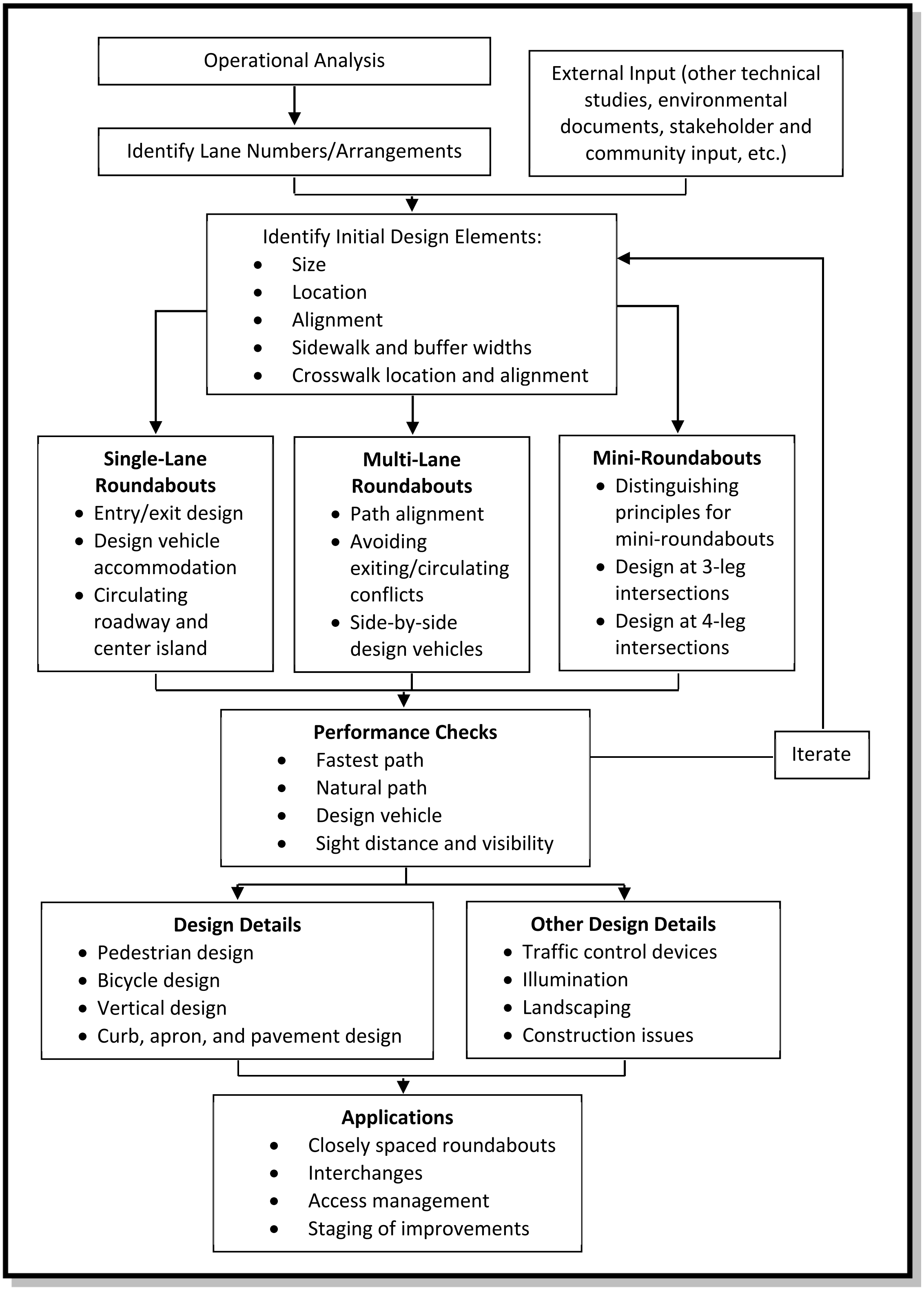


Figure 5-1: Roundabout design process (Source: NCHRP 672)

5.2. Roundabout Size

The following basic geometric elements of a roundabout are illustrated in Figure 5-2:

- Inscribed circle diameter;
- Central island;
- Entrance line;
- Circulatory roadway;
- Sidewalk;
- Landscape buffer;
- Truck apron;
- Accessible pedestrian crossings; and
- Splitter island.

5.2.1. Inscribed Circle Diameter

The inscribed circle diameter is the central island diameter plus twice the width of the traffic lanes within the roundabout. Several design objectives (e.g., design vehicle accommodation, providing speed control, and ensuring visibility for the central island) influence the inscribed circle diameter and iteration is necessary to achieve the best design. The turning path of the design vehicle has the most bearing on the size of the inscribed diameter in single-lane roundabouts. See Section 5.4, "Design Vehicle," for further discussion.

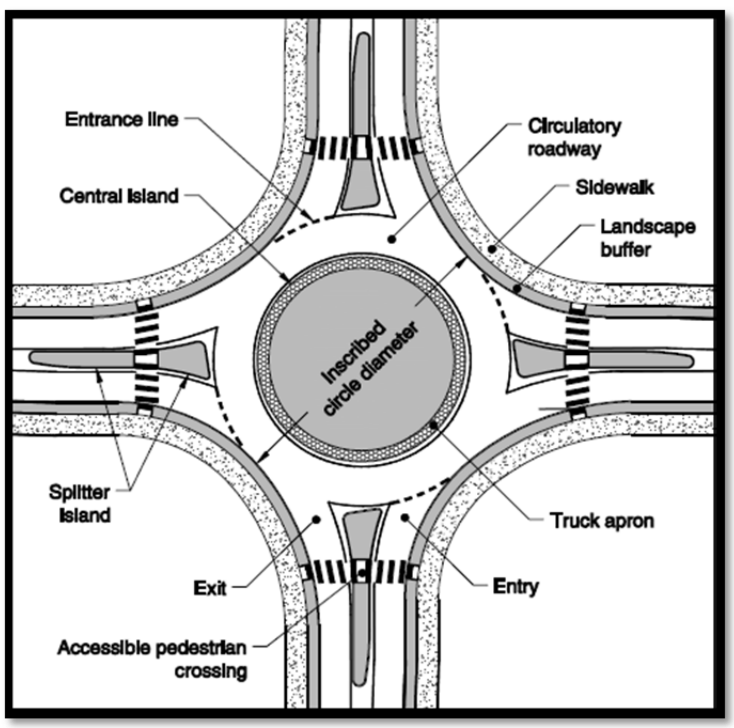


Figure 5-2: Basic geometric roundabout elements (Source: NCHRP 672)

A small inscribed circle diameter is necessary in some cases (i.e., limited right-of-way). A small diameter is possible with the right combination of circulatory roadway width, entry and exit widths, entry and exit radii, and entry and exit angles. These factors are important in accommodating the design vehicle and allowing for appropriate deflection.(Entry and exit radii are illustrated in Figure 5-6.) NCHRP 672 recommends a minimum inscribed circle diameter for a single-lane roundabout of 105 ft (32 m) for a WB-50 (WB-15) design vehicle. A larger inscribed circle diameter, ranging from 130 to 150 ft (40 to 46 m), is recommended to accommodate the longer WB-67 (WB-20) design vehicle. Single-lane roundabouts with more than four legs may also require a larger inscribed circle diameter.

Unlike single-lane roundabouts, the design vehicle does not usually provide limitations in multi-lane roundabouts. Instead, the inscribed circle diameter is governed by balancing the deflection requirements and entry and exit alignment. The recommended minimum inscribed circle diameter for a multi-lane roundabout is 150 to 250ft (46 to 76m). A typical double-lane roundabout has an inscribed circle diameter between 160 and 180ft (46 and 55m). As in single-lane roundabouts, multi-lane roundabouts with more than two lane entry legs may require a larger inscribed circle diameter of 180 to 330ft (55 to 100m).

Mini-roundabouts typically have inscribed circle diameters less than 90ft (27m). They can have such a small diameter because of the fully traversable central island. Smaller inscribed diameters are considered safer because they dictate lower speeds.

At intersections with high speeds (such as rural intersections), the approach geometry becomes more important. Safer approach geometry is often achieved by using a large inscribed diameter. This slows down vehicles that are approaching the roundabout and reduces the angle between entering vehicles and those within the roundabout. These effects contribute to lower crash rates between entering and circulating vehicles. It is recommended that diameters not exceed 200 ft (60 m) because vehicles have increasingly more time to pick up speed while maneuvering through the roundabout. Crashes that occur at higher speeds are generally more severe. Table -5-1 shows the recommended ranges of inscribed circle diameters and design vehicles depending on site locations.

Table 5-1: Recommended inscribed circle diameter ranges (Source: NCHRP 672)

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) WB-50 (WB-15) WB-67 (WB-20)	90 to 150 ft 105 to 150 ft 130 to 180 ft	(27 to 46 m) (32 to 46 m) (40 to 55 m)
Multi-Lane Roundabout (2 lanes)	WB-50 (WB-15) WB-67 (WB-20)	150 to 220 ft 165 to 220 ft	(46 to 67 m) (50 to 67 m)
Multi-Lane Roundabout (3 lanes)	WB-50 (WB-15) WB-67 (WB-20)	200 to 250 ft 220 to 300 ft	(61 to 76 m) (67 to 91 m)

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

Additional information on inscribed circle diameter is in Section 6.3.1 of NCHRP 672.

5.2.2. Central Island

A sizable fraction of the area of the inscribed circle is occupied by the central island. This raised, non-traversable area is surrounded by the circulatory roadway and is often landscaped for aesthetics and visibility to approaching drivers. NCHRP 672 recommends that the central island never be depressed because its visibility will be compromised. A traversable apron may be incorporated into the central island's design when right-of-way limitations or topography restrain the size of the inscribed circle diameter. The apron can accommodate the over-tracking of large semi-trailer vehicles so deflection is not compromised for smaller vehicles.

Another characteristic of the central island is that it is generally circular. This shape helps to encourage constant speeds in the circulatory roadway. Irregular shapes fail to accomplish this and can promote higher speeds on straight sections and lower speeds on tighter arcs. This speed differential can make it difficult for drivers to judge speeds. Non-circular roundabout central islands also complicate gap acceptability and maneuverability.

However, non-circular roundabouts are appropriate in some instances. For example, intersections where certain turning movements are not allowed or are difficult, rain-drop shaped islands are sometimes used.

The actual size of the central island is dependent on the inscribed circle diameter and the circulatory roadway width. The central island of a roundabout is typically larger in rural environments than in urban environments.

More information regarding central island design is in Section 6.4.4 of NCHRP 672.

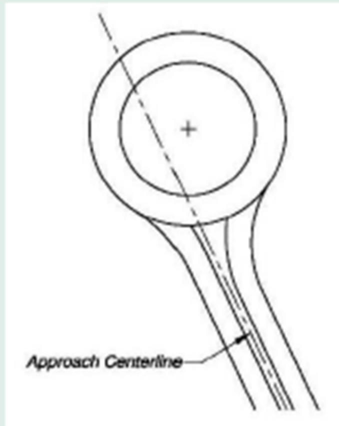
5.3. Horizontal Alignment Considerations

The most ideal location for a roundabout is an intersection where the centerlines of all the approach roadways (legs) pass through the center of the inscribed circle. This configuration typically results in a layout that preserves slow speeds on entry and exit legs. A radial alignment also helps to draw drivers' attention to the center island when approaching the roundabout. Figure 5-3 describes other options for alignment of approach legs.

As illustrated in Figure 5-3, if the legs will not align through the center point of the roundabout, the centerlines can be slightly to the left of the center point of the intersection to achieve adequate approach curvature. Sufficient curvature is of the highest priority when designing a roundabout. An offset left design is often necessary to improve entry curvature and speed control. However, the designer must be careful to not to make exit legs overly tangential. Insufficient exit path curvature can increase vehicle speed and put pedestrians in danger.

An offset right design is usually not appropriate. This layout can cause approaches to be excessively tangential. With this design, vehicles are able to enter the roundabout at higher speeds that could potentially cause them to lose control or increase the likelihood of collisions with circulating vehicles.

Alternative 1: Offset Alignment to the Left of Center



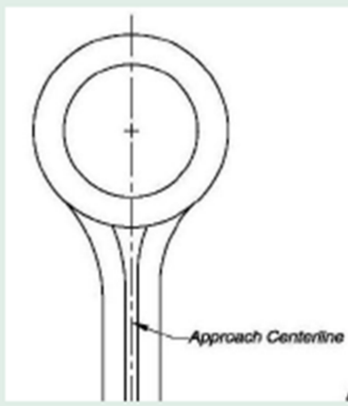
ADVANTAGES:

- Allows for increased deflection
- Beneficial for accommodating large trucks with small inscribed circle diameter—allows for larger entry radius while maintaining deflection and speed control
- May reduce impacts to right-side of roadway

TRADE-OFFS

- Increased exit radius or tangential exit reduces control of exit speeds and acceleration through crosswalk area
- May create greater impacts to the left side of the roadway

Alternative 2: Alignment through Center of Roundabout



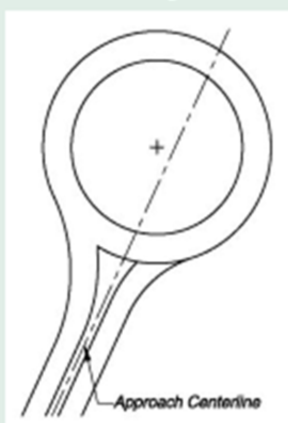
ADVANTAGES:

- Reduces amount of alignment changes along the approach roadway to keep impacts more localized to intersection
- Allows for some exit curvature to encourage drivers to maintain slower speeds through the exit

TRADE-OFFS

- Increased exit radius reduces control of exit speeds/acceleration through crosswalk area
- May require a slightly larger inscribed circle diameter (compared to offset-left design) to provide the same level of speed control

Alternative 3: Alignment to Right of Center



ADVANTAGES:

- Could be used for large inscribed circle diameter roundabouts where speed control objectives can still be met
- Although not commonly used, this strategy may be appropriate in some instances (provided that speed objectives are met) to minimize impacts, improve view angles, etc.

TRADE-OFFS

- Often more difficult to achieve speed control objectives, particularly at small diameter roundabouts
- Increases the amount of exit curvature that must be negotiated

Figure 5-3: Options for approach alignment (Source: NCHRP 672)

5.2.3. Angle between Approach Legs

The preferred angle between approach legs is perpendicular or near perpendicular to maintain slow and consistent speeds for all movements through the roundabout. Having an angle between approaching legs greater than 90° will often result in higher speeds for right-turn movements. On the other hand, when two approaching legs intersect at an angle less than 90°, navigating a turn movement becomes more difficult for large trucks. Increasing the corner radius to accommodate large trucks may widen a portion of the circulatory roadway, which in turn can increase speeds and decrease the safety of the roundabout. A significantly larger inscribed circle diameter is required for highly skewed intersection angles in order to provide speed control (NCHRP 672, Section 6.3.3).

Another element of design that is important to incorporate is the equal spacing of angles between entries. This results in ideal separation between consecutive entries and exits and angles that are optimal for the roundabout depending on the number of legs (90°for four-leg and 72°for five-leg, etc.).

5.2.4. Path Alignment

The natural path of vehicles should be considered to ensure that the geometry of the roundabout facilitates movement through the proper lane. The natural path must have smooth curvature transitions and similar radii between consecutive curves. Designers should work to avoid path overlap so that entering vehicles are aligned with the appropriate circulatory lane. Figure 5-4 illustrates a possible technique for determining the natural path of a given roundabout design. This technique involves freehand sketching of the natural path over the geometric layout.

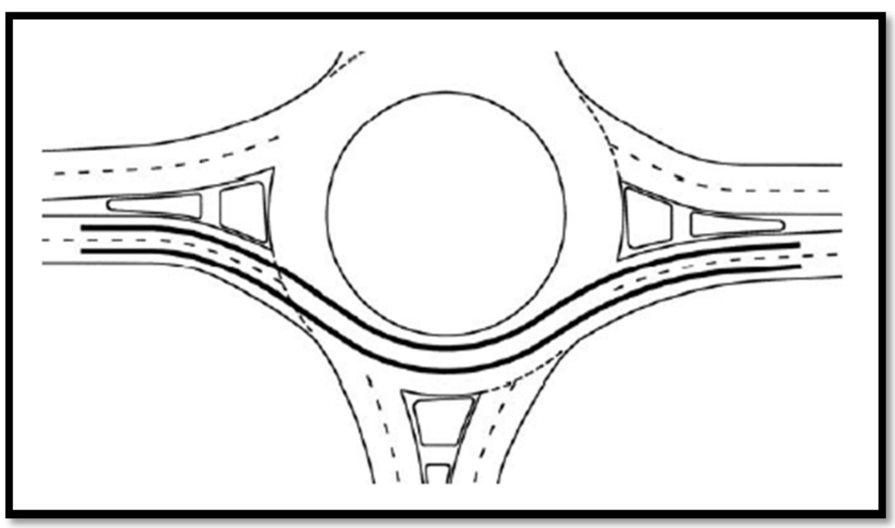


Figure 5-4: Natural vehicle path sketched through roundabout (Source: NCHRP 672)

Path alignment is also balanced with entry speed considerations and other factors such as design speed needs. Achieving an appropriate design usually involves iteration of the different factors.

Path alignment and design techniques for multilane roundabouts are in Section 6.1.2 of the Roundabout Technical Summary and in further detail in Section 6.5.4 of NCHRP 672. The Roundabout Technical Summary can be accessed at http://safety.fhwa.dot.gov/intersection/roundabouts/fhwasa10006/.

5.4. Design Vehicle

Designing for the largest motorized vehicle that could potentially use the intersection (the design vehicle) is an essential aspect of determining the layout for a roundabout. The dimensions of the roundabout must be able to facilitate the turning path of the design vehicle. Design vehicles vary for different roundabouts depending on the adjacent roadways and adjoining land use. Local and state agencies with authority over the intersection in question should be consulted in choosing the design vehicle. Information on the dimensions and turning path requirements of many common highway vehicles is available in *A Policy on Geometric Design of Highways and Streets* from the American Association of State and Highway Transportation Officials (AASHTO). Collectors and arterials are typically designed to accommodate WB-50 (WB-15) while interstate freeways or state highway systems often need to consider WB-67 (WB-20).Figure 5-5 illustrates the through-movement swept path of a WB-50 (WB-15) design vehicle.

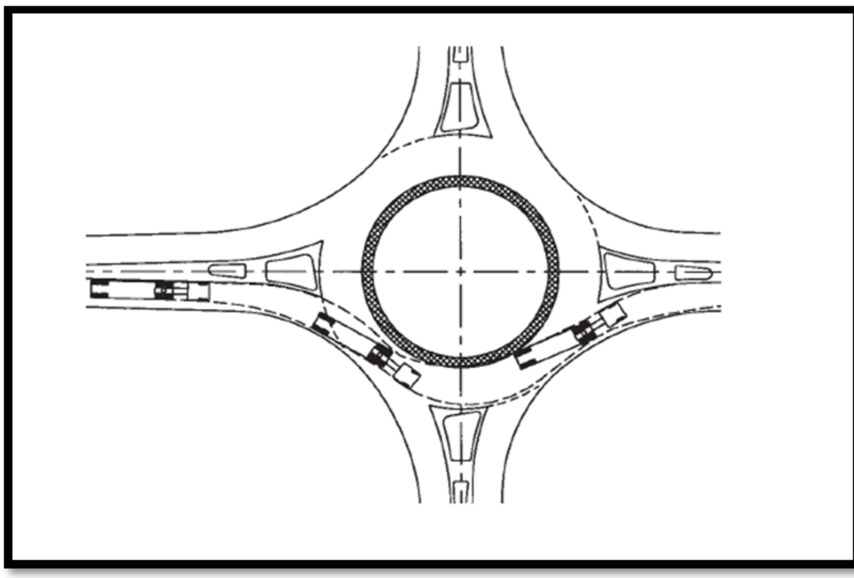


Figure 5-5: WB-50 (WB-15) through-movement swept path (Source: FHWA Roundabout Guidelines)

Large roundabouts less than 200 ft in diameter have the ability to retain low speeds when large vehicles will be using the intersection. Unfortunately, the proper amount of right-of-way for such conditions is not always available. In this case, truck aprons on the center island can allow for the turning movements of larger vehicles. However, truck aprons weaken the operational level of the roundabout and should be used if there is no other option for making sure large vehicles can maneuver safely through the roundabout.

Roundabouts in urban areas should accommodate emergency, transit, and single-unit delivery vehicles without these design vehicles having to use a truck apron. In rural areas, the design vehicles can include farming or mining equipment. The designer should also consider oversized vehicles in rural areas and at freeway interchanges.

5.5. Speed Management

Achieving low and consistent vehicular speeds at the entry and through the roundabout are critical design objectives. Speed management impacts the safety of a roundabout, because it makes roundabouts easier to use and it helps pedestrians and bicyclists to cross easily.

One of the most important contributions to a roundabout's safety is its operating speed. The entering and circulating speeds of a roundabout affects the severity of crashes that occur at the intersection. NCHRP 672 recommends a maximum entering design speed of 20 to 25 mph (32 to 40 km/h) for single-lane roundabouts. Assuming that vehicles ignore all lane lines, the recommended maximum entering design speed for multi-lane roundabouts is 25 to 30 mph (40 to 48 km/h). The speed limit for a roundabout depends on the geometry of the roundabout and the operating speed of the approaching roadways. Reducing the vehicle path radius may be considered when trying to reduce the relative speed between entering and circulating vehicles for single-lane roundabouts. On the other hand, increasing vehicle path curvature in multilane roundabouts can potentially be hazardous as it generates greater side friction between adjoining traffic streams. The potential for sideswipe crashes increases and vehicles become more likely to cut across lanes. These different effects, which depend on how many lanes a roundabout has, emphasize that every roundabout has an appropriate design speed for to help ensure safety.

In addition to managing the operating speed of a roundabout, an equally important design element is speed consistency for all movements through the roundabout. Achieving consistent speeds requires minimizing relative speeds between consecutive geometric elements and between conflicting streams of traffic. Speed consistency increases the safety of a roundabout by reducing the crash rate between conflicting traffic streams, making it easier for drivers to merge into conflicting traffic streams, and optimizing the entry capacity. NCHRP 672 recommends that the speed differentials between movements should not be greater than 10 to 15 mph (15 to 25 km/h). More information regarding speed consistency is in Section 6.7.1.3 of NCHRP 672.

5.2.5. Design Speed

Design speed is typically the theoretical speed that can be achieved if a vehicle takes the fastest path through the circular roadway of a roundabout. The fastest vehicle path is drawn as the smoothest and flattest path a single vehicle could navigate without traffic or adhering to lane markings. This is typically the through movement but can also be a right turn movement. It is important that the fastest path be calculated for all of the approaches and all of the movements of a roundabout. Figure 5-6 shows the five critical path radii for each approach.

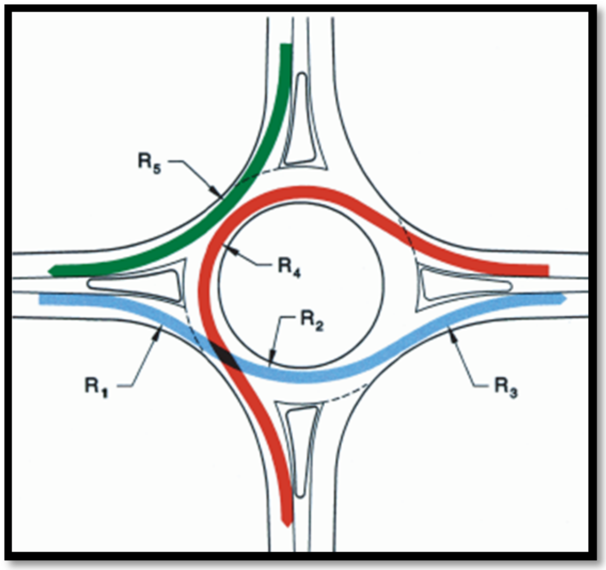


Figure 5-6: Vehicle path radii (Source: NCHRP 672)

More information regarding the fastest vehicle path is in Section 6.7.1 of NCHRP 672.

After establishing the fastest path, the radii illustrated in Figure 5-6 are measured and design speeds are back-calculated using AASHTO's standard horizontal curve guidelines.

The design speed is an upper bound on actual speed because vehicles will most likely be decelerating, yielding to other users, and trying to avoid encroaching on other lanes within the roundabout (in the case of multilane roundabouts). Figures 5-7 and 5-8 show the fastest vehicle path through single- and multi-lane roundabouts respectively, and Figure5-9 shows the fastest path for a right-turn movement.

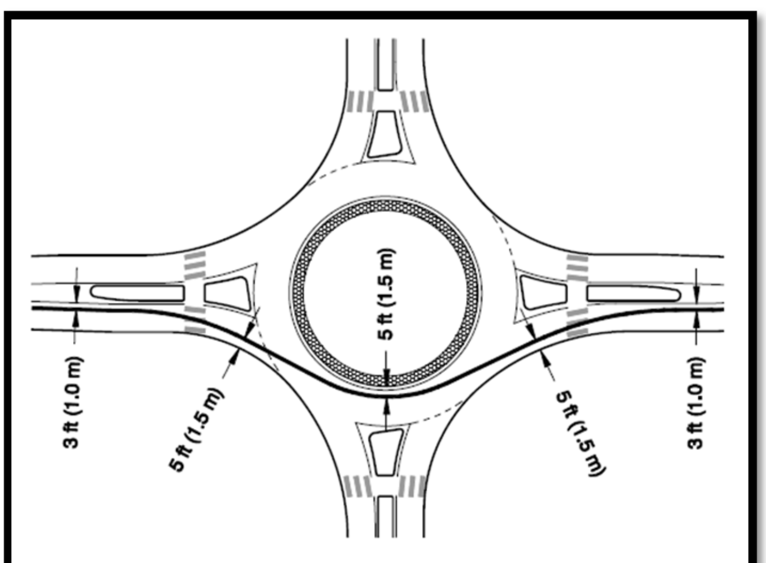


Figure 5-7: Fastest vehicle path through a single-lane roundabout (Source: NCHRP 672)

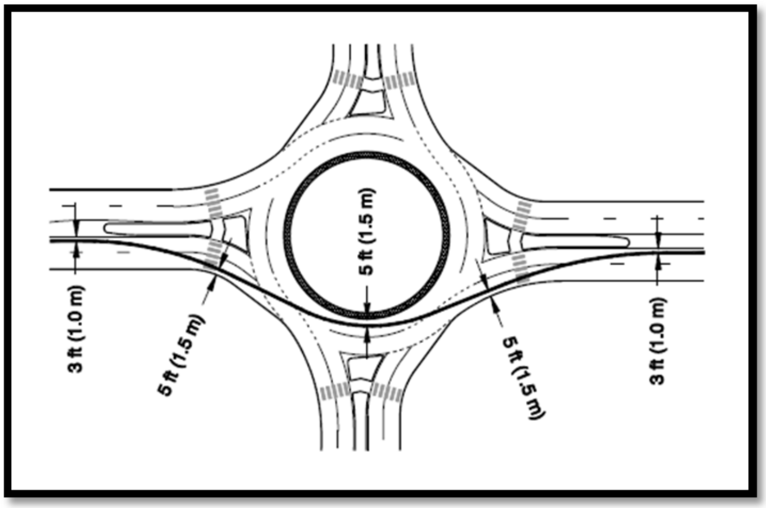


Figure 5-8: Fastest vehicle path through a multi-lane roundabout (Source: NCHRP 672)

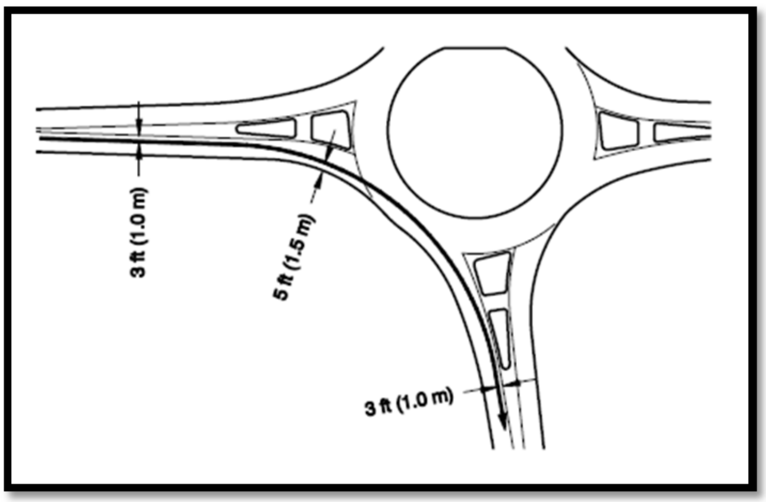


Figure 5-9: Example of critical right-turn movement (Source: NCHRP 672)

The fastest paths dictate other geometric features on a roundabout. Most often, the left-turning fastest path movement is the critical movement for determining circulatory roadway width while the right turn fastest path movement is the critical path when determining entry and exit width.

Roundabouts usually have a superelevation rate of ±0.02%. Roundabout superelevation is discussed in greater detail in the Section 4.8, “Vertical Alignment Considerations.” A graphical representation of the speed-radius relationships for given superelevation levels are shown in Figure 5-10.

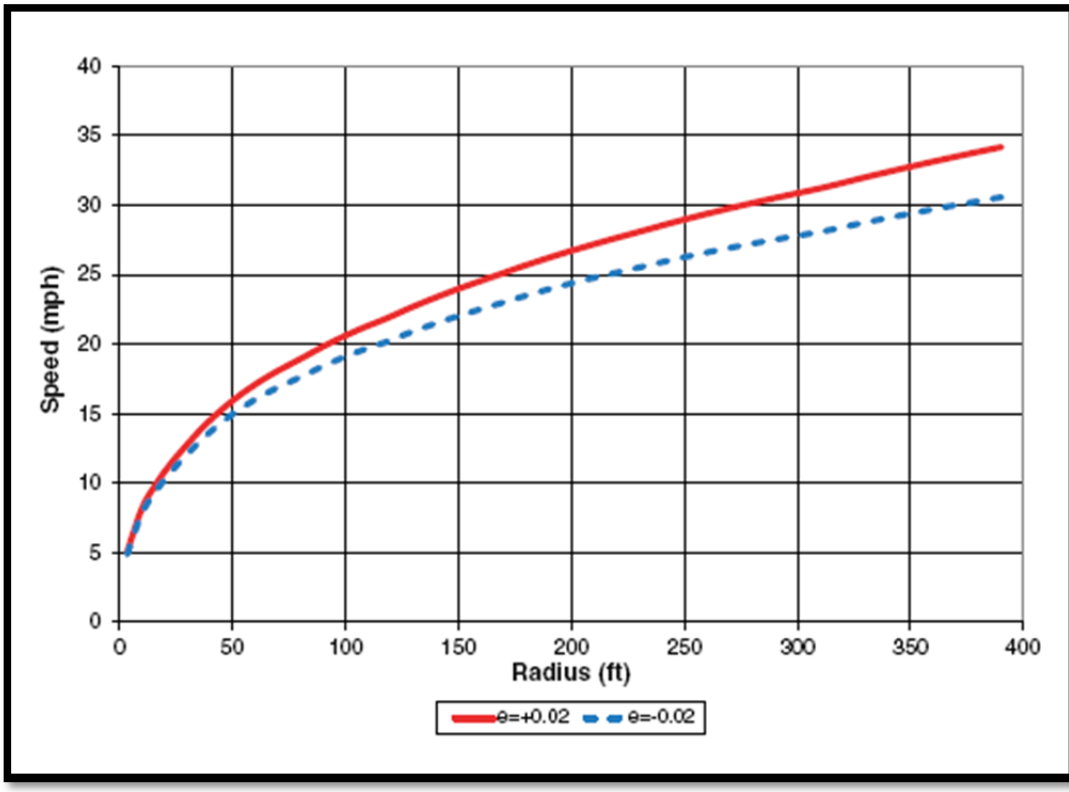


Figure 5-10: Speed-radius relationship profile (Source: NCHRP 672)

5.6. Sight Distance

5.2.6. Stopping Sight Distance

Considering the necessary stopping sight distance is important when designing a roundabout to ensure safe operation. At a minimum, adequate sight distance should be ensured for the approach and circulatory roadways and to the crosswalk upon exiting the roundabout (Figure 5-11).

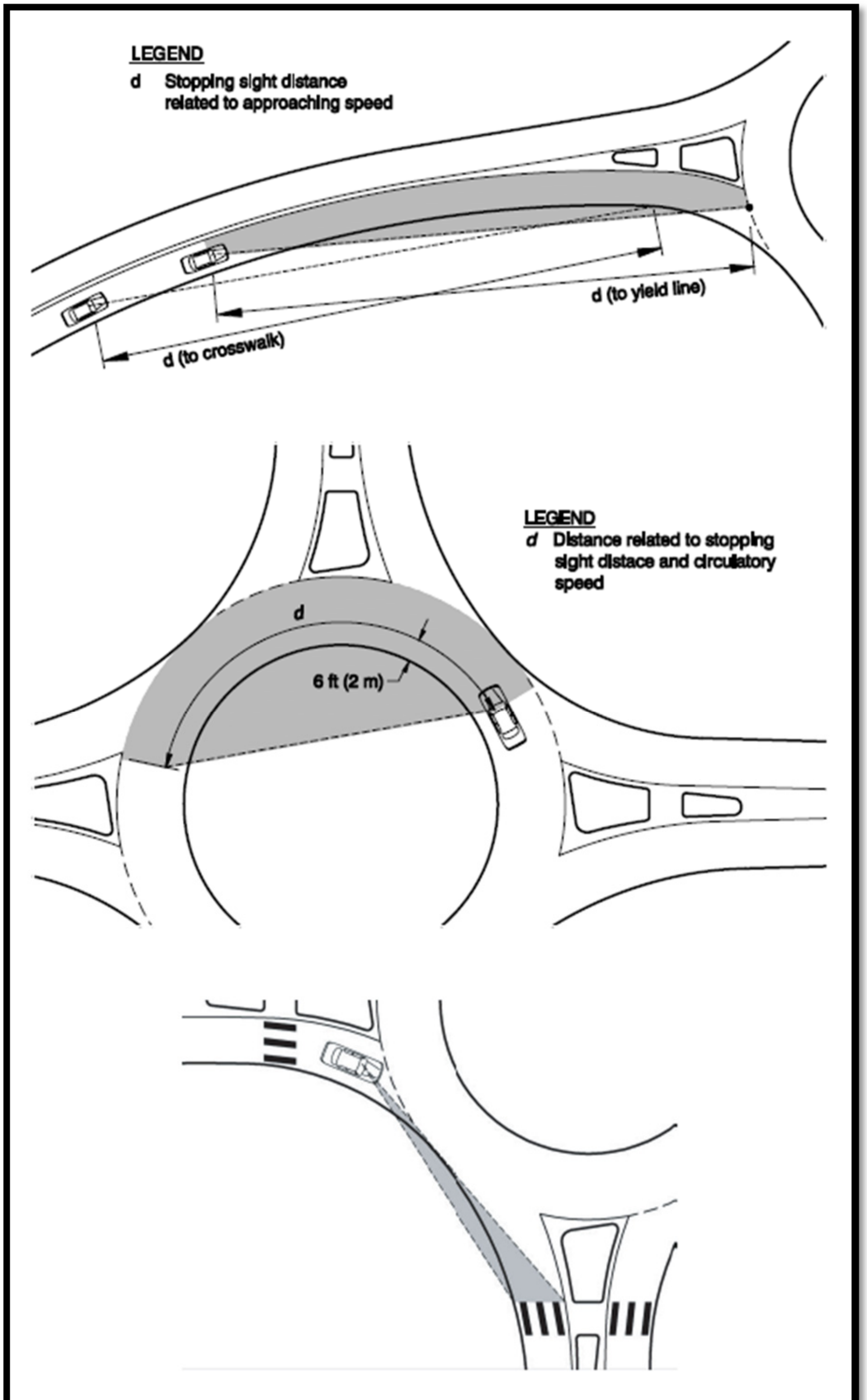


Figure 5-11: Stopping sight distance for three critical locations (Source: NCHRP 672)

NCHRP Report 400, *Determination of Stopping Sight Distances*, provides the information in Table 5-2. Sight distance is measured from a driver height of 3.5 ft (1.08 m) to an object height of 2 ft (0.6 m) as outlined in the AASHTO "Green Book." See section 6.7.3 of NCHRP 672 for more information on stopping sight distance.

Table 5-2: Recommended stop sight distances for various design speeds (Source: NCHRP 672)

Speed (km/h)	Computed Distance* (m)	Speed (mph)	Computed Distance* (ft)
10	8.1	10	46.4
20	18.5	15	77.0
30	31.2	20	112.3
40	46.2	25	152.7
50	63.4	30	197.8
60	83.0	35	247.8
70	104.9	40	302.7
80	129.0	45	362.5
90	155.5	50	427.2
100	184.2	55	496.7

*Assumes 2.5 s perception-breaking time, 3.4 m/s^2 (11.2 ft/s^2) driver deceleration

5.2.7. Intersection Sight Distance

In addition to stopping sight distance, care must be taken to ensure drivers at entries without right-of-way have adequate sight distance to recognize potential conflicts with circulating and other entering vehicles. Intersection sight distance is determined by a triangle made from the two vehicle paths leading to the potential conflict and a line connecting the two vehicles. For roundabouts, the vehicle paths are measured as the actual distance traveled along the vehicle's path. See Figure 5-12 for an example of how a sight triangle is constructed. The sight distances for circulating and other entering vehicles are considered when evaluating safety. The size and height of the center island is constrained by the sight triangles. Any decoration or landscaping on the center island must not obstruct the driver's view.

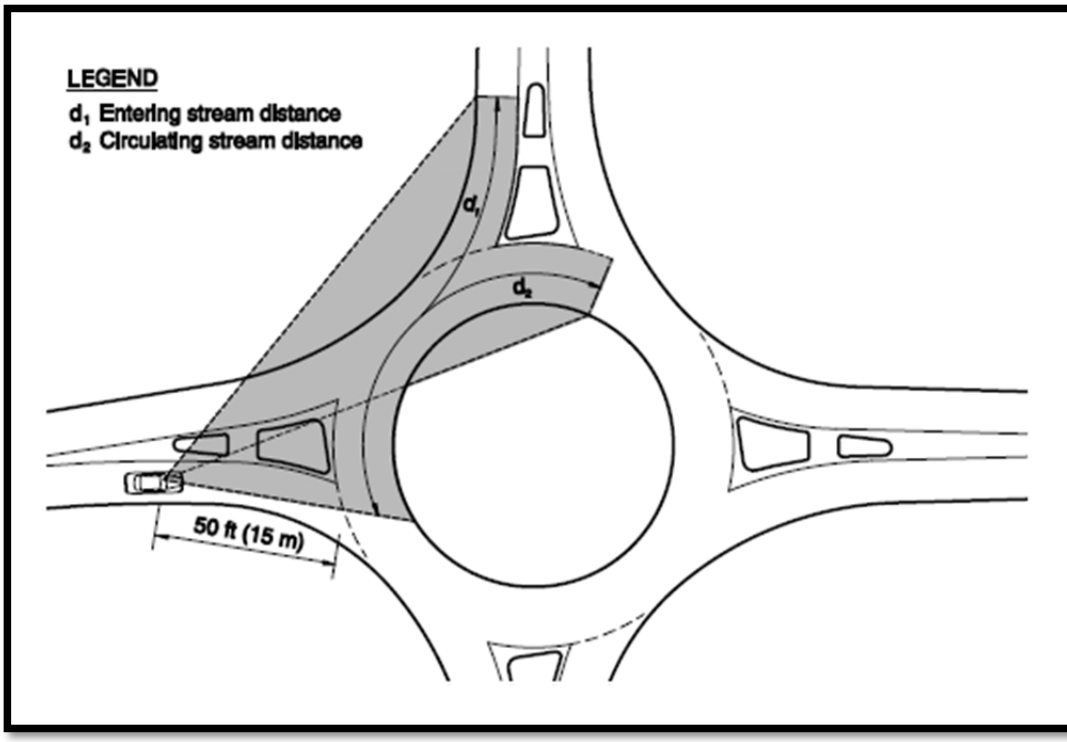


Figure 5-12: Intersection sight distance (Source: NCHRP 672)

For calculating intersection sight distance, the length of the approach leg should be limited to 50 ft or less. International experience shows that excessive length on the approach leg of the sight triangle is conducive to higher speeds and a higher frequency of crashes. Intersection sight distance is measured with an assumed driver height of 3.5 ft (1.08 m) and an assumed object height of 3.5 ft (1.08 m) as outlined in the AASHTO "Green Book."

Sight distance for the other conflicting traffic streams is checked independently and depends on the speed of entering and circulating traffic and the typical gap most drivers will accept. See NCHRP 672 Section 6.7.3.2 for more details on checking intersection sight distance.

5.7. Entry and Exit Design

5.2.8. Entry Curve

Entry curves on a roundabout approach leg are the curves along the right curb or pavement edge (see Figure 5-2). The entry curve is not the same as entry path curve, which is the fastest vehicular path through the entry geometry (i.e., R1 on Figure 5-6). Operationally, entry radius is important because it greatly affects the capacity and safety of a roundabout. Along with the entry width, circulatory roadway width, and the central island geometry, the entry radius dictates the deflection a vehicle faces upon entering the roundabout. The larger the entry radius, the faster vehicles will enter the circulatory roadway. Faster entry speeds can result in increased crashes between entering and circulating vehicles. However, certain operational benefits stem from larger entry radii, including increased capacity until the radius is larger than 65 ft (20 m). British research determined that capacity effects are minimal beyond this value. Avoid abrupt entry curb radii as they may lead to single-vehicle crashes.

The entry curve is curvilinearly tangential to the outside edge of the circulatory roadway. Furthermore, the inside (left) edge of the entry roadway's projection should be curvilinearly tangential to the central island (see Figure 5-13).

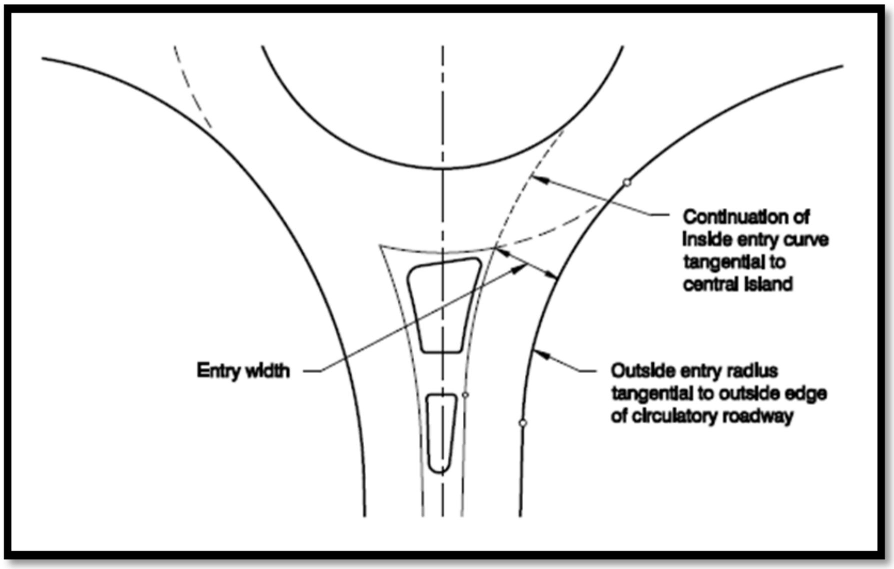


Figure 5-13: Single-lane roundabout entry design (Source: NCHRP 672)

As discussed in Section 5.5.1 "Design Speed," radii should be selected mainly to accomplish speed objectives. The design speed on the fastest vehicular path is dictated by the entry radius. A proper entry radius should result in an entry path radius (R1) equal to or less than the circulating path radius (R2).

Sections 6.4.5 and 6.5.4 of NCHRP 672 provide information on how to achieve appropriate entry curve dimensions for single and multi-lane roundabouts.

5.2.9. Exit Curve

Compared to entry curves, exit curves have a larger radius so the possibility of congestion at the exits is minimized and low exit speeds are maintained, creating safer conditions for pedestrians using crosswalks. The geometry of the exit curve should be such that the exit path radius (R3) is larger than the circulating path radius (R2). If this is not accomplished, vehicle speeds will be too high to navigate the exit geometry safely without an increased risk of colliding with the splitter island or oncoming traffic in the adjacent approach lane. The exit path radius (R3) should also be less than the circulating path radius (R2) so that vehicles will maintain low speeds at the downstream pedestrian crossing.

Similar to entry curves, exit curves are designed as curvilinearly tangential to the outside edge of the circulatory roadway. The inside edge of the exit roadway's projection should be curvilinearly tangential to the central island. Figure 5-14 illustrates these curves.

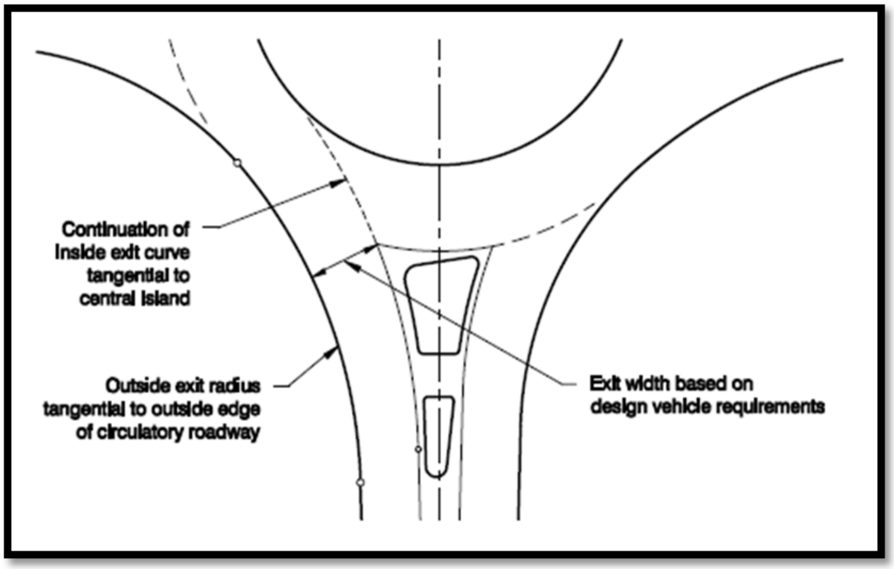


Figure 5-14: Single-lane roundabout curvilinear exit design (Source: NCHRP 672)

Sections 6.4.6 and 6.5.6 of NCHRP 672 provides information on how to achieve appropriate exit curve dimensions for single and multi-lane roundabouts.

5.8. Vertical Alignment Considerations

It is recommended that the circulatory roadway of a single-lane roundabout have a cross slope of 2% away from the central island (otherwise known as superelevation of -0.02%). This design practice improves safety by creating a central island that is raised and more visible, lowering circulating speeds, minimizing breaks in the cross slopes of the entrance and exit lanes, and draining surface water to the outside of the roundabout. The slope of a truck apron is recommended to be 1to 2%. Slopes above 2% increase the chances of loss-of-load incidents for large trucks. Additional information on truck aprons is in NCHRP 672 Section 6.8.7.4. Figure 5-15 illustrates a crowned section for a single-lane roundabout with a truck apron.

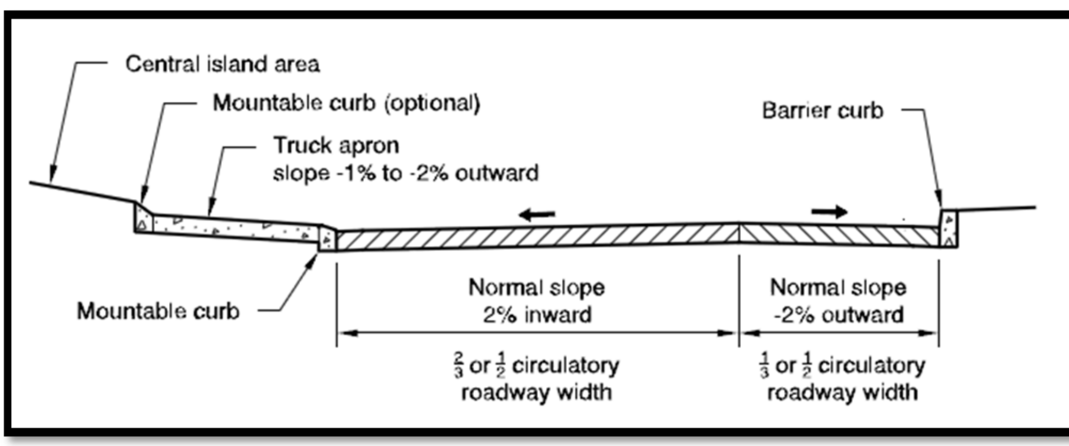


Figure 5-15: Crowned circulatory roadway section with truck apron (Source: FHWA Roundabouts Technical Summary)

A grade through an intersection greater than ±4% is not ideal for a roundabout. However, roundabouts have been installed at intersections with grades of 10% and higher. Steeper slopes make it difficult for drivers entering a roundabout to slow or stop. Additionally, sight distance can be compromised and semi-trailers face maneuvering issues. At entries and exits, steep grades are not recommended because they cause grade breaks and jeopardize safety upon entry and exit. Pavement warping or cross-slope transitions are usually implemented at entries and exits to provide an adequate cross-slope transition rate. The circulatory roadway cross slope should be adjusted along with the vertical grading to achieve the safest design.

The two most common methods for vertical design are outward sloping and crowned circulatory roadway. Outward sloping is used extensively for roundabouts in the United States. More information regarding these design methods is in NCHRP 672 in Section 6.8.7.3 and in Roundabout Technical Summary Section 6.5.

5.9. Splitter Island Design

Splitter islands, also referred to as separator islands or median islands, act as a refuge for pedestrians, help control vehicle speeds, guide vehicles as they enter the roundabout, physically separate entering and exiting vehicles, provide an area for sign placement, and discourage vehicles from using the roundabout incorrectly. It is important for all roundabouts to have splitter islands unless the diameter of the roundabout is small enough for the splitter island to obstruct drivers' view of the center island.

The area reserved for the splitter island is formed by exit and entry curves at a roundabout leg, as illustrated in Figure 5-16. Splitter island length is typically at least 50 ft (15 m) to provide approaching vehicles time to adjust to the geometry of the roundabout and to provided adequate protection for pedestrians. A splitter island length of 100 ft (30 m) is desirable. For roadways with higher speeds, splitter island lengths should be150 ft (45 m) or greater. The splitter island should go back past the end of the exit-curve so that vehicles cannot cross into oncoming traffic. The recommended minimum width of the splitter island is 6 ft (1.8 m) at the crosswalk to safely hold pedestrians and bicyclists waiting to cross.

Figure 5-16 illustrates the minimum dimensions for splitter islands at single-lane roundabouts and pedestrian crossing locations.

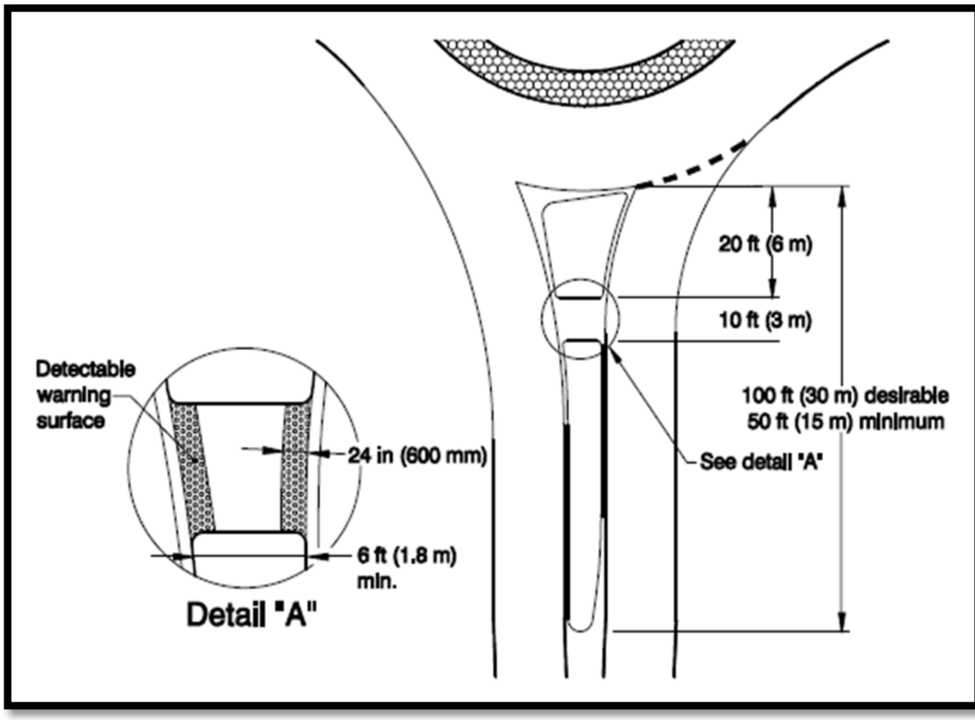


Figure 5-16: Minimum splitter island dimensions (Source: NCHRP 672)

Large splitter island widths can provide benefits such as greater separation between exiting and entering vehicles and increased time for drivers to differentiate exiting vehicles from circulating vehicles, thus decreasing confusion. Research has shown that maximizing splitter island widths can help minimize crashes between entering and circulating vehicles. NCHRP Report 672 does not specify a maximum splitter island width. A disadvantage of larger splitter islands is that they require a larger inscribed circle diameter. The designer must determine whether the safety benefits are worth higher construction costs and greater required land area.

The design of the splitter island should follow standard AASHTO guidelines. These guidelines include using larger nose radii on approach corners to maximize island visibility and offsetting curb lines on approaches to create a funneling effect, aiding in speed reduction as vehicles approach. Figure 5-17 illustrates these characteristics.

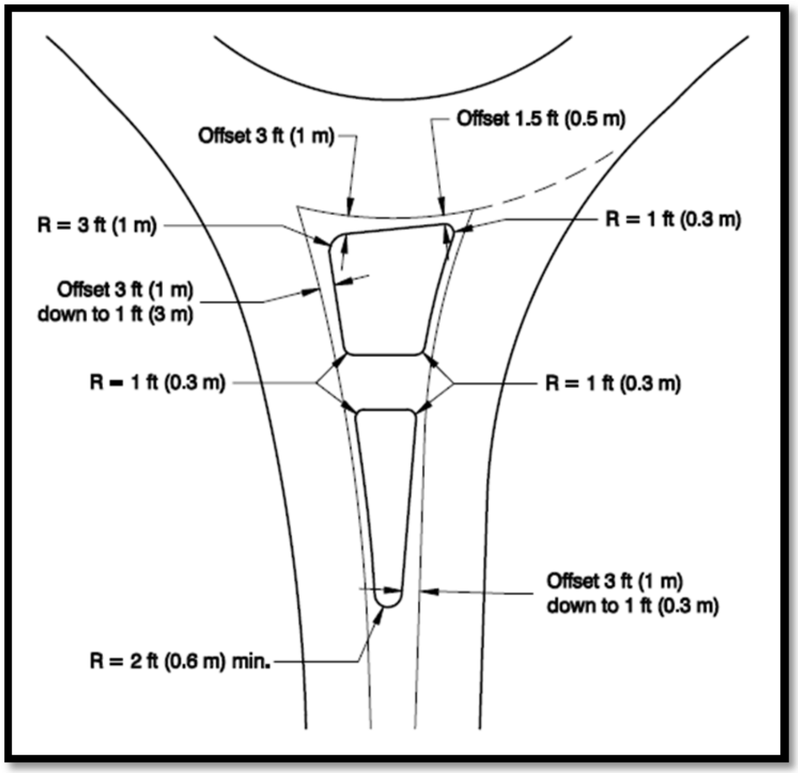


Figure 5-17: Minimum splitter island nose radii and offsets (Source: NCHRP 672)

5.10. Pedestrian and Bicyclist Considerations

5.2.10. Pedestrians Consideration

Designing pedestrian crossings at a roundabout requires the balancing of pedestrian convenience, safety, and efficient roundabout operation. Pedestrians want to cross as close to the intersection as possible. However, pedestrian crossing distance is minimized if the crosswalk is set back from the entry of the roundabout. For this reason, landscaping is important to create a buffer and encourage pedestrians to cross at the correct location. The landscape buffer also provides a clue to the visually impaired who might otherwise try to cross over to the center island. A recommended buffer of 5 ft (1.5 m) should separate the sidewalk from the circular roadway. Part of the splitter island and center island should also be landscaped to discourage pedestrians from crossing outside of the designated crosswalk and refuge area on the splitter island. The recommended buffers are low shrubs or grass, but if there is not enough room, then fencing or other barriers can be used.

The recommended width for a pedestrian sidewalk is 6 ft (1.8 m), with a minimum width of 5 ft (1.5 m).The sidewalk width should be larger at intersections with a high pedestrian volume. If bicyclists are able to access the sidewalk via a ramp, the recommended sidewalk width is at least 10 ft (3m),to accommodate shared use by pedestrians and bicyclists.

The splitter island at the crosswalk should be a minimum of 6 ft (1.8 m) wide to accommodate people with strollers or bicycles. The splitter island refuge area is designed at street level, eliminating the need for curb ramps. A detectable warning surface or tactile paving such as truncated domes, as recommended by the ADA guidelines, is installed at the edges of the refuge area as well as the curb ramps entering the crosswalk. NCHRP 672 recommends that the walkway is cut through the splitter island, making it easier for wheelchair users.

The crosswalk should be set back a minimum of 20 ft (6 m) from the circulatory roadway (distance should be measured in car lengths) so that exiting traffic will not queue into the circulatory roadway and pedestrians have the drivers' full attention (as opposed to the yield line where entering vehicles would be watching the roadway). For crossings with significant pedestrian traffic and multilane roundabouts, a greater setback from the roadway may be necessary to ensure the queue of vehicles wanting to exit and yielding to pedestrians does not back up into the circulatory roadway. However, this configuration may cause more pedestrians to cross at unsafe locations, as the greater walking distance is an inconvenience.

Pedestrian crosswalks can be aligned two ways. One way is to align each leg of the crosswalk so that it is perpendicular to the outside curb of the entrance and exit legs of the roundabout, which will create an angle point in the walkway across the splitter island. This option provides the shortest possible distance for pedestrians to come into conflict with vehicles. The second way to align the crosswalk is to place it perpendicular to the centerline of the approach roadway. Although this option provides pedestrians with a shorter overall walking distance, the crosswalk will be skewed and the curb ramp for mobility-impaired users will not be aligned parallel with the crosswalk. Figure 5-18 illustrates these two crosswalk alignment options.

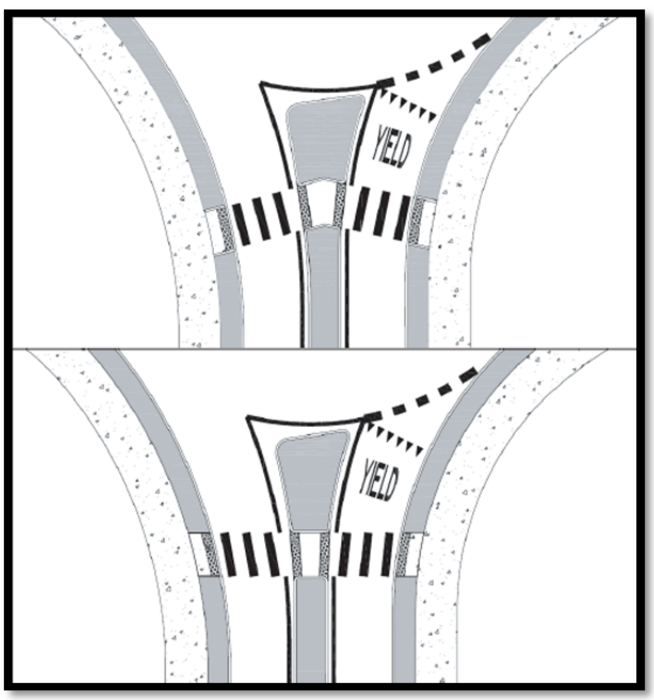


Figure 5-18: Crosswalk alignment options (Source: NCHRP 672)

The crosswalk area should be appropriately lit at night. Crosswalks can also be signalized. For more detail see Section 6.8.1.2 in NCHRP 672.

5.2.11. Bicyclist Considerations

Bicycle lanes are not striped through a roundabout. International experience has shown that doing so decreases bicyclist safety. Bicyclists sharing the full lane can operate as vehicles, especially in roundabouts with a slower design speed where the bicyclist can more easily match vehicular speed. Bicycle lanes approaching the roundabout should end 100 ft (30 m) before the yield line to allow time to merge with vehicles.

For bicyclists not comfortable operating in mixed traffic, ramps to the sidewalk can be provided, especially where higher vehicular speed and volumes exist. Ramps should be designed to prevent confusion with a crosswalk for pedestrians as well as visually impaired users of the roundabout. The sidewalk around the circular roadway should be designed as a shared use path with a recommended width of 10 ft to accommodate bicycles as well as pedestrians. For more detail see Section 6.8.2 in NCHRP 672.

6. Traffic Design

6.1. Pavement Markings

Pavement markings that indicate the entries, exits, and the circulatory roadway provide guidance to all roundabout users. Figure 6-1 illustrates typical markings, including pedestrian crossing markings, for single-lane and multilane roundabouts.

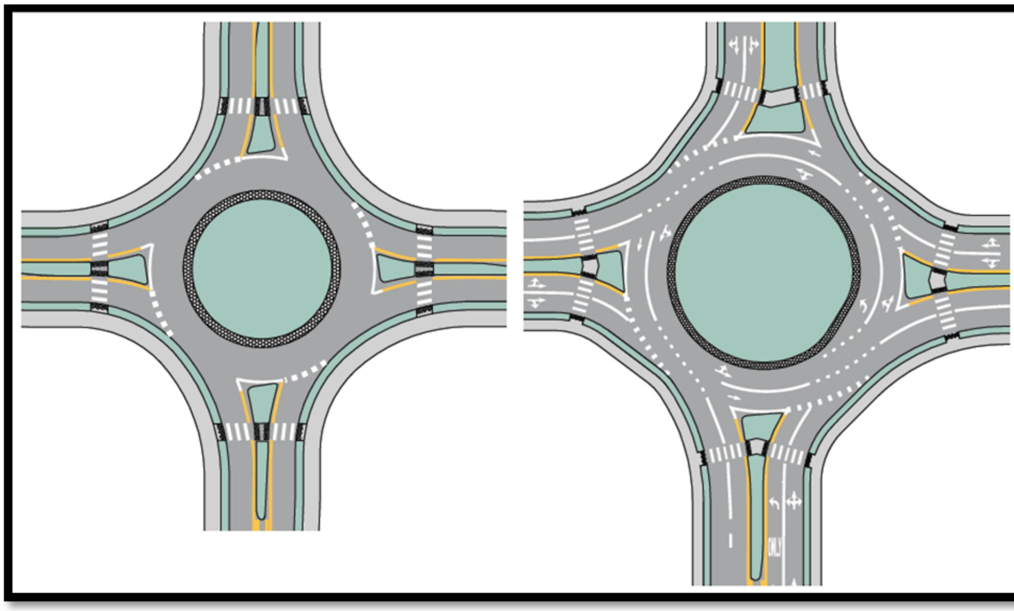


Figure 6-1: Pavement markings for single-lane and multilane roundabouts (Source: FHWA Roundabouts Technical Summary)

Pavement markings comprise series of solid and dashed white lines. Multilane roundabouts should have lane line markings in the circulatory roadway so vehicles can see the path they should be taking. These solid lines, along with lane-use arrows, can be used together to avoid incidence of vehicles changing lanes within the circulatory roadway. Other pavement marking configurations for single-lane and multilane roundabouts are in the Texas Manual on Uniform Traffic Control Devices (TMUTCD) and FHWA Roundabout Guidelines in Section 7.2. Lane-use arrows are used at roundabout approaches that have exclusive turn lanes and in multilane roundabouts for improved lane use. Figure 6-2 illustrates an example of these arrows.

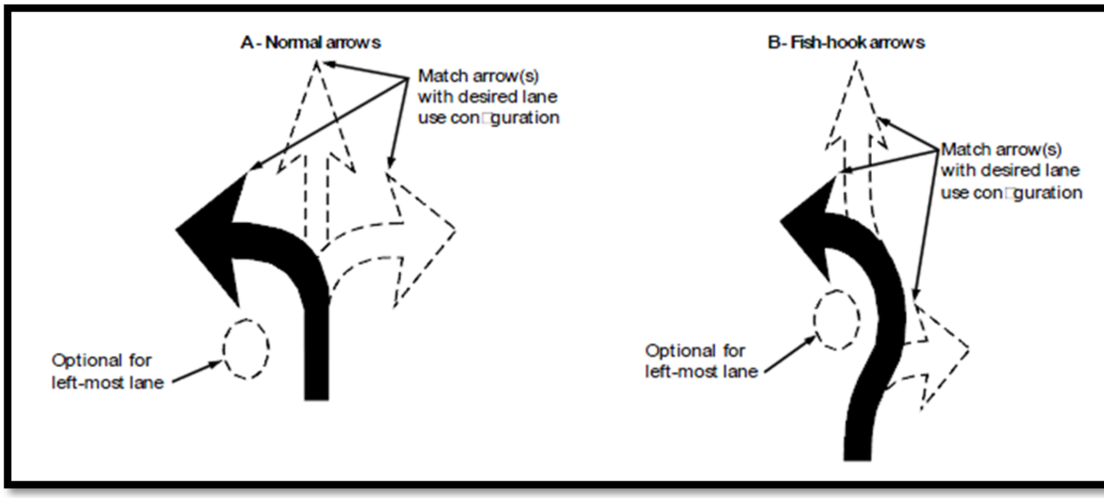


Figure 6-2: Lane-use arrows for roundabout approaches (Source: NCHRP 672)

6.2. Signage

Driver expectancy problems can be avoided with the use of regulatory, advance warning, and directional guidance signs. These signs must be placed where they are highly visible to users of the roundabout but do not create interference for pedestrians, motorcyclists, and bicyclists (Figure 6-3). Compared to conventional intersections, roundabouts have different signing needs depending on lane configuration and the context of surrounding land-use.

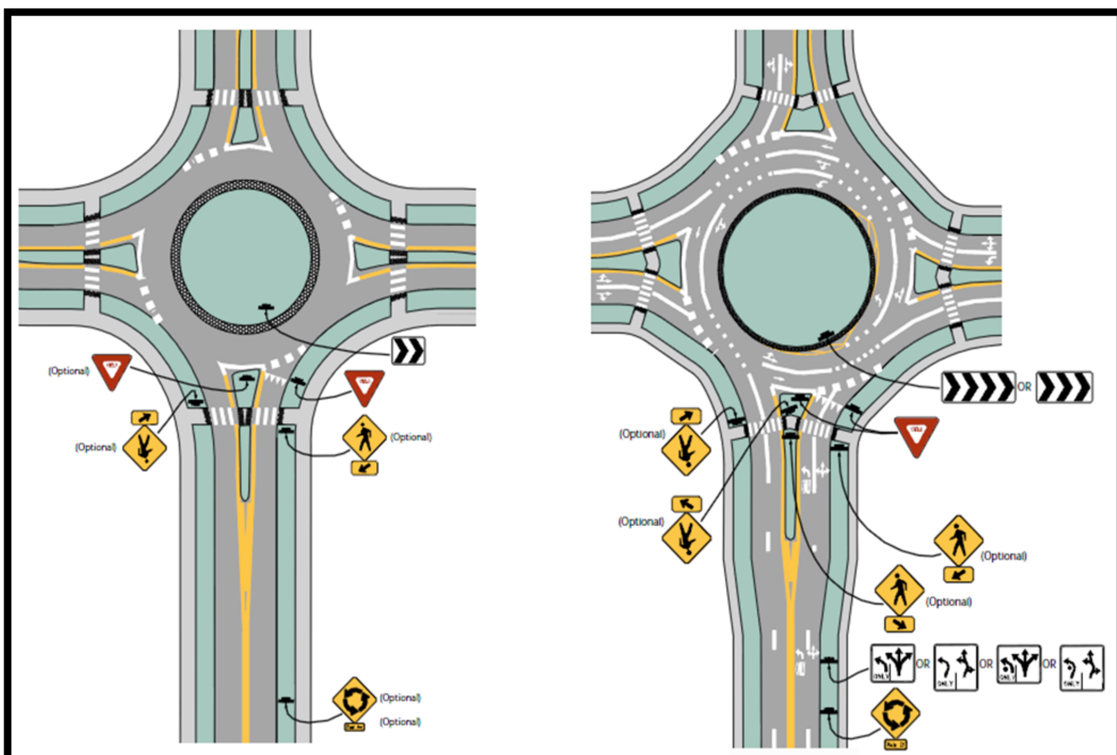


Figure 6-3: Regulatory and warning sign layouts for roundabouts (Source: FHWA Roundabouts Technical Summary)

Exit guide signs and advance guides signs are recommended at roundabouts. Exit guide signs should indicate the destinations of each departure leg. Although they are similar to conventional intersection signs, they differ in that they use diagonal upward point arrows as seen in Figure 6-4.

Figure 6-4: Advance diagrammatic guide signs (Source: NCHRP 672)

More information regarding signage and sign placement is in the TMUTCD and Section 7.1 of the FWHA Roundabout Guidelines.

7. Conclusions

Circular intersection forms have been part of the transportation system in the United States since at least 1905. Their widespread usage decreased after the mid-1950s due to high crash rates and problems with congestion. Therefore, the modern roundabout was developed to improve the safety and operations of the early circular intersection forms. Roundabout characteristics and design features include:

- Yield control on entering traffic to circulating traffic;
- Counterclockwise circulation of traffic around a central island; and
- Appropriate geometric curvature to induce slow and consistent speeds through the intersection.

Roundabouts are categorized according to size and number of lanes to facilitate discussion of specific performance or design issues. The categories include mini roundabouts, single-lane roundabouts, and multilane roundabouts.
Despite the fact that the U.S. had very few roundabouts at the time, a national set of guidelines was published in 2000. During the last ten years, data regarding U.S. roundabouts has become sufficient to enable roundabout research specific to the U.S. and a series of subsequent guidelines for analyzing, designing, and implementing roundabouts have been disseminated.

Although roundabouts have now been implemented in many parts of the U.S., very few have been built in Texas. Therefore this research effort was designed to develop guidelines for implementing them in Texas. The desired guidelines were to suggest best practices for choosing appropriate locations and design concepts for Texas roundabouts.

This research effort is comprised of the following components: synthesis, methodological development, validation and enhancement, implementation support, and knowledge transfer. Synthesis involved conducting a thorough and systematic review of previous guidance documents, current practices, and recent research findings to form a foundation for roundabout safety and operations methodologies and geometric design principles. The methodological development component involved developing an initial set of methodologies and guidance for assessing roundabout safety, evaluating roundabout operations, and designing roundabouts that build on existing guidance. In the validation and enhancement stage, researchers applied microsimulation techniques to validate and, as necessary, refine the initial methodologies to reasonably reflect conditions specific to Texas. The research done to this point was then implemented via a spreadsheet tool that provided a consistent means to strategically identify and evaluate candidate roundabout locations, and compare the roundabout with other intersection alternatives. The main knowledge transfer component of this project was a pilot workshop that was held for TxDOT planners and engineers.

The documents most heavily used in this research effort were the National Cooperative Highway Research Program Report (NCHRP) 672 Roundabouts: An Information Guide Second Edition and NCHRP Report 572: Roundabouts in the United States. Published in late 2010, NCHRP 672 covers many critical pieces of information including operations analysis, safety, geometric design, traffic design, and system considerations. This document updates the information found in the Federal Highway Administration's Roundabouts: An Informational Guide published in 2000. This first edition of the national guidelines is the document most state guidelines rely heavily on for their information. Published in 2007, NCHRP 572 provided updated, U.S. specific information regarding safety and operations.

Data was collected at several Texas roundabouts for use in the validation and enhancement phase of this research. Information regarding speed, traffic volumes, turning movements, geometric design, and crash statistics were recorded on and off-site. This information was used to simulate two roundabouts in VISSIM: one in Southlake, TX and one in San Antonio, TX. Entry lane capacity results from VISSIM, SIDRA, and the Highway Capacity Manual were compared. The effects of exiting vehicles, distribution of the origin of traffic, and mean speed were examined.

The elements of geometric design, safety, traffic operations, and traffic design were combined into a uniform planning process through a spreadsheet evaluation tool. The process allows the user to consistently and strategically identify and evaluate candidate roundabout locations. The result is a consistent and systematic screening procedure for determining the potential success of a roundabout in existing and planned intersections. For a detailed discussion of each element of the planning process, the reader is referred to The Texas Roundabout Guide, which was produced in this same project. The spreadsheet evaluation tool also compares the performance of a roundabout with traditional intersection forms. This will allow TxDOT to identify intersections where roundabouts provide superior service to motorized and non-motorized modes. The spreadsheet is based on methods outlined in NCHRP Report 672: Roundabouts: An Informational Guide Second Edition.

The research conducted for this project indicates roundabouts can be appropriately implemented in Texas. The effectiveness of roundabouts from both safety and operational viewpoints are dependent upon a number of very important design concepts. If designers fully understand and use these concepts the resulting intersections will become excellent examples upon which future designs can grow. Since Texas currently has very little experience with modern roundabout concepts and many false examples exist in other states, the best implementation path would include initial implementation at non-urban, lower traffic volume locations. Such locations would be less sensitive to problematic site specific compromises and would provide an opportunity to grow Texas operational experience before attempting implementation at locations with significant right-of-way restrictions or high traffic demands.

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